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Soil organic matter content and composition as influenced by soil management in a semi-arid Mediterranean agro-silvo-pastoral system

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ABSTRACT

The aim of this study was to assess the impact of different long term soil managements on soil organic matter (SOM) quantity and quality in a semi-arid Mediterranean dehesa-like agro-forestry system (North-East of Sardinia, Italy). Seven soil managements were compared: cork oak forest, pasture under oak trees, open pasture, hay crop under oak trees, open hay crop, grass-covered vineyard and tilled vineyard. Analyses include chemical and spectroscopic (FT-IR) characterization of the humic substances (fulvic acids, humic acids and humin) of the A horizons. Lower amounts of total organic C and humic substances were found in the more disturbed soils such as those of the tilled vineyard, while the other soil managements showed a rather similar pattern for many indices of SOM quality (e.g., HA-C/FA-C, fulvic H/C and humic and fulvic C/N ratios) and for spectroscopic characteristics. These results indicated that the impact of soil management on the humic composition was relatively low for these sub-acid (pH ranging from 5.1 to 6.4) sandy soils under Mediterranean type of climate. The relatively small differences between the forest and the grassland land uses also suggested that the periodical light tillage applied to the grassland did not strongly affect SOM accumulation in the topsoil of this land use. In the oak forest soils, a sharp decrease (−77%) of the organic C from the thin A1 to the A2 horizon was observed, which could constrain the resilience of these soils towards disturbance factors, while the grasslands soils, where the organic C sequestration occurred in a thick horizon, may be more resilient.

The compared soil managements revealed to be quite conservative, demonstrating that the traditional agro-silvo-pastoral management practices are effective in maintaining relatively good soil quality traits under semi-arid Mediterranean conditions.

1. Introduction

Agro-forestry systems, where trees and/or shrubs are deliberately combined with crops and/or livestock, have received increasing recognition in the last decades for their production and sustainability attributes and, hence, for their social, economic and environmental benefits (Nair et al., 2011). Agro-forestry systems are worldwide recognized to have a high potential to sequester C as they are more capable to capture and utilize resources than single-species cropping or grassland systems (Nair et al., 2011). The total area occupied in the world by agro-forestry systems covers over 1000 Mha (Nair et al., 2009), under diverse ecological conditions. This estimate does not include areas that could potentially be brought under agro-forestry, such as the vast areas of degraded woodlands and unproductive croplands and grasslands that are experiencing worldwide relevant management changes leading to woody encroachment (D'Odorico et al., 2012). These processes are particularly important for semi-arid pastoral and savanoid ecosystems where woody encroachment influences the biogeochemical cycling of SOC and nutrients in sometimes unpredictable ways (Creamer et al., 2011, and references therein).

Among the very diverse soil uses within the agro-forestry systems, which include alley croppings, silvo-pastures, shaded perennial crops, windbreaks, homegardens, etc., vineyards are experiencing an increasing trend in many regions of the world (OIV, 2012) and, in particular, the grass-covered vineyards are potentially considered important C sinks also under semi-arid conditions (Marques et al., 2010). However, tillage is still the most applied management practices in vineyards, particularly under semi-arid and arid conditions. Therefore, demonstrating potential benefits

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of cover cropping on soil C pools in vineyards can have potential for practical impact and adoption of conservative practices (Steenwerth and Belina, 2008).

Several studies have been carried out to relate SOM quality and sequestration to the management practices in agro-forestry systems, but the majority of these researches is referred to subtropical and tropical environments (Nair et al., 2011, and references therein). In contrast, only few studies were conducted in agro-forestry systems under semi-arid Mediterranean conditions such as the dehesa silvo-pastoral systems (Howlett et al., 2011; Moreno et al., 2007). The dehesa is the most widely extended European agro-forestry system (Simón et al., 2012), as it covers 3.5–4.0 Mha in Spain and Portugal (Eichhorn et al., 2006) and is a common landform in other Mediterranean countries such as Morocco, Algeria, Italy and Greece (Castro, 2009; Papanastasis et al., 2009). This agro-forestry system is characterized by scattered oak trees [mainly holm oak (*Quercus ilex* L.) and cork oak (*Quercus suber* L.)] mixed with grasslands or intercropped with cereal and/or fodder crops, usually in a rotation scheme. In the dehesa, a range of livestock, agricultural and forestry activities is practiced since the Middle Ages: livestock grazing is often integrated with cultivation of winter cereal and forage, vine growing, firewood and cork productions (Gómez-Gutiérrez and Pérez-Fernández, 1996). The dehesa has been recently studied to evaluate the impact of different soil managements on soil nutrient content and distribution (Moreno et al., 2007). In the dehesa systems, the presence of trees, although with a low density, has been recognize to positively affect soil physical and chemical properties (Joffre and Rambal, 1988; Gallardo, 2003; Moreno et al., 2007). Further, Howlett et al. (2011) highlighted the relevant role in increasing SOM storage of cork oak trees within the pastures with respect to the soils under native pasture alone. The potential soil C sequestration of the agro-silvo-pastoral ecosystems has been widely assessed (Garrity et al., 2006) since their high amount of organic C stored in the aboveground biomass compared to a forest (FAO, 2004). However, the high sensitivity to climate change of the geographical areas where dehesa systems are common (IPCC, 2007) could modify the capacity of these agricultural systems to sequestrate SOM. Other than climate change, both trends of land use abandonment and intensification that have been identified in the last decades in the dehesa systems (e.g. Caballero et al., 2009) could affect SOM balance in relation to specific management practices. The knowledge about the influence of different soil managements such as grazing, tillage, crop cultivation, etc., on the distribution and characteristics of the SOM pools in the dehesa systems is still insufficient to develop conservation strategies. In this sense, several authors highlighted the relevance of analysing SOM pools (Amelung and Zech, 1999; Kaiser and Ellerbrock, 2005; Piccolo, 1997) so to improve comprehension of the bio-chemical processes that control SOM stabilization and mineralization and, hence, of the impact of land use and management on SOM dynamics (Aranda et al., 2011). Among the different SOM pools, humic substances are considered stable and slowly mineralizable, and have been widely studied in relation to the different factors influencing organic matter sequestration and stabilization processes (Aranda et al., 2011; Pardo et al., 2012; Song et al., 2008; Tatzber et al., 2008). Further, humic substances were proved to be sensitive chemical proxies to reveal the impact of anthropic perturbations in Mediterranean soils (Tinoco et al., 2010).

The aim of this study was to evaluate the impact of different soil managements on SOM quantity and quality in a semi-arid Mediterranean dehesa-like agro-forestry system by analysing the humic substances (fulvic acids, humic acids and humin) of the superficial soil horizons. Our hypothesis was that the SOM quantity and quality in the topsoil are function of the soil management practices, and we tested if long term soil managements have changed the most stabilized SOM pools or not.

2. Materials and methods

2.1. Site characteristics

The study area has a size of 1454 ha and is located in the municipalities of Berchidda and Monti (40°46′ N, 9°10′ E) in the North-East of Sardinia (Italy), in a gentle slope hilly catchment at 275–320 m above sea level. The area is representative of the climate, vegetation type and management of some of the most common agro-forestry systems in the Mediterranean basin (Bagella et al., 2013). The vegetation landscape is characterized by cork oak (*Q. suber* L.) and at a lesser extent by holm oak (*Q. ilex* L.), wooded pastures, and vineyards. The bioclimate is pluviseasonal oceanic low meso-Mediterranean low sub-humid (Rivas-Martínez and Rivas y Sáenz, 2007), with a mean annual precipitation of 630 mm (70% from October to March) and a mean annual air temperature of 14.2 °C. The soil of the area developed from a granite, a parent material largely diffused in Sardinia (Aru et al., 1990), and was classified as Typic Dystroxerept (Soil Survey Staff, 2010). The potential vegetation of the area would be a *Q. suber* forest (Bagella and Caria, 2011).

In this area, a number of fields were identified and characterized for land use and soil managements in 2007 (Lagomarsino et al., 2011), in order to set up a long term observatory to assess the impact of management practices on soil traits and biodiversity.

2.2. Soil managements

The changes of the land use in the study area occurred during the past five decades, and were assessed through aerial photos[1] and farmers interviews. We hypothesized that, in origin, the soils of the area had a similar SOM content and composition and that the changes of the use during the past five decades were able to affect SOM content and composition in the topsoil, making these soils suitable to discriminate the net impact of anthropic management on their traits. In the study area three soil uses were selected: cork oak forest, grassland and vineyard. The choice of these soil uses was based on their diffusion in the region and in many other regions in the world under semi-arid and arid conditions, and on their long term adoption (at least twenty years). Within the chosen soil uses, we established seven plots corresponding to the following soil managements: cork oak forest, four types of grassland management (pasture under oak trees, open pasture, hay crop under oak trees, open hay crop), grass-covered vineyard and tilled vineyard. The selected plots were at a similar elevation (301 ± 14 m), slope (9 ± 4%) and exposure (130 ± 72° North). Plots size ranged from 1 to 15 ha and the maximum distance between them was about 1.5 km.

The cork oak forest (OAK) was established at the beginning of the past century and represented the soil use with the lowest anthropic pressure. The forest was comprised of uneven aged trees with an average density of more than 200 trees ha^{-1}. The grass under the forest has been and is still occasionally grazed by beef cattle. The cork harvest occurs manually every 10–11 years.

At least for the last two decades, the grassland has been managed according to a flexible rotational scheme consisting of a fallow pasture which is cropped every two to five years, depending on the dynamics of the thorny vegetation, with an annual hay crop mixture [two–four components including oats (*Avena* spp.), Italian ryegrass (*Lolium multiflorum* Lam.) and annual clovers such as crimson clover (*Trifolium incarnatum* L.), subclover (*T. subterraneum* L.) and balansae clover (*T. michelianum* Savi var. *balansae* Boiss.)]. Because of this, pasture and hay crops represent two phases of the same soil

[1] http://webgis.regione.sardegna.it/fotoaeree/ (consulted on 30 June 2012).

use (grassland) but, because of the expected impact of seed bed establishment practices on the topsoil, they were considered (and sampled) separately. At the time of soil sampling (February 2007), the fallow pasture was five years old and the hay crop had been sown four months before.

During the pasture phase, the vegetation cover is composed by annual self reseeding forage species such as annual clovers, annual medics (*Medicago* spp.) and oats, as well as by *Bromus* spp., *Vulpia* spp., *Lolium* spp. and thorny weeds (e.g. *Galactites tomentosa* Moench, *Carlina corymbosa* L., *Carduus pycnocephalus* L.). The hay crop is established following 25 cm deep disc ploughing and harrowing and a fertilization with about 50 kg ha^{-1} of N and 90 kg ha^{-1} of P_2O_5. Crop yields range from 3 to 5 Mg ha^{-1} of hay in a spring single cut. The pasture growth season starts at the rainfall season break (between the end of August and mid November with year-to-year variations) and lasts till the end of May, with minimum growth rates during winter because of temperature constraints and during summer because of drought. The pasture and the hay crop are grazed with a stocking rate ranging from 3 to 6 dairy ewes ha^{-1}, respectively. During the pasture phase, grazing occurs during the whole year, while grazing of the hay crop is suspended from the beginning of March to mid May to allow hay making. Both the grassland phases included spotted cork oak trees (between 15 and 35 trees ha^{-1}). Because of this, for both the pasture and the hay crop, two conditions were considered: open areas (OPA = open pasture; OHA = open hay crop) and the areas underneath the crown of the oak trees (UPA = under oak trees pasture; UHA = under oak trees hay crop). At the time of soil sampling, OPA was mainly composed of annual grasses (e.g. *Avena* spp., *Vulpia* spp.) and leguminous species (e.g. *T. michelianum* Savi var. *balansae* Boiss., *T. subterraneum* L.), while OHA was composed by a mixture of oats and Italian ryegrass.

The two vineyards were established in the early 1990s using the cv. Vermentino after decades of grassland-hay crop rotations. The plantation was preceded by a deep (60–80 cm) inversion tillage followed by harrowing. The inter-row of the grass-covered vineyard (GCV) was composed of native species and supplementary drip irrigation is provided along the rows by distributing up to 100 mm in June and July to partially restore crop evapotranspiration. The grass cover is chopped in spring once or twice per year, depending on the seasonal rainfall, and grass residues are left on the ground. Herbicides are sprayed on a 50 cm band across the row. Pruning residues at the end of January and in June–July are chopped and left on the ground. The inter-row is usually grazed in winter and early spring prior to the vine sprouting. Fertilizers are applied yearly at a rate of about 40 kg ha^{-1} of N, 25 kg ha^{-1} of P_2O_5 and 40 kg ha^{-1} of K_2O. Amendment with Thomas slag and lime was applied some ten years earlier than the soil sampling in order to provide P, Ca^{2+} and Mg^{2+} and buffer soil pH. The annual grapes yield is about 8–9 Mg ha^{-1}. In the tilled vineyard (TLV), the soil is ploughed down to 30 cm in March and harrowed in May. No irrigation is provided. The winter vegetation is occasionally grazed by sheep soon before ploughing. At the end of January organic and mineral fertilizers are distributed to provide about 50 kg ha^{-1} of N and 25 kg ha^{-1} of P_2O_5. The pruning residues are exported out of the field in February and June–July. The annual grapes yield is about 7–8 Mg ha^{-1}.

2.3. Soil sampling and sample preparation

Four soil profiles for OAK and TLV, three profiles for UHA and GCV and two profiles for UPA, OPA and OHA were opened. The profiles were dug down to about 1 m of depth and sampled according to the horizons. In the vineyards, the soil profiles were opened in the middle of the inter-row. The soil samples were oven-dried at 40 °C and sieved at 2 mm to remove skeleton, large roots and organic debris. All the analyses were run on the < 2 mm soil fraction, the fine earth. As the superficial horizons (A and Ap) are the most susceptible to the accumulation or loss of SOM, we focused attention on the SOM fractions of these horizons.

To determine the bulk density of the fine earth, soil cylinders of 493 cm^3 (height: 10.8 cm; diameter: 7.7 cm) were used to collect two cores from the face of each A horizon.

2.4. General soils characterization

The samples collected to determine bulk density were air-dried and then heated at 105 °C till they reached constant weight. The bulk density was obtained from the ratio between the dried mass and the volume of the cylinder. The skeletal particles were removed and their dried mass and volume subtracted from the total dried mass and volume of the sample.

The particle-size distribution was determined by the pipette method (Day, 1965) after treating a soil aliquot with 3 M H_2O_2 solution to destroy organic cements. The sand fraction was subdivided into coarse, medium and fine sand by wet sieving at 500, 250 and 20 μm, respectively. The silt was separated from the clay by sedimentation after the samples were dispersed in a 0.08 M sodium hexametaphosphate solution. The pH was measured potentiometrically in the supernatant of a suspension with 1:2.5 soil:liquid ratio, using both distilled water and 1 M KCl solution. The organic C content (OC) was determined by the Walkley–Black procedure without application of heat. Soil total N (TN) was measured by the Kjeldahl method. The C stocked (Mg ha^{-1}) by each A horizon was calculated as the product of its C concentration (g kg^{-1}), bulk density (kg dm^{-3}) and thickness (dm).

2.5. Extraction, fractionation and purification of humic and fulvic acids

The extraction of the humic substances was obtained following the procedure of Stevenson (1994). Briefly, a soil aliquot of 20 g was suspended in a NaOH 1 M and $Na_4P_2O_7$ 0.1 M solution with a soil:liquid ratio of 1:5 (w:v) and shaken for 12 h. The suspension was then centrifuged for 15 min at 15,300 × *g* and the supernatant collected. This extraction was repeated four times and the supernatants joined together. Then, the soil aliquot was washed two times with distilled water (1:5 w:v) and the supernatant obtained after centrifugation for 15 min at 15,300 × *g* was joined to the alkali extracts. The extraction residue, containing the humin fraction, was then oven-dried at 40 °C and weighted. The fractionation of the extracted organic matter into humic acids (HA) and fulvic acids (FA) and the successive purifications were achieved according to the IHSS procedure (Swift, 1996). The purified HA and FA were freeze-dried to submit them to chemical and spectroscopic analyses.

2.6. Chemical and spectroscopic analyses

A Carlo Erba CHNS-O EA1110 elemental analyser was used to determine C, N and H in HA and FA, and C and N in the extraction residue (and attributed to humin). Each sample of HA, FA and extraction residue was analyzed in duplicate.

The FT-IR spectra were recorded on a Perkin Elmer Spectrum GX 1 spectrophotometer; the pellets were prepared by pressing under vacuum 1 mg of HA, FA and residue with 400 mg of KBr. Spectra were acquired at 4 cm^{-1} resolution and 64 scans were averaged. The FT-IR bands were interpreted according to Agnelli et al. (2000).

2.7. Statistical analysis

Analysis of variance was carried out for all variables according to an unbalanced completely randomized design with the soil

Table 1
Means and results of the analysis of variance for the physical characteristics of the A and Ap horizons from the soil managements compared. For symbols and abbreviations see the legend.

Soil management	Horizon thickness (cm)	Bulk density (kg dm^{-3})	Coarse sand (2000–500 μm) (g kg^{-1})	Medium sand (500–250 μm) (g kg^{-1})	Fine sand (250–20 μm) (g kg^{-1})	Silt (20–2 μm) (g kg^{-1})	Clay (<2 μm) (g kg^{-1})
OAK–A1	4 ± 0	0.70 b	208 a	78 a	450 ab	134 ab	130 a
OAK–A2	20 ± 5	1.49 a	230 a	108 a	429 b	120 a	113 a
UPA–A	20 ± 5	1.30 a	238 a	123 a	360 b	141 ab	137 a
OPA–Ap	35 ± 0	1.34 a	222 a	122 a	396 b	129 ab	131 a
UHA–A	25 ± 5	1.35 a	204 a	97 a	431 b	137 a	131 a
OHA–Ap	42 ± 2	1.27 a	228 a	116 a	391 b	135 ab	130 a
GCV–Ap	22 ± 6	1.35 a	230 a	92.5 a	479 ab	93 bc	105 a
TLV–Ap	20 ± 2	1.22 a	191 a	96 a	542 a	49 c	122 a

Source of variation	d.f.	*P*-value	*P*-value	*P*-value	*P*-value	*P*-value	*P*-value
Soil management	7	0.011	0.511	0.904	0.046	0.014	0.162
Error	16						
CV (%)		12	13	36	13	24	9

Mean values with different letters significantly differ for $P \leq 0.05$.
OAK = cork oak forest; UPA = under oak tree pasture; OPA = open pasture; UHA = under oak tree hay crop; OHA = open hay crop; GCV = grass-covered vineyard; TLV = tilled vineyard.
d.f. = degrees of freedom.

managements representing treatments. Data expressed as concentration were log10 transformed to normalize their distributions before analysis. Means were separated according to the least significant difference using Fisher's protected test (Gomez and Gomez, 1984) at $\alpha = 0.05$.

Relationships between the measured variables were assessed using Pearson's correlation coefficients.

Statistical analyses were accomplished using the SAS software (SAS Institute, 1999).

3. Results

3.1. General soil characteristics

The contrasted soil managements produced different thickness of the A horizons with the highest values in the OPA and OHA (Table 1). In the OAK, the thickness of the A1 horizon was the lowest, although the summation thickness of A1 and A2 was similar to that of the Ap of UPA and UHA. The A1 horizon of OAK had the lowest bulk density, while the other soil managements did not show significant differences for bulk density, ranging from 1.22 g cm^{-3} in TLV to 1.49 g cm^{-3} in the A2 horizon of OAK (Table 1).

Particle-size analyses showed no significant difference among soil managements for the coarse and medium sand and for the clay contents (Table 1). The TLV soil showed a significantly higher fine sand content and lower silt content than the other soils, apart from the GCV. Despite these differences, the soil textures were all from sandy loam to loamy sandy.

The soil $pH_{(H_2O)}$ ranged between 5.1 and 6.4; the highest values were observed in the GCV and the lowest values in the TLV, OHA and OPA, with the other soil managements showing intermediate values (Table 2). As expected, the values of $pH_{(KCl)}$ were considerably lower than those of $pH_{(H_2O)}$; in particular, the lowest differences between $pH_{(H_2O)}$ and $pH_{(KCl)}$, accounting for 0.7–1.5 pH units, occurred in OAK–A1, UPA and GCV, all with a low C/N ratio (Table 2).

The highest content of OC was observed in the A1 horizon of OAK, while the lowest values were in OHA, TLV and GCV (Table 2). The UHA soil showed a higher OC content than OHA, while the OC content of UPA soil did not significantly differ from that of OPA (Table 2). The OC stored in the A and Ap horizons, because of their different thickness, assumed higher values in OHA, UHA,

Table 2
Means and results of analysis of variance for pH in water and KCl, contents of organic C (OC) and total N (TN), C/N ratio, and C stock of the A and Ap horizons from the soil managements compared. For symbols and abbreviations see the legend.

Soil management	$pH_{(H_2O)}$	$pH_{(KCl)}$	OC (g kg^{-1})	TN (g kg^{-1})	C/N	C stock (Mg ha^{-1})
OAK–A1	5.9 ab	5.2 a	59.2 a	5.39 a	10.9 b	15 b
OAK–A2	5.7 ab	4.2 b	13.6 d	0.89 c	15.3 a	35 b
UPA–Ap	5.8 ab	4.7 ab	23.5 b	2.38 b	9.9 b	74 a
OPA–Ap	5.2 b	3.9 b	20.3 bc	2.00 b	10.2 b	82 a
UHA–Ap	5.6 ab	4.2 b	26.0 b	2.18 b	11.9 b	84 a
OHA–Ap	5.5 b	4.0 b	16.6 cd	1.26 c	13.2 ab	106 a
GCV–Ap	6.4 a	5.4 a	12.6 d	1.19 c	10.6 b	32 b
TLV–Ap	5.1 b	3.8 b	14.0 d	0.99 c	14.1 ab	33 b

Source of variation	d.f.	*P*-value	*P*-value	*P*-value	*P*-value	*P*-value	*P*-value
Soil management	7	0.005	<0.001	0.001	<0.001	0.041	<0.001
Error	16						
CV (%)		5	5	21	28	12	22

Mean values with different letters significantly differ for $P \leq 0.05$.
OAK = cork oak forest; UPA = under oak tree pasture; OPA = open pasture; UHA = under oak tree hay crop; OHA = open hay crop; GCV = grass-covered vineyard; TLV = tilled vineyard.
d.f. = degrees of freedom.

Table 3
Means and results of analysis of variance for the main composition traits of the humic acids of the A and Ap horizons from the soil managements compared. For symbols and abbreviations see the legend.

Soil management	Yield (g kg^{-1})	C (%)	N (%)	H (%)	H/C	C/N	HA-C/OC ratio
OAK–A1	32.7 a	37.3 c	2.7 d	5.7 a	1.8 a	14.0 ab	0.21 b
OAK–A2	8.1 c	38.7 c	2.5 d	5.4 ab	1.7 a	15.8 a	0.23 b
UPA–A	17.0 b	41.1 bc	3.1cd	4.4 ab	1.2 b	13.6 b	0.38 a
OPA–Ap	12.2 bc	41.1 bc	3.4 bc	4.3 b	1.2 b	12.0 bc	0.25 b
UHA–A	16.1 b	47.0 ab	3.7 b	4.9 ab	1.2 b	12.6 bc	0.29 ab
OHA–Ap	10.5 bc	51.5 a	4.0 ab	5.2 a	1.2 b	12.7 bc	0.33 ab
GCV–Ap	10.1 bc	50.4 a	3.9 ab	5.4 a	1.3 b	12.8 bc	0.40 a
TLV–Ap	7.5 c	51.5 a	4.4 a	5.5 a	1.3 b	11.6 c	0.28 ab

Source of variation	d.f.	*P*-value	*P*-value	*P*-value	*P*-value	*P*-value	*P*-value	*P*-value
Soil management	7	0.004	0.008	<0.001	0.020	0.022	0.005	0.113
Error	16							
CV (%)		35	9	9	8	13	6	20

Mean values with different letters significantly differ for $P \leq 0.05$.
OAK = cork oak forest; UPA = under oak tree pasture; OPA = open pasture; UHA = under oak tree hay crop; OHA = open hay crop; GCV = grass-covered vineyard; TLV = tilled vineyard.
d.f. = degrees of freedom.

OPA and UPA (on average, 87 Mg ha^{-1}) than in OAK, GCV and TLV (on average, 29 Mg ha^{-1}).

The TN showed the highest values in the A1 horizons of OAK, while the lowest content was observed in GCV and TLV and in the A2 horizon of OAK (Table 2).

The C/N ratio of the A2 horizon of OAK was found to be significantly higher than that of the other samples, apart those from TLV and OHA (Table 2). The C/N ratio of the A1 horizon of OAK was found to be similar to that of UPA, OPA, UHA and GCV.

3.2. Characteristics of humic acids, fulvic acids and humin

Soil management significantly influenced the distribution of the SOM fractions, with the A1 horizon of OAK showing the highest HA yield and the A2 horizon of OAK and the Ap horizon of TLV the lowest yields (Table 3). Moreover, the HA yield was higher in UPA and UHA than in TLV. The HA of the OAK horizons had the lowest C and N contents and the highest H/C and, at least for the A2 horizons, C/N ratios. The C content as HA (HA-C) with respect to the OC content was higher in UPA and GCV than in all other soil managements, apart from UHA, OHA and TLV.

For the FA, the highest yield was found in the A1 horizon of OAK, while the lowest was in the A2 horizon of the same soil use and in OHA, GCV and TLV (Table 4). The C content as FA (FA-C) over the OC content was quite stable across soil managements as it ranged from 0.03 to 0.06. No significant difference among soil managements was observed for the N content, while small differences were observed for H/C ratios. The HA-C/FA-C ratio was significantly higher in the OHA than in the other soil managements apart from GCV.

The C content as humin (HU-C) was significantly higher in the A1 horizon of OAK than in all other soil managements, while GCV and TLV showed lower values than UPA, OPA and OHA (Table 5). For N as humin (HU-N), the values were highest in the OAK A1 horizon, while no significant differences were observed among the other soil managements (on average, 0.06 g kg^{-1}). No difference among soil managements was observed for the C/N ratio of humin.

All the FT-IR spectra of the HA (Fig. 1) showed a marked band around 3400 cm^{-1} (O—H stretching of phenols, water, OH-groups of aliphatic structures), that was particularly evident in the spectra of OAK A1 horizon, UPA and UHA, and signals around 2920–2840 and 1440 cm^{-1} attributed to aliphatic structures (stretching of C—H bounds of CH_2 groups, and CH deformation of CH_3 and –CH bending of CH_2, respectively). FT-IR spectra of the HA also revealed abundance of COOH groups (signals at 1700–1720 cm^{-1}, due to stretching of C=O of COOH groups, and at 1200–1230 cm^{-1} due to stretching of C—O and deformation of O—H of COOH groups), C of aromatic rings and C—N groups (signals around 1600 and 1540 cm^{-1} due to stretching of C=C of aromatic rings and amide I and II). Other bands observed in all the spectra were attributed to OH groups of phenols and/or COOH groups (1400 cm^{-1}), and

Table 4
Means and results of analysis of variance for the main composition traits of the fulvic acids of the A and Ap horizons from the soil managements compared. For symbols and abbreviations see the legend.

Soil management	Yield (g kg^{-1})	C (%)	N (%)	H (%)	H/C	C/N	FA-C/OC ratio	HA-C/FA-C ratio
OAK–A1	3.6 a	44.4 a	2.2 a	4.5 ac	1.2 b	19.9 a	0.03 a	7.6 b
OAK–A2	1.6 b	37.6 ab	2.2 a	3.5 c	1.1 b	17.2 a	0.04 a	5.2 b
UPA–A	2.4 a	43.4 a	2.3 a	4.8 ab	1.3 ab	19.6 a	0.06 a	6.7 b
OPA–Ap	2.0 ab	44.2 a	2.7 a	5.3 a	1.4 ab	16.2 a	0.04 a	5.7 b
UHA–A	2.7 ab	44.3 a	2.6 a	5.4 a	1.5 a	17.1 a	0.05 a	6.3 b
OHA–Ap	1.2 b	36.6 ab	2.4 a	4.0 bc	1.3 ab	15.1 a	0.03 a	12.3 a
GCV–Ap	1.4 ab	40.3 ab	2.4 a	4.5 ac	1.4 ab	16.9 a	0.04 a	9.2 ab
TLV–Ap	1.6 b	32.7 b	2.0 a	4.1 bc	1.5 a	17.2 a	0.04 a	7.4 b

Source of variation	d.f.	*P*-value	*P*-value	*P*-value	*P*-value	*P*-value	*P*-value	*P*-value	*P*-value
Soil management	7	0.049	0.051	0.906	0.042	0.041	0.613	0.172	0.024
Error	16								
CV (%)		33	14	25	14	9	14	31	34

OAK = cork oak forest; UPA = under oak tree pasture; OPA = open pasture; UHA = under oak tree hay crop; OHA = open hay crop; GCV = grass-covered vineyard; TLV = tilled vineyard.
d.f. = degrees of freedom.

Table 5
Means and results of analysis of variance for the content of C as humin (HU-C) and N as humin (HU-N) in the A and Ap horizons from the soil managements compared.

Soil management	HU-C ($g\,kg^{-1}$)	HU-N ($g\,kg^{-1}$)	Humin C/N
OAK–A1	2.02 a	0.17 a	11.8 a
OAK–A2	0.67 bc	0.04 b	15.5 a
UPA–Ap	0.83 b	0.06 b	13.1 a
OPA–Ap	0.86 b	0.07 b	12.9 a
UHA–Ap	0.73 bc	0.05 b	16.1 a
OHA–Ap	0.90 b	0.07 b	12.4 a
GCV–Ap	0.47 c	0.05 b	9.5 a
TLV–Ap	0.53 c	0.05 b	11.7 a

Source of variation	d.f.	*P*-value	*P*-value	*P*-value
Soil management	7	<0.001	<0.001	0.507
Error	16			
CV (%)		23	22	26

Mean values with different letters significantly differ for $P \leq 0.05$.
OAK = cork oak forest; UPA = under oak tree pasture; OPA = open pasture; UHA = under oak tree hay crop; OHA = open hay crop; GCV = grass-covered vineyard; TLV = tilled vineyard.
d.f. = degrees of freedom.

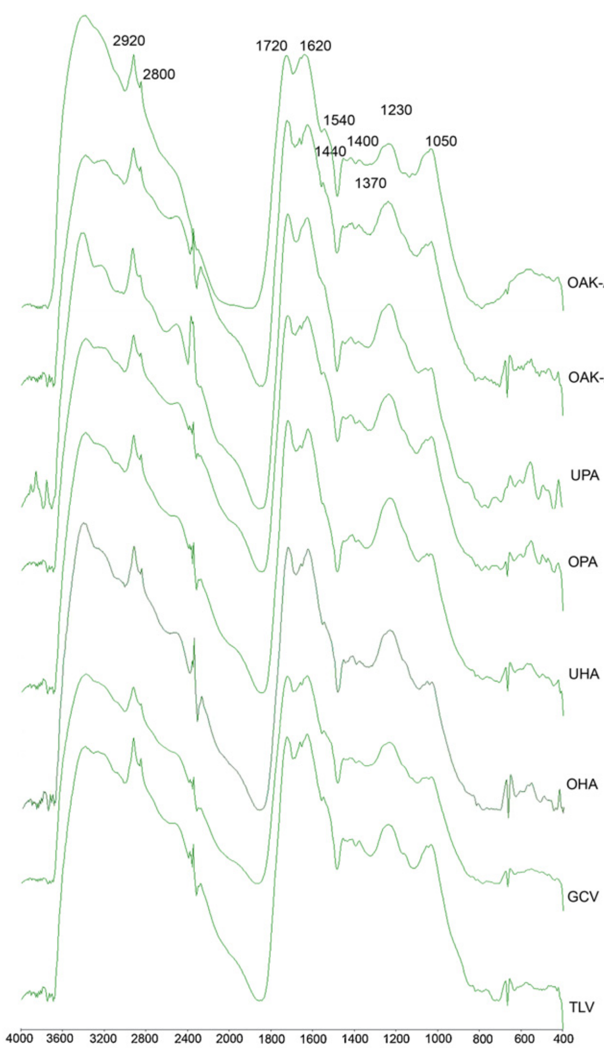

Fig. 1. Spectroscopic patterns of humic acids derived from soils submitted to different managements (OAK = cork oak forest; UPA = under oak trees pasture; OPA = open pasture; UHA = under oak trees hay crop; OHA = open hay crop; GCV = grass-covered vineyard; TLV = tilled vineyard).

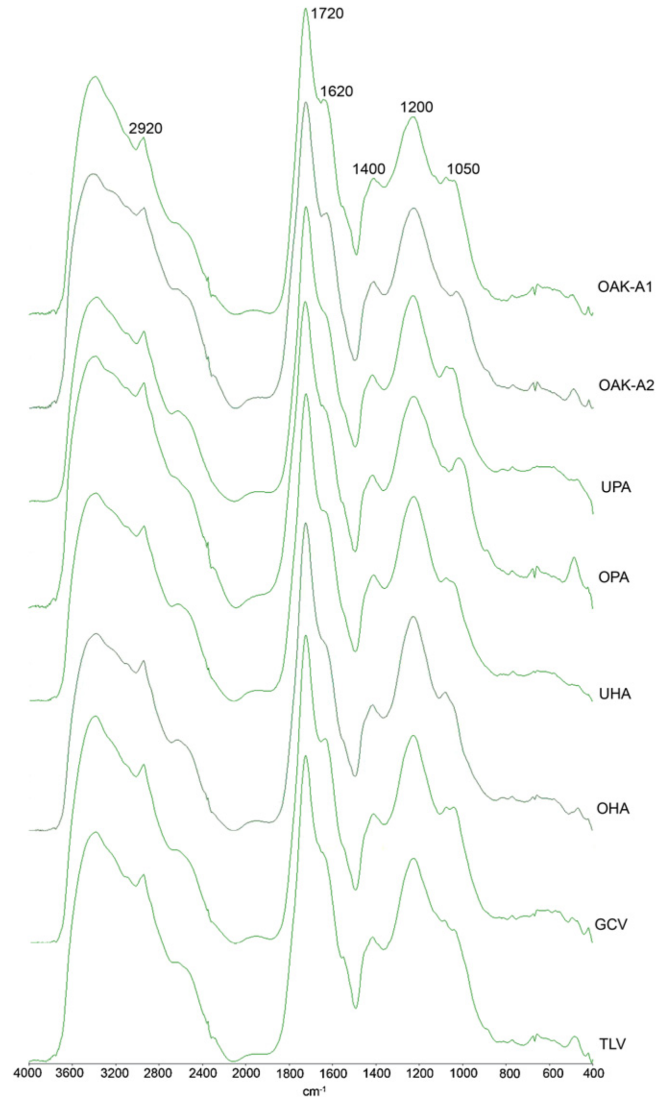

Fig. 2. Spectroscopic patterns of fulvic acids derived from soils submitted to different managements (OAK = cork oak forest; UPA = under oak trees pasture; OPA = open pasture; UHA = under oak trees hay crop; OHA = open hay crop; GCV = grass-covered vineyard; TLV = tilled vineyard).

CH_3 of metoxil groups (1370 cm^{-1}). The signal at 1050 cm^{-1} has been attributed to C—O stretching of polysaccharides and/or Si—O vibration due to possible mineral impurities that were not completely removed during the purification of HA, although it cannot be excluded that the band in this region may arise also from phosphate groups (Rulmont et al., 1991; He et al., 2006).

The FT-IR spectra of the FA (Fig. 2) indicated a richness of hydrophilic groups, COOH and OH, and a minor aromatic component with respect to those of the HA. The strongest signal was at 1720 cm^{-1}, but other main signals were at 3400, 2920, 1200, 1620–1530, and 1400 cm^{-1}. The signal at 1050 cm^{-1}, less intense than in the HA, has been assigned to C—O stretching of polysaccharides and, since the absence of peaks in the 900–700 cm^{-1} region, to the presence of phosphate groups (Rulmont et al., 1991).

The FT-IR spectra of the humin-containing extraction residue (Fig. 3) showed few and strong peaks due to C of aromatic structures and phenols (1620 and 1400 cm^{-1}), particularly evident in the A1 horizon of OAK, and to aliphatic chains. The presence of these latter structures was suggested by signals, other than those

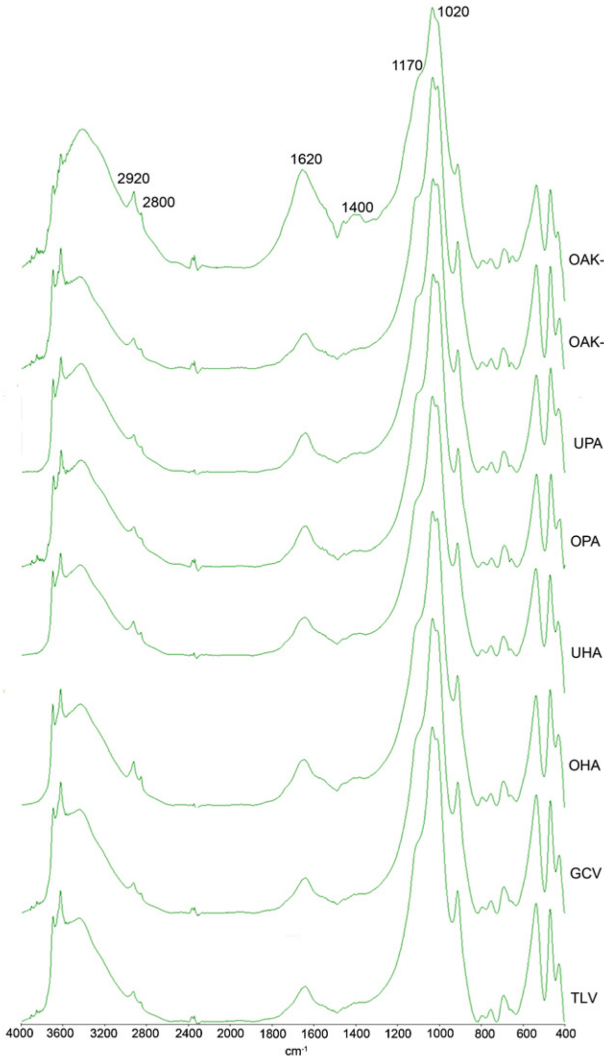

Fig. 3. Spectroscopic patterns of humin derived from soils submitted to different managements (OAK = cork oak forest; UPA = under oak trees pasture; OPA = open pasture; UHA = under oak trees hay crop; OHA = open hay crop; GCV = grass-covered vineyard; TLV = tilled vineyard).

at 2920 and 2850 cm^{-1}, at 1170 cm^{-1}. Strong signals in the region 1100–1000 cm^{-1} and 900–700 cm^{-1} should indicate an abundance of Si—O groups (Rulmont et al., 1991) due to the high amount of mineral forming the analyzed specimens.

The possible presence of phosphate groups in the humic molecules, although often masked by mineral impurities that produce signals in the same FT-IR region, has been considered as an artefact due to the use of NaOH plus $Na_4P_2O_7$ solution for extracting the humic substances from the soil samples (Francioso et al., 1998).

3.3. Relationships among soil properties

Negative significant correlations were found between the content of all humic substances and the bulk density (Table 6). The content of all the humic substances was also positively correlated to TN, HU-C, HA-C and FA-C. No significant correlations were found between OC, HA-C, FA-C and HU-C with the majority of the calculated indexes such as C/N, H/C, HA-C/FA-C ratios.

Table 6
Pearson's correlation coefficients between organic C (OC), C content as humin (HU-C), C content as humic acids (HA-C) and C content as fulvic acids (FA-C) and some soil physical and chemical properties/indices. Correlation coefficients in bold characters are significant at $P \leq 0.05$ ($n = 20$).

	OC	HU-C	HA-C	FA-C
Bulk density (kg dm^{-3})	**−0.70**	**−0.76**	**−0.61**	**−0.49**
Coarse sand (%)	−0.01	0.02	−0.04	−0.03
Medium sand (%)	−0.18	−0.23	−0.08	−0.20
Fine sand (%)	−0.19	−0.18	−0.19	−0.24
Silt (%)	0.35	0.39	0.28	**0.44**
Clay (%)	**0.44**	0.36	**0.47**	**0.56**
$pH_{(H_2O)}$	0.10	0.11	0.23	0.06
$pH_{(KCl)}$	0.38	0.40	**0.56**	0.36
Total N (g kg^{-1})	**0.95**	**0.88**	**0.83**	**0.85**
C/N	0.02	−0.22	−0.25	−0.31
Fulvic acids yield (g kg^{-1})	**0.74**	**0.70**	**0.72**	**0.97**
Humic acids yield (g kg^{-1})	**0.86**	**0.88**	**0.97**	**0.86**
Humic acids-N content (%)	−0.43	**−0.50**	−0.29	**−0.45**
Humic acids-H content (%)	0.16	0.03	−0.11	−0.35
Fulvic acids-N content (%)	0.16	−0.05	0.24	0.08
Fulvic acids-H content (%)	0.21	0.08	0.40	**0.45**
Humin C/N	−0.01	0.03	−0.08	0.08
Humic acids C/N	0.12	0.22	−0.02	0.02
Fulvic acids C/N	0.23	0.39	0.23	0.37
Humic acids H/C	**0.56**	**0.46**	0.21	0.27
Fulvic acids H/C	−0.27	−0.30	−0.16	−0.02
HA-C/OC	−0.41	−0.17	0.02	−0.14
FA-C/OC	−0.38	−0.16	−0.15	0.14
HA-C/FA-C	−0.08	−0.08	0.04	−0.38

4. Discussion

4.1. Effect of soil management on general soil traits

The thickness of the A horizons was influenced by the impact of tillage in the different soil managements (Table 1). The higher A thickness was observed in the soils characterized by recurrent ploughing such as OPA and OHA. In fact, the thickness of the A1 horizon of OAK, where ploughing does not occur, was the lowest. The A1 horizon of OAK had a very low bulk density (Table 1) due to the abundance of fresh and partly decomposed litter (Soane, 1990). Papini et al. (2011), along a range of land uses in Central and Southern Italy, found the largest differences of bulk density in the uppermost soil horizons, with the Mediterranean bush (mixture of broad-leaves trees, shrubs and herbaceous plant species) showing the lowest bulk density (0.96 g cm^{-3}) and the wheat cultivation the highest (1.40 g cm^{-3}). In our study, apart from the lower value of the OAK A1 horizon, the other soil managements did not show significant differences of bulk density.

4.2. Effect of soil management on soil organic carbon and nitrogen

The OC content of the uppermost horizons of all long term soil managements were never below 1.0%, which is the lower limit for identifying the status of pre-desertification (CEC, 2002). This result indicates that the range of soil managements practiced in the studied agro-silvo-pastoral system can contribute to maintain a satisfactory long term soil fertility, in the context of semi-arid Mediterranean climate. In the OAK soils, the sharp decrease of the OC from the A1 to A2 horizon (−77%) agreed with the results reported by Rovira and Vallejo (2003) for soil profiles on calcareous parent materials under a *Quercus rotundifolia* Lam. forest. These authors found a decrease of about 80% OC from the upper horizon (4 cm thick) to the underlying one. By calculating the weighed mean (for thickness) of the OC content for OAK A1 and A2 horizons, we obtained a value of 21.1 g kg^{-1}, consistent with that of 21.8 g kg^{-1} reported by Moreno et al. (2007) for a dehesa system in Central-western Spain dominated by holm oak trees. However, the content of OC in our oak forest soil was about 60% lower than that found by Vanmechelen et al. (1997) for Italian forest soils. The relatively low OC content in the A horizons of the forest here studied could be explained considering that the soil was under a semi-arid climate, and had a relatively coarse texture and an acidic reaction typical of the soils originated from granitic parent material. These factors were able to constrain the accumulation of organic matter into the soil and, consequently, fertility. The sub-acid soils (pH < 6.5) of Mediterranean temperate grasslands and forests of Spain were found to have lower levels of OC in the upper 25 cm than in the alkaline ones (Romanyà and Rovira, 2011). This was mainly explained by the higher physical protection of SOM in these latter soils than in the acidic ones, and this was attributed to a higher degree and stability of aggregation promoted by the presence of Ca ions derived from the alteration of $CaCO_3$-bearing parent materials. An opposite pattern was observed for the Atlantic and Mediterranean continental grasslands, highlighting on the interaction between climate, particularly the mean annual rainfall, and soil pH on SOM accumulation (Romanyà and Rovira, 2011). The potential increment of SOM associated to extensification of soil agronomic management in our case study is therefore expected to be constrained by soil pH and climate conditions, as found by Hernanz et al. (2002) under Mediterranean semi-arid conditions. However, the findings of Romanyà et al. (2000) suggested that, under Mediterranean temperate climate, grasslands acid soils are able to accumulate similar or even higher SOM levels than the natural forests after a few decades since afforestation. Therefore, even if an absolute increment of OC in these environments is not expected to be large when agricultural practices are extensified, agricultural soils can accumulate OC up to similar levels of the forest. These considerations can explain the relatively small differences among the compared soil managements, particularly between the forest (weighed mean of A1 and A2 horizons) and the grasslands, and between the pasture and the hay crop phases of the grassland. This fact suggested that a light tillage every 2–5 years did not strongly affect the OC accumulation in the topsoil of the grasslands under this type of climate. However, the lower OC content of OHA than that of UHA also suggested an impact in the short period of the tillage, which occurred just five months before the soil sampling. The negative long term impact of tillage on OC sequestration, as observed by several authors for Mediterranean cropping systems (e.g. Álvaro-Fuentes et al., 2007; De Sanctis et al., 2012), could have been partially offset by the contribution of the OC supplied by the grazing sheep dejections in both pasture and, at a lesser extent, hay crops soils. This interpretation is supported by the findings of Peco et al. (2006) in Central Spain, and Farris et al. (2010) in Sardinia (Italy). These authors, studying land uses under similar environmental conditions to those of this study, observed a significant OC decrease over time when grazing was suspended. Other than by the input of organic matter in form of faeces, grazing can produce a higher soil C content than ungrazed land because of the changes of plant composition resulting in an enhanced nutrient input through litter (Olofsson and Osaken, 2002).

In the Spanish dehesa, the amount of OC in the topsoil beneath the tree canopies projection was around twice as high as beyond the tree canopy (Moreno et al., 2007). In our situation, the mean content of OC in the soils of UPA and UHA was about 22% higher than the mean OC content of OPA and OHA, respectively.

The OC content of the A horizon in the vineyards was found to be similar to that reported by Marzaioli et al. (2010), who observed higher OC contents in coniferous and mixed (broad-leaves and coniferous trees) forests (80 g kg^{-1}) than in tilled vineyard (13 g kg^{-1}). However, our results showed a less marked difference between the OC contents of forest and tilled vineyard probably because the findings of Marzaioli et al. (2010) referred to the upper 10 cm of soil, a thickness where the OC content in a forest soil is mainly accumulated. In our case, the thickness of the A horizons of both forest (weighed mean of OAK A1 and A2 horizons) and tilled vineyard soils was about 20 cm.

The quite relevant OC stocked in the A horizons of the grasslands soils (OHA, OPA, UHA and UPA) compared to the lesser (OAK) and higher disturbed (GCV and TLV) soil managements suggested that, also under semi-arid conditions, the grassland ecosystem considerably affects the soil genesis through deepening of the A horizon. This thickening is favoured by inputs of OC depending on root deepening, root respiration, root turnover and rhizodeposition processes of the grasses, associated with an intense microbial activity (Baker, 1991; Cheng and Coleman, 1990; Coleman et al., 1992; Kuzyakov et al., 2001). Further, it appeared that long term light tillage practices have fostered the development of deep A horizons and storage of OC.

Some authors, working on fixed soil thicknesses, found a decrease of SOM from Mediterranean semi-natural to cultivated ecosystems as a consequence of the increasing application of ploughing and crop residues removal (Papini et al., 2011). Others observed differences in SOM stock only in the upper 5 cm by comparing tillage and no-tillage soils along a 20 years chronosequence in a Mediterranean cereal-based cropping systems; conversely, they did not find significant differences in the SOM stock considering the upper 30 cm of the same soils (Álvaro-Fuentes et al., 2012). Always considering a certain soil thickness in Mediterranean environments, other authors have found that tillage affects soil C sequestration (e.g. Hernanz et al., 2009; De Sanctis et al., 2012), but they considered more intensive cropping systems. However, when considering SOM stock in soils submitted to relatively small differences in terms of management intensity, a possible lack of differences could come from neglecting the thickness of genetic horizons. This parameter, in fact, allows us to consider all the processes that acted on the C sequestration, including root and microbial activity.

The drop of total N observed in the A1 vs. the A2 horizon of OAK (−84%) is consistent with the OC content pattern and with what was reported for Mediterranean calcareous forest soils in North–East of Spain by Rovira and Vallejo (2003). The higher total N content of the OPA compared to the OHA (+37%) could be interpreted as an effect of the higher stocking rate and hence input of additional N from sheep dejections, combined to the higher presence of legumes in the pasture. This interpretation is consistent to the findings of Fornara and Tilman (2008), who observed along a 12-years experiment an increase of 522% of soil OC accumulation in high-diversity mixtures of grassland plant species characterized by a joint presence of grasses and legumes, compared to monoculture plots of the same species. These authors suggested that the N fixation of the legumes and the efficient use of N of the grasses favour the development of the below-ground biomass and, therefore, soil C and N inputs.

4.3. *Effect of soil management on the characteristics of humic acids, fulvic acids and humin*

Soil management significantly influenced the SOM fractions (Table 3). The highest content of HA was observed in the A1 horizon of OAK (12.2 g kg^{-1} of humic C) followed by pastures, hay crops and GCV, while the Ap horizon of TLV (3.9 g kg^{-1} of humic C) and the A2 horizon of OAK (3.1 g kg^{-1} of humic C) had the lowest HA content. These results suggested that the less tilled soils accumulated stabilized SOM, possibly thanks to the absent or little disruption of aggregates induced by tillage. A stable soil structure is recognized as a functional factor for organic matter physical protection from degradation due to microbial attack (Baldock and Skjemstad, 2000). Nonetheless, the high content of HA, in turn, favours the development of a stable soil structure (Bronick and Lal, 2005).The amount and spectroscopic properties of FA were very similar under the different soil managements, with only small differences in terms of C/N and H/C ratios (Table 3). The H/C ratio is considered a measure of the degree of unsaturation of humic substances (Yonebayashi and Hattori, 1989), and the lower the H/C ratio, the larger is the degree of unsaturation of humic materials (Stevenson, 1994). The H/C ratio of the HA (Table 3) showed a similar high degree of unsaturation and a mostly aliphatic structure (Aranda and Oyonarte, 2005; Belzile et al., 1997) in pastures, hay crops and vineyards. In the case of FA, the higher degree of aliphaticity was displayed by the OAK soil samples. The C/N ratio of HA is often considered as an index of decomposition processes and its value varies in function of the crop residues (Miller and Gardiner, 1998). The SOM mineralization processes lead to a decreasing of the original crop C/N values towards a relatively constant value, and C/N ratios between 10 and 15 are generally believed characteristic of well developed HA, meaning that there is an equilibrium between decomposition and accumulation of SOM (Tan, 2003). Therefore, all the compared soil managements appeared to have reached this equilibrium condition.

With respect to the HA-C/OC ratio, under comparable climate conditions to those of this study, Caravaca et al. (2002) reported similar HA-C/OC ratio (44%) for a soil under a one-year-old vineyard in central-western Italy, but higher amount of FA-C (16%). The higher FA-C/OC values found by these authors could be due to the recent deep soil tillage made before the plantation of the vineyard. This fact should have allowed high oxygen diffusion through the tilled soil thickness favouring oxidation/mineralization processes that, in turn, could have produced smaller humic molecules operationally extracted as fulvic acids pool (Machado and Gerzabek, 1993; Ohno et al., 2009; Zalba and Quiroga, 1999) The HA-C/FA-C ratio, considered as an index to describe the intensity of humification process of SOM (Yang et al., 2004a), was relatively stable across the compared soil managements, confirming the similarity in terms of OC composition.

Low HU-C values were observed in the vineyard soils. This suggested a low stabilization capacity of the organic matter in the vineyard soils, and this could be attributed to the high disturbances occurring in the vineyards, which are mostly due to harrowing (TLV) and other agronomic practices such as irrigation (GCV) and nitrogen fertilization (both TLV and GCV). The relatively higher humin-C contents found in the pasture and hay crop confirmed the positive effect of the reduced tillage and the grass cover on the SOM stabilization. A reduction in the intensity of tillage has been widely recognized as a successful strategy to reduce OC losses (Halvorson et al., 2002; McConkey et al., 2003; West and Post, 2002). Further, Yang et al. (2004b) reported of an increase in the proportion of soil C in form of HA and humin in presence of grass covers or rotation with clover or rye grass that resulted in enhancing potential soil C sequestration.

The FT-IR spectra of the humic acids (Fig. 1) had the typical patterns for this type of organic substance (Stevenson, 1994), and showed small differences among soil managements. The FT-IR spectra of the fulvic acids (Fig. 2) and of the humin fractions (Fig. 3) showed the same pattern for all the soil managements. The fact that soil management has little impact on the FT-IR spectra was already reported by Schnitzer and Khan (1978) and Olk et al. (1999), although these authors found some differences between HA. Haberhauer et al. (2000), applying nonlinear statistical models to investigate the decomposition stages of SOM, also found no significant differences in the FT-IR spectra of a Tropudult soil that had been converted from forest to pasture 11 years before.

4.4. Relationships among soil properties

As expected, because of the fundamental role of the organic matter in the aggregation process, soil bulk density was negatively correlated to OC and all its fractions, indicating that the presence of large pores enhances the humification process by, for instance, decreasing the water holding capacity and, therefore, the humidity needed for bacterial growth and SOM breakdown (Hassink et al., 1993). Despite very small variations of clay content among the soils, positive significant correlations were found between clay and OC, HA-C and FA-C (Table 6); this suggested that protection mechanisms of the OC in soil increase with the clay content. These results confirmed that the soil texture, and particularly the clay content, could affect the dynamics and the quality of the major SOM pools and related availability and accumulation of soil nutrients, as it has been already found for semiarid grassland soils in Argentina (Galantini et al., 2004). Highly significant correlations were found between FA and HA yields and OC, indicating, for our conditions, a good predictive value of OC when humic substances pools are to be estimated.

5. Conclusions

In the various agro-forestry systems here studied, characterized by soils with a sub-acid reaction, sandy loam to loamy sand texture, and submitted to Mediterranean climatic conditions, the variation of OC content and quality was far less than expected. Although we observed a lower accumulation of stabilized SOM, i.e., HU-C, in the more disturbed soils such as the tilled vineyard, many indexes of organic matter quality (HA-C/FA-C, fulvic H/C and humic and fulvic C/N ratios) and the spectroscopic characteristics suggested a rather similar pattern to more extensive soil managements. Our results indicated that the impact of soil management on the humic composition is relatively low, at least for the superficial horizons. Other common features among the different soil managements that could have flattened differences are related to grazing practices, which were widely practiced for long time in the area. In contrast to other research findings, we found that a periodical light tillage of the grasslands did not strongly affect the SOM accumulation in the topsoil. Deep inversion tillage at the vineyard establishment could be considered the most relevant factor leading to a relatively low OC of the topsoil, particularly when vineyard inter-row is managed with recurrent tillage.

The accumulation of OC in a very superficial horizon (4 cm) of the oak forest soil and the sharp OC decrease in the underlying soil horizon may constrain the resilient capacity of these soils towards disturbance factors, while the grasslands soils characterized by a thicker preferential horizon for OC sequestration may be considered more resilient.

Finally, all the compared soil managements revealed to be overall quite conservative in terms of soil fertility, which is an indicator of the effectiveness of traditional agro-silvo-pastoral management practices for the maintenance of relatively good soil quality traits under semi-arid Mediterranean conditions. However, these results refer just to the A horizons, hence caution must be taken extending results to the entire soil depth. Because of this, further research is needed to estimate the OC and its fractions accumulation along the soil profile.

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