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Research article

Effects of soil erosion on agro-ecosystem services and soil functions: A multidisciplinary study in nineteen organically farmed European and Turkish vineyards

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ABSTRACT

This multidisciplinary research work evaluated the effects of soil erosion on grape yield and quality and on different soil functions, namely water and nutrient supply, carbon sequestration, organic matter recycling, and soil biodiversity, with the aim to understand the causes of soil malfunctioning and work out a proper strategy of soil remediation.

Degraded areas in nineteen organically farmed European and Turkish vineyards resulted in producing significantly lower amounts of grapes and excessive concentrations of sugar. Plants suffered from decreased water nutrition, due to shallower rooting depth, compaction, and reduced available water capacity, lower chemical fertility, as total nitrogen and cation exchange capacity, and higher concentration of carbonates. Carbon storage and organic matter recycling were also depressed. The general trend of soil enzyme activity mainly followed organic matter stock. Specific enzymatic activities suggested that in degraded soils, alongside a general slowdown in organic matter cycling, there was a greater reduction in decomposition capacity of the most recalcitrant forms. The abundance of Acari Oribatida and Collembola resulted the most sensitive indicator of soil degradation among the considered microarthropods. No clear difference in overall microbial richness and evenness were observed. All indices were relatively high and indicative of rich occurrence of many and rare microbial species. Dice cluster analyses indicated slight qualitative differences in Eubacterial and fungal community compositions in rhizosphere soil and roots in degraded soils.

This multidisciplinary study indicates that the loss of soil fertility caused by excessive earth movement before planting, or accelerated erosion, mainly affects water nutrition and chemical fertility. Biological soil fertility is also reduced, in particular the ability of biota to decompose organic matter, while biodiversity is less affected, probably because of the organic management. Therefore, the restoration of the eroded soils requires site-specific and intensive treatments, including accurately chosen organic matrices for fertilization, privileging the most

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easily decomposable. Restoring soil fertility in depth, however, remain an open question, which needs further investigation.

1. Introduction

Intensive management of vineyards and other permanent tree crops has replaced the traditional mixed cultivation model in Europe (Bignal and McCracken, 2000). Most of intensive management models are applied without taking into account the nature of local soils and thus might originate severe impairment of soil functions (Costantini, 1992; Vaudour et al., 2015; Costantini et al., 2015). Mediterranean woody crops, in particular, are usually cultivated in soils low in organic matter, with limited water availability and on medium to steep slopes, where the occurrence of severely eroded areas, characterized by excessive low yield, is rather frequent (Le Bissonnais et al., 2002; Costantini and Barbetti, 2008). In addition to reduced yield, the accelerated soil water erosion can be responsible for soil compaction, reduced C sequestration and increased greenhouse gas emissions, loss of nutrients, and dispersion of heavy metals, especially copper (Battany, and Grismer, 2000; Cerdan et al., 2010; Prosdocimi et al., 2016; Fernández-Calviño et al., 2008). Climate change is deemed to exacerbate the sustainability of rainfed tree crops in Mediterranean, since a reduced and more erratic rainfall regime is foreseen (Schultz, 2000). The consequence would be an increased water need for irrigation and a resulting harsher competition for freshwater with other utilization types (Van Leeuwen et al., 2013).

In previous studies, much attention has been given to soil degradation occurring after plantation and to the consequent agronomic, environmental and economic damages (Martínez-Casasnovas and Ramos, 2006; Novara et al., 2011). Some studies have also focused on the impact of improper land preparation activities before planting, such as intense levelling and deep ploughing, which may cause destruction, truncation and burial of soil horizons (Cots-Folch et al., 2006; Bazzoffi et al., 2006; Martínez-Casasnovas and Ramos, 2009). The excessive earthworks may result in the disturbance of the natural contour of slopes and significant modifications of soil chemical, physical, biological, and hydrological balances, in turn affecting soil suitability for grapevine (Brye et al., 2003; Costantini et al., 2006; Ramos and Martínez-Casasnovas, 2007; Stanchi et al., 2012). Furthermore, they can be responsible for reduction of soil fertility, enrichment of calcium carbonate and soluble salts, affecting the development and health of grapevines (Costantini et al., 2010; Sharp-Heward et al., 2014). Low water retention capacity, in particular, can lead to increased water stress during dry season, decreased water permeability and circulation of oxygen in the soil, increased runoff volume, surface erosion and landslide risk, reduced soil biodiversity, and limitation of biochemical processes, such as organic matter mineralization and bioavailability of nutrients (Ramos, 2017).

Few studies documented the impact of soil erosion and loss of organic matter and organisms on soil functions and biodiversity (Tsiafouli et al., 2014). Generally, soil microorganisms and meso- and macrofauna suffer from management systems involving the use of synthetic pesticides and intensive tillage (Gagnarli et al., 2015; Holland, 2004; Schreck et al., 2012), which impair their activity and ecosystem services, such as organic matter decomposition and humification, regulation of nutrient cycles and beneficial antagonisms against pests and diseases (Lavelle et al., 2006). Most of small invertebrates, such as nematodes, pot worms, springtails, and mites, called 'biological regulators' (European Comminssion, 2010) are important components of soil functions in regulating the population of other soil organisms, including pests and diseases, through grazing, predation or parasitism. The composition and abundance of springtails and mites, which are the largest biological regulators, are often used as "early-warning" bioindicator of environmental changes (Cole, 2002). Fromm et al., 1993, for example, registered that the distribution of springtails in agricultural landscape can follow large-scale soil carbon gradients and type of land cultivation.

Soil enzyme activity is another proximal driver of soil functioning, contributing to biogeochemical cycling, organic matter transformations and nutrient availability. Soil enzyme activities also are widely accepted as sensitive indicators of soil health and candidate "sensors" of changes in soil management, soil health, microbial activity patterns, soil ecological stress and soil fertility (Aon et al., 2001; Badiane et al., 2001; Vepsäläinen et al., 2001). Furthermore, being synthesized by microorganisms, roots and soil micro- and meso-fauna (e.g., earthworms, nematodes), enzymatic activity encapsulates complex information in a simple and informative manner.

Restoring degraded areas is rather problematic and still much debated, since the complex network of interactions between hydrological, chemical, biochemical, and biological processes that impair soil functions is site specific and difficult to disentangle (Nunes et al., 2016; Costantini et al., 2016). A promising option is the implementation of recommended management practices, which include plant cover in the inter-row area, minimum or no tillage and off- and on-farm organic matter amendments (Vicente-Vicente et al., 2016). Organic viticulture is considered another sustainable cultivation method, which may reduce the environmental impacts of conventional grape growing (Merot and Wery, 2017; Costantini et al., 2013).

The first aim of this research work was to understand the causes of reduced soil functionality in the degraded areas of nineteen organically farmed European and Turkish vineyards. Selected methodologies involving soil physics and hydrology, chemistry and biochemistry, micro- and mesobiology, and soil genesis and classification, were tested and related to the viticultural and oenological result.

Our contribution is finally intended to support the definition of a set monitoring methods able to assess soil functionality in vineyards. This is fundamental to work out a proper strategy of soil remediation and to recommend agricultural practices that could be successfully adopted to recover soil fertility in the degraded areas of vineyards and other tree crops.

2. Materials and methods

2.1. Study areas

Commercial organic farms from important viticultural areas of five European countries were selected (Fig. 1 and Table 1). Being placed in well-known and affirmed territories of grape production, they

Fig. 1. Locations of experimental farm and vineyards for wine (rectangles) or table grape (circles) production. LOG: Bodegas Puelles, Abalos, Logroño; MB: Château Maison Blanche, Saint Emillion; PR: Château Pech Redon, La Clape; FON: Fontodi, Greve in Chianti; SD: Sand Disdagio, Civitella Marittima; VS: Brajiniki, Bonini; VL: Brajiniki, Prade; CC: Celebi, Ceyhan; ET: Evran, Tarsus.

Table 1
Experimental vineyards over different farms across Europe and Turkey.

Country	Municipality	Wine/grape region	Farm	n. of vineyards	Cultivar	Vine spacing (m)	Year of plantation	Years of organic management	Standard soil management
Italy	Civitella Marittima, Grosseto	Maremma	San Disdagio	3	Sangiovese	0.85 × 2.5	2000/2002	2 years	Tillage
	Greve in Chianti, Firenze	Chianti Classico	Fontodi	3	Sangiovese	0.75 × 2	2003/2008	15 years	Natural grass cover
France	Montagne Saint Emillion, Gironde	Saint Emillion	Château Maison Blanche	3	Cabernet Franc	1.1 × 1	1947	11 years	Alternate natural grass cover/tilled rows
	Narbonne, Aude	La Clape, Languedoc	Château Pech Redon	3	Syrah	1 × 2	1974/1989	> 15 years	Alternate natural grass cover/tilled rows
Spain	Abalos	La Rioja	Bodegas Puelles	3	Tempranillo	1 × 2.3	1999/2004	> 10 years	Tillage
Slovenia	Bonini, Koper	Primorska	Brajniki	1	Refošk	1 × 3	1998	> 10 years	Natural grass cover
	Prade, Koper	Primorska	Brajniki	1	Refošk	0.8 × 4	1980	> 10 years	Natural grass cover
Turkey	Ceyhan, Adana	Adana	Çelebi	1	Early Cardinal	1.8 × 3.0	2006	2 years	Tillage
	Tarsus, Mersin	Mersin	Evran	1	Yalova Incisi	1.6 × 3.0	2006	2 years	Tillage

Table 2
Geology, morphology, soils, and climate of the experimental vineyards over different farms across Europe and Turkey.

Country	Farm	Main lithology	Morphology	Soil classification (IUSS Working Group WRB, 2015)	Mean annual temperature (°C)	Annual precipitation (mm)	Köppen climate classification	Huglin index	Winkler index
Italy	San Disdagio	Ancient marine deposits (Pliocene)	Gentle slopes	Cambic Calcisols, Calcic Vertisols	14.1	792	Warm Mediterranean	2308	1720
	Fontodi	Clayey-calcareous flysch (Cretaceous)	Slopes	Cambic Calcisols, Calcaric Cambisols	13.9	817	Warm Mediterranean	2194	1887
Spain	Bodegas Puelles	Ancient fluvial terraces (Pleistocene)	Plain and gentle slopes	Cambic Calcisols, Calcaric Cambisols	13.9	405	Temperate Oceanic	2286	1747
France	Château Maison Blanche	Alluvial deposits (Pleistocene-Olocene)	Plain and gentle slopes	Stagnic, Haplic and Gleyic Luvisols, Eutric Cambisols, Cambic Calcisols	12.8	944	Temperate Oceanic	1883	1405
	Château Pech Redon	Limestone, marl and gypsum (Cretaceous)	Head slope	Haplic Calcisols	15.4	558	Warm Mediterranean	2283	1947
Slovenia	Brajniki Bonini Brajniki Prade	Sandy-calcareous flysch (Eocene)	Head slope	Calcaric Cambisol	8.7	938	Temperate Oceanic	2270	1730
Turkey	Çelebi	Carbonate clastic rocks (Miocene)	Slopes	Leptic Calcisols, Cambic Calcisol	18.3	724	Warm Mediterranean	3020	2765
	Evran	Clastic rocks (Upper Miocene)	Gentle slope	Petric Calcisols	20.0	581	Warm Mediterranean	3698	2797

represented medium to high level of viticulture in Europe. All farms adopted organic farming prescription. Fertilization was limited to the use of compost and manure. In Turkey table grapes were irrigated, if needed, whereas all the other vineyards were rainfed.

Environmental factors characterizing the experimental vineyards were rather differentiated (Table 2). Climate ranged from the mild and relatively more humid sites in Koper (Slovenia) and Maison Blanche (France) to the rather hot and dry sites in Evran (Turkey) and Bodegas Puelles (Spain), while vineyards in Italy showed intermediate values of the climatic indices. Although geology was variable and representative of major formations where grape is cultivated in Europe, morphology was typically gentle.

The experiment layout involved nine farms, each one including three vineyards, with the exception of Slovenia and Turkey, where there was only one vineyard per farm. The vineyards were selected by the farmers, who had observed areas with symptoms of soil malfunctioning such as lower grape yield than the rest of the vineyards, stunted growth or higher frequency of grapevine mortality. The delineation of degraded areas within vineyards was possible through a very detailed soil survey carried out by means of proximal sensors and soil profile analyses (Priori et al., 2013). Areas where vines showed stresses caused by waterlogging, pests and pathogens were avoided. Nearby degraded (D) and non-degraded (ND) areas of a vineyard were compared. The dimension of plots used for monitoring inside D or ND was about 100 square metres.

2.2. Soil description and analysis

The studied soils were described and sampled in the year 2015 by digging a profile of about 1 m depth in each D and ND plot of every vineyard. The soil profile was described following the national and international references (Jahn et al., 2006; Costantini, 2007). Grapevine root distribution was described to highlight soil horizons with limitations to root deepening. Soil profiles were sampled and analysed according to international standards (see below for details). Each soil profile was sampled by horizon and analyzed for physical and chemical properties. The studied soils were classified following the WRB system (IUSS working group FAO, 2015).

2.3. Soil agro-ecosystem services and functions

Vineyard soils provide many different agricultural and environmental services, including regulation of runoff, ground water recharge, sediment production, and greenhouse gas emissions, while also supporting the beauty and heritage of the landscape (Costantini et al., 2012; Galati et al., 2015). However, the main agro-ecosystem service of vineyards is the provision of grape of good quality and in satisfactory quantity. In our study we focused on the soil functions that are deemed to support the delivery of grape yield and its quality, namely i) water and nutrient supply, ii) carbon sequestration and organic matter cycling, and iii) soil biodiversity. The research hypothesis was that there is a relationship between the different agronomic results obtained in D and ND, and the features characterizing soil functions.

2.3.1. Grape yield and quality

At harvest time in 2015, a number of vines ranging between five and fifteen was harvested in both D and ND. For each vine, the number of bunches was counted and the yield per vine was measured using a hanging scale in the field. The average bunch weight was then calculated. A sample of 100 berries was collected, put in plastic bags and brought to the laboratory of each institution at 10 °C in portable refrigerators, where the weight of 100-berry sample was measured.

In Italy, Spain and Slovenia, 200-berry samples were also analysed following the OIV methods (Oiv, 2009) for the determination of total soluble solids (TSS) considered equivalent to the percentage of sucrose (sugar) in the solution, titratable acidity (TA) and pH. In Spain, anthocyanin and phenolic contents were determined according to the Iland method (Iland et al., 2004), while in Italy and French by the Glories method (Glories, 2001).

Statistical analyses for grape yield and composition were performed using InfoStat (2007 edition; Cordoba, Argentina), running a combined analysis of variance over sites (two-way ANOVA with replications) after checking normality distribution with the Modified Shapiro Wilks test. Mean separation between treatments was accomplished with the Student t-test. The interaction term site x degradation was tested over the pooled error and considered only if significant. We limited the comparison to only one year, since our interest was to confirm the empirical farmers' multi-annual observation about soil malfunctioning in the degraded areas.

2.3.2. Water and nutrient supply

Water supply was estimated through the calculation of the Soil Aridity Index (SAI) (Costantini et al., 2009) and the Available Water Capacity (AWC). Calculated SAI referred to the average number of days per year with dry soil in the moisture control section, i.e., upper soil layer where roots accumulate (Soil Survey Staff, 1999). Soil AWC was the amount of water held between conventional field capacity and wilting point, estimated according to texture and organic matter up to the rooting depth, excluding stones (Saxton and Rawls, 2006). Particle size distribution was determined with the pipette method or by the equivalent X-ray/sedimentation method (Andrenelli et al., 2013). Soil pH was measured potentiometrically in a 1:5 soil/water suspension. Electrical conductivity (EC) was measured in a 1:5 soil/water filtered extract after 2 h shaking and overnight standing. The total equivalent $CaCO_3$ was determined by the gas-volumetric method using a Dietrich-Fruhling calcimeter. Soil cation exchange capacity (CEC) and exchange bases were analysed with the $BaCl_2$-triethanolamine (pH 8.2) method. The amount of Ca, Mg, K and Na in the extracts was quantified by flame atomic absorption spectrometry (Bascomb, 1964; Gessa and Ciavatta, 2000). Soil data were processed statistically using a Generalized Linear Mixed-Models (GLMM), using the effect of degradation as fixed, that of farm as random, and the other soil properties as covariates. The Statistica 7 software (StatSoft Inc., Tulsa, OK, USA, 2004) was used to run the statistical tests. The effect of soil management with tillage or grass cover was tested pooling farms (Table 1).

2.3.3. Carbon sequestration and organic matter recycling

2.3.3.1. Carbon stock and carbon nitrogen ratio. The amount of soil organic carbon was estimated for the topsoil (upper 20 cm) and subsoil (20–60 cm); carbon nitrogen ratio (C/N) was calculated for the topsoil. The total organic carbon (TOC) and total nitrogen (TN) contents were assessed by dry combustion, using a CN analyser; the analysis was performed on 20–40 mg of air-dried soil sample, previously grinded to 0.5 mm size and pre-treated by 10% HCl to remove carbonates. Carbon stock was calculated from TOC and bulk density, corrected for the skeleton content estimated in the field. The statistical analysis of the cause of variation of these soil properties followed the same procedure as for the water and nutrient supply.

2.3.3.2. Soil enzymes. For the analysis of soil enzymes, soils were sampled at 0–10 and 10–30 cm in Italy (San Disdagio and Fontodi), Spain (Logroño), Slovenia (Prade and Bonini), Turkey (Tarsus and Ceyhan) and France (Maison Blanche and Pech Redon; in this case, 0–30 cm depth). We choose to consider the two depths sampled as measure replicates rather than a fixed effect in the analyses. Samples were air dried and sieved at 2 mm and then kept at room temperature until analysed.

Enzyme activity was measured by the same laboratory in Italy (CREA-AA, Firenze) according to the methods of Marx et al. (2001) and Vepsäläinen et al. (2001), based on the use of fluorogenic methylumbelliferyl (MUF)-substrates. Soil was analysed for N-acetyl-β-glucosaminidase (NAG), β-glucosidase (β-G), butyrate esterase (BUT), acid

phosphatase (AP), arylsulphatase (ARYL), β-xylosidase (XYL), cellulose (CELL) and acetate esterase (AC) activity using methylumbelliferyl (MUF) conjugated surrogate substrates (Sigma, St Louis, MO, USA). Briefly, 2 g soil sample was weighed into a sterile jar and incubated for 24 h at 20% soil moisture. A homogenous suspension was obtained by homogenising samples with 50 ml deionized water with UltraTurrax at 9600 rev/min for 3 min. Aliquots of 50 µL were withdrawn and dispensed into a 96 well microplate (3 analytical replicates/sample/substrate). Fifty µL of Na-acetate buffer (pH 5.5) was added to each well. Finally, 100 µL of 1 mM substrate solution were added giving a final substrate concentration of 500 µM. Fluorescence was measured after 0, 30, 60, 120, 180 min of incubation at 30 °C. Fluorescence (excitation 360 nm; emission 450 nm) was measured with an automated fluorimetric plate-reader (Fluoroskan Ascent).

The order of magnitude of the values obtained for the different enzymatic responses varied considerably depending on the specific activity being determined, thus leading to some enzyme having more weight than others. To solve this problem, the sum of the percentage of the maximum value found for a specific enzymatic response across all enzymes was used for the calculation of the sum of enzymes (SUM).

Discriminant function analysis (DFA) was performed using soil enzymatic activities as grouping variables for soil and fractions. Squared Mahalanobis distances between group centroids were determined. Two significant discriminatory roots were derived and the results of DFA were graphically presented in two dimensions.

2.3.3.3. Collembola and Acari. Soil samples were collected in April 2015 in four organic farms (2 French and 2 Italian) and three plots of D and ND, in the middle of the row, avoiding soil compacted because of earth-working' machines. Three replicates were homogenised in a single sample. Soil microarthropods were collected by Berlese-Tullgren selectors; after the extraction, the abundances of Acari Oribatida, Acari Mesostigmata and Collembola were determined at stereo microscope. The Collembola and Oribatida inhabiting soils constitute two of the most species-rich components of this ecosystem (van Straalen, 1998), i.e. reaching the 95% of the total number of microarthropods in grasslands (Seastedt, 1984). These detritivores are involved in the decomposition of organic matter and in the regulation of microbial activity: their stability in community composition, at a specific site, is a good bioindicator for environmental monitoring. Among the Acari, the predatory Gamasina (Mesostigmata) form an important group with control function on pests (i.e. Nematoda) (Karg, 1962) and provide indication on soil quality and anthropogenic impact (e.g. Koehler, 1999).

The respective abundances of Collembola, Gamasina and Oribatida were analysed using GLMM with a fixed effect corresponding to the degradation of soil (D vs. ND in each vineyard) and a random effect accounting for the replication of measures (3 fields/farm) and using Poisson family, adapted for these count data. All these analyses were performed using R software (2016) and lme4 package (Bates et al., 2015). The percentage of explanation from random and fixed factors was estimated using the function r.squared GLMM from the package MuMIn.

2.3.3.4. Decomposition rate measured with tea bags (TBI). We followed the protocol proposed by Keuskamp et al. (2013) but applied at a field level. During the decomposition of commercially available tea bags, two parameters were calculated according to the weight loss of the two tea types (Lipton green tea and Lipton rooibos packed in pyramid bags). The two parameters indicate the decomposition rate k and stabilisation factor S, which is more associated to the labile compounds that become recalcitrant and do not decompose. These two variables were analysed as a function of soil parameters known to influence soil humidity and thus influencing decomposition rates. Selected and uncorrelated parameters included clay content, C/N and TN content measured in upper soil layer where tea bags were buried. S and k values were analysed using LMM (Linear Mixed-Models) with a fixed effect corresponding to the degradation of soil and a random effect accounting for the replication of measures (3 vineyards) in each farm. Secondly, with the same random factor in the models, we performed LMM with soil parameters as fixed and uncorrelated factors. All these analyses were performed using R software and lme4 package.

2.3.4. Biodiversity

2.3.4.1. Genetic fingerprinting of microbial communities. Total DNA was extracted from bulk and rhizosphere soil, and grapevine roots. Bulk soil was sampled in April 2015 in France (Maison Blanche) and Italy (San Disdagio and Fontodi), in 3 plots at each site, close to where sample for microarthropods analysis were collected. In Italy, soil samples were taken from depths of 0–10 cm and 10–30 cm. Samples from both depths were interpreted as measure replicates. In France, a single sample was taken from across 0–30 cm soil depth. Samples were air dried and sieved at 2 mm and then kept at −20 °C until analysed.

Rhizosphere soil from soil profile exposed roots were sampled in France (Maison Blanche), Italy (Fontodi) and Slovenia (Koper Bonini and Prade). Soil DNA extraction was performed on 250 (100–250) mg of bulk (rhizosphere) soil with the Power Lyzer™ PowerSoil® DNA Isolation Kit (MOBIO Laboratories). Cell lyses was done with a FastPrep Instrument, MOBIO Power Lyzer, or Qiagen Retsch Tissue Lyser.

DNA extractions from soil profile exposed terminal roots of ca. 1 mm or less diam. were obtained from 100 mg pulverized root material and performed with the NucleoSpin Plant II kit (Macherey-Nagel). For pulverizing root material, 1 g of fine roots were cut in up to 2 cm long pieces and put in 50 ml Falcon tubes. Rhizosphere soil was collected by washing roots with sterile distilled water (SDW) and environmental DNA was extracted with the PowerSoil® DNA Isolation Kit as described above. Root pieces were washed 5 times with SDW, once in 75% ethanol for 1 min, once in a 1% NaClO solution (kemika 14552, Zagreb) for 3 min, once in 75% ethanol for 30 s, and 3 times again with SDW. Washed roots were pulverized with an Ultra-Turrax T25 (IKA Labs) and pieces of 100–250 µm were retrieved by using Retsch sieves. Obtained root pieces were then washed 5 times in 30 ml SDW in 50 ml Falcon tubes. Each washing step was followed by centrifugation at 2200*g* for 5 min (Biofuge Stratos, Heraeus instruments) and discarding the supernatant from the tubes.

DNA extracted from bulk and rhizosphere soil and roots was used for the amplification of phylogenetic marker genes by using primers specific for the V6-V8 region of Eubacterial 16S rDNA following procedures described in Castaldini et al. (2005). DNA extracted from rhizosphere soil and roots was also used in a nested PCR system with primers targeting the internal transcribed spacer region 1 of the fungal ribosomal DNA gene cluster following protocols described by Anderson et al. (2003) and the Kapa 2G Robust HS PCR Kit with amplifications at a temperature of 55 °C. Mixed amplification products from three individual PCR reactions per DNA extract were separated from each other and analysed on DGGE gels. sCalculated indexes (Shannon, Pielou Evenness) were used to describe observed taxon diversity, while similarities of community fingerprints were assessed in Dice cluster analyses of DGGE gel profiles.

Microbial community indexes were analysed using LMM or GLMM with a fixed effect corresponding to the degradation of soil and a random effect accounting for the replication of measures (3 fields) in each farm. Bands (richness) was analysed using a Poisson family, adapted for this count data, while the other variables were normally distributed. All LMM and GLMM analyses were performed using R software and lme4 package.

3. Results

3.1. Grape yield and composition

The effect of the site was preeminent on total variance, but the effect

of soil degradation was also highly significant and highlighted a marked decrease of the yield and number of bunches per vine, as well as the average bunch weight and the weight of 100 berries (Table 3). The interaction between site and degradation was significant only for the number of bunches per vine. The highest effect of soil degradation was observed for grape yield, which overall was decreased by more than 50%, while lower reductions were recorded for the number of bunches per vine (about −37%), average bunch weight (−35%), and weight of 100 berries (−26.5%). In Slovenia, where only mean yield per vine was measured, soil degradation caused 87% decrease at vineyard Bonini (0.4 vs 3.0 kg) and 17% at Prade (2.5 vs 3.0 kg). The lower yield was caused either by a decrease in the number of bunches per vine (France), by a lower average bunch weight (Spain), or a combination of both variables (Italy). Berry weight only showed a trend towards higher values in ND, but the difference was only significant in the Spanish farm and at San Disdagio (Table 3). In both Turkey farms, hosting irrigated table grape production, no significant differences due to degradation in any of the four evaluated yield components were detected (average yield per vine 13.1 kg, number of bunches per vine 27, average bunch weight 469 g, 100 berry weight 728 g).

The amount of total soluble solids and berry titratable acidity significantly increased in D by ca. 9% and 4%, respectively, as well as pH (more 2.5%). The effect of farm was dominant, also in interaction with that of degradation; therefore, the increase of acidity due to degradation was significant only in San Disdagio and Bonini. With the exception of the vineyard in Prade, berries of degraded soils were richer in total soluble solids and showed higher pH values.

The quality of grapes for red wines is characterized by phenolic composition. Anthocyanins and polyphenol content of berries from Italy and France were positively influenced by the strong yield reduction, while in Spain, where the difference in production were less pronounced, no significant effect of degradation was observed (Table 1-suppl.). The coefficient of variation (CV) of all agronomic variables was generally larger in D than in ND plots.

3.2. Water and nutrient supply

The field observation of root pattern along the soil profile highlighted that all the studied vineyards had some limitation to deep rooting, like shallow occurrence of hard saprolite, or presence of horizon features such as compaction, scarce fertility, and high content of carbonates. Thus, rooting depth was always somehow limited. As all studied farms were located in climatic zones characterized by a more or less pronounced water deficit, an effect of a reduced water supply on soil functionality was expected, particularly in rainfed vineyards.

3.2.1. Impairment of water supply

Several soil physical and hydrological properties determining water supply were actually significantly influenced by soil degradation in the experimental vineyards. The main effect of degradation was on soil rooting depth, which was on average 88 cm in D, while it was 112 cm in ND. Rooting depth was more influenced by the effect of degradation ($F = 23.3$; $p < 0.01$) than by farm and not by the interaction term. Degradation increased bulk density ($F = 10.1$; $p < 0.05$) (Table 2, supplementary materials), while it did not impact clay content significantly, since the farm effect was dominant ($F = 24.7$; $p < 0.001$), although produced a significant interaction, pointing to a site-specific impact of erosion on soil texture. In all farms, AWC in D was lower than in ND ($F = 18.1$; $p < 0.001$). The SAI was deeply influenced by the farm ($F = 477.7$; $p < 0.001$) and the effect of degradation was not significant. The soil management with tillage or grass cover did not differentiate significantly soil hydrological properties.

3.2.2. Nutrient supply

Main soil features related to nutrient supply are TOC and TN contents. Although TOC is mainly indirectly related to nutrition, its value is actually deemed to characterize soil element availability (Campbell, 1978). Both TOC and TN were significantly affected by degradation throughout the 0–60 cm layer.

The highest differences in TOC content were observed at San Disdagio, Pech Redon, Bonini, and Prade farms, where D had 71%, 53%, 68% and 48% less TOC than ND, respectively. Instead, no significant TOC differences were found at Maison Blanche, Puelles and Celebi farms (Table 4).

Soil TN variations across the different sites and vineyards closely reflected that of TOC, as highlighted by the tight statistical correlation between TOC and TN ($R^2 = 0.809$, $p \leq 0.01$ at 0–20 cm depth and 0.877, $p \leq 0.01$ at 20–60 cm depth).

The TOC to TN ratio (C/N) showed only a few significant differences in relation to degradation, which occurred in the San Disdagio vineyards and consisted of a C/N reduction under D compared to ND (by 15% at 0–20 cm and 9% at 20–60 cm depth). Overall, C/N was highest at Tarsus site and lowest at San Disdagio site.

Ordinary surface soil tillage significantly lowered TOC (7.7 vs 12.4 g kg^{-1}, $F = 9.66$, $p \leq 0.01$) and TN (0.96 vs 1.39 g kg^{-1}, $F = 10.45$, $p \leq 0.01$) at 0–20 cm depth, in comparison with grass cover, but not C/N.

As far as soil cationic exchange properties are concerned, there was a significant effect due to degradation on soil CEC and exchangeable Ca in the 0–20 cm layer, and on the exchangeable K in the whole 0–60 cm depth range. Overall, in the surface layer degradation reduced CEC, Ca

Table 3
Influence of soil degradation on the main grape yield components over different farms across Europe.

Country	Farm	Bunches/vine (n)		Bunch w[b] (g)		Yield/vine (kg)		100 berries w (g)		TSS[c] (°Bx)		TA[d] (g/l)		pH	
		D[e]	ND	D	ND	D	ND	D	ND	D	ND	D	ND	D	ND
Italy	Fontodi	4.9**B**[a]	7.0**A**	144B	209A	0.71**B**	1.45**A**	180	193	24.5**A**	22.3**B**	6.19	6.20	3.15	3.12
	San Disdagio	6.5**B**	9.8**A**	99**B**	190**A**	0.81**B**	2.06**A**	156B	193A	24.9A	22.6B	5.01b	5.80a	3.4a	3.21b
France	Maison Blanche	7.5B	12.3A	124	176	0.97**B**	2.35**A**	121	142	–	–	–	–	–	–
	Pech Redon	5.9**B**	13.3**A**	73	153	0.53**B**	2.05**A**	128	174	–	–	–	–	–	–
Spain	Bodegas Puelles	9.1	9.3	184B	334A	1.72b	3.09a	210b	254a	25.1A	22.1B	–	–	3.30A	3.16B
Slovenia	Bonini	–	–	–	–	–	–	–	–	22.8A	19.7B	5.10b	5.41a	3.31B	3.41A
	Prade	–	–	–	–	–	–	–	–	18.3A	21.9B	6.69	5.99	3.18b	3.39a
All sites	*Mean*	*6.1***B**	*10.1***A**	122**B**	194**A**	*0.80*B	*2.00***A**	151**A**	175**B**	*24.0***A**	*22.0***B**	*5.68*	*5.92*	*3.28*	*3.20*
	CV[f]	*56*	*30*	*49*	*41*	*80*	*46*	*27*	*24*	*9*	*6*	*15*	*8*	*5*	*4*

[a] For each yield component, means followed by different letters are statistically different (lowercase, $p \leq 0.05$; uppercase, $p \leq 0.01$; uppercase-bold, $p \leq 0.001$).
[b] w: weight.
[c] TSS: total soluble solids (sugar).
[d] TA: titratable acidity.
[e] D: Degraded soil ND: Non-degraded soil.
[f] Coefficient of variation (%).

Table 4
Influence of soil degradation on soil total organic carbon (TOC, g kg^{-1}), total nitrogen (TN, g kg^{-1}) and TOC stock (Mg ha^{-1}) at the different experimental vineyards over different farms across Europe and Turkey.

Country	Farm	TOC		TN		TOC stock		TOC 20–60 cm		TN 20–60 cm		TOC stock 20–60 cm	
		0–20 cm depth						20–60 cm depth					
		D[a]	ND	D	ND	D	ND	D	ND	D	ND	D	ND
Italy	Fontodi	6.7b[b]	9.3a	0.98	1.16	14.4b	20.8a	5.7	6.0	0.82	0.85	21.4	25.4
	San Disdagio	3.4**B**	11.6**A**	0.78**B**	1.57**A**	6.9**B**	27.2**A**	3.5**B**	9.8**A**	0.73 **B**	1.34**A**	17.8**B**	50.5**A**
France	Maison Blanche	6.8	6.2	0.76	0.82	19.1	17.3	1.9	3.3	0.32	0.50	11.5	19.2
	Pech Redon	3.7**B**	7.9**A**	0.56**B**	0.97**A**	9.8B	19.3A	2.0	2.3	0.37	0.50	11.1	12.2
Spain	Bodegas Puelles	6.1	7.7	0.86	1.01	16.8	20.6	5.5	5.8	0.85	0.82	31.1	31.4
Slovenia	Bonini	4.8**B**	15.2**A**	0.60**B**	1.60**A**	10.4**B**	36.0**A**	3.3**B**	11.9**A**	0.41**B**	1.34**A**	10.0 **B**	60.1**A**
	Prade	12.0**B**	23.0**A**	1.40**B**	2.40**A**	28.3b	40.6a	9.4b	14.1a	1.03b	1.46a	45.7	33.7
Turkey	Celebi	4.8	7.6	0.53	0.64	13.9	21.0	–	–	–	–	–	–
	Evran	7.8b	11.1a	0.70	0.78	21.5b	29.4a	–	–	–	–	–	–
All sites	*Mean*	*5.9***B**	***9.7*****A**	*0.76***B**	*1.16***A**	*15.0***B**	*23.3***A**	*4.0***B**	*6.3***A**	*0.63***B**	*0.87***A**	*19.7***B**	*30.0***A**
	CV[c]	*39*	*42*	*31*	*37*	*39*	*32*	*60*	*59*	*42*	*43*	*59*	*53*

[a] D = degraded plot; ND = non-degraded plot.
[b] Within each site and depth range, means followed by different letters are statistically different (lowercase, $p \leq 0.05$; uppercase, $p \leq 0.01$; uppercase-bold, $p \leq 0.001$).
[c] Coefficient of variation (%).

and K in the surface layer by 15%, 18% and 24%, respectively (Table 5).

Based on all experimental cases pooled together, soil CEC was related to the clay and TOC contents by the multiple regression CEC = 0.46 + 0.42 Clay +0.38TOC (R^2 = 0.730, $p < 0.001$). However, when performing the regression analysis for D areas separately, TOC contribution to the relationship was no longer significant and the clay content was the only variable that correlated significantly to soil CEC (CEC = 2.86 + 0.41Clay; R^2 = 0.568, $p < 0.001$). Conversely, both TOC and clay were still significantly related to CEC across ND plots, according to the equation CEC = −1.32 + 0.41Clay +0.58TOC (R^2 = 0.895, $p < 0.001$).

The statistical analysis showed that degradation did not affect soil texture or pH across the considered depth range, but it increased the $CaCO_3$ content by 28% in the 0–20 cm layer, and decreased EC by 13% at 0–20 cm depth and by 17% at 20–60 cm depth.

3.3. Soil carbon sequestration and organic matter recycling

3.3.1. Soil carbon storage

In the studied vineyards, the degraded soils showed a clear reduction of their capacity to store carbon. Soil TOC stock in the 0–20 and 20–60 cm layers had the same trend as the respective TOC concentrations, with similar statistical results when evaluated in relation to degradation and farm factors (Table 4). The TOC stock was on average 35% and 34% lower in D than in ND, respectively, at 0–20 cm and 20–60 cm, but it was not statistically different in the two depth ranges. The carbon stock in both depth ranges was lower under tillage (Table 1) than under grass cover (respectively, 18.6 vs 22.0 Mg ha^{-1} on surface and 24.0 vs 28.1 Mg ha^{-1} in depth), but the difference did not reach the statistical significance, because of the high local variability.

3.3.2. Soil enzymes

On average, the degraded areas showed a 19% lower enzyme activity (Table 3, supplementary materials). In particular, Bodegas Puelles in Spain, the two French and Italian sites, Bonini in Slovenia and Evran in Turkey showed higher activities of all enzymes in ND, but Prade in Slovenia and Celebi in Turkey showed lower enzyme activities in ND.

The discriminant function analysis highlighted a leading effect of the site, which accounted for the maximum variation (Fig. 2). Soils from Slovenia showed the maximum separation between D and ND. Non-degraded areas of Bonini, Prade and San Disdagio were positively correlated with Root 1 and negatively with Root 2, reflecting mostly BUT activity. Root 1 was correlated with all enzymes with the exception of NAG, AC and ARYL; Root 2 with all enzymes with the exception of β-G.

3.3.3. Collembola and Acari

The effect of degradation was significant (χ^2 = 12.0, df = 1, $P < 0.001$) and explained about 14% of the variation of Collembola abundances, while the farm effect explained about 26% of the total variance. On average over all farms and samples, Collembola abundance was 18% higher in ND than D (Fig. 3a, b, c). Focusing on the different functional groups within Acari, the responses were contrasted between predator and parasitic taxa (Gamasina), with no effect of degradation (χ^2 = 0.25, df = 1, P = 0.615), and decomposers (Oribatida) which showed, similarly to Collembola, a significant increase of their abundance in ND (χ^2 = 103.3, df = 1, $P < 0.001$).

3.3.4. Decomposition rate

Litter stabilisation factor S and decomposition rate k values were not significantly different between D and ND (χ^2 = 0.17, df = 1, P = 0.68 and χ^2 = 0.76, df = 1, P = 0.39, respectively). However, as

Table 5
Influence of soil degradation on soil cation exchange capacity (CEC), exchangeable Ca and K, total equivalent $CaCO_3$ and electrical conductivity (EC) at the different experimental vineyards over different farms across Europe.

Soil feature[a]		0–20 cm depth		0–60 cm depth	
		D[b]	ND	D	ND
CEC cmol(+) kg^{-1}	Mean	13.0B[c]	15.3A	14.1	14.6
	CV[d]	*48*	*52*	*48*	*50*
Ca cmol(+) kg^{-1}	Mean	11.3B	13.8A	12.4	13.2
	CV	*56*	*55*	*56*	*51*
K cmol(+) kg^{-1}	Mean	0.31B	0.41A	0.22B	0.26A
	CV	*37*	*39*	*44*	*41*
$CaCO_3$%	Mean	33.5a	26.7b	32.7	27.5
	CV	*61*	*74*	*63*	*71*
EC mS cm^{-1}	Mean	0.12b	0.14a	0.11b	0.14a
	CV	*16*	*15*	*19*	*35*

[a] No data available for Turkish sites; EC data not available from French sites.
[b] D = degraded plot; ND = non-degraded plot.
[c] Within each depth range, mean values followed by different letters are statistically different (lowercase, $p \leq 0.05$; uppercase $p \leq 0.01$).
[d] Coefficient of variation (%).

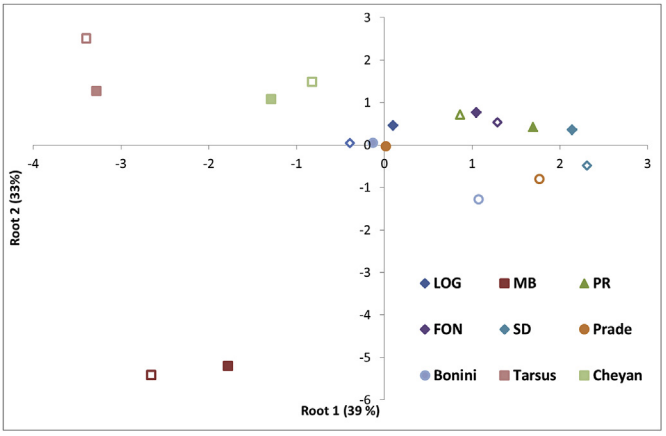

Fig. 2. Discriminant function analyses performed with enzyme activities in the different sites and degradation status (degraded filled symbols, non-degraded open symbols). Group centroids represent the average of replicates for each site. LOG: Bodegas Puelles; MB: Maison Blanche, PR: Pech Redon, FON: Fontodi, SD: San Disdagio.

already shown, soil parameters are different between D and ND and are supposed to influence decomposition processes, such as k and S. We then tested the effects on uncorrelated soil parameters that were different in D and ND: clay content, C/N ratio and nitrogen content. Decomposition rate significantly increased with clay content ($t = 1.99$, $df = 65$, $P = 0.049$) and marginally with nitrogen content ($t = 1.83$, $df = 65$, $P = 0.072$) but no effect of C/N ratio was found ($t = -0.66$, $df = 65$, $P = 0.51$). Conversely, S significantly decreased with the increase of C/N ratio value ($t = -2.53$, $df = 65$, $P = 0.014$) but marginally increased with clay content ($t = 1.88$, $df = 65$, $P = 0.064$). No effect of nitrogen content was found ($t = 1.26$, $df = 65$, $P = 0.21$).

3.4. Biodiversity

3.4.1. Genetic fingerprinting of microbial communities

In microbial community assessments of bulk soil, richness and evenness were not significantly different between D and ND ($\chi^2 = 1.07$, $df = 1$, $P = 0.30$ and $\chi^2 = 2.13$, $df = 1$, $P = 0.14$, respectively) whereas Shannon diversity significantly decreased in ND ($\chi^2 = 8.53$, $df = 1$, $P = 0.00530$ and t-value $= -2.92$).

Microbial community analyses targeted fungi and Eubacteria from both rhizosphere soil and roots, leading to 16 DGGE dendrograms. In 5 out of the 16 analyses, 3–5 more bands were seen in ND compared with D. In 7 of the 16 analyses, 3–7 less bands were seen in ND compared with D of the same location.

Dendrograms illustrating Dice cluster similarities suggested for 11 of the 16 analyses that communities from either D or ND were relatively similar, but dissimilar when D were compared with ND. In 8 of the 11 inferences from France and Slovenia clear groupings were retrieved (Fig. 4 A, B, D, E). All dendrograms from Italy showed that groupings of samples from D or ND were inconsistent (Fig. 4C, F).

4. Discussion

The results of grape yield confirmed the empirical observation of farmers. Degraded areas clearly differed from non-degraded in terms of yield and yield components, with the exception of the Turkey sites, where vines were irrigated for table grape production. The fact that grapevines grown on D soils yielded more ripened fruits than in ND may seem contradictory. However, the results call for a larger concentration of solutes and higher levels of maturity in berries coming from D plots, because of the strong reduction in yield caused by the impairment of certain soil functions. Decoupling the specific impact of soil degradation on metabolic processes from the physiological effect of sharp yield cutback could not be fully addressed with the available data. However, a tentative analysis of variance for total soluble solids and acidity variables that considered the yield per vine as a co-variable (data not shown) also confirmed the differences in grape composition. Therefore, it can be inferred that soil degradation potentially altered berry composition, beyond the indirect effect of yield reduction. Similar results were found for the total anthocyanins and polyphenols content of berries, with soil degradation leading to more intensely coloured berries and a higher polyphenol content.

Agronomic results always showed a larger coefficient of variation in D than in ND. Spatial fickleness of vine phenology can jeopardize a proper agricultural husbandry and stress the need of a site-specific agrotechnique. A larger vine variability can be attributed to the erosion processes and pre-planting deep ploughing, which have brought to the surface substrata of different characteristics, as evidenced by the site-specific effect of degradation on soil clay content.

One of the major factor explaining the anomalous vine behaviour in D was the lower soil potential water supply, determined by the shallower rooting depth and lower AWC, as well as the higher bulk density. As for soil chemical fertility, it must be considered that red wine quality benefits from relatively low soil fertility, and high levels of organic matter may have negative effects on wine quality, by increasing nitrogen concentration and reducing flavour (Arnó et al., 2011). On the other hand, low values of organic matter may seriously compromise soil aptitude to meet the minimum nutritional requirements of the vines, and reduce the ecological sustainability of viticulture, because of the strong implications for soil physical stability, water flow regulation and soil biodiversity. In the soils studied, organic matter content was a key component of chemical fertility, as highlighted by the close correlation between TOC and TN, as well as by the contribution of TOC as explanatory variable of CEC. Soil organic carbon showed a high sensitivity to soil degradation, resulting one of the most effective soil component in differentiating degraded from non-degraded areas.

The capacity to stock carbon is a major soil function. Degraded plots

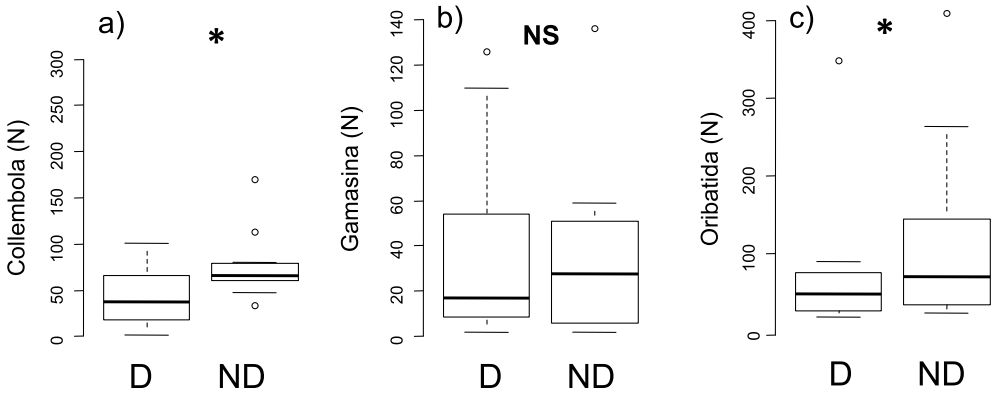

Fig. 3. Box-and-whisker plot of a) Collembola, b) Acari Gamasina, c) Acari Oribatida abundances in degraded (D) and non-degraded (ND) areas in Italian and French vineyards. Black horizontal lines are median values, boxes are interquartile ranges (27–75 percentiles) and whiskers represent maximum and minimum ranges. * significant at $p < 0.05$; NS: not significant.

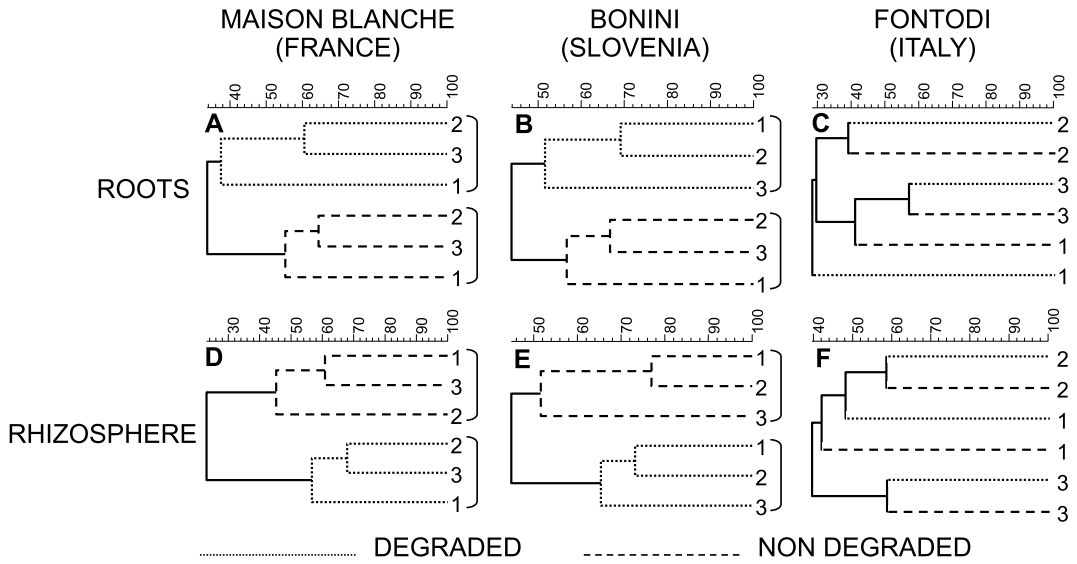

Fig. 4. Dice cluster analyses of DGGE gel profiles from eubacterial (A, C, F) and fungal (B, D, E) communities obtained from roots (A, B, C) or rhizosphere soil (D, E, F) in vineyards of France/Maison Blanche (A, D), Slovenia/Bonini (B, E), and Italy/Fontodi (C, F). Dashed lines represent samples from non-degraded areas; dotted lines from degraded areas. Scale bar numbers indicate similarities among microbial profile patterns.

had, in absolute terms, the lowest TOC concentrations and stocks (and accordingly the lowest TN). However, it is worth noting that in a number of sites, such as Maison Blanche, Pech Redon, Bodegas Puelles and Celebi, TOC concentration was low even in ND, averaging below 0.8%, and below 21 Mg ha^{-1} as carbon stock in the 0–20 cm depth increment. The carbon stock values in ND resulted lower than reported by Chiti et al. (2012), who found mean stock values (0–30 cm) of 41.9 ± 15.9 Mg ha^{-1} in Italian vineyards, comparable with about 28 Mg ha^{-1} in 0–20 cm. Values were more similar to those of France, where Arrouays et al. (2001) found carbon stock in tree crops (0–30 cm) ranging from 15 to 39 Mg ha^{-1} (correspondent to 10–26 Mg ha^{-1} in 0–20 cm).

Although carbon density lowered in depth, the accumulation in the 20–60 cm resulted higher than in the 0–20 cm layer. This result confirms what reported in vineyards of central Italy about the ability of vines to increase the total organic C content in the deepest soil horizons, because of root turnover and rhizodeposition processes (Agnelli et al., 2014).

Agricultural husbandry can improve soil functionality, however, irrigation, coupled with tillage, was not able to improve carbon sequestration in the Turkish vineyards, although grape yield was higher. Grass cover, in comparison with surface tillage, was found to slightly improve TOC and TN, but not soil physical properties. Organic management was the same in D and ND, nevertheless, soils of the degraded areas showed different symptoms of nutrient deficiency or unbalance, possibly arising from: i) reduced levels of TOC and ii) TN, iii) lower CEC, consequence of the TOC reduction, iv) lower C/N, thus a worse stability of organic matter, v) higher amount of carbonates in the topsoil.

Biological diversity and activity, monitored by different proxies (microarthropods, TBI for decomposition rate and litter stabilisation), did not show clear differences between D and ND. A slightly higher abundance of the main groups of decomposers, such as Collembola and Oribatida, was registered in ND in Italy and France. These groups, as biological regulators, are particularly sensitive and can show intermediate stages during environmental changes, because of their resistance to environmental stresses and specific role in bottom-up biotic interactions (European Commission, 2010).

Observed diversity indexes on microbial communities suggested high species richness and evenness, but also these parameters did not describe clear differences between D and ND. Nonetheless, a qualitative evaluation of microbial communities of Eubacteria and fungi from rhizosphere soil and roots suggested that the specific conditions present in either D or ND have an influence on microbial community structure. While these differences were found in France and Slovenia, no such tendencies were observed in Italy, where compost had been applied in both D and ND for several years. It is possible that this long-lasting addition of compost has had an effect on the development of more similar microbial communities.

Soil enzyme activities are widely used as sensitive indicators of changes in soil functioning and health, contributing to biogeochemical cycling, organic matter transformations and nutrient availability (Aon et al., 2001; Badiane et al., 2001; Vepsäläinen et al., 2001). Overall, higher enzyme activities found in ND than D suggested a better soil functionality and organic matter cycling. The general trend mainly followed that of soil organic matter stock, with few exceptions related to the particular sites of Celebi and Prade. In these sites, enzyme activities were lower in ND, although TOC was higher, suggesting different sources of substrates other than soil organic matter. Indeed, most of the measured hydrolytic enzymes have been detected in microorganisms, plants and animals, thus several mechanisms for enzyme release may be hypothesized. In particular, the only two enzymes showing higher activity in ND in Celebi were NAG and ARYL, which are indicators of N and S demand and high fungal biomass (Bandick and Dick, 1999). Both enzymes showed on average the largest difference between D and ND, confirming DGGE profiles results, which highlighted a clear separation of fungal communities between the two thesis. Moreover, C mineralizing enzymes involved in the degradation of cellulose (β-G and CELL) and hemicellulose (XYL) were highly responsive in most sites, suggesting a better functioning of soil organic matter cycling and providing early indication of changes in C sequestration (Debosz et al., 1999; Bergstrom et al., 2000). Even if not so evident, the general lower activity of AC and BUT suggested a less active microbial community in degraded soils. In fact, both enzymes are endocellular and their activities are considered to describe intracellular processes and active presence of microbial biomass (Wittmann et al., 2004). Taken together, these results suggest an unbalance in the capacity of soil organisms to decompose recalcitrant compounds and/or macromolecules (e.g. cellulose, chitine) with high C/N ratio in D, with respect to ND. Therefore, the application of recalcitrant residues might delay or even worsen the restoration of these severely eroded soils.

5. Conclusions

This multidisciplinary study highlighted that eroded soils of rainfed vineyards showed a marked decrease of wine grape yield. The reduced production induced a concentration of juices in berries that led to an excess of sugar and polyphenols accumulation, which can be detrimental to wine grape quality. On the other hand, irrigation could effectively counterbalance natural low water supply for table grape production.

In parallel with the detriment of agro-ecosystem services, we observed an impairment of soil functions related to water and nutrient supply, evidenced by shallower rooting depth, lower AWC, total nitrogen and cation exchange capacity, higher bulk density and concentrations of carbonates. Thus these physical, hydrological and chemical soil features can be considered the main indicators of the soil malfunctioning observed by farmers.

Soil degradation was also highlighted by the reduced biological functionality, in particular, the ability of sequester carbon and recycle organic matter. To this regard, the abundance of Acari Oribatida and Collembola, which have specific key functions in soil ecosystems as biological regulators, resulted the most sensitive indicator of soil degradation among the considered microarthropods.

Another sensitive indicator was the enzymatic activity. Our research work evidenced the poor capacity of eroded soil to decompose recalcitrant organic matter, because of the scarcity of organisms able to attack the more complex organic forms.

In conclusion we can say that, in spite of the ability of vine to expand the rooting system to depth, the decreased soil functionality caused by excessive earth works before plantation, or by accelerated erosion, could not be remediated by ordinary organic viticulture, and more intense and specific organic treatments are needed to restore soil fertility in the degraded areas. A strategy to soil restoration should be addressed to the application of easily decomposable organic substances to increase, or accelerate, soil ability to recycle organic matter. Instead, the spreading of organic matrices more resistant to decomposition, and with high C/N ratio, should be avoided, since it might reduce the speed of soil organic matter cycling.

Future research works should be oriented in testing the effectiveness of the use of different organic matrices, such as cover crops, grass dry mulching, compost organic fertilizers, green manure, coupled with different soil cultivation methods, to restore carbon content and biological activity not only at the soil surface, but also deeper in soil profile and rooting depth.

It is also recommended that agricultural policies would consider planning earth works before planting new vineyards, so that they are properly dimensioned according to both original and desired soil functionalities. Actually, the sustainable approach to crop management should start before vine plantation and continue until the end of the cultivation, so to maintain or possibly increase soil fertility along the years, and support adequately all agro-ecosystem services.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2018.06.065.

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