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The soil quality concept as a framework to assess management practices in vulnerable agroecosystems: A case study in Mediterranean vineyards

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ABSTRACT

Land management aiming to sustain ecosystem services is an important issue, especially in biodiversity hot spots such as found in Mediterranean areas. In Mediterranean areas, viticulture is an important land use. Vineyards are frequently found on inherently poor soils and are submitted to intensive management practices, which threaten soil functioning and associated ecosystem services. To encourage winegrowers and stakeholders to be reflective and adapt their vineyard practices, we evaluated the effects of three soil management practices (inter row plant cover duration, weeding and fertilization strategies) on soil functioning in 146 commercial plots distributed in Southern France, by a complementary set of biological and physico-chemical indicators. We used the concept of soil dynamic quality to evaluate some soil management practices on soil functioning. The influence of inherent soil properties derived from pedogenesis on soil dynamic indicator response was accounted for by considering the response of soil indicators for three soil groups differing in their stoniness and Ca carbonate content. The three soil management practices systematically influenced some nematode-based indicators, whereas other indicators were ascribable to a specific soil type or practice. We demonstrated that the potential of soil management practices to enhance soil functioning is restricted by soil type. In particular for calcareous soils, the soil functioning is very stable limiting effects of soil management practices. The presence of a cover crop, even temporary, in the inter row, is the only practice which benefits soil functioning whatever the soil type whereas organic fertilization and chemical weeding exhibit contrasting results on soil functioning.

1. Introduction

Viticulture is an important economic activity and a cultural legacy in many Mediterranean regions around the world (Jones et al., 2005). Ecosystem services provided by Mediterranean vineyards are particularly threatened, because soil functions are often impaired by yearly-repeated intensive agricultural practices for vine vigour control or weed and pest management. Soil erosion, soil organic matter (SOM) depletion, compaction, pollution, and loss of biodiversity are regularly cited in the literature (Chaignon et al., 2003; Chopin et al., 2008; Coulouma et al., 2006; Komarek et al., 2010; Le Bissonnais et al., 2007; Martinez-Casasnovas et al., 2009; Raclot et al., 2009, Polge de Combret-Champart et al., 2013). Moreover, the Mediterranean climate is characterized by severe summer drought with violent storms promoting soil degradation (González-Hidalgo et al., 2007; Ruiz-Colmenero et al., 2011), erosion and run-off to surface waters. The boom of organic viticulture (Stolz and Schmid, 2007; Schmid et al., 2011) and more generally the increased demand for wine products with a smaller environmental footprint (e.g. reduced loss of nutrients, lower net greenhouse gas emissions, less energy use and pollution), underscore the need to enhance soil organic matter (SOM) content and consequently

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ecosystem services. The concept of soil quality, defined by Doran and Parkin (1994) as "the ability of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health", is central in the notion of ecological intensification to achieve sustainable yields (Cassman, 1999). It is nowadays commonly used in response to concerns about the contribution of soil functioning to ecosystem services (Bispo et al., 2011). Two different aspects of soil quality are distinguished (Karlen et al., 1997; Wienhold et al., 2004): (i) inherent (or use-invariant) soil quality and (ii) dynamic soil quality. The former is intimately linked to pedogenetic processes and associated soil types and climates, whereas the latter refers to agricultural practices affecting soil functioning and applies to the surface layer (the first 0–30 cm of soil (Karlen et al., 2003)). Both aspects can be estimated by measurable physico-chemical and biological indicators (Salome et al., 2014).

Vineyard management includes diverse agricultural practices, which all affect soil functioning. Mechanical weeding, for instance, can decrease the soil organic carbon (SOC) content (Mazzoncini et al., 2011; Six et al., 1999), induce physical degradation of vineyard soils (Coulouma et al., 2006), or modify soil biological communities at different trophic levels (Sanchez-Moreno et al., 2006; Schreck et al., 2012). Conversely, soil amendment or organic fertilization improves soil structure and SOM content (Pérès et al., 1998; Navel and Martins, 2014), with contrasting results depending on both quantity, and quality of the organic matter applied (Navel and Martins, 2014). Plant cover in vineyards contributes to essential services such as water infiltration, carbon sequestration, nutrient supply and retention, and reduction of soil erosion (Mazzoncini et al., 2011; Peregrina et al., 2010; Ruiz-Colmenero et al., 2013; Smith et al., 2008; Steenwerth and Belina, 2008b). Wine growers in Mediterranean regions are nevertheless reluctant to use cover crops, due to concerns about water competition between cover crops and grapevines (Celette et al., 2009; Celette and Gary, 2013; Tesic et al., 2007) even if in the last years the use of intercropping has increased in Mediterranean vineyards (Mercenaro et al., 2014). Trade-offs between competition for resources and services provided by cover crops have to be reduced (Ruiz-Colmenero et al., 2011) through adapted cover crop management. Dynamic soil quality monitoring, using responsive indicators adapted to the local soil type and climate, could help to fine-tune management practices aiming to optimize soil functioning. Soil quality monitoring is a promising component of innovative and flexible soil management strategies that would respond to the complexity of vineyard soils and practices combined with climatic constraints (Ripoche et al., 2010). Recent developments in soil biology and ecology contribute to the evaluation of soil quality, as they offer new and complementary dynamic indicators to the classical, chemical indicators of soil functioning (Coll et al., 2011; Probst et al., 2008; Steenwerth and Belina, 2008a; Virto et al., 2012; Salome et al., 2014).

While land management is reasoned at the landscape or farm level (Herrick, 2000), most soil quality evaluations are point-based, which reduces their usefulness for land management. Winegrowers have the additional concern of tailoring their land management to the specificities of their *Terroir* (Van Leeuwen et al., 2004), which are partly based on inherent soil quality derived from pedogenesis.

The objective of our study was to evaluate the influence of soil management practices on soil quality in Languedoc-Roussillon vineyards of Southern France, in order to encourage winegrowers to be reflective and adapt their own practices to achieve environmental, social and economic sustainability. The soil quality concept is a useful framework to discuss soil management practices in the context of agroecological paradigms. In a previous study in the same region, Salome et al. (2014) measured the values of 23 soil indicators on a large number of vineyard plots, in order to produce a precise and comprehensive reference dataset of soil dynamic quality. The mean value and range of these indicators were presented for the different soil groups found in the studied region. In the present study, we focused on the effects of farming practices according to soil groups. We selected the three practices that were most commonly cited by surveyed winegrowers, and for which strongly contrasting strategies were observed: (i) inter-row plant cover, which could be inexistent, temporary or permanent; (ii) weeding, which could be chemical, mechanical or replaced by mowing; and (iii) fertilization, which could be based on organic or mineral compounds. We thereafter considered these strategies as different proxies of soil perturbation intensity like in Cluzeau et al. (2012). Finally, we analyzed the response of 23 physical, chemical and biological indicators of dynamic soil quality to these management options, in 146 vineyard soils clustered into three soil groups according to their inherent soil quality.

2. Materials and methods

2.1. Localization and sampling

In a previous study, Salome et al. (2014) described 164 vineyard plots representative of the heterogeneity of landscapes and management practices in the Languedoc Roussillon region (France), which were sampled between March and May 2009. We encourage readers to refer to Salome et al. (2014, Fig. 1) for a map with details of studied areas. We ensured from winegrowers that all plots were conducted with the same management during the 5 years preceding the sampling year. None of the selected plots were irrigated. The initial dataset of Salome et al. (2014) is reduced to 146 plots for the present study. Indeed, the 18 plots from the Aigues Mortes zone (43°36′27″N, 2°46′14″E, Arenosols, WRB soil classification) included in the dataset of Salome et al. (2014) were not selected in the present study because management practices were specifically adapted to this particular soil type (with saline, alkaline and sandy soils) and therefore insufficiently contrasted in terms of practices. In the present study, the 146 selected vineyard plots are located around the towns of Jonquière Saint Vincent (43°49′38″N, 4°33′48″E, mainly Red Grenache and Syrah with double Royat cordon trellising, and Rhodic Luvisol), Montagnac (43°28′50″N, 3°29′02″E, a variety of cultivars, dominated by White Picpoul and Red Syrah with double Royat cordon vine training, Calcisols), Faugères (43°33′57″N, 3°11′19″E, mainly Red Grenache, Syrah and Carignan with Gobelet and double Royat cordon, Cambisols), Lesquerde (42°48′01″N, 2°31′47″E, mainly Red Syrah and Carignan with a dominance of Gobelet, double Royat cordon and simple Guyot, Arenosols), Saint-Hippolyte-du-Fort (43°57′56″N, 3°51′28″E, mainly Red Grenache conducted with double Royat cordon, Calcisols), Saint-Victor-la-Coste (44°03′38″N, 4°38′29″E, mainly Red Syrah, Carignan and Cinsault with exclusively double Royat cordon, Calcisols), Terrats (42°36′27″N, 2°46′14″E, a variety of cultivars with a dominance of White Muscat and exclusively Gobelet and double Royat cordon, Luvisols and Cambisols) and Vergèze (43°44′37″N, 4°13′14″E, mainly Red Cabernet Sauvignon and to a lesser extent Merlot with a majority of double Royat cordon, Cambisols). The 146 plots were assigned to 3 main soil groups (A, B, C), defined on the basis of their Ca carbonate and stone contents, in order to take into account the influence of the most determining inherent soil properties on soil dynamic indicators, identified in Salome et al. (2014) i.e. Ca carbonate content, stoniness and texture. Group A includes all non-stony calcareous soils in the fine or medium FAO textural class (sub-classified according to texture as groups 2 and 3 in Salome et al., 2014); Group B corresponds to non-stony and non-calcareous soils characterized by the medium or coarse FAO textural class (sub-classified as groups 4 and 5 in

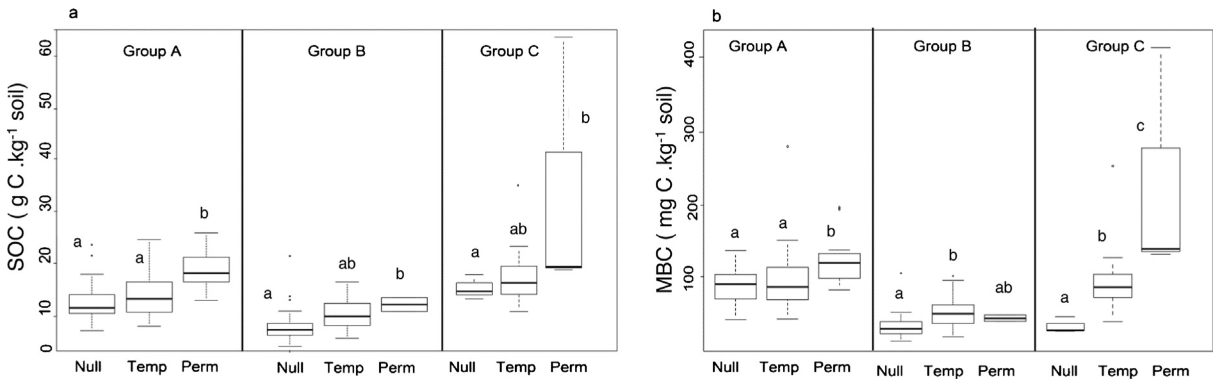

Fig. 1. Effect of plant cover duration on (a) Soil Organic Carbon SOC (g C kg^{-1} soil) and (b) Microbial Biomass Carbon MBC (mg C kg^{-1} soil) for each of the three soil groups. Different letters indicate significant differences between plant cover durations ($p \leq 0.05$). Null, Temp and Perm correspond to respectively Null (NPC), Temporary (TPC) and Permanent Plant (PPC) Cover duration. Numbers of plots per group and practices are indicated in Table 1. Box plots represent dispersion of the data with the median (thick line), first and fourth quartile (thin lines), whiskers extend to the most extreme data point which is no more 1.5 times the interquartile range from the box), outliers being represented by circles.

Salome et al., 2014); and Group C corresponds to stony (more than 50% of particles larger than 1 cm diameter) and non-calcareous soils (i.e. group 6 in Salome et al., 2014). In this way, each of the three soil groups contained plots with contrasting management strategies, and was therefore adapted for further statistical analysis, which would not have been possible with the finer initial classification of Salome et al. (2014).

Per plot, ten subsamples were taken in the inter-row of the vineyard from the 0–15 cm topsoil using a gouge auger and carefully homogenized to form a soil composite. Any plant residues or roots were carefully removed before analysis. The 0–15 cm layer was selected according to other studies on soil quality in vineyards (Reeve et al., 2005; Reuter and Kubiak, 2003). Each soil composite was then analyzed to determine the soil physical, chemical and biological indicators as fully described in Salome et al. (2014) and summarized in part 2.2. Furthermore 3 samples per plot were taken in the 0–15 cm layer using a cylinder (15 cm in height and 8 cm in diameter) for bulk density measurements.

The classification of vineyard plots according to soil type and strategy for three main practices: (i) type of fertilization, (ii) inter row weeding, and (iii) plant cover in the inter row, is presented in Table 1. After extraction of qualitative data on these practices from the questionnaire answers, plots were categorized into strategies given as proxies of perturbation intensity, in a similar way as Cluzeau et al. (2012). Fertilization practices were separated into two main options: organic (or organo-mineral) inputs versus mineral fertilization. Inter row weeding was categorized as mechanical, chemical, or inexistent (i.e. replaced by mowing). Finally, plant cover in the inter row was categorized into three types according to its duration: null plant cover or NPC (0–4 months per year, corresponding to winter-time plant cover), Temporary Plant Cover or TPC (4–7 months per year), and permanent plant cover or PPC (more than 8 months per year).

2.2. Soil indicators

Table 2 gives the list of the 23 measured or calculated indicators of dynamic soil quality. We encourage readers to refer to Salome et al. (2014) for a full description of the corresponding methods (section 2.2, pp. 84 and 85). The composite soil samples were sieved using a 1 cm mesh before biological analyses and sieved at 2 mm before physical and chemical analyses. The physical indicators are water content at field capacity (WFC) and bulk density (BD). The chemical indicators are soil organic carbon (SOC) and total nitrogen (N_{tot}) contents, cobaltihexamine cation exchange capacity or effective CEC at soil pH as determined with cobalthexamine extraction (CEC), available phosphorus (P), potassium (K) and copper (Cu) contents, based on water extraction. Microbial biomass carbon (MBC), Total abundance of Nematodes (TotNem) and abundance of nematodes in five trophic groups – obligate plant-feeders (OPF), facultative plant-feeders (FPF), bacterial-feeders (Ba), fungal-feeders (Fu) and omnivores and predators (Om-Pr) are the biological indicators of this study. In addition, five nematode ecological indices were calculated, as further explained in Table 2: Maturity Index (MI), Plant Parasitic Index (PPI) (Bongers, 1990; Bongers et al., 1997), Enrichment Index (EI), Structure Index (SI) (Ferris et al., 2001) and Nematode Channel Ratio (NCR) (Yeates, 2003). The calculation of these indices is based on the cp-value (colonizer-persister scale) of nematode genera. Finally, the MBC/SOC ratio was calculated to indicate the availability of substrate to microorganisms (Anderson and Domsch, 1989). For obvious practical reasons, bulk density (BD) was not measured in the stony soils (soils in group C).

2.3. Statistical analysis

We first conducted a variance partitioning analysis of our dataset, using a series of partial Redundancy Analyses (RDA), to display variability of the patterns constrained by factors of interest (plant cover duration, fertilization, and weeding). The significance of the full model and partial RDA models was tested with the Monte Carlo permutation test. We used the Vegan package with R software (R Core Team, 2012) to conduct this analysis. After this preliminary study, we performed a three way ANOVA to test the effect of plant cover duration, weeding, and fertilization for each of the indicators listed in Table 1. To take into account the unbalanced design of our data set we chose to use the “Car” package with ANOVA type II (Langsrud, 2003) and we repeated ANOVAs by changing the order of the factors in the models. Square root or log transformation of variables was in some cases necessary to achieve conditions of ANOVA application. These statistical analyses were carried out for the three soil groups separately. The interactions between the three factors were not tested, as the design did not allow it. In the present study, we considered the alternative hypothesis as true only if all combination of models were significant, with a threshold p-value <0.05. Tukey post hoc tests were afterwards performed. Box plots were performed by the default R method.

Table 1
Fraction (%) of plots managed according to different weeding techniques, plant cover and fertilization strategies for each soil group. Non org F refers to mineral fertilization only, whereas Org F stands for farmers applying at least some organic fertilizers. NA = not available.

Group A: non-stony, calcareous soils Number of plots = 77	Null plant cover		Temporary plant cover		Permanent plant cover		Total by weeding type
	Non org F	Org F	Non org F	Org F	Non org F	Org F	
Chemical weeding	3%	5%	13%	4%	4%	1%	**30%**
Mechanical weeding	5%	17%	4%	27%	–	3%	**56%**
Mowing	–	–	–	–	8%	6%	**14%**
Total by plant cover duration	**30%**		**48%**		**22%**		**100%**
Group B: non-stony, non-calcareous soils **Number of plots = 50**	**Null grass cover**		**Temporary grass cover**		**Permanent grass cover**		**Total by weeding type**
	Non org F	Org F	Non org F	Org F	Non org F	Org F	
Chemical weeding	10%	2%	4%	NA	–	–	16%
Mechanical weeding	12%	18%	16%	34%	–	–	80%
Mowing	–	–	–	–	–	4%	**4%**
Total by plant cover duration	**42%**		**54%**		**4%**		**100%**
Group C: stony, non-calcareous soils **Number of plots = 19**	**Null grass cover**		**Temporary grass cover**		**Permanent grass cover**		**Total by weeding type**
	Non org F	Org F	Non org F	Org F	Non org F	Org F	
Chemical weeding	16%	–	21%	5%	–	–	42%
Mechanical Weeding	–	–	21%	21%	–	–	42%
Mowing	–	–	–	–	11%	5%	**16%**
Total by plant cover duration	**16%**		**68%**		**16%**		**100%**

Table 2
List of the dynamic 23 soil quality indicators and associated soil functions.

	Abbreviation	Units	Meaning as indicators of soil quality
Physical indicators			
Bulk density	BD	$g\,cm^{-3}$	Compaction
Water content at field capacity	WFC	% (w/w)	Water retention
Chemical indicators			
pH		without unit	
Total soil organic carbon content	SOC	$gC\,kg^{-1}$ soil	
Total soil nitrogen content	N_{tot}	$gN\,kg^{-1}$ soil	
C/N			Soil resources
Available P content	P	$mg\,kg^{-1}$	
Available K content	K	$mg\,kg^{-1}$	
Effective cation exchange capacity	CEC	$cmol^{+}\,kg^{-1}$	
Available Cu content	Cu	$mg\,kg^{-1}$	Soil contamination
Biological indicators			
Total nematode abundance	TotNem	ind. 100 g^{-1} dry soil	Micro food web
Obligate plant-feeding nematodes	OPF	ind. 100 g^{-1} dry soil	
Facultative plant-feeding nematodes	FPF	ind. 100 g^{-1} dry soil	
Bacterial-feeding nematodes	Ba	ind. 100 g^{-1} dry soil	
Fungal-feeding nematodes	Fu	ind. 100 g^{-1} dry soil	
Omnivores + predatory nematodes	Om_Pr	ind. 100 g^{-1} dry soil	
Microbial biomass carbon	MBC	$mgC\,kg^{-1}$ soil	Soil biological activity
Contribution of microbial biomass to soil organic carbon	MBC/C_{org}	without unit	Provides information on the availability of substrate for microorganisms
Nematode ecological indicators			Indicators of the structure of nematode communities
Maturity Index (MI)	MI	Without unit	Provides information on environmental perturbation and contamination. Scored between 1 and 5, MI increases with environmental stability.
Plant Parasitic Index (PPI)	PPI	Without unit	A maturity index taking into account only plant feeding nematodes. Scored between 2 and 5.
Enrichment Index (EI)	EI	Without unit	Provides information on the availability of resources. Scored between 0 et 100, EI increases with the availability of resources.
Structure Index (SI)	SI	Without unit	Provides information on environmental stability and the length of the micro-foodweb. Scored between 0 and 100, SI increases with environmental stability
Nematode Channel Ratio (NCR)	NCR	Without unit	Expresses the decomposition pathways. When the ratio is close to 1, bacterial-feeders dominate; when the ratio is close to 0, fungal-feeders dominate.

Table 3
Results of ANOVAs testing the effect of the 3 management practices on the 23 indicators (list in Table 1) and for 3 different soil groups. **, *** stand for *p* value significance, respectively $p < 0.05$, and $p < 0.01$; ns = non-significant; ND = not determined.

	Soil indicators																						
	BD	WFC	C_{org}	N_{tot}	C/N	pH	P	K	Cu	CEC	MBC	TotNem	OPF	FPF	Ba	Fu	OmPr	MBC/C_{org}	MI	PPI	EI	SI	NCR
Group A: non stony, calcareous soils																							
Plant cover duration	ns	ns	**	***	ns	ns	ns	ns	ns	ns	***	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Weeding management	***	ns	ns	ns	ns	**	ns	ns	***	ns	ns	ns	ns	ns	ns	ns	ns	ns	***	ns	***	***	**
Fertilization	ns	ns	ns	ns	**	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Group B: non stony, non-calcareous soils																							
Plant Cover Duration	ns	ns	**	ns	ns	ns	ns	ns	ns	ns	**	ns	ns	ns	ns	ns	ns	ns	ns	**	ns	ns	ns
Weeding management	ns	***	ns	ns	ns	***	ns	ns	ns	***	ns	ns	ns	***	ns	ns	**	ns	ns	ns	ns	ns	ns
Fertilization	***	***	***	***	**	ns	ns	ns	**	***	***	ns	**	**	ns	ns	ns	**	ns	ns	ns	ns	ns
Group C: stony, non-calcareous soils																							
Plant cover duration	ND	ns	**	ns	ns	ns	**	ns	***	ns	***	***	**	ns	***	***	***	***	***	ns	ns	***	**
Weeding management	ND	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	***	ns	ns	**	***	**	ns	ns	ns	ns	ns	ns
Fertilization	ND	ns	ns	ns	**	ns	**	ns	***	ns	ns	***	ns	ns	**	***	ns	ns	**	ns	ns	***	ns
All soil groups																							
Plant cover duration	ND	ns	ns	ns	ns	ns	**	ns	***	ns	***	***	**	ns	***	***	***	***	***	ns	ns	***	**
Weeding management	ND	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	***	ns	ns	**	***	**	ns	ns	ns	ns	ns	ns
Fertilization	ND	ns	ns	ns	**	ns	**	ns	***	ns	ns	***	ns	ns	**	***	ns	ns	**	ns	ns	***	ns

3. Results and discussion

3.1. *Variance partitioning and interpretation of agricultural practices per soil group*

Agricultural practices were not equally distributed within and between soil groups in our database (Table 1). For all soil groups, more than half of the studied vineyards were managed with a temporary plant cover (TPC) (respectively 48%, 54% and 68% of plots in groups A, B and C). Permanent plant cover (PPC) was a marginal practice in our sampled vineyards, as it represented 22%, 4% and 16% of plots sampled respectively in groups A, B and C. Null plant cover (NPC) was found in 30%, 42% and 16% of cases respectively in groups A, B and C. Concerning weed management, most vineyard inter rows were managed mechanically (56%, 80% and 42% respectively in groups A, B and C). Organic and mineral fertilization were recorded in all soil groups, but were not equally distributed among the different plant cover duration and weeding management combinations. In group C, management with NPC was recorded in 16% of vineyards, and weeds were systematically destroyed by chemical weeding together with mineral fertilization. In groups B and C, PPC (cover observed more than 8 months a year) was only managed by mowing. In soils from group A, PPC was managed by chemical or mechanical weeding. One should note here that mowing and PPC in groups B and C can be considered as co-variables and in the following sections we will consider plant cover duration as the main effect.

Different indicators of soil status are likely to covary and, given their associated financial costs, this raises the crucial question of the selection of the most relevant indicators sufficient to evaluate soil quality (de la Paz et al., 2002). However, in the present study, all indicators except K availability were impacted by a given practice in at least one soil group, highlighting the complementarity of these indicators (Table 3). Variance partitioning performed on the three soil groups showed that the three studied practices explained respectively for groups A, B and C, 13%, 19% and 37% of the total variance of the 23 soil indicators ($p < 0.001$, data not shown). Given the diversity of winegrower practices, and of soil types within a soil group of the commercial vineyards, the part of explained variance is acceptable. One should note that a part of the explained variance was split between the three studied practices due to the collinearity of the factors of interest caused by the unbalanced design. Nevertheless, we found between 3% and 4% of variance significantly ascribable only to weeding management for each soil group (data not shown). Fertilization type explained a significant part of the variance for groups B and C (around 9%), and plant cover duration alone explained 8% of indicator variance for group C.

Table 3 summarizes the results of the ANOVAs testing the effect of practices on the 23 soil indicators, for each soil group separately and also without distinguishing by soil group. When soil groups were not considered separately in the statistical analysis, plant cover duration influenced the responses of 12 indicators whereas weeding and fertilization strategies only influenced 4 and 8 soil indicators, respectively. Most indicators were only affected by one specific practice or within one specific soil group. Only nematode indicators (TotNem, Ba and Fu indicators) showed a response in all soil groups. We expected a more generalized response of MBC and C/N because according to Wardle et al. (1999), microbial biomass responds to tillage practices, but also to fertilization, organic residues, and plant cover species through litter characteristics.

We were also interested by the comparison of the number of indicators affected by practices in each soil group, as an indication of the influence of inherent soil quality on dynamic soil quality. The number of indicators that were sensitive to management practices was lower for soil group A (11 indicators) than for groups B and C (14 indicators, see columns per soil groups) (Table 3). For group B and C, we found 19–25 significant differences, which suggests that the same indicators responded to different management practices (lines of the Table 3) within a soil group. We suggest a more stable soil functioning in calcareous soils than in non-calcareous soils due to the buffering of nutrient availability and pH by Ca carbonate (Hinsinger, 2001; Zavarzin, 2002) or their greater aggregate stability (Bronick and Lal, 2005). The respective importance of the 3 management practices also depended on the soil group. In soil groups A and B, weeding management affected more than 5 soil indicators whereas plant cover duration only affected 3. In soil group C however, plant cover duration had more weight as it affected 13 indicators whereas weeding management and fertilization only influenced 4 and 8 indicators respectively. In soil group C plant cover duration modified almost all nematode ecological indicators, but also the availability of P and Cu and MBC. These differences between soil groups can be explained by the effect of inherent soil properties on the sensitivity of different facets of soil functioning to soil management.

Table 4
Mean values of the indicators that were significantly affected by fertilization (p value < 0.05). Letters a, b within a column indicate significant differences between the organic and mineral fertilization for each soil group (A, B or C).

Group A: non stony, calcareous soils	C/N										
Non organic fertilization	13.6 b										
Organic fertilization	12.2 a										
Group B: non stony, non-calcareous soils	C/N	Cu (mg kg^{-1})	BD (g cm^{-3})	WFC (% w/w)	C_{org} (g kg^{-1} soil)	N_{tot} (g kg^{-1} soil)	CEC (cmol^{+} k^{-1} soil)	MBC (mgC kg^{-1} soil)	MBC/C_{org} (%)	OPF (ind. 100 g^{-1})	FPF (ind. 100 g^{-1})
Non organic fertilization	11.8 b	0.17 a	1.52 b	13.60 a	6.92 a	0.66 a	4.74 a	23.37 a	0.34 a	11.2 a	40.2 a
Organic fertilization	9.8 a	0.25 b	1.39 a	21.60 b	11.03 b	1.14 b	8.31 b	49.46 b	0.45 b	48.1 b	101.7 b
Group C: stony, non-calcareous soils	C/N	Cu (mg kg^{-1} soil)	P (mg kg^{-1} soil)	TotNem (ind. 100 g^{-1})	Ba (ind. 100 g^{-1})	Fu (ind. 100 g^{-1})	MI	SI			
Non organic fertilization	14 b	0.76 b	7.9 b	860.6 b	309.5 b	261.3 b	2.3 a	48.7 a			
Organic fertilization	12.2 a	0.51 a	5.7 a	616.0 a	185.9 a	119.2 a	2.4 b	61.9 b			

3.2. Contrasting effects of organic fertilization

Soils receiving organic rather than mineral fertilization had 1.2–2 unit-lower soil C/N ratios, in all soil groups (Table 4). In group B, organically-fertilized soils had lower bulk density, and higher WFC, SOC, N_{tot}, CEC, MBC and MBC/SOC. These trends were expected, as they are consistent with results reported by other authors about vineyard soil responses to organic fertilization (e.g. Bustamante et al., 2011; Coll et al., 2011; Morlat and Chaussod, 2008). Copper availability showed inconsistent trends: it was higher in organically fertilized soils in group B, thus corroborating results reported in Beni and Rossi (2009) and Navel and Martins (2014), but lower in group C.

In both groups B and C, organic fertilization affected the soil food web, as evidenced by nematode indicators, but with unexpected and different responses in these two soil groups. Other authors have reported that organic fertilization generally stimulates nematode density, with a positive impact on all ecological groups (Treonis et al., 2010; Villenave et al., 2010; Bulluck et al., 2002; Okada and Harada, 2007). In our dataset, while in group B phytophageous nematode populations were indeed higher in organically fertilized soils, in group C total nematode, bacterivore and fungivore populations were depressed in organically fertilized soils (Table 4). As a consequence, the nematodes indices are also significantly affected in soil group C. Possibly as a result of relatively lower bacterivorous and fungivorous nematode densities, the maturity and structure indices showed a slight increase, which was not clearly visible in the above-cited studies. These unexpected results for soil group C could be largely explained by other differences in fertilization practices, such as quantity, quality and timing of fertilizer application, but also interactions with tillage practices, that could not be taken into account in our study based on farmers' plots. A possible indication of such confounding effects can be found in P availability, which was lower in plots receiving organic fertilization, thus conceivably limiting soil organism population development (Li et al., 2010; Zhao et al., 2014).

3.3. Positive effects of a plant cover, whether temporary or permanent

Vineyards with permanent plant cover (PPC) had significantly higher SOC content and microbial biomass carbon (MBC) compared to vineyards with Null or temporary plant cover in groups A and C (Fig. 1). One should note that in soil group B, PPC is represented in only 4% of the plots, which suggests that statistical tests could not discriminate a significant effect in this case. Significant differences were found between Null and temporary plant cover for SOC and MBC in group B soils, and to a lesser extent in group C soils, while no improvement was observed in group A. Due to the Ca carbonate content of soil group A, we did not expect a strong response of MBC, because the presence of Ca^{2+} can contribute to stabilize the OM derived from plant residues providing protection against degradation by microbes (Grünewald et al., 2006). This latter hypothesis is reinforced by the strong effect of a temporary plant cover on MBC in stony and non-calcareous soils from group C.

Specifically in soil group C, a higher MBC/SOC ratio (interpreted as microorganisms' accessibility to resources) was observed with longer plant cover duration, as well as a strong increase in nematode densities (Table 5). The MI, SI and NCR indices were lower in TPC than in NPC or PPC (Table 5). Furthermore PPC exhibited higher values for P and Cu availability compared to the two other plant cover durations in group C. Our Tables and Figures only report differences for a p-value <0.05. Note however that increasing plant cover duration tended to improve other physical and chemical properties such as CEC, K and WFC ($0.05 < p < 0.1$, data not shown). The fact that temporary plant cover improved the soil organic status in group B suggests that TPC may be an interesting alternative to null or permanent plant cover, because it provides potential services during winter (soil protection, water soil profile refilling (Gaudin et al., 2010)) and at the same time, avoids the risk of water and nitrogen competition with the grapevine during dry years (Monteiro and Lopes, 2007; Celette et al., 2008, 2009; Giese et al., 2014). Moreover, our results showed in group B that TPC displayed the lowest stress when the Plant Parasitic nematode Index (PPI) was considered (data not shown).

Table 5
Mean values of the indicators that responded significantly ($p < 0.05$) to plant cover duration in soil group C. Letters a, b and c within a column indicate significant differences between the three durations of plant cover.

Group C: stony, non-calcareous soils	TotNem (ind. 100 g^{-1})	OPF (ind. 100 g^{-1})	Ba (ind. 100 g^{-1})	Fu (ind. 100 g^{-1})	Om_Pr (ind. 100 g^{-1})	MBC/C_{org} (%)	MI	SI	NCR	P (mg kg^{-1} soil)	Cu (mg kg^{-1} soil)
Null plant cover (NPC)	351 a	40 a	178 a	67 a	46 a	0.3 a	2.7 b	72.3 b	0.7 b	6.6 a	0.61 a
Temporary plant cover (TPC)	747 b	76 a	224 a	225 b	60 ab	0.6 b	2.2 a	46.7 a	0.5 a	6.5 a	0.61a
Permanent plant cover (PPC)	1371 c	188 b	564 b	330 b	145 b	0.7 b	2.3 ab	60.3 ab	0.6 ab	11.1 b	1.04 b

The positive effect of a plant cover on MBC/SOC and on nematode populations could be explained by the dissolved organic carbon originating from plant cover roots. We hypothesized that this energy supply stimulates microbial populations and increases their accessibility to substrate, leading in turn to an adjustment of the food web to higher microbial biomass through bottom-up control. The observed increase in MBC/SOC and in total nematode density with increasing plant cover duration in soil group C corroborates this hypothesis. According to Bongers (1990) and Ferris et al. (2001) the higher MI and SI indices found in vineyards without plant cover, or with permanent plant cover, would indicate a more stable environment with less perturbation than in vineyards with temporary plant cover. We suggest that microbial communities favoured by root exudates of fast-growing temporary plant cover benefit opportunist microbivore nematodes, leading to a decrease in MI and SI indices. Chemical changes brought about by PPC may also impact soil organism communities, with opposite effects expected from the observed higher P and Cu availability. Copper may accumulate more in vineyards with PPC because of Cu-treated leaf litterfall retention by the plant cover and/or lesser losses of Cu through erosion of topsoil particles. While Cu is known to have a toxic effect on soil biota (Komarek et al., 2010) involved in SOM turnover, the likely toxic effect of Cu could be largely compensated by the higher resource supply provided by the plant cover.

3.4. The influence of weeding management is barely interpretable

Wardle et al. (1999) hypothesized that weed management selects above ground plant composition and then the nature of organic matter returns to the soil, which in turn modify soil biological activity. However, unlike in Wardle et al. (1999), no indicator systematically differentiated the three weeding management strategies in all soil groups (Figs. 2–4 for soil groups A, B and C respectively).

According to our statistical methodology, the preliminary statistical analysis described in Section 3.1 reveals colinearity between "mowing" and "permanent plant cover" factors for soil groups B and C. Thus we estimated that mowing could not be compared to the two other weeding management techniques, noted "chemical" and "mechanical", although it is presented for soil groups B (Fig. 3) and C (Fig. 4) for reader's information. In soil group A, mechanical weeding significantly decreased bulk density despite a high variability (see Fig. 2). In the same way, when focusing on nematode communities, we observed that the three soil groups were differently impacted. Results mainly showed an effect on the structure of nematode communities in soil group A for the three different weed management techniques, whereas abundances of some nematode trophic groups were affected by mechanical or chemical weed management in soil groups B and C. Concerning nematode ecological indices in soil group A, our data corroborate results reported by Lenz and Eisenbeis (2000), Okada and Harada (2007) and Treonis et al. (2010) and, at a broader scale van Capelle et al. (2012) and Villenave et al. (2013), who pointed out tillage as a significant perturbation promoting opportunist nematodes relatively to others and therefore, lowering SI and MI, while increasing EI. Tillage promotes a higher short-term accessibility to resources, as it releases soil organic matter previously protected in soil aggregates (Six et al., 1999) and allows incorporation of weed residues. Interestingly, in soil group A, the mowing treatment displayed similar ecological index values to the mechanical weeding treatment, with lower MI and SI and higher EI than in the chemical treatment. We suggest that repeated herbicide applications may benefit omnivorous persistent nematodes and therefore MI and SI, as found by Zhao et al. (2013). Alternatively, mowing could alter root exudation patterns (Antonsen and Olsson, 2005), modifying the changes in the micro food web structure (Bardgett et al., 1998; Binet et al., 2013; Guitian and Bardgett, 2000; Shahzad et al., 2012). Finally, we observed significant differences in the Nematode Channel Ratio (NCR) in soil

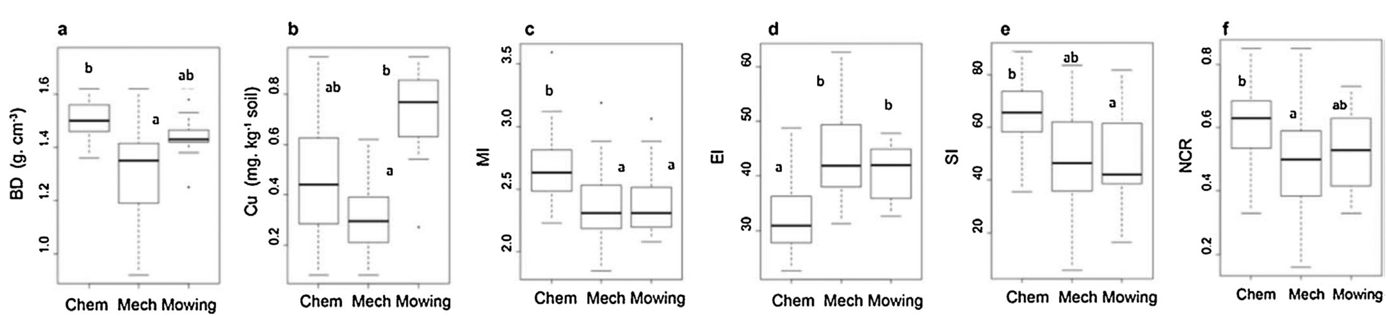

Fig. 2. Effect of weeding management in soil group A on (a) bulk density (BD), (b) available Cu content (Cu) and nematode indices ((c) Maturity Index (MI), (d) Enrichment Index (EI), (e) Stability Index (SI) and (f) Nematode Channel Ratio (NCR)), for three weeding management options: Chemical Weeding (Chem), Mechanical Weeding (Mech) and Mowing (Mowing). Different letters indicate significant differences between treatments ($p \leq 0.05$). Box plots represent dispersion of the data with the median (thick line), first and fourth quartile (thin lines), whiskers extend to the most extreme data point which is no more 1.5 times the interquartile range from the box), outliers being represented by circles. Numbers of plots for each practice are indicated in Table 1.

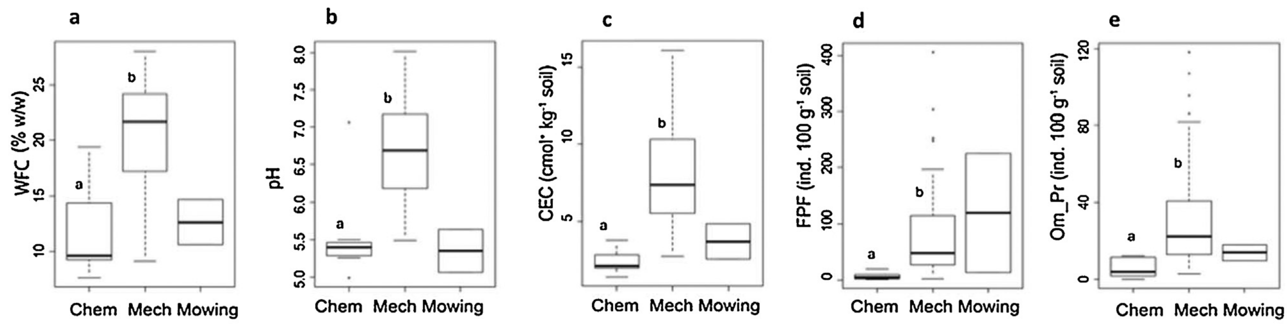

Fig. 3. Effect of weeding management in soil group B on (a) Water Holding Capacity (WFC), (b) pH, (c) Cation Exchange Capacity (CEC), and abundance of some nematode populations: (d) Facultative Plant Feeders (FPF) and (e) Omnivores and Predators (Om_Pr) for three weeding management options: Chemical Weeding (Chem), Mechanical Weeding (Mech) and Mowing (Mowing). Box plots represent dispersion of the data with the median (thick line), first and fourth quartile (thin lines), whiskers extend to the most extreme data point which is no more 1.5 times the interquartile range from the box, outliers being represented by circles. Mowing was not tested as the data set was not suited for these statistical analyses, but the results are nonetheless presented for information. Numbers of plots for each practice are indicated in Table 1.

group A, indicating that the decomposition pathway was more dominated by bacteria than by fungi in the case of chemical weeding.

In soil group C, chemically-treated plots exhibited the lowest nematode abundance in many trophic groups, fungivores in particular. Herbicides were pointed out by Wilkinson and Lucas (1969) to interfere with fungal growth. As symbiotic fungi can benefit vines, providing better water or nutrient deficiency tolerance (Schreiner, 2007) especially for calcareous soils, decreases in the density of fungivorous nematodes should be a cause of concern.

In soil group B, characterized by a coarser texture and an absence of Ca carbonates, mechanical weeding improved soil water holding capacity, bulk density and pH. According to our farm practice survey, a majority of winegrowers practicing mechanical weed management mentioned lime application, which could explain the greater pH and CEC. A more neutral pH favours nematode abundance (Mulder et al., 2005; Salome et al., 2014), and more particularly that of omnivorous and predatorcious nematodes as we observed in soil group B (Korthals et al., 1996). We suggest that lime application is a stronger driver of soil organisms and soil chemical properties than weeding management in those particular soils. Nevertheless, due to inherent water limitations of Mediterranean vineyards, we suggest that the effect of mechanical weed management on water holding capacity is of particular importance, and further studies would be useful to understand related soil processes. For all three soil groups, we did not find any decrease in SOC in mechanically-managed plots, contrary to results reported by Mazzoncini et al. (2011) for field crops in Mediterranean soils. Many winegrowers in the Languedoc Roussillon practice chiselling, which was shown by Melero et al. (2011) to cause no depletion in SOC, contrary to mouldboard ploughing.

3.5. Adaptation of practices to soil types is possible for vulnerable Mediterranean vineyards

The benefit of a combination of mowing and permanent grass cover was evident on many indicators for soil group C. Although these soils were not characterized by particularly low resources (i.e. SOC content), they seemed to be more vulnerable to soil management than the two other soil groups, because many indicators were simultaneously affected by practices and because we noticed the highest percentage of variance explained in the RDA model in this group. In contrast, in soil group A, few indicators were affected by management practices, probably because of the buffering effect of Ca carbonates. Permanent plant cover is typically used to control vine vigour, and therefore to limit fungal diseases and the need for fungicides (Mercenaro et al., 2014; Guerra and Steenwerth, 2012). We suggest that the fungi-oriented decomposition pathway (lower NCR) noted in calcareous soils with permanent plant cover, is probably ascribable to lower fungicide and herbicide applications when PPC is implemented. Calcareous soils are more resilient to modifications by practices (Thorsen et al., 2010). However, a permanent plant cover or chemical weeding can modify soil functioning, whereas organic fertilization is not influent. In calcareous soils, Chaignon et al. (2003) attributed Cu retention in

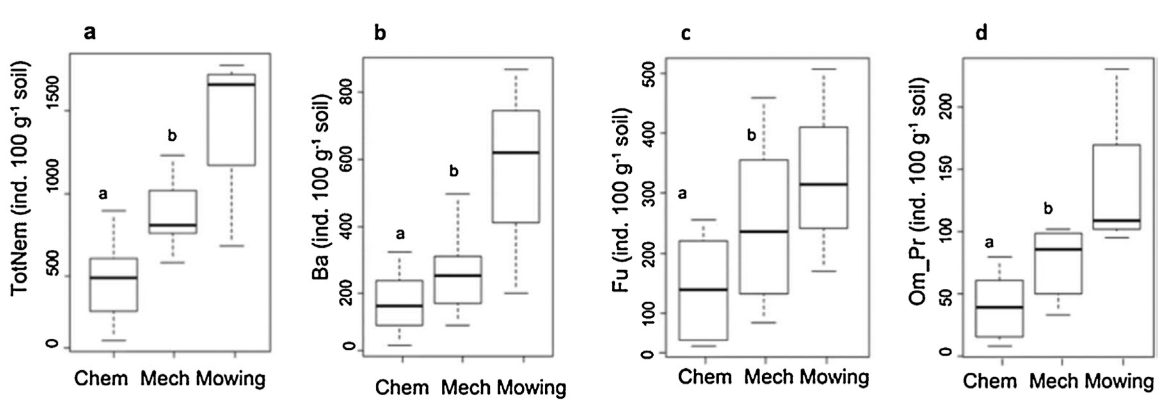

Fig. 4. Effect of weeding management in soil group C on nematode abundances: (a) total nematodes (TotNem), (b) Bacterivorous nematodes (Ba), (c) Fungivorous nematodes (Fu), and (d) Omnivorous and predator nematodes (Om_Pr) for three weeding management options: Chemical weeding (Chem), Mechanical weeding (Mech) and Mowing (Mowing). Box plots represent dispersion of the data with the median (thick line), first and fourth quartile (thin lines), whiskers extend to the most extreme data point which is no more 1.5 times the interquartile range from the box, outliers being represented by circles. Mowing was not tested as the data set was not suited for these statistical analyses, but the results are nonetheless presented for information. Numbers of plots for each practice are indicated in Table 1.

soils to SOM that increases its availability. For non-calcareous soils, mechanical weed management with a chisel and mineral fertilization, associated in some cases with plant cover, can be profitable. Under Mediterranean conditions, adoption by winegrowers of a permanent plant cover is unlikely because of water and nutrient competition with vines. Nevertheless, we agree with Wardle et al. (1999) who state that weeds can be beneficial for cultivated plants if they are not repeatedly selected by intensive herbicide application, because they can provide a high biomass and easily decomposable litter, which can in turn enhance soil biological activity. Other studies have shown that remnant vegetation, adapted to pedoclimatic situations, can also contribute to the biological control of pests (Nicholls et al., 2000). Benefits of plant cover biodiversity should be better evaluated for its contribution to vineyard functioning, as it could contribute to adapting vineyard practices to current and future agri-environmental issues.

4. Conclusions

Our study highlights the importance of adapting vineyard soil monitoring to the various pedological situations encountered at the regional scale, in order to select best management strategies according to their impact on soil processes. Vineyard soils responded to the three soil management practices tested in this study, but the intensity of the response and the indicators impacted varied between the soil groups we defined. Even if soil quality studies are sometimes a source of debate regarding the multiple and concurrent soil functions under consideration, we warmly recommend an assessment of practices through different soil indicators without any scoring or weighting to identify which soil functions or soil processes are affected. We think such an approach can reasonably be used by winegrowers to preserve their soil functioning and adapt their practices to their specific Terroirs, which are also our common legacy.

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