THESE DE DOCTORAT

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EN SCIENCES AGRONOMIQUES DE MONTPELLIER

Ecole doctorale : Systèmes Intégrés en Biologie, Agronomie, Géosciences, Hydrosciences et Environnement
Spécialité : Ecosystèmes

par

PATRICE COLL

Ingénieur Agronome (Montpellier SupAgro)
Spécialisé en Viticulture et Œnologie – Œnologue

VINEYARD SOIL QUALITY IN LANGUEDOC-ROUSSILLON
EFFECTS OF AGRICULTURAL PRACTICES

QUALITE DES SOLS VITICOLES EN LANGUEDOC-ROUSSILLON
EFFETS DES PRATIQUES AGRICOLES

Soutenue publiquement le 8 décembre 2011 devant le jury composé de :

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Edith LE CADRE	Maître de Conférences, Montpellier SupAgro	Co-directrice de thèse
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A mon oncle Alphonse

Tonton, je tiens à te rendre hommage en te dédiant ce travail que tu n'auras pas vu abouti. Tu as beaucoup compté pour moi. Tu m'as tant appris ! Combien de fois avons-nous battu la campagne ensemble ? Tu m'as transmis ta passion pour la terre, la vigne et ton amour pour le monde paysan. Tu m'as souvent dit : « Quand je serai mort, tu penseras au Vieux qui te disait… ». Tu vois, je ne t'oublie pas !

Je souhaite mettre en préambule de cette thèse, une des fables de Jean de La Fontaine que tu me comptais souvent : « Le laboureur et ses enfants ». Héritage, transfert de savoirs et amour du travail sont autant de valeurs auxquelles je suis particulièrement attaché aujourd'hui.

Le laboureur et ses enfants

Travaillez, prenez de la peine :
C'est le fonds qui manque le moins.
Un riche Laboureur, sentant sa mort prochaine,
Fit venir ses enfants, leur parla sans témoins.
"Gardez-vous, leur dit-il, de vendre l'héritage
Que nous ont laissé nos parents :
Un trésor est caché dedans.
Je ne sais pas l'endroit ; mais un peu de courage
Vous le fera trouver : vous en viendrez à bout.
Remuez votre champ dès qu'on aura fait l'oût :
Creusez, fouillez, bêchez ; ne laissez nulle place
Où la main ne passe et repasse."
Le père mort, les fils vous retournent le champ,
Deçà, delà, partout....
si bien qu'au bout de l'an
Il en rapporta davantage.
D'argent, point de caché. Mais le père fut sage
De leur montrer avant sa mort
Que le travail est un trésor.

Jean de La Fontaine

Déjà trois ans... Cette thèse n'aurait pas eu le même sens sans les nombreuses personnes qui ont été présentes à mes côtés, aussi bien dans ma sphère professionnelle que privée. Chacune d'entre elles a joué un rôle dans ce travail et a contribué à sa réussite. Je souhaite aujourd'hui toutes les remercier.

Je voudrais tout d'abord remercier l'ADEME et Montpellier SupAgro pour avoir financé mon travail. Merci aussi à Jean-Luc Chotte, Philippe Hinsinger et Jean-Michel Harmand, de m'avoir accueilli au sein de leur équipe de l'UMR Eco&Sols.

Je remercie Cécile Villenave et Edith Le Cadre, pour m'avoir encadré. Vous avez respecté un de mes souhaits les plus chers : travailler sur le terrain, en lien direct avec les professionnels de la filière viticole. La grande confiance que vous m'avez accordé m'a permis de m'approprier totalement le sujet afin que cette thèse devienne mon projet à part entière, « mon bébé » comme on dit dans le jargon. Edith, tu as particulièrement été présente et attentive pendant cette fin de thèse. Ton soutien si sincère m'a permis de faire face aux moments difficiles, tu as toujours su trouver les mots justes pour me remotiver : je tiens à te témoigner toute ma reconnaissance.

Je voudrais également remercier toute l'équipe d'Eco&Sols. Bien que je n'ai pas eu la chance de travailler avec chacun d'entre vous, vous avez tous à un moment ou un autre, eu un mot de soutien, un conseil ou manifesté de l'intérêt pour mon travail. Je voudrais particulièrement remercier Eric Blanchart pour avoir toujours trouvé le temps pour m'écouter et me conseiller. Ta gentillesse et ton soutien moral m'ont beaucoup apporté. Un grand merci aussi à tous les volontaires qui m'ont donné de leur temps pour venir à bout des différentes campagnes de terrain, notamment lors des prélèvements de vers de terre. Je pense à Josiane Abadie, Hervé Aholoukpé, Hubert Alcin, Didier Arnal, Adnane Bargaz, Bernard Barthès, Eric Blanchart, Didier Blavet, Florent Brunaud, Edith Le Cadre, Georg Carlsson, Benoît Cloutier-Hurteau, Cathy Coll, Gabrielle Daudin, Fan Deng, Antonin Grau, Marney Isaac, Sylvia Julien, Siham Khoulassa, Ernest Kouakoua, Egidio Lardo, Rym Maougal, Anthony Marmeys, Claire Marsden, Jennifer Marasi, Agnès

Martin, Aurélie Metay Bernardi Rakotomanga, Agnès Robin, Nicolas Romillac et Emilie Russello, Cécile Villenave, Manon Villeneuve et Laure Vogel.

J'ai également eu beaucoup de chance de recevoir un soutien technique très précieux lors des analyses de sols. Alors un grand merci à Didier Arnal, Jean-Louis Aznar, Charline Guilleré, Anne Jimenez, Emilie Russello, Joëlle Toucet et Manon Villeneuve qui ont vraiment été d'une grande aide dans mes analyses de laboratoire, et merci aussi pour votre bonne humeur à toute épreuve !

Je remercie aussi Didier Blavet, Benoit Cloutier-Hurteau, Philippe Deleporte, Benoit Jaillard et Julien Papaïx pour leur aide dans l'analyse statistique des données. A combien de pièges sournois j'ai échappé grâce à vous ! Merci aussi pour avoir contribué à mon initiation au logiciel de statistiques R, qui n'est certainement pas des plus conviviaux...

Je voudrais aussi remercier Corinne Allegre, Farid Medacci et Michelle Tigny, qui, bien des fois, m'ont aidé à me sortir des méandres administratifs...

Je n'oublie pas non plus les stagiaires, doctorants et post-doctorants que j'ai croisés. Je souhaite plus particulièrement remercier Inès Snessens et Marylène Brey que j'ai encadrées lors de leur stage. J'ai également une pensée pour Heesham Hamza, Zeeshan Majeed et Rym Maougal avec qui j'ai partagé pendant 2 ans notre fameuse Algéco. Un petit clin d'œil à Didier Brunet, grâce à qui nous avons pu travailler dans de bonnes conditions matérielles.

Je voudrais finir cette rubrique « Eco&Solienne » en remerciant Egidio Lardo, doctorant d'Eco&Sols par adoption. Nos thèses ont permis à nos chemins de se croiser pour finalement, collaborer pendant plus d'un an (et ce n'est pas fini) ! Certes, tu as été un collègue de travail (Dieu sait, les heures que nous avons passé ensemble au labo !) mais très vite notre passion pour la vigne et le vin a fait naître une amitié très forte qui n'est pas prête de s'estomper. Egidio, je ne saurais comment te remercier pour le travail acharné que tu as fourni. Grâce à cette très belle collaboration franco-italienne, nous avons pu accomplir un travail colossal, et l'expérimentation du « Réseau Référentiel » est un bel aboutissement de ce projet commun. Merci également à Giussepe Celano, Bartolomeo Dichio et Christos Xiloyanis, tes encadrants pour s'être déplacés de Bassilicata jusqu'à Montpellier pour nous rencontrer.

Au-delà des frontières de l'UMR Eco&Sols, d'autres unités m'ont été d'un très grand soutien. Je pense notamment à l'UMR LISAH avec Jean-Pierre Barthès, Guillaume Coulouma et Stéphane Follain pour leur aide précieuse dans le choix des zones à échantillonner. Vous m'avez transmis vos connaissances sur les sols de la région Languedoc-Roussillon et je vous en remercie. Jean-Pierre, je voudrais vous témoigner toute ma reconnaissance pour m'avoir accompagné plusieurs fois dans les vignes, pour m'avoir initié à l'expertise des sols sur le terrain et pour m'avoir raconté leur histoire. Je souhaite également remercier Jean-Luc Belotti, Yves Le Bissonnais et Chantal Geniès pour nous avoir initiés, Egidio et moi, au test de stabilité structurale et pour nous avoir permis de réaliser les tests dans les locaux de l'UMR LISAH.

Je souhaite également remercier l'UMR System et plus particulièrement Yvan Bouisson, Alain Capillon, Christian Gary, Anne Mérot, Aurélie Metay et Jacques Wery avec qui j'ai échangé à de nombreuses reprises, dans le cadre du projet AIDY notamment.

Merci également à Pierre Berthomieu de l'UMR Biochimie et Physiologie Moléculaire des Plantes de m'avoir permis d'utiliser le spectrophotomètre d'adsorption atomique à flamme lorsque le nôtre était défaillant.

Je n'oublie pas non plus de remercier Jean-Louis Aznar et Françoise Dordor pour m'avoir permis de réaliser les mesures d'humidité à la capacité au champ et de densité réelle dans le laboratoire du Cœur d'Ecole du Montpellier SupAgro.

Je souhaite également remercier Didier Ollé et Aude Vernhet, responsables de la spécialisation Viticulture-Œnologie d'avoir accepté que j'encadre une journée de terrain sur les prélèvements de la macrofaune du sol, alliant enjeux scientifiques et pédagogiques. Je tiens bien sûr aussi à remercier tous les étudiants en spécialisation Viticulture-Œnologie de la promo 2011 d'avoir participé à cette sortie malgré de mauvaises conditions climatiques (heureusement, le vin de Saint-Victor la Coste nous a réchauffés…). Merci à Alexandre Abellan, Florent Audibert, Matthieu Avignon, Romain Chapacou, Jeanne Chaumont, Alexis Des Portes de La Fosse, Nicolas Dietrich, Pierre Duprat, Marion Enard, Ines Fay, Clément Fraigneau, Sophie Guillemot, Arnaud Iffat, Carole Koestel, Lucie Lauilhe, Sarah Lumbrosco, François Michel, Armelle Rouault, Florian Sabadie, Corinne Trarieux, Caroline Tribaudeau, Cécilia Trimaille et Benoît Velut.

Je voudrais aussi exprimer ma gratitude envers Clotilde Sauboa et Géraldine Chamussy pour avoir soutenu ma proposition de projet d'élèves ingénieurs, sur la « perception de la qualité des sols viticoles par les viticulteurs ». Je ne pourrais oublier de noter la grande implication et le sérieux avec lesquels Boris Hiro Lhie, Mathilde Mellin, Arwa Osseiran et Charlotte Ngo-Dinh se sont investis dans ce travail. Merci également à Ronan Le Velly, tuteur de ce projet, pour son suivi et ses conseils.

Je remercie également la Maison des Sciences de l'Eau qui m'a permis de réaliser des analyses au sein de son laboratoire. Merci également à Bruno Buatois, de l'UMR CEFE pour ses conseils pour la réparation de l'analyseur TOC.

Cette thèse n'aurait jamais pu voir le jour sans tous les viticulteurs, techniciens et directeurs de caves coopératives des 10 zones du Languedoc-Roussillon étudiées. Je voudrais tous les remercier pour l'intérêt que vous avez porté à ce travail et pour m'avoir consacré du temps. C'est grâce à vous tous que j'ai pu trouver toute la motivation pour mener à bien mon projet de thèse. Ainsi, je voudrais remercier les professionnels de :

- Saint-Victor la Coste, avec James Bellegarde, Eric Dapchier, Stéphanie Daumas, Hubert Delacroix, Jean-Marc Estournel, Richard Evesque, André Fabrol, Franck Lacombe, Jean-Marie Rambert, David Roux et Simón Tornello.

- Saint-Hippolyte du Fort, avec Pascal Arnoux, Eric Benezech, Marie-José et Jean-Marie Boudouresque, Chantal Costa, Jean

Fesquet, Marie-France Fesquet, Michaël Hausdorff, Olivier Jaussaud, Michel Julien, Laurent Olivier et Jérôme Pépin.

- Jonquières Saint-Vincent, avec Daniel Arnaud, Alain Blayrat, Régis Blayrat, Pierre Collard, Christian Gomez, Christian Gourjon, Daniel Hugues, Sabine Lagarde, Bruno Manzone, Pascal Mazoyer, Jean-Marc Supplien, Bertrand Vidal et Robin Vitry.

- Vergèze, avec Didier Béchard, Jean-Fred Coste, Philippe DelmasJean-Luc Delranc, Jacques Floutier, Guillaume Puccini, Elian Ranieri et Adrien Warnery.

- Aigues-Mortes, avec Eric Amiel, René Barbier, Alban Béchard, Laëtitia Carbonell-Borel, Corinne Donnadieu, Patrick Guiraud, Robert Mezy et Bernard Vila.

- Faugères, avec Frédéric Albaret, Didier Barral, Patrick Calmette, Cyril Camacho, Nathalie et François Caumette, Jacques Chabert, Brice DelbravoPatrice Laffond, Michel Louison, Laurent Mazel, Jacques Roméro, Marc Roque et Julien Seydoux.

- Montagnac, avec Cédric Arnaud, Serge Azaïs, Christian Boineau, Philippe D'Allaines, Pierre Delsol, Daniel Garcia, Alexis Manez, René Moréno, Christian Pagès et Jean-Louis Rèfle.

- Cruscades, avec Louis Fabre, Regis Loevenbruck, Jean-Jacques Loze, Gérard Pélissa et Xavier Sabouraud.

- Lesquerde, avec Jacques Barthès, Jacques Bayona, Patrick Calvet, Manuel Jorel, Eric Laguerre, Georges Rognon et Gabriel Zafra.

- Terrats, avec Louis Aliès, Vincent Barrière, Magalie Cabocel, Hervé Camsouline, Denis Ferrer, Xavier Hardy, Pierre Lenen, Alain

Mauran, Jean-Michel Paraire, Jean-Luc Pujol, Alain Roca et Denis Ruiz.

Je voudrais également témoigner toute ma gratitude auprès de l'interprofession et remercier en particulier Nicolas Constant (Association Interprofessionnelle des Vins Biologiques- Languedoc-Roussillon), Xavier Delpuech (Institut Français de la Vigne et du Vin) et Nathalie Goma-Fortin (Chambre d'Agriculture de l'Hérault) qui ont témoigné un grand intérêt pour mon travail de thèse.

Je voudrais aussi remercier les membres de mon comité de pilotage : Antonio Bispo, Eric Blanchart, Philippe Hinsinger, Christian Gary et Cornelis van Leeuwen. Les discussions que nous avons eues à mi-parcours ont nourri ma réflexion et ont contribué à la réussite de ce projet. Je remercie également les membres du jury : Antonio Bispo, Thibaud Decaëns, Camille Dumat, Nathalie Goma-Fortin, Thierry Mateille et Kerri Loraine Steenwerth. Je remercie les rapporteurs pour le temps qu'ils ont passé à lire mon manuscrit dans le détail pour évaluer mon travail et pour leurs commentaires très développés et pertinents. Je souhaite remercier tous les membres du jury pour toutes leurs remarques qui ont fait naître une série de discussions intéressantes me permettant de prendre du recul par rapport à mon sujet.

Je voudrais aussi remercier Aurélie Chassagne pour son aide dans la définition de mes projets professionnels de l'après-thèse. Un très grand merci également à Nathalie Camus qui a été mon mentor lors du module de formation "Valorisation des Compétences: Nouveau Chapitre de la thèse". Vous avez été très présente, très attentive et m'avez poussé dans ma réflexion sur mon avenir professionnel. Vous êtes intervenue à une période où tous les doctorants doutent de leur travail et de leurs qualités. Votre soutien et nos discussions ont été comme une "thérapie" pour moi et m'ont permis de rebondir pour la dernière ligne droite.

Je ne pourrais finir ces remerciements sans exprimer toute l'affection que j'éprouve envers mes parents. Je profite de ce moment pour vous remercier pour l'immense soutien moral que vous m'avez apporté tout au long de cette thèse mais aussi pour tout ce que vous avez fait pour moi ces 27 dernières années... Vous m'avez inculqué des valeurs fortes comme le respect, le courage et la ténacité. Très tôt, vous m'avez aussi donné le goût du travail, du travail bien fait. Les proverbes occitans "Un pau d'ajudo fa grand bèn !", "Tan val un pichon desgordit qu'un grand estabosit ! " et "Mal de crabit dema sara guerrit !" sont autant d'expressions qui sont chargées de symboles et qui m'accompagneront tout au long de ma vie. Vous avez rempli votre rôle de parent haut la main. Bravo et merci !

Anne, tu devais certainement te demander quand tu aurais ton nom dans ce manuscrit. Et bien voilà ; j'ai gardé le meilleur pour la fin ! Cela fait plus de six ans que nous partageons nos vies. Nous avons fait beaucoup de sacrifices, notamment ces dernières années, durant lesquelles nous étions tous les deux en thèse. Tu as été omniprésente, toujours à l'écoute, m'épaulant, me conseillant, me rassurant alors que je doutais de mes compétences. Tu sais me donner du courage et me faire aimer la vie. Que de patience tu as eue à me voir partir tôt, rentrer tard, partir plusieurs jours sur le terrain ! La page de notre vie étudiante est maintenant tournée, place au prochain chapitre que nous écrirons à trois ! Merci de me donner un fils.

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INTRODUCTION

Vine is one of the oldest crops cultivated by humans. Wine, its associated food product, is a mythical beverage which ancient Greeks and Romans personified into the Gods Dionysos and Bacchus. In France, vine was introduced by the Etruscans, inhabitants of northern Italy, prior to the Roman era, between the Xth and the Vth Century before J.-C.. From then onwards, vine spread all over the French territory. In 2006, French vineyards covered 837,000 ha, 3% of agricultural lands (Agreste, 2007) which, in 2010, represented 47.3 millions hl (Agreste, 2010) with a ranking as the second wine producer in the world. Among all of the different regions, the Languedoc-Roussillon, located in the South of France, is the first wine producer in terms of land area (236,500 ha, 30% of national vineyard, (Agreste, 2011) (1). Thus, wine production plays a very important social and economic role in this region. French wines are among the most prestigious wines and are inseparable from the Terroir concept. Many crops claim a relationship to the Terroir but this is particularly true for vine and wine. The Terroir can be defined as a unique ecosystem in a given place including soil, climate and vine combining rootstock and cultivar and occasionally viticultural and oenological practices (Van Leeuwen *et al.*, 2004). According to Van Leeuwen and Seguin (2006), soil contribution to Terroir can be summarized according to its geology or parental rock , its pedology or soil type and finally in relation to agronomic practices which influence the temperature, water and nutrients supplied to vines. On this subject, a great deal of research has attempted to link soil properties to wine quality as de Andres-de Prado *et al.* (2007) have recently shown.

Up to now, it has been impossible to link soil or climate properties to wine quality, because relationships are too complex. Nevertheless a question still remains with regard to a definition of soil quality capable of encountering the sustainability of vine production. Soils are a non-renewable resource (Kibblewhite *et al.*, 2008). Moreover, vineyard soils are often located in areas where other crops could be difficult to produce. Winegrowers have specific agricultural practices as chemical weeding, tillage, pesticide inputs, green pruning in order to maintain vine beyond its yield potential and to obtain high quality grape. Consequently, it is well known that some of these practices lead to soil degradation by erosion, organic matter depletion, pollution and loss of biodiversity (Chaignon *et al.*, 2003; Chopin *et al.*, 2008; Coulouma *et al.*, 2006; Komarek *et al.*, 2010; Le Bissonnais *et al.*, 2007; Martinez-Casasnovas and Ramos, 2009; Raclot *et al.*, 2009). Soil degradations are often insidious for a long time but can irremediably affect soil and, in turn, ecosystem functioning in the span of one human life alone (Karlen *et al.*, 2003). Thus, as defined by Doran and Parkin (1994): "*soil quality is the ability of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health*".

Currently, the wine sector is facing an economic crisis because of a reduction in wine consumption for health considerations but also because of a negative image associated with intensive and environmentally harmful practices. For these reasons, a more sustainable viticulture needs to be adopted, characterized by low inputs of fertilizers, pesticides and herbicides in order to limit pollution, guarantee the non-toxicity of wines and reach economic goals. During the last decades, winegrowers adopted alternative practices to meet consumers' food safety and environmental concerns. Organic practices represent the most popular alternative. From 2001 to 2008, the surface area of organically managed French vineyards increased by 110%: 13,426 ha in 2001 (Agence BIO, 2002) and 28,190 ha in 2008 (Agence BIO, 2009) demonstrating the intensity of changes in practice. Until now, few studies have focused on the evaluation of vineyard management on soil functioning (Probst et al, 2008) whereas several studies have focused on the importance of soil for site selection for planting vines (Bodin and Morlat, 2006; White, 2003a). However, it is crucial to evaluate the effects of vineyard practices on soil quality (Blavet *et al.*, 2009; Ripoche *et al.*, 2011; Steenwerth *et al.*, 2010a). Given the complex nature of soils, a large number of soil properties can be determined. Thus, a great number of indicators for soil quality are available to evaluate crop management (Bispo *et al.*, 2011; Karlen *et al.*, 1997; Warkentin and Fletcher, 1977). As a consequence, it is important to select the indicators that are appropriate to estimate changes in soil properties as a result of soil use and management, which is defined as "dynamic soil quality" (Bastida *et al.*, 2008). Physical and chemical indicators are paramount for an agronomic approach. The assessment of communities of soil organisms can provide an integrative approach to soil quality (Nuria *et al.*, 2011). However, methodological aspects restrict their common use, especially in the case of small organisms (Decaëns *et al.*, 2006; Parr *et al.*, 1994). The winegrower's knowledge is also a great source of information that can be gathered to define soil quality (Barrios and Trejo, 2003) and assist researchers in soil surveys (Bastida *et al.*, 2008). As a consequence, researchers, advisers and producers have to combine their knowledge to give a broad picture of dynamic soil quality. Until now studies have given a holistic evaluation of vineyard soils using all of the above mentioned indicators.

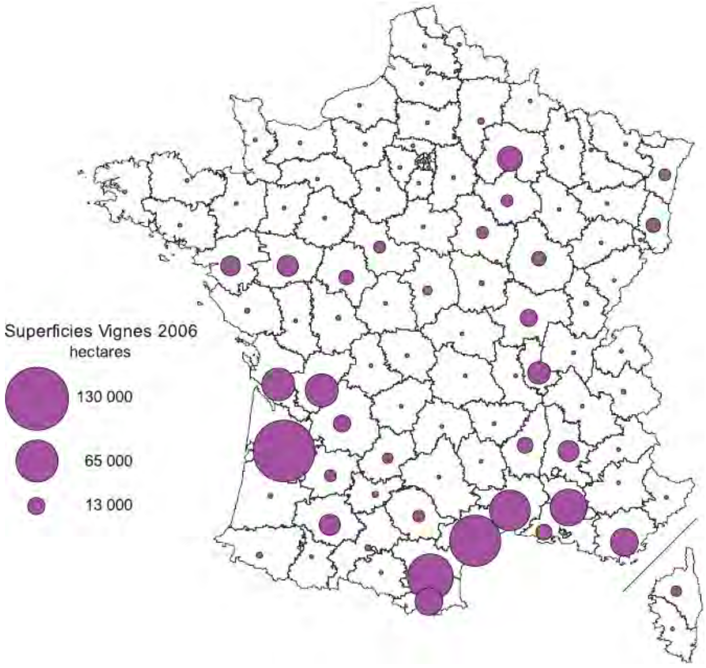


Figure Int- 1: Surface areas of French vineyard in 2006 (Agreste, 2007)

In this context, the main objective of my dissertation was to evaluate the vineyard soil quality of the Languedoc-Roussillon region. I focused on the upper soil layers where main soil processes, as influenced by vineyard management, occur. To achieve this goal, I developed an original approach combining field surveys and laboratory analyzes over a large network of vineyard plots. To broaden the scope of my study, I confronted my analytical approach to the winegrower’s perception of soil quality. In the short term future, my research will contribute to the understanding of the direction and magnitude of soil dynamic quality in the Languedoc-Roussillon region. From an operational point of view, my research will also provide a useful referential of vineyard soil status and can guide advisers to select appropriate soil quality indicators.

CHAPTER I

LITERATURE REVIEW

1. SOILS AND ECOSYSTEM SERVICES

1.1. ECOSYSTEM SERVICES TO MAN

The authors of the 2005 Millennium Ecosystem Assessment (MEA) report defined an ecosystem as *"a dynamic complex of plants, animals, microorganism communities, and the nonliving environment, interacting as a functional unit*." The concept of ecosystem services as developed in the MEA refers to Maslow's original studies (1943) regarding the "hierarchy of needs," which classifies man's fundamental needs. The goals of the MEA were to assess the consequences of ecosystem evolution for man's well-being, to examine the beneficial contributions of the world's ecosystems to man, and to establish a scientific basis for the actions required for the conservation and sustainable exploitation of ecosystems. Daily (1997) defined ecosystem services as "*the conditions and processes through which natural ecosystems, and their component species, sustain and fulfill human life."* De Groot *et al.* (2002) identified 23 ecosystem functions, goods, and services that can be divided into four main categories: regulation, habitat, production and information services. The MEA (2005) uses a different but similar classification that distinguishes between support, production, regulation and cultural services (Figure I- 1). Although man controls much of culture and technology, he is dependent on the services provided by ecosystems. However, the efficient management of ecosystems is affected both by the lack of knowledge and information about various aspects of these systems and by the non-adequate use of existing information in support of management decisions.

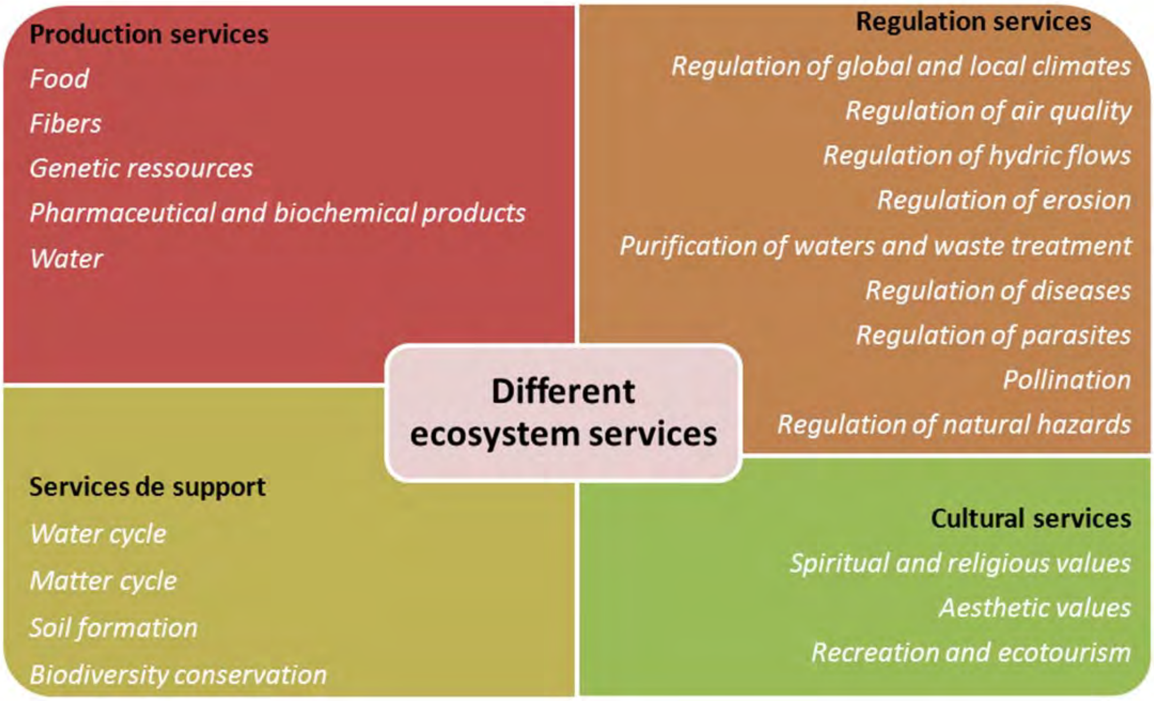


Figure I- 1: Different ecosystem services defined in the Millennium Ecosystem Assessment (2005)

1.2. SOIL AS AN ESSENTIAL COMPONENT OF ECOSYSTEMS

Soil is a porous, open, polyphasic (solid, liquid, and gaseous), multifunctional, and organized system that contains elements of highly diverse natures, sizes, and origins. It consists of mineral matter, decomposed or decomposing organic matter, and living organisms that serve different functions.

Along with constituting an integral part of larger ecosystems, soil itself can also be considered an ecosystem in which abiotic and biotic components constantly interact. The significance of soil functioning in ecosystems has been addressed by many scientists (Arshad and Martin, 2002; Cameron *et al.*, 1996; Costanza *et al.*, 1997; Dale and Polasky, 2007; de Groot *et al.*, 2002; Lavelle *et al.*, 2006; MEA, 2005; Porter *et al.*, 2009; Sombroek and Sims, 1995; Straton, 2006). These studies have documented the roles of soil in human activities. First, soil supports the infrastructure of civilization, in particular farm production, by guaranteeing the water and nutritive nutrition of plants. Moreover, it provides humankind with raw material such as clay, sand and coal as well as even more precious resources such as gold and silver.

Since approximately the 1980s, people have become aware that soil should be regarded as a fundamental functional component of the environment. Indeed, soil represents an interface between water and air, and it affects the quality of these two resources, both of which are indispensable to life (Doran, 2002). Soil contributes to the water cycle because, depending on soil characteristics, water that falls as precipitation either (1) infiltrate through the soil and recharges groundwater stocks, (2) is stored and used in the soil, or (3) run off at the soil surface (Citeau *et al.*, 2008). Soil can also modify water quality (Zalidis *et al.*, 2002) because as water infiltrate through it, the soil solution can undergo biochemical reactions (such as mineralization) or chemical reactions (such as precipitation or adsorption) (Figure I- 2).

For example, clays and organic matter can fix heavy metals such as copper (Michaud *et al.*, 2007; Yaron *et al.*, 1996). More generally, soil recycles exogenous organic matter such as plant residues and animal waste. Some microorganisms are also known to degrade xenobiotics (Schloter *et al.*, 2003). Finally, soil can influence the climate (Lal *et al.*, 1998) by capturing and storing carbon or by emitting, under certain conditions, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which are three of the contributing gases to the greenhouse effect.

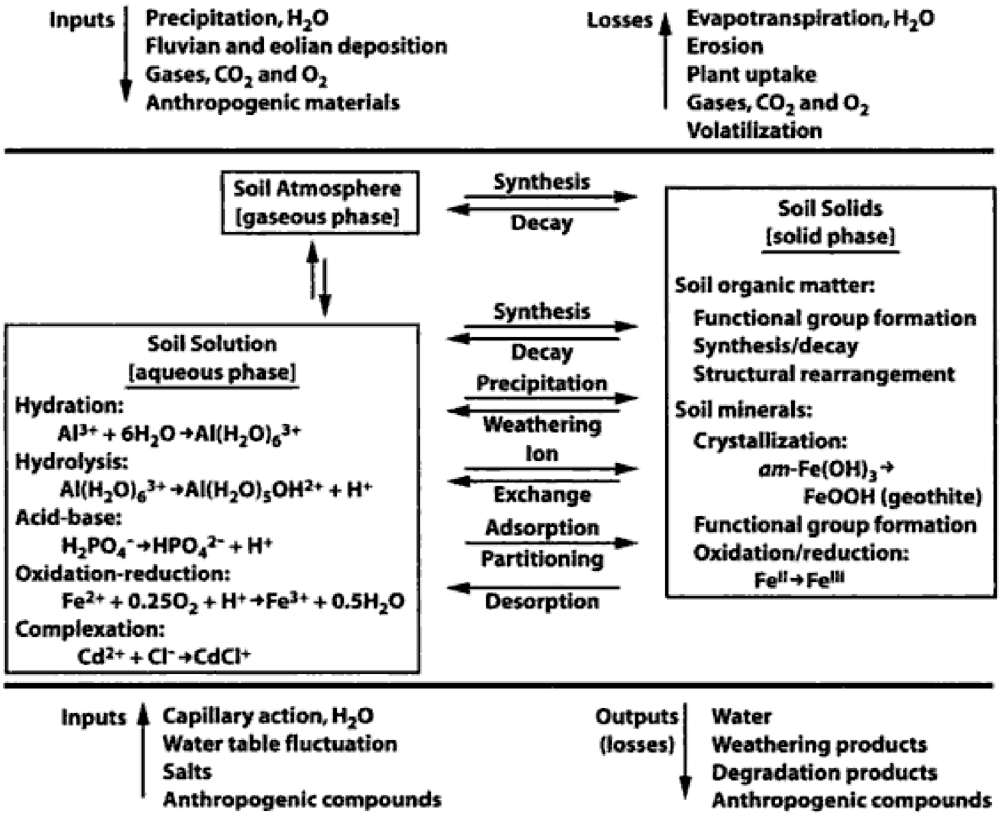


Figure I- 2: Reactions affecting the composition of soil solutions (Essington, 2004)

1.3. SOIL AS AN ENDANGERED RESOURCE

Unlike water or air, soil is often considered a non-renewable resource that is physically fixed in space (except when subject to extraction or erosion). The multifunctional characteristics that make soil necessary for all human activities have caused it to become an over-exploited resource, directly or indirectly (and deliberately or not deliberately) exposed to considerable degradation (Cassman, 1999). Soil disturbances can have natural or anthropogenic origins (Dominati *et al.*, 2010). Occasional natural phenomena such as storms, strong rains, earthquakes, and volcanic eruptions can cause rapid and substantial soil degradation (Dominati *et al.*, 2010). Among the main anthropogenic causes of degradation, agriculture, industry, and urbanization are likely to have long-term consequences for soil. Citeau *et al.* (2008) and Dominati *et al.* (2010) summarized the various types of physical, chemical, and biological soil disturbances. The most common physical perturbations include compaction, soil sealing, and erosion. Erosion by water and wind leads to soil loss, and consequently, a loss of nutritive elements (Vrsic *et al.*, 2011). The soil sealing sometimes called soil artificialization diminishes soil porosity and water infiltration. This disruption is strongly related to urbanization. The compaction of the upper soil layers due to the movement of machines or heavy materials across the soil surface decreases soil aeration, which can in turn modify the redox status of the soil. This modification influences biological functioning, which can lead to an increase in released N_2O or to the development of an environment that is unfavorable to soil fauna due to a lack of oxygen (Jackson *et al.*, 2003). Significant chemical disruptions of soil include salinization, acidification, the loss of nutritive elements and contamination by various components such as heavy metals or synthetic phytosanitary products. Another major disruption is the reduction of organic matter levels, as organic matter is required for the development of biological soil components. According to Citeau *et al.* (2008), 45% of European soils have an organic matter content of less than 2%. Among the most evident consequences of the loss of organic matter, the most commonly observed are nutrient level reduction, soil disintegration, decreased water retention, and modification of biological activity (Reeves, 1997). The reduction of soil biodiversity, often associated with the reduction of organic matter, is also an important concern (Altieri, 1999).

2. THE EFFECTS OF AGRICULTURE ON SOILS

2.1. FROM CONVENTIONAL AGRICULTURE TO SUSTAINABLE AGRICULTURE

Farming systems currently cover a quarter of the Earth's land surface (MEA, 2005). The conversion of natural spaces into farmlands has been more extensive since the beginning of the 20th century than it was during the 18th and 19th centuries combined. Moreover, since 1945, farming has undergone a "Green Revolution," the primary objective of which is to increase yields in order to produce enough to feed the entire human population of the planet. This has resulted in significant modifications to cultivation practices. For example, the Haber-Bosh process (1913), which involves the fixation of atmospheric nitrogen into soluble nitrogen, has led to the extensive use of mineral fertilizers (Figure I- 3). More generally, the development of the chemical industry has also led to pesticide and herbicide use. Monoculture, together with the use of high-yielding varieties and mechanization, especially concerning tillage, has increased yields (Sturz and Christie, 2003).

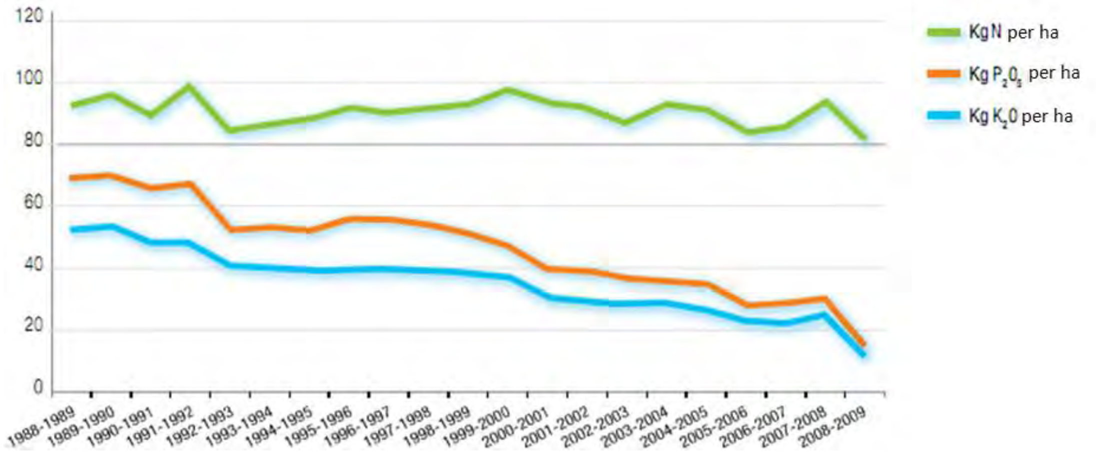


Figure I- 3: Fertilizer use in France in thousands of tons according to the Fertilization Industries Union (l'Union des Industries de la Fertilization)

Current agro-ecosystems and their associated practices, although very efficient in terms of productivity, have proved to cause much degradation (FAO, 2002). Consequently, alternative practices have been developed with the goal of sustainability. Sustainable agriculture was described by Parr *et al.* (1994) as a long-term objective that strives to overcome the problems and constraints faced by farming production systems in the areas of economic viability, environmental safety, and social acceptance. The Food, Agriculture, Conservation, and Trade Act of 1990 defined sustainable agriculture as a site-specific, integrated system of plant and animal production practices that will, over the long term:

- satisfy human food and fiber needs
- maintain the quality of the environment and of natural resources
- make efficient use of nonrenewable resources
- integrate natural cycles and biological controls
- sustain the economic viability of farm systems
- enhance the quality of life for farmers and for society as a whole

The idea of sustainable agriculture has led to the notion of ecological intensification as presented by Cassman (1999). Ecological intensification consists of using, as effectively as possible, ecosystem functions and ecological processes as well as information and knowledge (Bonny, 2010). Its objective is to design sustainable, lower-input, and more environmentally-friendly production systems. These systems are part of an approach that aims to reconcile increased productivity with the preservation of ecosystem services related to nutrient cycling.

Farming practices are thus evolving from high-input agriculture to sustainable agriculture. Currently, the terms conventional, organic, and biodynamic agriculture are commonly used. The boundaries between these various types of farming are sometimes unclear, and these terms must be used cautiously.

2.2 EFFECTS OF WINE-PRODUCTION PRACTICES ON SOIL

It is difficult to comprehensively describe all of the effects of crop managements on soils, because they are numerous and vary depending on the cultivated crop. Here, we will discuss the effects of the practices of the one singular crop that is the wine.

2.2.1. WHY STUDY VINEYARD SOILS?

Wine grapes are a perennial crop, and given its longevity, it is necessary to examine the sustainability of the vineyard system. In addition, vines are generally grown in regions in which another cropping is difficult. The vineyard soils often contain little organic matter, with a lot of coarse elements and stones, with steep sloped, and wherein irrigation is often impossible despite severe summer droughts in some regions. Growing vines requires considerable effort toward plant health protection, aerial part management (cutting, tying and topping) and soil maintenance. For this reason, wine grape cultivation is often deemed very intensive. It is therefore important to examine the potential effects of such intensive practices on soils that are naturally sensitive to the disruptions detailed in section I.3. Commercially, wine is associated with the terms Terroir and typicity. The Terroir refers to the site, environment or geographic area of origin of the wine, which influences the characteristic, commonly recognized organoleptic quality of a wine called typicity (Vaudour *et al.*, 2011). Together with climate, soil is considered to be a key component of the Terroir (Van Leeuwen *et al.*, 2004). For all of these reasons, the study of vineyard soils is important.

2.2.2. GLOBAL EFFECTS OF VITICULTURE ON SOILS

Several studies (Lagomarsino *et al.*, 2011; Lumini *et al.*, 2010; Pastorelli *et al.*, 2009; Zancan *et al.*, 2006) have compared conventional vineyards to other environments, including grasslands, fallow lands, and forests. These studies have shown that conventional vineyards exhibit lower microbial biomass, enzymatic activity, and microbial diversity than the other environments. Dequiedt *et al.* (2011) recently mapped soil microbial biomass throughout France using molecular quantification. The highest values were found in meadow soils (11.6 ± 5.8 mg DNA g^{-1} of soil), and the values in vineyard and orchard soils were the lowest (5.7 ± 3.3 mg DNA g^{-1} of soil). These results could be explained by the generally low organic matter content of vineyard soils. In a similar study, Saby *et al.* (2011) highlighted, on a map of France (16-km grid size), that the soils in the vineyards of Languedoc Roussillon and Bordeaux have among the highest levels of copper, a heavy metal that is toxic to soil organisms. Carlisle *et al.* (2006) examined soil respiration in a vineyard that had been converted from an oak woodland 30 years previously. The main conclusion of this study was that vine cultivation has reduced the organic matter content and increased the bulk density of the soil, thus affecting soil gas diffusion.

2.2.3. EFFECTS OF PARTICULAR VITICULTURE PRACTICES ON SOIL

A wide variety of viticulture practices exist that involve different approaches to soil management (chemical herbicide use, tillage, and the use of cover crops), fertilization (mineral, organic, or none), the maintenance of any temporary vegetal cover, vine pruning, and training and strategies for disease and pest control. The combination of these factors leads to numerous practices that can vary extensively. Then, it is difficult to generate a simple typology of all of these methods. Thus, we will discuss only the effects of soil management, fertilization and phytosanitary product use. We will also review current knowledge about the effects of the conversion to organic farming on soil.

Regarding the effects of soil management, Smith *et al.* (2008) and Raclot *et al.* (2009) found that superficial tillage significantly reduced soil loss compared to the use of chemical weed control. Regarding chemical weed control, Bois *et al.* (2011) identified bacterial populations that are tolerant of certain herbicides, such as glyphosate or Diuron, likely because Diuron is mineralized by soil microorganisms (Pesce *et al.*, 2009). In France, until recently, vineyard soil was typically maintained without any grass cover, through either chemical herbicide use or tillage, in order to avoid competition for water and nutritive elements. However, temporary or permanent cover crops provide benefits for soil preservation, including the prevention of erosion and the augmentation of organic matter content (Célette, 2007). Moreover, cover crops tend to reduce soil bulk density (Whitelaw-Weckert *et al.*, 2007) and to increase aggregate stability (Goulet *et al.*, 2004) relative to bare soils. Several authors have also examined the effects of cover crops on the biological functioning of vineyard soils. One of the most significant effects of the presence of a grass cover that is maintained by mowing is an increase in soil organic matter content that leads to greater microbial biomass than is seen in soils that are chemically weeded or mechanically managed (Ingels *et al.*, 2005; Reuter and Kubiak, 2003; Smith *et al.*, 2008; Steenwerth and Belina, 2008; Whitelaw-Weckert *et al.*, 2007; Xi *et al.*, 2009). Other authors have studied soil nematodes (Parker and Kluepfel, 2007;

Rahman *et al.*, 2009) and have observed that the structure of nematode communities is influenced by the presence and management of a cover crop. Addison and Fourie (2008) tested the effects of various types of cover crops on wine grape phytoparasitic nematodes, but this study was inconclusive. Finally, Vrsic (2011) compared the effects on earthworms of three soil management methods (mulching, periodic surface tillage and chemical weed control). In this study, cover crops had the most positive effect on earthworm populations, and the smallest earthworm populations were observed in conjunction with the chemical weed control. Periodic surface tillage had a negative effect, but only within the first horizon, and most earthworms were sampled at a depth of 10-20 cm. Paoletti *et al.* (1998) and Pérès *et al.* (2010) have also highlighted the negative effect of plowing on earthworms.

In addition to the effects of cover crops on organic matter content, the effects of adding exogenous organic matter have also been studied. Indeed, the loss of organic matter is a central problem in viticulture systems. A decrease in stable organic matter content has been highlighted as being directly linked to increased erosion (Le Bissonnais *et al.*, 2007). Following 10 years of organic amendments, Bartoli and Dousset (2011) measured an increase in organic matter content within the surface horizon of a silty soil, which considerably increased the aggregate stability and thus limited the risk of erosion. Morlat and Chaussod (2008) observed a decrease in bulk density and an increase in water holding capacity after 28 years of the addition of various types of compost (wood prunings, bovine manure and mushroom compost). The water holding capacity is related to the distribution of porosity, especially mesoporosity, or the abundance of pores with sizes ranging from 0.1 to 30.0 µm (Musy and Soutter, 1991). In addition, Pérès *et al.* (1998) observed that organic matter content indirectly increases the macroporosity (>30 µm) of the surface horizons due to its positive effects on the abundance and biomass of the earthworm community. The decrease in erosion due to increased organic matter content reduces the loss of soil micro- and macronutrients (Bustamante *et al.*, 2011) and thus limits the costs associated with erosion (Martinez-Casasnovas and Ramos, 2009). In French regions, the study of the chemical composition of soil is often limited to the study of macronutrients, whereas in other wine regions such as Australia and California, acidification and salinization are also significant problems (Fisarakis *et al.*, 2001; White, 2003b).

The copper content of soil has also been extensively studied because it is toxic to soil organisms and can be present in high concentrations in vineyard soils. Copper is the heavy metal component of fungicides derived from cupric salts ("Bordeaux mixture" type, $CuSO_4$ + $Ca(OH)_2$) that are used to fight the phytopathogenic fungus *Plasmopara viticola*. Copper has a negative effect on the soil microbial community (Diaz-Ravina *et al.*, 2007; Marzaioli *et al.*, 2010a) and on root colonization by mycorrhizae (Almaliotis *et al.*, 2008). However, Kostov and van Cleemput (2001) have shown that fungi are significantly more tolerant than bacteria to copper toxicity. At the same time, other authors (Andreazza *et al.*, 2011; Diaz-Ravina *et al.*, 2007; Viti *et al.*, 2008) have found that some bacteria are copper-resistant. Lejon et al. (2010) demonstrated that the organic status of the soil has a strong influence on the diversity of tolerant bacteria and their response to metals. Earthworms are also sensitive to copper (Eijsackers *et al.*, 2005; Paoletti *et al.*, 1998). Helling *et al.* (2000) documented negative effects of copper on *Eisenia fetida* at low doses (8.92 mg Cu kg^{-1} of substrate). In addition to copper, other synthetic phytosanitary products also have negative impacts on soil organisms. Cheng and Baumgartner (2004) observed that fungus diversity was higher in non-fumigated vineyards than in fumigated vineyards. In a laboratory study, Schreck *et al.* (2008) highlighted the neurotoxic effect on *A. caliginosa nocturna* of a mixture of six pesticides typical of those used in viticulture.

Various social, environmental, ethical, and economic factors motivate the conversion of French vineyards to organic farming practices. From 2001 to 2008, the surface area of French vineyards managed according to the organic principles increased eight-fold, from 3,426 hectares in 2001 (Agence BIO, 2002) to 28,190 hectares in 2008 (Agence BIO, 2009). The conversion to organic management requires alternatives practices. The synthetic products (pesticides or fertilizes) are banned and replace by natural origin ones. Moreover, the chemical weeding is replaced by cover crops or tillage. Several studies have focused on measuring the effects of organic farming on soil organisms. Freitas *et al.* (2011) and Okur *et al.* (2009) observed increased microbial biomass in parcels converted to organic farming. Probst *et al.* (2008) found that soil organic carbon content and microbial biomass are higher in vineyards following organic farming practices compared to conventional vineyards. Reinecke *et al*. (2008) showed that organic viticulture leads to increased soil biological activity, in particular, earthworm activity. In contrast, Vavoulidou *et al.* (2006) found no earthworms either in conventional vineyards or in organic vineyards. Regarding other organisms, Gaigher and Samways (2010) documented a lower diversity of arthropods in parcels cultivated using organic viticulture than in vineyards managed using integrated practices. Moreover, most studies pointed out that conversion increases the copper content of soils (Beni and Rossi, 2009). Finally, some conversions that involve giving up the use of synthetic inputs are categorized as biodynamic management which differs from organic practices by the use of particular solutions. Reeve *et al.* (2005) found almost no difference in the physical, chemical, and biological properties of soil between vineyards managed using organic methods and those cultivated using biodynamic practices. To summarize, we can say that a greater soil biological activity is usually observed in organic farming. However, the microbial component is shown to be affected by the conversion to organic farming wheras meso- and macrofauna are not systematically found in greater abundance or diversity in organically farmed soils.

3. SOIL QUALITY

3.1. WHY AND HOW WAS THIS CONCEPT BORN?

The first writings concerning soil and its production potential date back to the Roman agronomists Columelle (in the first century) and Palladius (in the fourth century). Until the mid-twentieth century, the majority of the literature on agricultural production mentioned soil only as a simple root anchoring media. It was not until the 1970s that Warkentin and Fletcher (1977) introduced the term "soil quality" in reaction to the negative effects of human activity on the environment and, in particular, on soils. These authors emphasized (1) the diversity of soil uses, (2) the diversity of their beneficiaries, (3) the evolution of the requirements and priorities concerning this resource, and (4) the human and institutional contexts in which decisions are made regarding soils. Doran *et al.* (1996) viewed the evaluation of soil quality as an indispensable tool for addressing three major challenges of our society: (1) the increase in world demand for food and fiber, (2) the increase of public demand for environmental protection, and (3) the decrease in non-renewable resources. Additionally, research on soil quality facilitates the comparison of different agricultural practices involving soils (Karlen *et al.*, 2003) and should aid governments in making decisions regarding sustainable agriculture policy (Granatstein and Bezdicek, 1992).

3.2. DEFINITIONS OF SOIL QUALITY

From its earliest definitions, beginning in 1990, the notion of soil quality has been a complex one. Different approaches have been taken to defining this term (Arshad and Martin, 2002; Bispo *et al.*, 2011; Doran and Zeiss, 2000; Hornick, 1992; Karlen *et al.*, 1997; Warkentin, 1995). Among the most general definitions is that published in Agronomy News (1995), stating that soil quality is "*its capacity to function*," with function defined in terms of physical, chemical, and biological properties and processes. Other definitions have made reference to soils in terms of production support. An example is that of Karlen *et al.* (1997), in which soil quality is linked to the quantity of the harvest produced. Hornick (1992) emphasized the degree to which soil quality also affects harvest quality (for both animals and man). Warkentin (1995) focused on the relationship between soil quality and the environment. They explained that beyond supporting production, soil quality also influences the habitats of a large variety of living organisms. These two components, production and the environment, were integrated for the first time by Doran et Parkin (1994), who defined soil quality as "*the capacity of a soil to function by supporting biological production, the quality of the environment* *and the health of plants and animals*." In their review, Arshad and Martin (2002) highlighted the same three components. To date, no author has included the notion of sustainability in the definition of soil quality, despite the non-renewable nature of this resource. However, Doran and Safley (1997) made reference to this notion in using the expression "continual capacity," and Doran and Zeiss (2000) stated: "*soil quality determines the sustainability of agriculture, the quality of the environment and, as a consequence, the health of man, animals and plants.*" Nevertheless, soils exhibit extensive diversity (in features such as slope, quantity of coarse elements, texture, pH, and micronutrient content) which, in combination with different climactic conditions, leads to widely contrasting situations. Indeed, Doran and Safley (1997) mentioned the importance of considering soil quality within an appropriate context. They redefined soil quality as "*the continual capacity of soil to function as a vital living system, within the boundary of a given ecosystem and land use, to promote air and water quality, and to maintain the health of plants, animals and humans*." Martin *et al.* (1999) proposed a definition of soil quality that does not invoke sustainability but insists on the importance of considering soil use. According to this definition, soil quality is "*the capacity of soil to function in a given ecosystem and for a given use, to support plant production, to contribute to environmental quality and to promote the health of plants, animals and humans*." This same idea was stated differently by Johnson *et al.* (1997) in their definition of soil quality as "*a measure of the condition of the soil relative to the needs of one or many biological specie(s) and/or for a human end*." Of all of the definitions proposed for soil quality, that of Doran and Parkin (1994) remains the most often cited. However, others, such as those of Doran and Zeiss (2000) or Martin *et al.* (1999), can be considered as more complete.

Up to this point, we have discussed soil quality, but some researchers (Doran, 2002; Doran and Zeiss, 2000; Karlen *et al.*, 2003; Karlen *et al.*, 1997; Wienhold *et al.*, 2004) distinguish two soil qualities: "*inherent quality*" and "*dynamic quality*." Inherent quality refers to the natural properties of soils determined by bedrock, topography, climate, vegetation, and the age of the soil (Dominati *et al.*, 2010). The analysis of inherent quality is used to estimate potential land use, and it currently serves as the fundamentals of soil assessment, soil classification, and land use recommendations. The principal parameters of inherent quality considered in most assessments are depth, stoniness, texture, pH, and slope. The dynamic quality, in contrast, is linked to the use and management of the soil. Dynamic soil quality assessment is necessary to determine the direction and the magnitude of a change of practice. One example of its application is in the examination of the effects of different soil management practices on a single soil subjected to a single use. Dynamic evaluation is also crucial for determining the direction and magnitude of a practice change. This approach typically concerns relatively short time periods (<10 years). The understanding and management of inherent and dynamic soil qualities are not independent, but complementary (Karlen *et al.*, 2003). According to Karlen *et al.* (2003), this distinction results in differences in the soil contribution to ecosystem functioning. For example, traditional classification and interpretation of soils was based almost entirely on inherent characteristics, often studied using a soil profile from a depth of approximately 2 m. More recently, researchers have focused on the top 20-30 cm of soil in order to evaluate dynamic soil quality, which appears to allow a more holistic approach based on physical, chemical, and biological parameters.

Our review indicates that the majority of soil quality definitions were published before the year 2000. Progress toward a clear and complete definition of soil quality appears to have stalled. Thus, no single definition of soil quality is accepted by the entire scientific community, but various complementary definitions are instead recognized. Thus, it may be more appropriate to speak of “the qualities of soils.”

3.3. OTHER CONCEPTS RELATED TO SOIL QUALITY

3.3.1. SOIL HEALTH

Acton *et al.* (1995) proposed the following definition for soil health: “*the capacity of the soil to support the growth of crops without degrading or otherwise harming the environment*.” Numerous authors (Acton *et al.*, 1995; Blum and Santelises, 1994; Cameron *et al.*, 1996; Chaussod, 1996; Doran and Parkin, 1994) have considered the words “*soil quality*” and “*soil health*” to be interchangeable. Other authors have expressed reservations concerning the equivalence of the two wordings. According to Romig *et al.* (1995), scientists are more attracted to the term “*soil quality*,” which they evaluate using quantitative analyzes. Such analyzes can be used afterwards to correlate the properties and the functions of the soil. In contrast, farmers tend to prefer the term “*soil health*” and to use qualitative information based on their value judgments. For Bispo *et al.* (1996), the notion of “*soil health*” is independent of uses and users because soil is considered a non-renewable resource that should retain all of its functions. Also, the soils of natural ecosystems are generally considered healthier than soils used in conventional agriculture, even if this has yet to be proven conclusively (Van Bruggen and Semenov, 2000).

It can be pointed out that the majority of articles that make reference to “*soil health*” are relatively old (1990s). Currently, the majority of researchers have abandoned this term, which is exclusively centered on production, in favor of "*soil quality*." For the same reason, we will use the term soil quality.

3.3.2. SOIL FERTILITY

Many farmers and some researchers (Bhogal *et al.*, 2011; Chambers *et al.*, 2003) have used (or still use) the terms "*soil fertility*" and "*soil quality*" equally. However, the term fertility refers only to the production component (Gasselin *et al.*, 2010). In measuring the water and mineral nutrition of crops, with a view to increasing yields, Riedel (1955) considered fertility to be the chemical richness of the soil. At the same time, certain notions associated with soil fertility are identical to those associated with soil quality. Indeed, Sebillote (1989) wrote that the fertility of soil depends on the functions for which the soil is used. Mazoyer and Roudart (1997), in turn, defined the fertility of an ecosystem as its capacity to sustainably produce. Despite these definitions, the term "*soil fertility*" is too restrictive because it does not include the environmental and health elements inherent in soil quality. For this reason, we will avoid using this term throughout the remainder of this review.

3.4. THE DIFFICULTIES OF EVALUATING SOIL QUALITY

The difficulty of producing a single, universally acceptable definition of soil quality was previously discussed. The evaluation of soil quality requires the answering of six main questions:

1- **In what context is soil quality being evaluated**? In order to evaluate soil quality, it is necessary to define not only the pedoclimactic context, but also broader aspects of context such as economic, historical, social, cultural, legislative, and political factors. This broader context will influence the responses to the remaining questions.

2- **Who is the evaluation for? The** user might be a farmer or a person not directly linked to agriculture. The former will be concerned with productivity and put less weight on other factors, whereas the latter might be more sensitive to the environmental roles of the land (as a biodiversity reserve, for example). The importance that these two users attribute to each component of soil quality will thus be different.

3- **What are the functions of interest?** Defining the user is not sufficient; when studying soil quality, one should also ask which functions are performed by the soil (Karlen *et al.*, 2003; Karlen *et al.*, 1997; Letey *et al.*, 2003) and particularly, which functions are of primary importance for the chosen use.

4- **What is the scale of the study?** The conceptual model proposed by Karlen *et al.* (1997) for the evaluation of soil quality emphasizes that soil quality can be evaluated at five different scales. The first two scales concern understanding soil quality at the finer scales of the experimental plot and the rhizosphere. The other three scales concern the evaluation of soil quality management at the field level, at the crop-production level, and at a more global scale (region, country, or world). This question is crucial from a strategic point of view because it influences aspects of the sampling protocol such as the number of replicates, the type of sampling, and the depth at which samples are taken.

5- **What are the parameters to be measured**? When studying soil quality, one must identify the parameters appropriate for undertaking this evaluation (Karlen *et al.*, 1997). Defining the user, the functions of interest, and the scale of the study will facilitate the selection of the parameters to measure in order to best understand the quality of the soil in the correct context.

6- **What are the threshold values of each parameter?** Karlen *et al.* (1997) suggested that, taking into consideration the potential diversity of soil use, evaluations of soil quality should be viewed in a relative rather than an absolute manner. However, a farmer might be interested in the evaluation of only one of his parcels. Thus, it is necessary to set threshold values for each parameter in relation to the soil function studied. The selection of a threshold value is subjective, as it necessitates a value judgment. The parameters considered and the threshold values assigned also depend upon socioeconomic contexts, which evolve over time.

This in-depth examination of soil quality reveals the degree to which the definition and evaluation of soil quality remains complex. A rigorous approach of soil quality merges in three well-defined elements (production, environment, and health) within a given context.

4. INDICATORS FOR THE EVALUATION OF SOIL QUALITY

4.1. INTEREST IN THE USE OF INDICATORS

The evaluation of multiple parameters is essential in the understanding of overall soil quality (Bispo *et al.*, 2011; Karlen *et al.*, 1997; Warkentin and Fletcher, 1977). However, the number of parameters that can be used as indicators of soil quality is almost unlimited. Farmers have developed observational tools that allow them to evaluate the overall quality of soils. Whether in Bangladesh

(Ali, 2003), Kenya (Mairura *et al.*, 2007), Latin America (Barrios *et al.*, 2006), or Honduras (Ericksen and Ardón, 2003), farmers use crop yields, the topography, slope and depth of the soil, the thickness of the surface horizon, the texture and color of the soil, the presence of macrofauna, and the abundance and diversity of weeds. To our knowledge, only one study of the indicators used by farmers has been undertaken in France (Baillod *et al.*, 2010). This study asserted that despite their simplicity, field indicators remain limited and operationally questionable. Moreover, Ali (2003) indicated that the soil quality indicators used by farmers are often qualitative.

4.2. INDICATOR DEFINITIONS AND CRITERIA

Wery *et al*. (2011) defined an indicator generally as a tool that provides information about an element of a system that is difficult to access, in order to aid in its analysis and management. The INRA (1983) defined soil quality indicators as "*criteria facilitating the characterization of the state and development of the soil*." One generally distinguishes physical and chemical indicators from biological indicators. Physical indicators are used to obtain information about the soil structure and its permeability. The measurement of chemical indicators is based on the use of chemical reagents used to extract a portion of the element or compound being studied. The extract is then measured using a variety of methods. The idea of measuring the quality of an environment by examining living organisms has long existed. Blandin (1986) analyzed different conceptions and practices relating to biological indicators. Far earlier, Nylander (1866) presented an interest in studying lichens to obtain information on the healthfulness of the air. Clements (1928) was the first to develop a broad perspective concerning the use of plants as indicators. Other authors (Diekmann, 2003) have also worked along these lines. Wilhm (1975) contributed significantly to the development of biological indicators to estimate the water pollution in the United States. Blandin (1986) proposed the following definition: "*a biological indicator (or bioindicator) is an organism or group of organisms that, by reference to biochemical, cytological, physiological, ethological or ecological variables, allow practically and surely, the characterization of the state of an ecosystem or of an ecocomplex and as soon as possible, to highlight natural or artificial induced modifications occurring within them.*"

Many scientists (Schoenholtz *et al.*, 2000; Van Bruggen and Semenov, 2000; Wienhold *et al.*, 2004) have distinguished two types of indicators: static indicators and dynamic indicators. The former change little at the human scale and are linked to inherent qualities of the soil. As for the latter, these indicators are linked to dynamic soil quality and are much more sensitive to land use and to agricultural practices. The chemical properties of soil are difficult to classify into one or the other of these two categories (inherent or dynamic). Indeed, the pH, the total calcareous content, and the total organic matter content are dependent on soil type. Moreover, these properties can be modified by certain agricultural practices such as liming or manure spreading. In the case of earthworms as bioindicators, Cluzeau *et al.* (1999) distinguished two major roles. Earthworms can be considered as indicators of states and the uses of the soil, or as regulators that intervene in different soil processes (e.g. the decomposition of organic matter). Thus, an abundance of earthworms can provide information concerning the copper toxicity of a soil (indicator role) or concerning soil porosity in terms of worm tunnels (regulator role). Each bioindicator can thus provide two types of information: descriptive and functional.

Numerous authors (Blandin, 1986; De Bruyn, 1997; Doran and Zeiss, 2000; Kinyangi, 2007; Schloter *et al.*, 2003) have addressed the criteria that should be met by a parameter in order to be considered as a valuable soil quality indicator. The chosen indicator should be reactive and sensitive to management changes in order to facilitate the evaluation of dynamic soil quality. It should also be appropriate for the function being studied and make explicit reference to this function. Its evaluation should provide a broad view of the soil system and help in the anticipation of situations in order to facilitate decisions and preventative action. From a practical perspective, the measurement of the indicator should be cheap, easy, reliable and reproducible. Its interpretation should be easy, which requires a guideline that is understandable and usable by farmers and other land managers.

Arshad and Martin (2002) emphasized the quantitative data that indicators should provide. According to these authors, a valuable indicator should provide the direction of a change (positive or negative), its scope (as a percentage increase or decrease with respect to reference values), its pace (in months or years for example), and its spatial extent (the percentage of the parcel or farm in which the soil quality has changed). Other authors have been more concerned about the operational potential of indicators for professionals. Simple measures should be created for farmers (Mairura *et al.*, 2007; Murage *et al.*, 2000) and for politicians who need to make regional development decisions (Barrios *et al.*, 2006). However, this task is not easy. Barrios and Trejo (2003) acknowledged the genuine challenge presented by developing soil quality standards that are practical and useful for farmers.

4.3 SELECTION OF INDICATORS

It is widely recognized that a single indicator cannot provide adequate information on soil quality. Schloter *et al.* (2003) asserted that it is unlikely that a single ideal soil quality indicator can be defined with a single measure due to the multitude reactions that exist in soils. For a task as broad as the evaluation of soil quality, Karlen et al (1997) argued that parameters should be selected, measured and interpreted with an emphasis on the extent to which they can be generalized and extrapolated more than on the precision of the information. The complex nature of soil and the exceptionally large number of parameters that can be measured necessitates the selection of indicators that are appropriate to the particular functions of interest (Bastida *et al.*, 2008). Karlen et al. (1997) emphasized the importance of adopting a systemic approach in the evaluation of soil quality due to the many interactions that are involved and the variety of societal and environmental objectives under consideration (e.g., improving water quality, maintaining productivity, assuring food quality, and increasing biodiversity). Each soil function is associated with different physical, chemical, and biological parameters (Karlen *et al.*, 2003; Karlen *et al.*, 1997). The diversity and the development of new analytical methods leads to an increasing list of indicators (Bispo *et al.*, 2011). Because time, funding, and analytical resources are limited, not all indicators can be measured. For this reason, several researchers (Arshad and Martin, 2002; Bastida *et al.*, 2008; Cassman, 1999; Kinyangi, 2007; Marzaioli *et al.*, 2010b; Wienhold *et al.*, 2004) have proposed minimum sets of indicators, or Minimum Data Sets (MDS), of soil quality. Among the parameters most commonly included in such sets are soil depth, texture, bulk density, infiltration, water retention capacity, aggregation, pH, organic matter content, the availability of macronutrients (N, P and K), soil respiration, and microbial biomass. Although soil evaluation depends on the functions being studied, the parameters included in the MDS indicators provided by various authors are largely essential regardless of the aspects of soil quality being studied. The physical and chemical indicators represent a significant proportion of the MDSs proposed by scientists. Mc Grath (1998) has indicated that the most commonly used soil quality indicators are physical, followed by chemical indicators. The biological dimension is least considered in this type of approach.

4.4. PHYSICAL AND CHEMICAL INDICATORS

Efforts to characterize soil quality have focused principally on chemical and physical properties. In their review, Schoenholtz et al. (2000) summarized the state of the art for physical and chemical indicators of forest soil quality. The Table I- 1 presents these indicators along with their associated functions. Of the indicators presented, some are more closely associated with the inherent quality such as texture, pH, or active and total lime content of the soils rather than dynamic qualities. The bulk density (X31-501, 1992) is an indicator of soil compaction (Bouwman and Arts, 2000; Briar *et al.*, 2007). Measurements of water capacity in the field (ISO 11274, 1998) stands for evaluation of the available water in soils. The aggregate stability reflects the capacity of soil to resist to physical degradation as erosion (Bastida *et al.*, 2008). The stability of aggregates can be visualized as histograms showing the size distribution of particles after moistening. It has also been used to calculate a more global indicator known as MWD (Mean Weight Diameter).

Table I- 1 : Presentation of physical and chemical indicators and associated information

Indicators	Associated information
texture	The composition of sand, silt, and clay is the most fundamental qualitative property of the soil. It controls water, nutrient and oxygen exchange. It changes little over time for a given soil (except in the case of strong erosion) and thus is not very useful for evaluating the effects of cultural practices on the quality of soils.
apparent density	Varies for soils with different textures, structures, and organic matter content, but for a given type of soil, it can be used to evaluate the compaction of the soil.
porosity	This is an indicator of soil structure and it is sensitive to physical changes caused by soil management.
water holding capacity	This is a very important piece of information because it measures the water availability for plants.
aggregate stability	This reflects the capacity of the soil to resist degradation. Testing by rapid humectation makes it possible to study the behavior of dry materials when subjected to sudden flooding, such as irrigation by submersion or intense rains (spring and summer storms).
organic matter	This plays a role in practically all soil functions, and it is recognized as one of the key chemical parameters for soil quality. Through its role in stabilizing aggregates, it influences the porosity of the soil as well as gas exchange reactions and water content. It is a critical pool in the carbon cycle and a source of nutrient elements. It also influences fundamental biological and chemical processes.
pH	Various chemical reactions are influenced by the chemical environment of the soil, and in particular by the pH of the soil. Thus, pH is included as a key chemical indicator. The soil pH also influences many biological and chemical relations simultaneously. The pH influences the availability of nutrients, the absorption of nutrients and the mobility of pesticides.
calcareous (total and active)	Limestone in soils is the principal source of calcium. When high levels of lime are associated with a particular type and fine grain, it can exert unfavorable influences.
availability of macronutrients (P and K)	The evaluation of their quantity in extractant solution is an evaluation of the availability for plants.
CEC	CEC can be observed as an index of the availability of cations in soils that are naturally extremely leached. CEC is a critical parameter for the capacity of an agricultural soil to retain or supply nutrients.

The Soil Organic Matter (SOM) content is recognized as one of the key parameters for soil quality. The SOM is correlated with soil texture and it is also influenced by methods of soil management, such as type of fertilization or soil management. The measurement of total or exchangeable nutrient content, especially the macronutrients (N, P, and K) is among the most recently used by farmers, scientists or agricultural advisers. In agriculture, macronutrients are a critical consideration because they affect both the quantity (as a limiting factor) and the quality of harvests. Their content depends on fertilization, but it also depends on various methods of soil management. Different concentration of these nutrients (total content, available content, and bioavailable content) are measured using extraction with the aid of standard protocols that define the type of solution, the nature of exchange and the duration of exchange. The availability of an element is defined as the quantity of the element available to an organism, and it only represents a portion of the total fraction of that element. This term is distinct from bioavailability, as defined by Thornton (1999), whose definition was included as a norm (ISO/DIS 17402, 2006). Thornton defined bioavailability as the fraction of an element (nutritive and/or potentially toxic) absorbed by a living target organism (microorganism, animal or plant) from soil during a given period by different physiological processes of absorption. The bioavailability is difficult to measure, thus, classic soil analysis only provide information about availability. The interpretation of soil chemical analysis has to take care of the type of extraction used. Moreover, the use of standardized protocols is necessary to compare results produced by different operators. In some cases, it can be useful to measure the content of trace elements or salts. Finally, Cation Exchange Capacity (CEC) provides information about the ability of the soil to retain cations. This measurement is closely correlated to the content of clay and SOM. There are three different types of CEC measurement. Thus, the investigator should be aware of his goals and of the limits of each of method when choosing a measurement for CEC.

4.5. BIOLOGICAL INDICATORS

4.5.1. SOIL BIODIVERSITY

The biological parameters of soils have been largely neglected due to (i) the difficulty of quantifying them and (ii) the difficulty of predicting the biological behavior of soils (Parr *et al.*, 1994), particularly for small-sized taxonomic groups (Decaëns *et al.*, 2006). If they are associated with physical and chemical measurements, biological parameters can nevertheless enable better characterization of soils. In fact, soil organisms develop close relationships with their environment (Franzle, 2006) and can thus provide information about the general soil functioning because they are sensitive of the various perturbations and stresses suffered by the soils (pollution, climatic variations, physical state of the soil, etc.) (Bongers and Ferris, 1999; Paoletti, 1999).

Soil organisms live in the soil, either permanently (even if they are not always active) or temporarily (on a daily basis, to hide, or on a seasonal basis to hibernate or carry out part of their development cycle). They exhibit great diversity in terms of morphology, behavior, and function. Decaëns et al. (2006) estimated that soil animals could represent 23% of the total diversity of living organisms. Soil organisms can be divided into different groups according to their size: microorganisms, microfauna, mesofauna, macrofauna, and megafauna (Figure I- 4).

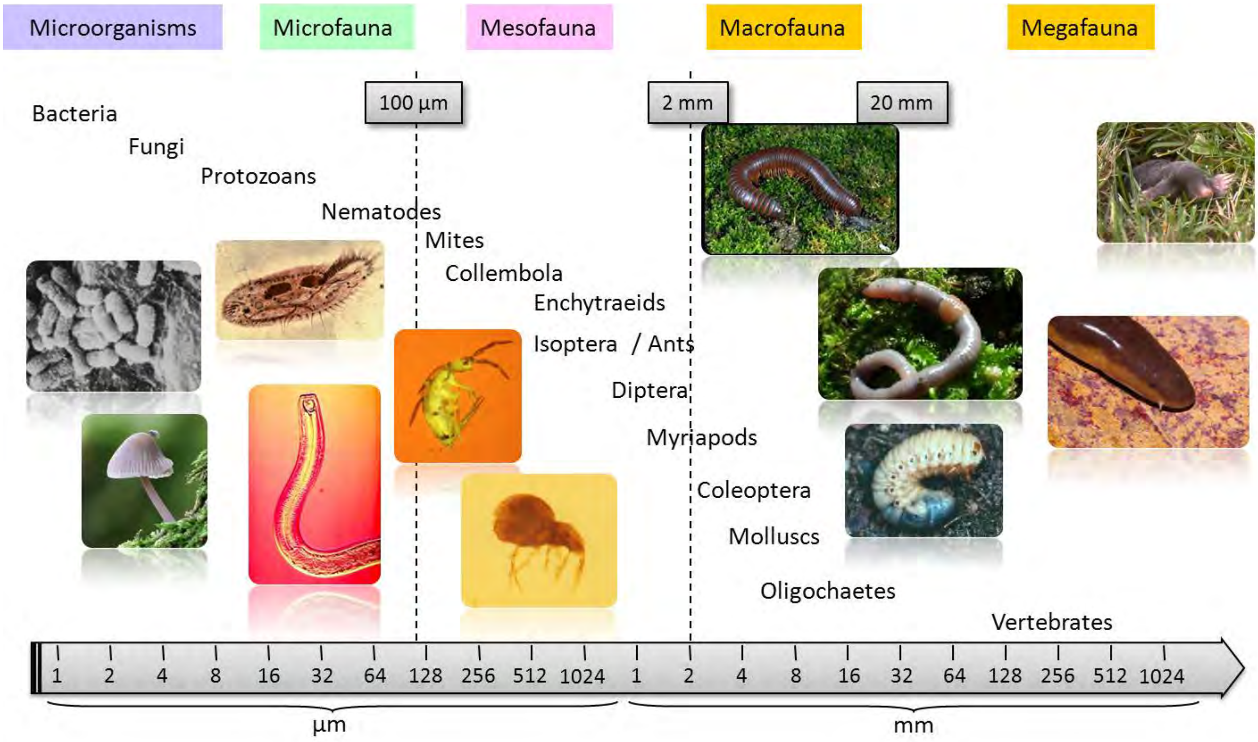


Figure I- 4 : Classification of organisms as a function of their size (after Swift et al. (1979))

These interactions involve a complete range of physical, chemical, and biological processes that help to maintain ecosystem function and allow ecosystem services to take place in the soil. In their review, Lavelle et al. (2006) discuss the contributions of soil organisms in terms of their physical, chemical, and biological properties. The effects of soil organisms on their environment result from their ability to change the environment through their physical activities. Thus, arbuscular mycorhizal fungi improve the stability of aggregates (Cavagnaro *et al.*, 2006), and burrows made by earthworms increase the macroporosity of the soil (Pérès *et al.*, 1998). The mineralization of organic phosphorus by phosphatases excreted by certain fungi (Rodriguez and Fraga, 1999) is an example of a chemical effect that takes place in the soils. The activities of soil invertebrates can also have consequences for communities of other organisms (biological effects). For example, microbial biomass affects the abundance of bacterial-feeding and fungal-feeding nematodes (Ferris *et al.*, 1996), and microbivorous nematodes are known for regulating the dynamics of microorganisms and the fluxes of nutrient elements in soils (Denton *et al.*, 1999).

Soil microorganisms and soil invertebrates play a dominant role in the decomposition of organic matter and then nutrient cycle. As a consequence, both microorganisms and invertebrates are important indicators of soil quality (Parr *et al.*, 1994). The study of soil organisms is a useful of information because they give extensive information about the abundance, diversity, and the structure of trophic networks and/or the stability of communities (Doran and Zeiss, 2000). In addition, there are very close relationships between the biological functions of soils (microbial decomposition of organic matter) and numerous physical and chemical measurements of the nutrient elements (such as C/N, organic C, total N, and P mineralization) (Schoenholtz *et al.*, 2000). Van Bruggen and Semenov (2000) claim that soil microorganisms and fauna such as earthworms, nematodes, collembola and predatory mites can serve as indicators of soil quality. In turn, Barrios et al. (2006) recommend the study of the bioindicators presented in Table I- 3 Changes in the biodiversity of organisms (microorganisms, insects, and earthworms) can provide information about the degradation and rehabilitation of soils (Stork and Eggleton, 1992; Visser and Parkinson, 1992). However, Doran and Zeiss (2000) and Ekschmitt et al. (2003) warned about the use of species richness as an indicator because measuring species richness involves challenges in terms of the efficiency of sampling, extraction, and taxonomic identification; considerable time and money may be required to characterize species richness. It is thus desirable to use simpler indicators.

Table I- 2 List of bioindicators recommended by Barrios et al. (2006)

Indicators	Significance
mineralization of nitrogen	a measure of the release of inorganic nitrogen from organic matter
microbial biomass	measure of the total quantity of soil microorganisms
ratio of microbial biomass / organic carbon	metabolic quotient representing the level of microorganism activity
soil respiration	quantity of CO_2 generated by the biological activity of the soil
soil fauna	diversity of sizes of soil arthropods and invertebrates
rates of decomposition of litter	an integrated measure involving the interactions of vegetation, the availability of soil nutrients and the population sizes of microorganisms, microfauna, and macrofauna

4.5.2. MICROORGANISMS

In natural ecosystems and those affected by man, microorganisms are abundant and diverse. We can measure, on average, 6 tons of bacteria and 5 tons of fungi per hectare (Bachelier, 1978). These organisms interact with each other, with other organisms (plants, animals, etc.), and with the abiotic environment, which makes their study complex. Soil microorganisms are involved in various key processes for ecosystems, such as the decomposition of organic matter, the formation of humus, aggregation of soil, the cycling and retention of nutrients, and various symbioses and parasitic relationships with plants (Paul and Clark, 1996). Microbial biomass has been measured through studies of carbon flow, nutrient cycles, and plant productivity (Voroney *et al.*, 1989). Microbial biomass constitutes also an important pool of nutrient elements potentially available for plants, and microbial turnover acts as a dynamic source of nutrient elements available in the soil.

In her dissertation, Pascaud (2007) identified certain problems with the study of microorganisms as bioindicators. She distinguished two major technical obstacles that make certain analyzes cumbersome and incompatible with routine tracking, and she showed that sampling bias causes high variability in the spatial distribution of microorganisms and their associated processes (Chenu *et al.*, 2001; Nunan *et al.*, 2003).

The two methods of measuring microorganisms most commonly used in the past were microbial biomass and respirometry. Microbial biomass of the soil can be defined as the quantity of organisms living in the soil that are generally in a size range smaller than 10 µm (Schloter *et al.*, 2003). Microbial biomass is an integrative signal as it measures all microorganisms in total, regardless of whether they are dormant or metabolically active. Microbial biomass is generally dominated by bacteria and fungi, but it also includes protozoans. Microbial biomass is related to biological activity, the recycling of nutrients and the ability of soil to degrade pesticides (Karlen *et al.*, 1997). The ratio between microbial carbon content and total organic carbon content has been proposed as an index that is sensitive to changes in the soil (Bastida *et al.*, 2008). In fact, microbial biomass reacts more rapidly than organic matter to changes in the soil. Microbial activity in the soil promotes the release of nutrient elements available for plants, but it also enables the mineralization and mobilization of pollutants. Thus, microbial activity is crucially important to biogeochemical cycles (Schloter *et al.*, 2003). The metabolic quotient, which is the ratio between the production of CO_2 (respirometry) under standardized conditions and the microbial carbon content, is often used to evaluate the quality of environmental conditions (Schloter *et al.*, 2003).

4.5.3. NEMATOFAUNA

Soil nematodes are non-segmented roundworms that are variable in size, ranging from 300 µm to 4 mm long. Nematodes act as indicators that are sensitive to perturbations, and to the enrichment of soil with readily available resources. In fact, the permeable nature of their cuticle puts them in direct contact with solvents because they live in the film of water that surrounds soil particles. They also have a high capacity for colonization, and they do not migrate rapidly. Furthermore, nematodes are abundant (more than 10 nematodes g^{-1} of dry soil), and they are present in all types of soil. They are also taxonomically diverse. Indeed, more than 10,000 species have been described (Bongers and Ferris, 1999). In practice, nematodes can be easily sampled throughout the year. Moreover, nematodes can be sampled in an intensive and repeated way because it requires only a small quantity of soil (250 g of soil). Interestingly, the extraction of nematodes is standardized (NF ISO 23611-4, 2007). In addition, identification at the family level is possible using simple morphological characteristics. Families of nematodes show various alimentary behaviors, and Yeates et al. (1993) described nematode genera as obligate plant-feeders or facultative plant-feeders (PF), bacterial-feeders (Ba), fungal-feeders (Fu), predators (Pr), or omnivores (Om) (Figure I- 5). Those that are not obligate plant-feeders or facultative plant-feeders are referred to as free-living nematodes.

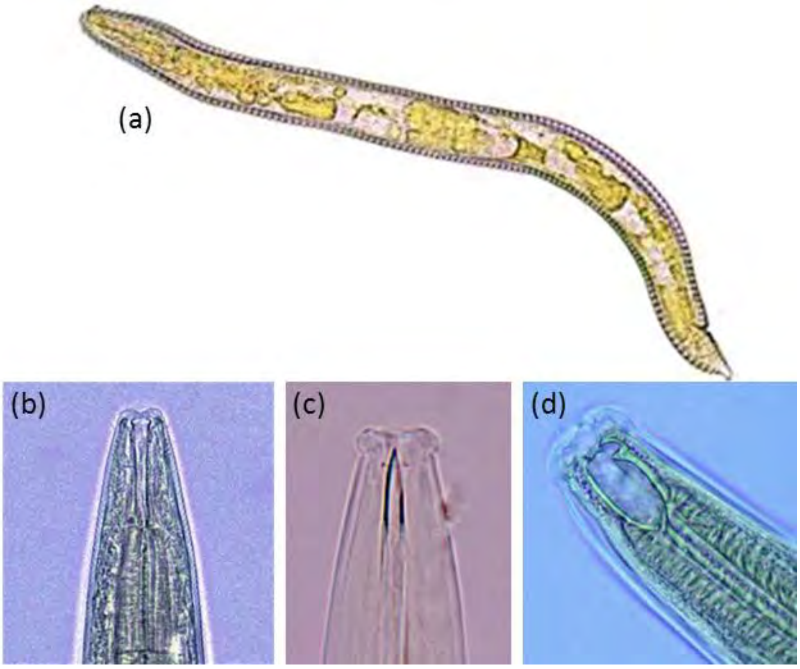


Figure I- 5 : nematode trophic groups

Each family also has its own demographic characteristics, from type r to type K (Table I- 3). Nematodes that increase rapidly in number under favorable conditions can be considered colonizers (c). In general, colonizers are dominant in ephemeral habitats. In contrast, persistent nematodes (p) are very rarely dominant in a sample. They occupy habitats that have long-term stability (Table I- 3). Families of nematodes are classified on a “colonizer-persistent scale” (Table I- 3), or cp scale, ranging from 1 (for colonizers) to 5 (for persistents) (Bongers, 1990). Colonizers and persistents have extreme demographic characteristics, but many species have intermediate characteristics (Table I- 3)(Ferris *et al.*, 2001).

Analyzes of nematofauna include the trophic groups of nematodes (Yeates *et al.*, 1993) on the cp scale of values in a classification matrix of functional guilds (Table I- 3) (Bongers and Bongers, 1998). Thus, each family of nematodes belongs to one of the fifteen functional guilds defined by the classification matrix. They are named in as follows: Plx, Bax, Fux, Omx, and Prx, with x equal to the cp value of the taxon. Nematodes from the same functional guild respond in a similar way to the enrichment of the trophic chain and to environmental perturbations (Ferris *et al.*, 2001).

Table I- 3 : Definition of terms relating to the study of nematofauna (adapted from (Ferris *et al.*, 2001)

Base notions relating to nematodes	Definitions
strategy K	developmental strategy adopted by organisms that experience predictable conditions, with a constant supply of resources and low risks that lead to an investment in the survival of adults.
strategy r	developmental strategy adopted by organisms that experience variable or perturbed conditions, with unpredictable resources and elevated risks that necessitate a high rate of growth and fecundity.
colonizer-persistent scale (cp scale)	categorization of soil nematode taxa on a linear scale ranging from 1 to 5, according to their r or K strategies: • cp-1: short generation time, small eggs, high fecundity, feeding continuously in a rich environment (bacterial-feeders), • cp-2: longer generation time, fecundity lower than cp-1, very tolerant of hostile conditions, continuing to feed as resources diminish (principally bacterial-feeders and fungal-feeders), • cp-3: longer generation time, greater sensitivity to hostile conditions (fungal-feeders, bacterial-feeders and predators), • cp-4: longer generation time, weaker fecundity, greater sensitivity to perturbations (bacterial-feeders, fungal-feeders, omnivores and predators), • cp-5: longest generation time, larger sizes, greatest sensitivities to perturbations (principally omnivores and predators).
functional guild	Group of taxa of nematodes belonging to a single group and having the same coloniser-persistant value: Ba(x), Fu(x), Om(x), Pr(x) or PF(x) (Ba = bacterial-feeders, Fu = fungal-feeders, Om = omnivores, Pr = predators, and PF = plant-feeders, x can take values of 1 to 5).

Ferris et al. (2001) have classified functional guilds within three qualitative components of trophic networks: the basal component, the enrichment component, and the structure component. Functional guilds of the basal component (Ba2 and Fu2) describe a simple trophic network due to limited alimentary resources, unfavorable environmental conditions, or contamination. These nematodes are adapted to stress conditions and defined as opportunistic generalists (Bongers, 1999). The enrichment component includes the Ba1 and Fu2 nematodes. This is a food web for which resources become available due to the death of organisms, the dynamics of organic matter, or a favorable change in the environment, such as the addition of fertilizers. Many Ba1 nematodes survive periods of limited resources by passing into a phase of limited metabolic activity (*dauer larvae*). Fu2 nematodes are abundant when environmental conditions are stable, such as in forests or prairies where food is abundant (Ferris *et al.*, 2001). The final component is the structure component, described as a food web for which resources are more abundant and/or a food web in which recovery takes place after stress. The functional guilds of the structure component are Pr2, Ba3, Fu3, Pr3, Fu4, Pr4, Om4, Pr5, and Om5. Nematodes that are part of the structure component are sensitive to soil perturbations, and they are often absent from perturbed, polluted, or overexploited environments (Bongers, 1999).

The data set collected after analyzing the diversity of nematofauna was used to calculate the different nematological indices. Defining these indices was a key step in the development of diagnostic tools for trophic networks (Freckman and Ettema, 1993). The ecological indices, including the maturity index (MI), enrichment index (EI), and structure index (SI), are based on the analysis of nematofauna. They serve as useful indicators of environmental perturbations of the soil, and they are indicators of the state of the food web in the soil (Ferris *et al.*, 2001). The Table I- 4presents the calculations and interpretations of these indices. The maturity index (MI) indicates the state of perturbations in an ecosystem. The enrichment index (EI) is based on the sensitivity of the opportunistic non-plant-feeding guilds to the enrichment of trophic resources. The structure index (SI) describes the sensitivity of the functional guilds to perturbations (Bongers, 1990). It has been shown that plant-feeders and non-plant-feeders respond differently, and this has led to the creation of another index, the plant-parasitic index or PPI (Bongers *et al.*, 1997). This behavioral difference is due to the close relationship of the plant-parasitic nematodes with their plant hosts, which are more stable in time and space than the other resource on which free-living nematodes depend. Plant-feeders require separate analyzes as indicators of environmental perturbations and trophic network conditions (Bongers *et al.*, 1997). The NCR (Nematode Channel Ratio) indicates the decomposition pathway between bacterial- and fungal-pathway for organic matter. The CI (Channel Index) also provides information on the decomposition pathway, but its calculation is solely based on functional guilds Ba1 and Fu2.

To summarize, knowledge of the structure of the nematode community provides information on (1) the intensity of different processes taking place in the soil, such as the decomposition of organic matter and the mineralization and detoxification of pollutants, (2) the structure of the (non-nematode) trophic chain in the soil, i.e., bacterial and fungal components and predation, (3) the state of the stability of the system (absence of stress or important perturbations) characterized by the trophic micro-chain of the soil and the resistance and resilience of the soil and (4) biodiversity, defined by the number of taxa and functional guilds present (Villenave *et al.*, 2009a).

The characteristics of soil nematodes suggest that the structure of nematode communities is a useful bio-indicator for the study of environmental changes, both in temperate and tropical environments (Bongers and Ferris, 1999; Ferris *et al.*, 2001; Schloter *et al.*, 2003; Villenave *et al.*, 2001).

Table I- 4 : Calculation and interpretation of different nematode indices (MI: maturity index, PPI: plant-parasitic index, EI: enrichment index, SI: structure index, NCR: Nematode Channel Ratio and CI: Channel Index)

Index	Formula	Detail of calculations and interpretations
Maturity Index (MI)	MI = Σ vi × pi	vi = cp-value of the taxon i in the community of non-plant-feeders, pi = relative abundance of the taxon i in the community of non-plant-feeders. MI provides information on environmental perturbation and contamination. Scored between 1 and 5, it increases with environmental stability.
Plant-Parasitic Index (PPI)	PPI = Σ vj × pj	vj is the cp-value of the taxon j in the community of obligate and facultative plant-feeders, pj is the relative abundance of the taxon j in the community of obligate and facultative plant-feeders. The PPI is scored between 2 and 5.
Enrichment index (EI)	EI = 100 × (e / (e + b))	e = Σ pei x kei, where • pei is the relative abundance of the guild i of the enrichment component • kei is the weight assigned to the guild i of the enrichment component b = Σ pbj x kbj, where • pbj is the relative abundance of the individuals of the guild j of the basal component, • kbj is the weight assigned to the guild j of the basal component. Scored between 0 et 100, EI increases with availability of resources.
Structure index (SI)	SI = 100 × (s / (b + s))	s = Σ psi x ksi, where • psi is the relative abundance of the guild i of the structural component, • ksi is the weight assigned to the guild i of the structural component. b = Σ pbj x kbj, where • pbj is the relative abundance of the individuals of the guild j of the basal component , • kbj is the weight assigned to the guild j of the basal component. Scored between 0 and 100, SI increases with environmental stability.
Channel index (CI)	CI = 100 × (0.8Fu2 / (3.2Ba1 + 0.8Fu2))	Ba2 is the relative abundance of bacterial-feeders cp-2. Fu2 is the relative abundance of fungal-feeders cp-2. CI indicates the predominant pathway of decomposition.
Nematode Channel Ratio (NCR)	NCR = Ba / (Ba + Fu)	Ba is the relative abundance of bacterial-feeders , Fu is the relative abundance of fungal-feeders. NCR is a mean to express the decomposition pathways. When the ratio tends toward 1, bacterial-feeders dominate; when ratio tends toward 0, fungal-feeders dominate.

4.5.4. EARTHWORMS

Earthworms are annelid worms of variable size, usually longer than 2 mm. De Bruyn (1997) and Rombke et al. (2005) described the usefulness of earthworms as bio-indicators of soil quality. First, the biology, ecology and ecotoxicology of earthworms are very well understood. Almost all earthworms are permanent residents of the soil, and their contributions to the physical structure of soil have earned them the name “soil engineers.” Second, in their review, Rombke et al. (2005) summarized the principal functions of earthworms; they improve the structure of the soil, increasing water infiltration and macroporosity. They also regulate the decomposition of organic matter and supply nutrients to plants by concentrating them on the walls of their burrows and increasing their availability. They alter the diversity and improve the activity of microbial communities by supplying feces rich in nutritive elements. The permeability of their cuticle and their limited mobility make them very good bio-indicators for tracking the impact of pollutants, changes in soil structure, and cultural practices. Their reactions to stress are measurable and reproducible in the laboratory and in the field. From a practical point of view, raising and capturing earthworms is easy. Their analysis has been the subject of guides and norms developed by the Organization for Economic Co-Operation and Development (OECD) and the International Organization for Standardization (ISO) (ISO 23611-1, 2006). In addition, there are identification keys available, principally for the temperate regions, and above all for Europe. In France, approximately 120 species of earthworms (of the 3,600 found worldwide) are classified into three ecological categories (Bouché, 1972): epigeics, endogeics, and anecics (Figure I- 6). Epigeic earthworms are small (1-5 cm), active on the surface of the soil, and pigmented. They generally do not burrow, and they live in the litter. They ingest little mineral material and participate in the fragmentation of organic matter. Anecic earthworms are large (10-110 cm) and partially pigmented, with red, light grey, and brown coloration. They come to the surface of the soil when it is more humid, usually during the night, and carry litter to distant locations. They mix organic and mineral materials, they dig permanent tunnels that are sub-vertical to vertical in orientation and open to the surface, and they discharge their excrement, in part, at the surface of the soil (as castings). Endogeic earthworms measure from 1 to 20 cm. They are slightly pigmented (pink to light gray), live in organic material, and dig temporary, branched tunnels that are sub-horizontal or horizontal. They almost never go to the surface, and they feed on partially degraded organic matter.

Finally, earthworms are indicators that are already familiar to farmers, and farmers may not be ready to adopt soil quality indicators that rely on expensive supplies or complex interpretation. In addition, farmers already observe, without quantification, the effects of that changes in their practices have on earthworms.

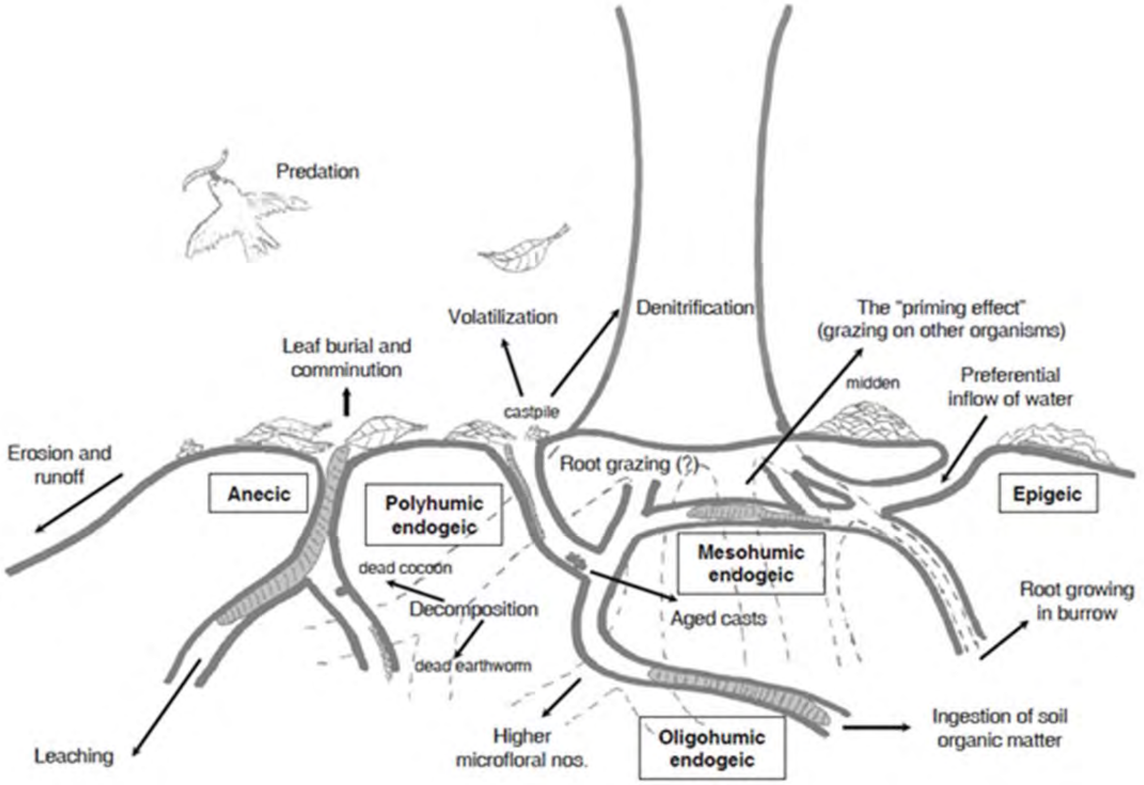


Figure I- 6 Schematic representation of the functional relationships between earthworms and their external environment (Doube and Brown, 1998)

4.6. LIMITATIONS OF INDICATORS

The goal of this section is present the limitations of soil quality indicators. The first challenge is to choose a set of measurable indicators that will be the most parsimonious and also the most relevant for evaluating the desired functions. The proposed MDS (Minimum Data Set) is a framework for making this decision. However, the primary limitation, which is crucial for the interpretation of the MDS, is sampling. In fact, the mode of sampling affects the interpretation of the indicators. Thus, it affects the evaluation of soil quality. Depth, positioning on the parcel, number of repetitions, equipment used, time of sampling, storage of the samples, and budget size are all criteria to be considered for a high-quality study. The representativeness of the sample analyzed with respect to the system under study should be the primary concern of the researcher (Schloter *et al.*, 2003). Furthermore, the researcher must keep in mind that the selection of a type of analysis from a broad range of options is crucial for chemical indicators. In their review, Lebourg et al. (1996) examined the various possible extraction methods, which can be “simple” or “ sequential.” McGrath (1998) noted that the standardization of protocols for the measurement of physical and chemical parameters was more advanced than for biological parameters. Although techniques and protocols have evolved, certain standards continue to be quite unclear. For example, the incubation conditions for the measurement of soil respiration (norm (ISO 16072, 2002)) are imprecise (Chevallier *et al.*, 2011a; b). Few authors have addressed the methodological problems that complicate the measurement of certain indicators. As an example, the measurement of the bulk density or the aggregate stability of a stony soil to achieve sufficient precision is difficult to manage. The last critical stage is the interpretation of certain indicators. Unfortunately, reference values and threshold values are often too scarce (Arshad and Martin, 2002), too old, or too closely tied to context. McGrath (1998) explains that establishing references is a fundamental step that allows users to make decisions regarding the level of pollution at a site and the impact of cultural practices. However, Rutgers et al. (2009) participated in the construction of references for soil quality based on a network of 300 sites in the Netherlands. On a greater scale, there is the French network RMQS (Network of Measurements of Soil Quality). This network is based on tracking of 2,200 sites chosen according to a regular 16-km grid. It constitutes a national framework for observation of the evolution of soil quality. Physical and chemical measurements and observations will be taken every 10 years at the center of each grid (beginning in 2008). In addition, for a subsection of this network, at the scale of Brittany, biological indicators have also been measured to complement the physical-chemical indicators (Cluzeau *et al.*, 2009; Villenave *et al.*, submited). In summary, there are few studies that have produced reference values for biological indicators on a large scale. Reference values targeted at particular systems (agro-ecosystems or natural ecosystems) should be developed.

As it has been discussed, researchers should be aware of the limitations of soil quality indicators. Whether they are physical, chemical, or biological indicators, an awareness of the limitations will help users to avoid over-interpreting results, which could lead to erroneous diagnoses.

4.7. TOWARD MORE OPERATIONAL INDICATORS

4.7.1. ESTABLISHMENT OF INDICES TO SIMPLIFY INTERPRETATION

Numerous studies aimed to develop global indices for soil quality that combine measurements of different parameters. The idea is that it is simpler and more effective to interpret a single index than a large panel of indicators. In part III of this chapter, we described the bundling of information in the form of nematode indices (MI, PPI, EI, SI, CI, and NCR) and the MWD as a global index of aggregate stability. These indices synthesize variables of the same type. Multiparametric indices have also been developed for agro-ecosystems and non-agricultural soils (Bastida *et al.*, 2008). However, as described by Karlen et al. (1994), these early studies subjectively assigned weights to each variable instead of using statistical or mathematical techniques to assign weights. Andrews et al. (2002b) suggested another approach based on statistical-mathematical methods. This approach has been afterwards followed by numerous other authors (Bastida *et al.*, 2006; Sharma *et al.*, 2005). Wienhold et al. (2004) also proposed a global index for soil quality based on the construction of scoring curves for each indicator. This combination of indicators is the basis of a global index. In the same idea, a multi-criterion analysis was developed by Velasquez et al. (2007) to identify the relevant indicators for ecosystem services of interest and to analyze their durability when faced with changing practices. By combining chemical, physical and biological indicators, they created the General Indicator of Soil Quality (GISQ), which includes 5 sub-indicators (physical, chemical, organic, micromorphological, and soil fauna) that are, in turn, derived from 54 parameters related to ecosystem services of the soils. GISQ provides a general evaluation of soil quality, with assigned scores between 0.1 and 1. This value can be broken down to evaluate each one of the components, which makes it possible to identify potential soil problems in a more precise way. Another index, the BISQ (Biological Index of Soil Quality), developed by Ruiz Camacho et al. (2009), is based on the study of populations of soil macro-invertebrates (in particular, their abundance and diversity) as bioindicators of the physical, chemical and ecological soil quality. This index produces a score between 0 and 20.

The methods described above are advantageous because they simplify interpretation. This advantage is also their principal limitation because grouping information often masks certain effects. Thus, global indices are useful for comparing different situations: the effects of different practices on the same soil or the effects of the same practice on the same soil at different times.

4.7.2. TOOLS FOR DATA COLLECTION

As shown above, the evaluation of soil quality involves measuring physical, chemical, and biological parameters. Some measurements may be too expensive, or they may require observations too frequently (Doran and Zeiss, 2000). Furthermore, some parameters, as biological parameters, can be quite complex to evaluate, often requiring additional technical training. Thus, the acquisition of data is a technical and practical challenge.

(Doran and Zeiss, 2000) have proposed that, rather than making direct measurements of soil functions, it is preferable to measure substitutes that are well correlated with soil functions. This approach has been followed in numerous other studies. The use of spectrometry in the near infrared

(SPIR or NIRS - Near Infra Red Spectrophotometry) or medium infrared (SMIR or MIRS - Mean Infra Red Spectrophotometry) enables the estimation of parameters linked to soil quality. This type of measurement involves subjecting a soil sample to a light beam with a wavelength between 800 and 2,055 nm for NIRS and between 2,500 and 25,000 nm for MIRS. The absorbance of the sample in these wavelength ranges is then used to generate a spectrum. Multivariate statistical analyzes allow the construction of a predictive model for each variable studied. The three major advantages of this method are its rapidity (1 minute per sieved sample), its low cost (few consumables are used), and its non-destructiveness (samples are not lost).

With respect to predicted parameters, advances have principally centered on physical and chemical parameters such as texture, pH, moisture, organic carbon, total nitrogen, and exchangeable bases (Cecillon *et al.*, 2009; Rossel *et al.*, 2006; Shepherd and Walsh, 2002). Research on biological parameters is ongoing but less advanced. Some studies have led to promising results for biomass and microbial respiration (Chang *et al.*, 2001; Ludwig *et al.*, 2002), as well as nematode communities (Barthès *et al.*, 2011). Though spectrometry is undeniably an attractive and promising method, it has three major limitations. The analysis of spectra requires a certain understanding of specific statistical techniques. Further, it is often difficult to know precisely the relationships that exist between spectra and the parameters measured. Finally, the purchase of spectroscopy equipment represents a significant investment. Above all, to obtain a prediction with NIRS or MIRS, one needs to have modeled the parameter response using a large set of samples (>50) for which classic measurements have been collected.

Other options such as geoelectric methods have been suggested, but they are still in their infancy. Thus, Joschko et al. (2010) were not able to predict the abundance of earthworms with great success, whereas Priori et al. (2010) predicted clay content very well.

4.7.3. MAKING METHODS ACCESSIBLE TO FARMERS

A good indicator of soil quality should be easy for professionals to use. This is why farmers should be consulted in studies dealing with the evaluation of agricultural soil quality. In fact, scientific and local knowledge are complementary (Barrios and Trejo, 2003). According to Barrios et al. (2006), farmers and scientists share concepts, but each have gaps in their knowledge that in many cases can be filled by the other. Thus, farmers can define the goals of the field (Barrera-Bassols and Zinck, 2003) and guide research, while scientists can broaden the notion of soil quality so that it is not restricted to the single dimension of production. This will help to improve the sustainability of agro-ecosystems. Both scientists and farmers are interested in tools that are valid from both a practical and a scientific perspective. Building a consensus for the use of certain indicators is an important step in the integrated management of soils on a large scale. According to Romig et al. (1995) and Andrews et al. (2003), the use of simple indicators for soil quality, those that make sense for farmers and other managers of the land, would probably be the most fruitful link with the sciences. It would also be of practical use in the evaluation of sustainability of management practices. Thus, the perceptions and knowledge of farmers about their soil should be considered in evaluating the transferability of indicators. There are few studies that consider this in detail. For example, Ericksen and Ardón (2003) studied commonalities and differences between the perceptions of farmers from the center of Honduras and scientists from the USA regarding soil quality. A similar study was carried out by Ingram et al. (2010) in England, Switzerland, and France. Studies by Barrios et al. (2006), Ali (2003) and Mairura et al. (2007) focus on the use of indicators by local populations. In France, in addition to this research project, a CASDAR (Special Trust for Agricultural and Rural Development) project directed by Krotoum Konaté and Monique Jonis, the director and agronomy commissioner at ITAB (Technical Institute for Biological Agriculture), began in 2009. The goal of this project is to study the effects of different innovative soil management for organic agriculture on soil fertility. This project also studies the methods of evaluation. Annual crops (field crops, vegetables) and perennials (fruit trees and vines) are both involved. The goals of this project include the development of simplified diagnostic tools for farmers and advisers, tools that are based on various indicators of the physical, chemical, and biological components of the soil.

CHAPTER II

OBJECTIVES AND RESEARCH STRATEGY

1. OBJECTIVES

State of the art analysis has shown that it is essential to assess soil quality, as the soil plays critical roles in the functioning of agro-ecosystems. For this purpose, various physical, chemical and biological indicators have been developed. Among agro-ecosystems, vineyards are unique because they refer to a perennial crop grown in areas that are generally not conducive to other agricultural activities. Moreover, the cultivation guidelines are complex and diversified. Vineyard soils are particularly vulnerable, as many scientific studies have highlighted various phenomena associated with these soils, such as erosion, compaction, accumulation of pesticides and reduction in the levels of soil organic matter and biological activities. However, very few studies have examined the effects of vineyard management on soil quality.

In the context of the sustainability of vineyard agro-ecosystems, the main objective of my dissertation is to evaluate the influence of vineyard managements on soil quality measured using indicators.

To meet this goal, I asked the following questions:

- Question 1. Are known soil quality indicators also relevant in view of the specificities of the soils and viticultural practices in Languedoc-Roussillon?
- Question 2. Are soil quality indicators sufficiently sensitive to changes in viticultural practices?
- Question 3. Can these indicators be used by winegrowers and agricultural advisers?

2. RESEARCH STRATEGIES

To answer these questions, I implemented an original research strategy combining different disciplines. I combined measures of physical, chemical and biological indicators in soil samples collected from a large network of selected vineyard fields managed by professionals (187 plots). All of the results obtained were then analyzed using univariate and multivariate statistical tests. Through a participatory approach involving winegrowers, I studied their perceptions of soil quality to facilitate the use of the indicators studied in my dissertation.

Thus, 4 studies have been conducted:

1. The first study was performed to establish baseline indicators by setting their range of variation. A total of 164 plots spread over 9 different soil and landscape zones of Languedoc-Roussillon associated with a wide variety of agricultural practices were sampled. This dataset will be referred to as the "*Referential Network*". (Question 1)

2. The second study focused on changes in soil quality in the case of conversion from conventional viticulture to organic viticulture. Thus, soils of 14 plots that had been converted for 7, 11 and 17 years were analyzed and compared with 10 plots cultivated in a conventional mode with the same soil type and climate zone. This group of plots will be designated the *"Organic Network"*. (Question 2)

3. The third study was designed to facilitate the acquisition of data, which may represent a significant barrier. Thus, the potential of prediction by a field tool (Geoprofiler: GSSI Profiler EMP-400) of several soil indicators was tested in 9 plots of the "*Referential Network*" located in the same area. (Question 3)

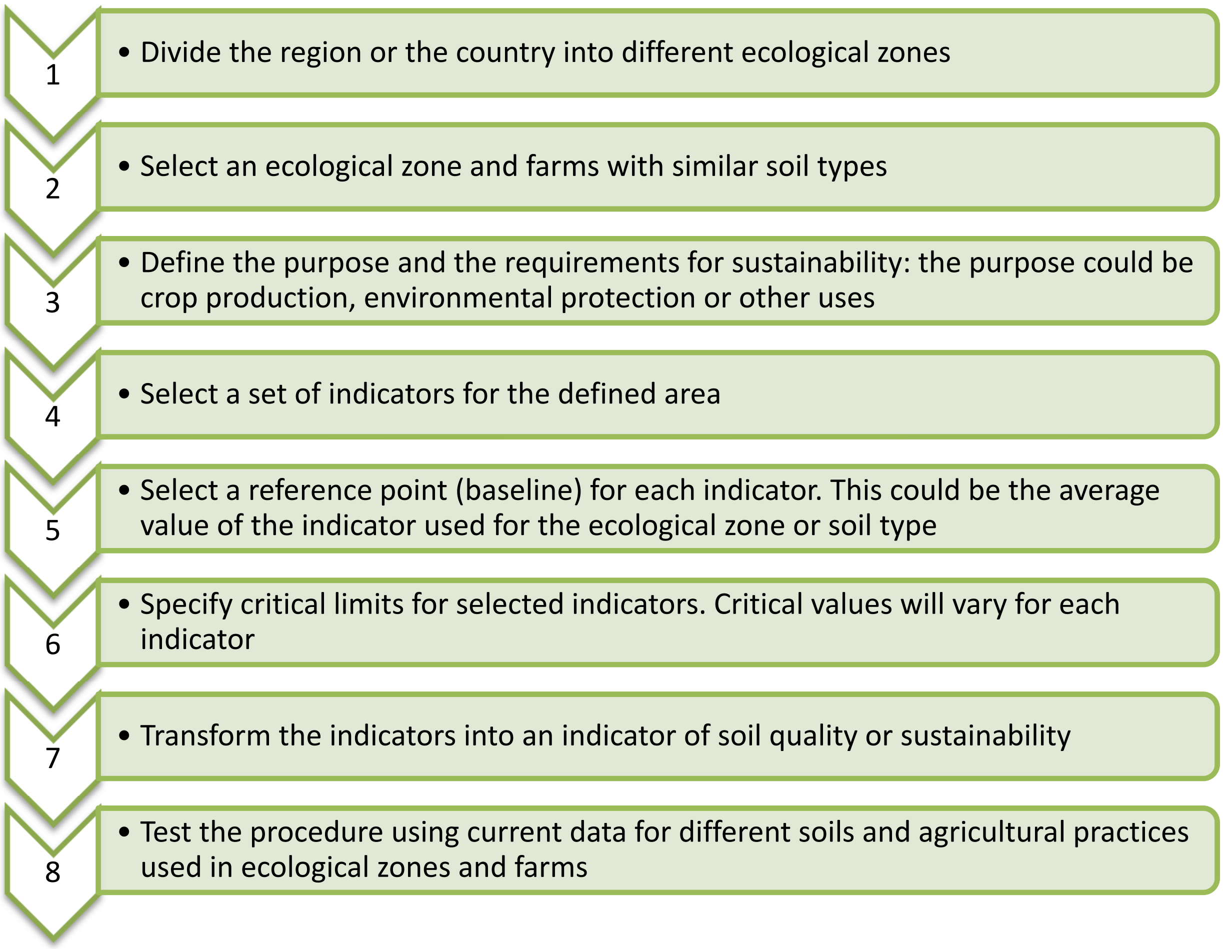
4. Finally, a sociological study was conducted based on comprehensive interviews with 29 winegrowers living in 4 out of 9 areas of the "*Referential Network*". (Question 3)

3. STUDY AREAS AND EXPERIMENTAL PROCEDURES

3.1. "REFERENTIAL NETWORK"

The conception of this network was inspired by the methodology proposed by Arshad and Martin (2002) (Figure II- 1). Thus, the first step was to identify representative viticultural areas of Languedoc-Roussillon in terms of diversity of soil types and viticultural practices. Indeed, the Languedoc-Roussillon extends over more than 27,800 km² (5% of the French territory) and exhibits very high soil variability. Large areas of landscapes can be identified on particular characteristics related to altitude, rocks, forms of relief and the type of vegetation cover. These landscapes delimitate geographical areas in which a finite number of soils exist. Identification of the potential areas was based on analysis of maps of the soil and landscapes of Languedoc-Roussillon (scale 1:250,000)

(Barthès *et al.*, 1999a; b; c; d) and using the expertise of Jean-Pierre Barthès and Guillaume Coulouma, engineers at LISAH UMR (personal communication, 2009-2010). Then I contacted a large number of professionals (winegrowers, directors of cooperative cellars, viticulture representatives of the Chambers of Agriculture, viticulture consulting engineer of AIVB-LR (Association Interprofessionnelle des Vins Biologiques du Languedoc-Roussillon) to create a network and to select plots such that soil variations are minimized, but where the diversity of vineyard practices is maximized for each area.



1. Divide the region or the country into different ecological zones
2. Select an ecological zone and farms with similar soil types
3. Define the purpose and the requirements for sustainability: the purpose could be crop production, environmental protection or other uses
4. Select a set of indicators for the defined area
5. Select a reference point (baseline) for each indicator. This could be the average value of the indicator used for the ecological zone or soil type
6. Specify critical limits for selected indicators. Critical values will vary for each indicator
7. Transform the indicators into an indicator of soil quality or sustainability
8. Test the procedure using current data for different soils and agricultural practices used in ecological zones and farms

Figure II- 1 : Guidelines for monitoring soil quality according to Arshad and Martin (Arshad and Martin, 2002)

Thus, the “*Referential Network”* included 164 commercial vineyards plots divided among 9 different soil areas of Languedoc-Roussillon. Each zone was referred to by the name of the town where the majority of its plots were sampled. All of the “*Referential Network”* is subject to the same type of Mediterranean climate (Figure II- 2).

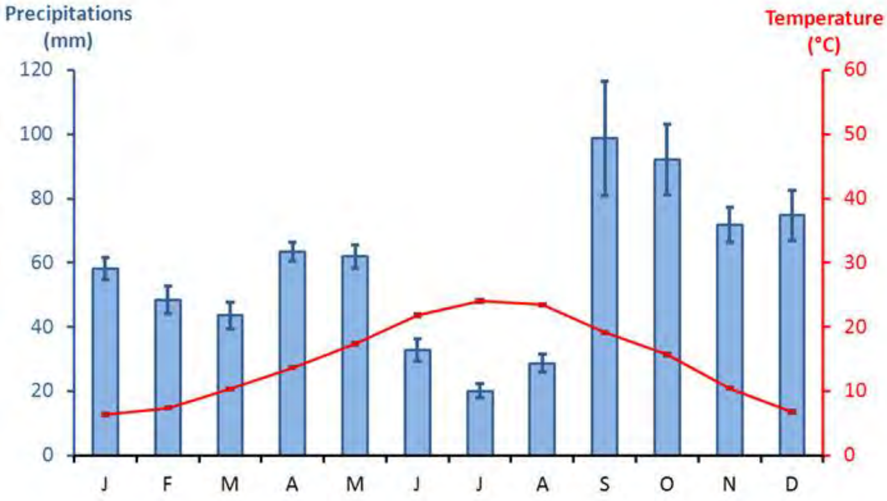


Figure II- 2: Mean ombrothermic diagram with standard errors for the 9 areas of the "Referential network" based on data collected from 2000 to 2010 by *Météo France*.

The distribution of the areas is presented in Figure II- 3.

Figure II- 3: Location of the 9 areas of the "Referential network" : Terrats, Lesquerde, Montagnac, Faugères, Aigues-Mortes, Vergèze, Jonquières Saint-Vincent, Saint-Hippolyte du Fort and Saint-Victor la Coste.

The characteristics of the studied areas are as follows:

- Terrats (Pyrénées-Orientales, 42°36'27" N, 2°46'14" E, 135 m altitude): 11 plots. The soils are deep and were developed on the crests and glacis of the Catalan Pliocene. They exhibit silty-clayey-sandy textures and average stoniness. The water pH indicates acidic to neutral soils, and the colors range from red brown to red.
- Lesquerde (Pyrénées-Orientales, 42°48'01"N, 2°31'47" E, 358 m altitude): 19 plots. The soils are present on low to average slopes of Fenouillèdes, a crystalline massif of the northern Pyrenees. They are shallow (50 cm), were developed on cracked, slightly altered or intact granite and exhibit a sandy to sandy-silty texture with a typical structure. The water pH is acid to neutral.
- Montagnac (Hérault, 43°28'50" N, 3°29'02" E, 54 m altitude): 21 plots. The soils are of variable depth and were developed on hills of medium slopes, glacis and valleys on sandy-sandstone molasses. They have silty-clay textures and low stoniness, are highly calcareous, with up to 400 g of $CaCO_3$ kg^{-1} of soil being detected, and present a water pH of 8.3.
- Faugères (Hérault, 43°33'57" N, 3°11'19" E, 284 m altitude): 21 plots. The soils were developed on medium to high slopes and are irregularly deep on shale and siliceous sandstone (ranker). They exhibit a sandy-silty texture and variable stoniness, are brown in color, and the pH can be as low as 5.
- Aigues-Mortes (Gard, 43°34'02" N, 4°11'33" E, 5 m altitude): 18 plots. This is an area corresponding to ancient dune systems that are well developed in Camargue and are often leveled for the implementation of vineyards. These soils are young of wind-contributed formation and established on the former quaternary dune ridges. They are deep to very deep, and their sandy textures result in sensitivity to wind erosion. Additionally, they range from not very to moderately rich in organic substances.
- Vergèze (Gard, 43°44'37" N, 4°13'14" E, 32 m altitude): 17 plots. The soils are colluvial-alluvial or colluvial, deep to very deep (up to 2-3 m thick) and slightly to moderately pebbly (based on the % of gravel and pebble quartz or visual evaluation). They exhibit a silty-clay to silty-sandy-clay texture and variable limestone contents, leading to a neutral or alkaline pH level.
- Jonquières-Saint-Vincent (Gard, 43°49'38" N, 4°33'48" E, 37 m altitude): 19 plots. Villafranchean alluvia of rhodano-durancean origin are typical of the old rhodanean alluvium of Costières of Nîmes. The soils are very deep and very stony from the surface downward and are composed of 40 to 90% gravels and rolled quartz pebbles. They have a sandy-silty texture, are situated over layers of red clay and generally present a neutral pH.

- Saint-Hyppolyte Fort (Gard, 43°57'56"N, 3°51'28" E, 170 m altitude): 15 plots. The soils in this area develop on irregular slopes on limestone, marl-limestone beds, marl limestone or marlstone, limestone, dolomites and gypsum from the Triassic. They are moderately deep to very deep, exhibit variable stoniness and are silty-clayey-sandy to clay-silty with high levels of limestone, especially active limestone, leading to a high pH level (> 8.0).
- Saint-Victor Coste (Gard, 44°03'38" N, 4°38'29" E, 143 m altitude): 23 plots. This area is located on the bottom of slopes and edges of ponds in Uzégeois and Montpellierais and is covered by colluvial formations and/or local inputs of alluvial cones. The soils are deep to very deep with a silty-sandy to silty-sandy-clay texture and an average stoniness. They are calcareous, with varying levels of total limestone.

The diversity of the studied soils is presented in Figure II- 4:

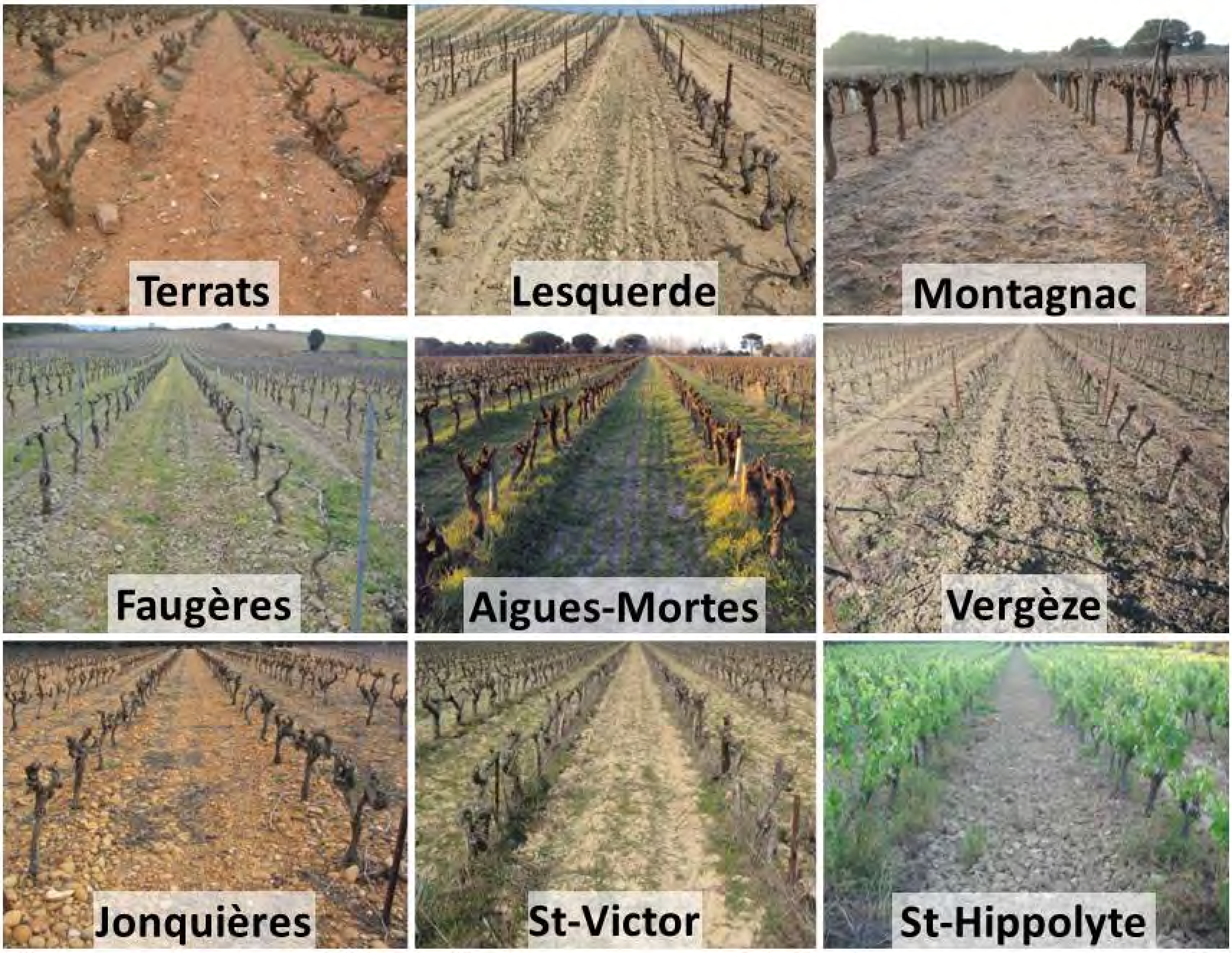


Figure II- 4: Soil surface of each area of the "*Referential Network*": Terrats, Lesquerde, Montagnac, Faugères, Aigues-Mortes, Vergèze, Jonquières Saint-Vincent (Jonquières), Saint-Victor la Coste (St-Victor) and Saint-Hippolyte du Fort (St-Hippolyte).

3.2. "ORGANIC NETWORK"

The *"Organic Network"* consisted of a vineyard located in the South of France at Cruscades (Languedoc-Roussillon; Aude, 43°11'29.13"N, 2°49'1.78" E; 26-50 m altitude). The climate was typically Mediterranean, with an average annual temperature of 14.7°C, annual precipitation of 600 mm and annual Penman-Monteith ETP of 1,380 mm (average based on data from 2000 to 2010 by *Météo-France*). The soil consisted of limestone gravel predominantly on marlstone and marl limestone and did not have any slope. The soil is silty clay containing 42 ± 2% silt, 36 ± 1% clay and 22 ± 2% sand, and it is calcareous (208 ± 7 g $CaCO_3$ total kg^{-1}), with a water pH of 8.3 (soil:water of 1:5). The water holding capacity was 20.6 ± 0.5% (w/w). This study was conducted in 24 plots of commercial winegrapes with an average surface area of 1.5 ha. Different types of grapes were present among the plots, such as Cabernet-Sauvignon, Carignan N, Chardonnay, Cinsault, Grenache N, Merlot, Mourvèdre, Pinot N and Syrah. The rootstocks were mainly R110 and the R140, but Riparia and 410a were also present. The planting dates ranged from 1932 to 2003. The planting density was between 3,300 and 5,000 vines per hectare.

The 24 plots were divided into 4 categories (Figure II- 5):

- 10 plots cultivated under conventional agricultural practices (Conventional),
- 14 plots cultivated under organic agricultural practices (Organic),
    - 4 since September 2001, officially certified since 2004 (Organic7),
    - 5 since September 1997 (Organic11),
    - 5 since September 1991 (Organic17).

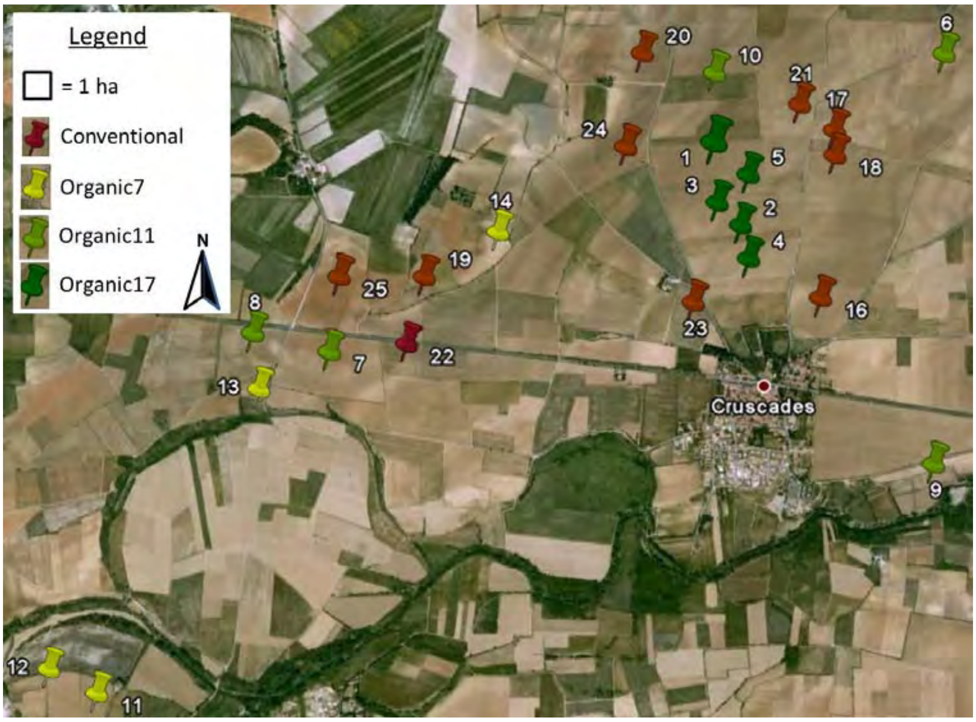


Figure II- 5/ Location of the 24 vineyard plots of the *"Organic Network"* : 10 for Conventional, 4 for Organic7, 5 for Organic11 and 5 for Organic17

The vineyard practices were similar for all 4 categories prior to conversion to organic farming, as well as being the same after conversion (Table 1). Each plot was divided into 4 smaller plots (5 x 4 inter-rows) evaluated as being representative of the soil characteristics of the plot based on field expertise (e.g., stoniness, limestone content, texture, color) (Jean-Pierre, personal communication, 2009). Thus, 96 sub-plots were analyzed.

Table II- 1: Agricultural practices in Conventional and Organic treatments

	Soil management		**Fertilisation** (N-P-K)	**Vine phytosanitary protection**	**Tractor frequency per year** (year^{-1})
	Rows	**Inter-rows**			
Conventional	Chemical weeding (glyphosate, 700 g ha^{-1}, 1 year^{-1})	Tillage with tined tools (15 cm depth, 2 year^{-1})	Mineral (10-10-20, 200 kg ha^{-1}, 1 year^{-1})	Synthesis and natural (6 treatments year^{-1})	14
Organic	Tillage (10 cm of depth, 1 year^{-1})	Mouldboard ploughing (25 cm depth, 4 year^{-1})	Compost (90% of OM; 9-5-0, 500 kg ha^{-1}, 1 year^{-1})	Natural (8 treatments year^{-1})	18

4. SELECTION OF INDICATORS

The choice of indicators was a key step in my thesis. The approach adopted here was inspired by Bispo et al. (2011). It enabled determining the procedures and functions that I wanted to study. Marzaioli et al. (2010b) have proposed a set of data (a minimum dataset, or MDS) for studying soil quality under different land uses, including vineyards. Thus, they measured physical (texture, bulk density and water holding capacity), chemical (pH, cation exchange capacity, electrical conductivity, organic carbon, total and mineral nitrogen, levels of available P, K, Ca and Mg and total levels of Cd, Cr, Cu, Pb and Zn) and biological (microbial biomass, fungal mycelium, potential soil respiration and potentially mineralizable nitrogen) indicators. In our case, the choice of indicators has therefore focused on a set of indicators combining physical, chemical and biological components to take advantage of their complementarity. Our choice was also motivated by the existence of standardized and controlled measurement methods within the Eco&Sol Joint Research Unit. Mainly for economic reasons, not all of the selected indicators were measured in each of the two networks of plots described previously (Table II- 2).

Table II- 2: Indicators measured in each network

	"Referential Network"	"Organic Network"
Stoniness	x	x
Texture with 5 fractions	x	x
Bulk density	x[(a)]	x
Water holding capacity	x	x
Humidity	x	x
Soil particle density	x[(a)]	
Total porosity	x[(a)]	
Aggregate stability	x[(b)]	
Calcareous (total and active)	x	x
pH	x	x
Total organic carbon	x	x
Total nitrogen	x	x
Available phosphorus	x	x
Available potassium	x	x
Available copper	x	x
Cation exchange capacity	x	x
Resistivity (Geoprofiler)	x[(c)]	
Microbial biomass	x	x
Respirometry	x	
Nematofauna (counting, identification, calculation of indices)	x	x
Earthworms (counting, weighing, identification of ecological category)	x[(d)]	x

[(a)]: for bulk and soil particle density measurements and calculations of total porosity, plots with too many coarser elements than 2 mm could not be sampled

[(b)]: for reasons of representativeness, measures of structural stability were not conducted in plots that were too stony and sandy (> 80% of sands)

[(c)]: only 9 plots in Saint-Victor la Coste.

[(d)]: only 13 plots in Saint-Victor la Coste.

5. SOIL AND EARTHWORM SAMPLING

5.1. "REFERENTIAL NETWORK"

Sample collection in this network took place from March 5 to May 22, 2010 (Table II- 3). Samples were collected in the 0-15 cm soil layer in the center of the inter-row. According to Karlen et al. (2003), the dynamic quality of soils altered by crop managements should be assessed in the surface layer (the first 20-30 cm of the soil). However, the 0-15 cm layer is commonly used to evaluate soil quality for various annual crops in rotation (Andrews *et al.*, 2002a; Ayuke *et al.*, 2011; Briar *et al.*, 2007; Neher and Olson, 1999; Overstreet *et al.*, 2010) and grapes vines (Reeve *et al.*, 2005; Reuter and Kubiak, 2003).

Table II- 3: Details regarding the dates and conditions during soil sampling

Area	**Number of plots**	**Date of soil sampling**	**Water content** (%)	**Water holding capacity** (%)	**Water content / water holding capacity**(%)
Aigues-Mortes	18	March 5 and 6, 2010	10.7 ± 0.5	6.9 ± 0.4	155*
Montagnac	21	March 12 and 13, 2010	19.1 ± 0.6	28.2 ± 0.8	68
Vergèze	17	March 15 and 16, 2010	20.4 ± 0.5	28.8 ± 0.6	71
Jonquières Saint-Vincent	19	March 17 and 18, 2010	17.0 ± 1.0	23.9 ± 1.3	71
Saint-Victor la Coste	23	March 19 and 20, 2010	16.8 ± 0.6	23.1 ± 1.0	73
Lesquerde	19	March 30 and 31, 2010	6.7 ± 0.5	11.2 ± 0.6	60
Terrats	11	April 1 and 2, 2010	12.1 ± 0.5	22.8 ± 0.6	53
Faugères	21	April 12 and 13, 2010	11.5 ± 0.4	22.5 ± 0.6	51
Saint-Hippolyte du Fort	15	May 21 and 22, 2010	14.8 ± 0.5	23.9 ± 0.5	62

Regarding the sampling areas, I made the choice to sample only in the inter-row for both practical (time of sampling and analysis) and economic reasons (number of analyzes realized). However, I took note of the work of Whitelaw-Weckert et al. (2007), Goulet et al. (2004) and Rahman et al. (2009), who obtained different results in soil samples collected from the row and the inter-row separately. So, I followed the method of Morlat and Chaussod (2008) and only collected samples in the middle of the inter-row.

In each plot the following samples were collected:

- A composite soil sample of 10 subsamples that were representative of the plot, collected with a gouge auger.
- Three soil samples to measure the bulk density according to the cylinder method (NF X 31-511, (in preparation)) using a cylinder 8 cm in diameter and 15 cm in height.

The soil samples (except those collected for bulk density) were prepared as described in Figure II- 6.

In view of the large number of plots included in the "*Referential Network*", earthworm collection was performed only in 13 parcels at Saint-Victor la Coste on February 17, 2011, by 41 persons (Montpellier SupAgro students and members of the Eco&Sol joint research unit).

In each of these 13 plots, 4 representative sub plots were identified based on a map of soil heterogeneity establisheweryd between February 14th and 16th, 2010. This map was produced by a multi-frequency sensor EMI (GSSI Profiler EMP - 400) measuring the bulk electrical conductivity (ECa). The conductivity of soil is an integrative measure indicating soil spatial properties. In each area, the collection of earthworms was carried out in the middle of the inter-row. For sampling earthworms, the ground was watered with an irritating solution of mustard (Amora® "Fine and Forte" Mustard at a concentration of 15 g per liter of water (Pelosi et al., 2009)). Three applications of 10 liters of the solution were done in a quadrat of 1 m x 1 m, with 10 minutes between applications. Earthworms were collected as they appeared at the surface when they exited the ground. Ten minutes after the third application, a 25 cm x 25 cm monolith of soil till 15 cm depth was excavated, and earthworms were extracted by manual sorting. The earthworms were then placed in a solution of 75% ethanol for storage. Commercial mustard, as used by Pelosi et al. (2009) and Lawrence and Bowers (2002), was preferred to the formalin solution commonly used, as formaldehyde is known to be carcinogenic and harmful to the environment (Eichinger et al., 2007). Moreover formalin solution is a chemical synthesis-derived product, so it was prohibited from being used in the 4 organic-certified plots.

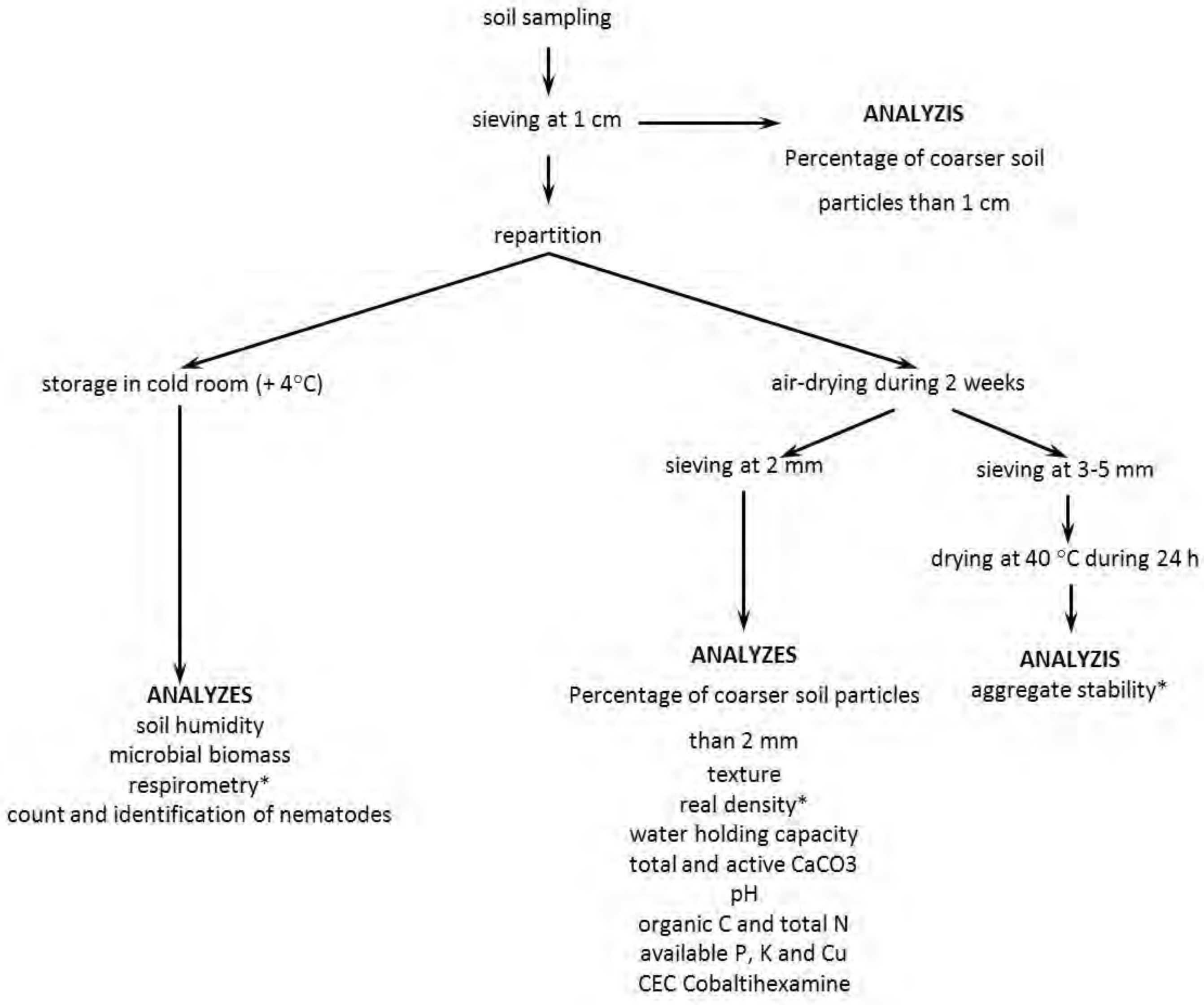


Figure II- 6: Soil sample preparation

5.2. “ORGANIC *NETWORK*”

Sample collection in this network took place from May 4 to 28, 2009. All of the samplings were conducted in the 0-15 cm soil layer in the middle of the inter-row.

In each plot, the following samples were collected:

- A composite soil sample of 4 subsamples, collected with a gouge auger.
- A soil sample to measure bulk density using the cylinder method (NF X 31-511, (in preparation)), collected with a cylinder 8 cm in diameter and 15 cm in height.
- Earthworms were sampled by hand sorting of a 45 cm x 45 cm monolith of soil from 0 to 15 cm deep.

For the collection of earthworms, several authors (Cluzeau et al., 1999; Pelosi et al., 2009) advised combining watering with an irritant solution (formaldehyde type) to sample anecic earthworms, which can quickly escape in deeper layers, and hand sorting to remove less mobile earthworms. However, performing both of these steps requires a great deal of time, manpower and a logistical means to carry the irritant solution. Thus, in view of the 96 subplots to be sampled, I chose to carry out sampling of earthworms only by hand sorting in this case.

After sampling, the soil samples (except those collected for bulk density analysis) were prepared as shown in Figure II- 6, and then collected earthworms were killed in a 75% ethanol solution, then transferred to a 4% formol solution to be stored.

6. MEASUREMENT OF INDICATORS

Among the measures outlined below, the texture, total lime content, active lime, total organic carbon, total nitrogen and the cation exchange capacity were determined at the Laboratory of Soil Analysis of Arras. Laboratory analyzes of samples from the *“Referential Network”* were done by the active participation of Egidio Lardo, pHD student from the University of Basilicata (Italy) through a collaboration program between the Joint Unit Research Eco&Sols and the University of Basilicata (Italy).

6.1. PHYSICAL AND CHEMICAL INDICATORS

COARSER THAN ELEMENTS 2 MM

After sieving dry soil samples to separate fractions above and below 2 mm, the fractions were weighed. The percentage of refusal was calculated by dividing the weight (g) of greater-than-2 mm fraction by the total mass (g) of the two fractions.

TEXTURE

The proportions (%) of 5 soil size fractions (clay: < 2 µm, fine silt: 2-20 µm, coarse silt: 20-50 µm, fine sand: 50-100 µm and coarse sand: 200-2000 µm) were determined after decarbonation by adding excess of hydrochloric acid (HCl) (NF X 31-107, 1983).

DETERMINATION OF BULK DENSITY

The entire sample collected using the cylinder method was dried in an oven at 105°C for 1 week and weighed soon thereafter. The bulk density (BD) was calculated by dividing the mass of dry soil (g) by the volume of the cylinder (cm^3) (ISO 11272, 1998), which was determined in the laboratory.

WATER HOLDING CAPACITY OF SOIL

The water holding capacity was measured by the pressure plate extractor method (ISO 11274, 1998). Rings with a 2.8 cm inner diameter and 1.0 cm height were filled with soil and deposited on a porous plate. Following water saturation, the samples were subjected to a pressure of 0.2 bar for 24 h. The samples were then weighed, dried in an oven at 105°C for 48 h and subsequently weighed again. The moisture-holding capacity (%) was calculated by dividing the loss of mass (g) of the sample after drying by the mass of the dry soil (g).

SOIL MOISTURE DURING SAMPLINGS

For each sample of soil and earthworms, the residual moisture weight (mass %) of the soil was measured. This was calculated by dividing the mass loss of a sample of fresh soil (g) of 20-30 g after drying in an oven at 105 °C for 2-3 days by the mass of the same dry soil (ISO 11465, 1994).

SOIL PARTICLE AND BULK DENSITIES

The soil particle density (SPD) was measured by a method adapted from that described by Musy and Souttier (1991) using a class A 50 ml volumetric flask instead of a water pycnometer. The soil particle density was calculated by dividing the mass of dry soil ground to 200 µm (g) by the volume of the same sample (cm^3) determined using a 50 mL volumetric flask and demineralized and degassed water.

TOTAL POROSITY

The total porosity (Tp, expressed as a %) was calculated as following (Equation II-1):

$$Tp = 1 - \frac{BD}{SPD} \times 100$$ **Equation II-1**

In which SPD represents the soil particle density ($g.cm^{-3}$), and BD the bulk density ($g.cm^{-3}$).

AGGREGATE STABILITY BASED ON RAPID WETTING BY IMMERSION IN WATER

Approximately 5 g of aggregates of 3 to 5 mm was carefully poured into a 50 mL beaker of water for 10 min. After sieving in ethanol, the fraction greater than 0.05 mm was dried at 40°C. After 48 h, these aggregates were passed through a column containing 6 sieve screens of 2 mm, 1 mm, 0.5 mm, 0.2 mm, 0.1 mm and 0.05 mm. Each fraction was weighed, and the percentage of each fraction was calculated. Aggregates larger than 2 mm were washed with water to retrieve gravel and were then dried and weighed (NF X 31-515, (in preparation)). The average weight diameter (Mean Weight Diameter, expressed in mm) after breakdown was calculated as following (Equation II-2):

MWD = (3,5 x [% >2mm]) + (1,5 x [% 1-2mm]) + (0,75 x [% 0,5-1mm]) + (0,35 x [% 0,2-0,5 mm]) + (0,15 x [% 0,1-0,2mm]) + (0,075 x [% 0,05-0,1mm])+ (0,025 x [% <0,05mm])/100 **Equation II-2**

TOTAL CALCAREOUS

The total lime ($g.kg^{-1}$ soil) content was assessed by measurement of the volume of carbon dioxide (CO_2) generated after adding a solution of hydrochloric acid (HCl) (ISO 10693, 1995).

ACTIVE CALCAREOUS

The active lime content ($g.kg^{-1}$ soil) is the fraction of unsolubilized calcium after blending soil with a solution of ammonium oxalate. It was measured according to standard protocol (NF X 31-106, 1982).

PH

Water extraction was carried out by combining 1.5 g of soil with 15 mL of deionized water (soil:extractant ratio = 1:10) via stirring for 2 h. Each sample was then centrifuged (2,000 g for 20 min at 20°C), filtered to a size of 0.2 µm and stored in a cold room (+ 4°C). The pH of the water extracts was measured using Metrohm 744 pH meter.

ORGANIC CARBON AND TOTAL NITROGEN

The total organic carbon (g kg^{-1}) and total nitrogen (g kg^{-1}) contents were measured by dry combustion according to standards NF ISO 10694 (1995) and ISO NF 13878 (1998), respectively.

CONTENTS OF AVAILABLE ELEMENTS (PHOSPHORUS, POTASSIUM AND COPPER)

Phosphorus (mg kg^{-1}) was measured using the malachite green method (Ohno and Zibilske, 1991) adapted to microplates. Briefly, 40 µl of an acidic solution of molybdate (H_2MoO_4) was added at a concentration of 0.1 M to 200 µl of water extract (same extract used to determine the pH), followed 10 min later by 40 µl of malachite green oxalate ($C_{23}H_{25}ClN_2$) at 0.35 g l^{-1}. The absorbance was measured at 630 nm and read with an ELx808 DIALAB microplate reader. The potassium content (mg kg^{-1}) of the water extracts (same extraction as for the pH) was measured using a flame atomic absorption spectrophotometer (Varian A600) after dilution by a factor of 8 for the *"Organic Network"* and a factor of 5 for the *"Referential Network"*. The copper content (mg kg^{-1}) of the water extracts (same extraction as for pH) was measured using a flame atomic absorption spectrophotometer (Varian A600) without dilution.

CATION EXCHANGE CAPACITY

The cationic exchange capacity was determined after extraction with cobalt hexamine chloride (ISO 23470, 2007).

RESISTIVITY (GEOPROFILER)

The GSSI Profiler EMP-400, which is a multifrequency EMI sensor, was used to measure the apparent soil electric conductivity (ECa) (mS m^{-1}). This device simultaneously measured up to 3 frequencies: 3, 8 and 15 kHz. The instrument was used in vertical dipole mode (POV). The EMP-400 calibration was automatically set and run in the field. Data were collected by walking along each inter-row at a regular speed (approximately 4-5 km h^{-1}). The data were then analyzed using the MagMap2000 software provided with the Profiler EMP-400. The Surf program was used for data processing, gridding and contouring of the EMP-400 data.

6.2. BIOLOGICAL INDICATORS

6.2.1. MICROORGANISMS

MICROBIAL C BIOMASS BASED ON THE FUMIGATION-EXTRACTION METHOD

Forty grams of fresh soil were reduced to 100% of their field moisture-holding capacity and incubated for 1 week at 28 °C in a hermetically sealed 500 ml chamber with a 20 mL water dispenser. The carbon content of the soil microbial biomass was determined using the fumigation-extraction method(Wu et al., 1990):

- a subsample of 7 g of soil was fumigated with chloroform ($CHCl_3$) vapors for 16 h;
- two sub-samples (fumigated and non-fumigated) were extracted by adding 35 ml of 0.05 N K_2SO_4 (soil:extractant ratio = 1:5) followed by agitation (45 min for the fumigated subsample and 60 min for the non-fumigated subsample), centrifugation (3,500 g for 10 min at 20 °C) and filtration through a 0.2 µm filter.

The total organic carbon content of the extracts from each subsample was determined using a TOC-V CSH carbon analyzer (Shimadzu). The difference between carbon content before fumigation and after fumigation was adjusted with a correction factor based on the soil moisture of the subsamples to give the microbial carbon content (mg g^{-1} soil C).

MEASUREMENT OF THE RESPIRATION POTENTIAL BY RESPIROMETRY

Ten grams of fresh soil were moistened to 100% of their water-holding capacity. They were then incubated for 28 days at 28 °C (ISO 14239, 1997) hermetically sealed 500 ml chambers with two 20 ml plastic vials : one containing water and the other containing 0.5 N sodium hydroxide (NaOH). The carbon dioxide produced by microorganisms was trapped into sodium carbonate. After incubation, the remaining NaOH was titrated by acid-base titration, which was performed with a Titrino 848 titrator using 1 N hydrochloric acid to avoid any reaction of remaining sodium carbonate by ambient CO_2 after chamber opening Respirometry measurements are expressed in mg CO_2 g^{-1} soil or in mg C g^{-1} soil.

6.2.2. NEMATODES

EXTRACTION (ISO 23611-4, 2007)

Nematodes were extracted from 200 g of fresh soil by elutriation (Oostenbrink elutriator) followed by active passaging of nematodes through a cotton wool filter. Living nematodes were allowed to cross the filter separating them from organic particles during 48 h.

ESTIMATING NEMATODE DENSITY AND FIXATION (ISO 23611-4, 2007)

The nematode suspensions were concentrated to a volume of 50 ml. Nematodes were counted in a representative 5 ml subsample under a dissecting microscope; the density of nematodes is expressed as the number of individuals 100 g^{-1} dry soil. They were then fixed in a 4% formalin solution for preservation.

IDENTIFICATION OF NEMATODES (ISO 23611-4, 2007)

Aliquots of the nematode suspensions were mounted in mass slides. Between 100 and 150 specimens were identified on average (to the family or genus level) by light microscopy using Bongers' book (1994).

INDEX CALCULATION

Nematodes were then grouped according to their families, genera, trophic groups, cp values and functional guilds. The ecological indices (MI, PPI, SI, EI and NCR) presented in Chapter 1, part IV.5 were calculated.

6.2.3. EARTHWORMS

IDENTIFICATION OF EARTHWORMS

Earthworms were identified at the level of ecological categories: epigeic, endogeic or anecic. Adults were also distinguished from juveniles based on the presence of the clitellum (sexual organ).

COUNTING AND WEIGHING

Earthworms were gently dried on paper towels to remove all traces of formol. For each ecological category, earthworms were counted and weighed, distinguishing adults from juveniles. The abundance of earthworms is expressed as individuals m^{-2}, and the biomass is expressed as g m^{-2}.

7. STATISTICAL ANALYSIS

7.1. "REFERENTIAL NETWORK"

Vineyard management systems and soil types were grouped into homogeneous types using a classification methodology. Basic physical and chemical properties such as content of soil particles coarser than 1 cm and 2 mm, soil texture, soil particle density, pH and calcareous (total and active) content were used for soil type classification as they generally do not change over a short time scale (<10 years). The type of pesticide used (2 categories: with non-synthetic and synthetic pesticides), the type of fertilization (2 categories: with organic fertilizers only and other strategies), the type of weeding in the inter-row (3 categories: non-weeding, mechanical weeding and chemical weeding) were used to classify the vineyard management systems. The soil types and vineyard management systems were classified using the “hclust” function from the “ade4” library of the R.2.11.1 (R Development Core Team, 2011) software using the “ward” method. Before clustering, all data were centered and scaled. Principal component analysis (PCA) was applied for each classification with the same library. The soil and vineyard types were then used as factors in a two-way ANOVA to determine the significant differences in dynamic soil quality indicators. Before analysis if necessary, the distribution of the observed variables was adjusted to Gaussian distribution by logarithmic transformation. The variables describing the density for nematode trophic groups were not normalized because they followed a Poisson distribution. The functions “lm” and “glm” from the “lme4” library of the R 2.11.1 software (R Development Core Team, 2011) were used for variables with Gaussian and Poisson distributions respectively. When there were significant differences between variables at a threshold level of $p>0.05$, pairwise testing was applied for soil types and/or vineyard management systems without significant interactions. In these cases, separate box plots were constructed for the 7 soil types and 9 vineyard management systems. However, when variables showed significant interaction between soil type and vineyard management system, pairwise testing was carried out for vineyard management systems within each soil type. A single box plot combining soil types and vineyard management systems was constructed. Combinations were not considered if they were represented by a single plot. 30 combinations were analyzed. The pairwise test based on Tukey test ($p < 0.05$) was used for non-count variables and the pairwise test based on Bonferonni test ($p<0.05$) was used for count variables corresponding to nematode density. The XLstat 2008.6.01 software was used for these pairwise tests and R 2.11.1 software (R Development Core Team, 2011) was used to construct box plots.

A different model was used for variables relating to earthworms, considering the various plot designs in comparison with soil sampling. A univariate approach using generalized and linear mixed models for hierarchical data (Bolker *et al.*, 2009; Pinheiro and Bates, 2000) was used to study the effects of types of weeding on density and biomass of total, endogeic and anecic earthworms. Before analysis, the biomass data distribution was adjusted to Gaussian distribution using logarithmic transformations. The earthworm density variables were not normalized because they followed Poisson distribution. The "lmer" and "glmer" functions from the "lme4" library of the R 2.11.1 software (R Development Core Team, 2011) were used to calculate mixed models from variables with Gaussian and Poisson distribution, respectively. Multiple comparisons between the means of the treatments were tested using Markov Chain Monte Carlo samples.

7.2. "ORGANIC NETWORK"

7.2.1. UNIVARIATE ANALYZES

The experimental site of the "*Organic Network*" referred to generalized linear mixed model. It was generalized because the plot effect was nested in the treatment effect (Conventional, Organic7, Organic11 and Organic17). Thus, I assumed that there was a plot inside each treatment effect in this case. I also considered this model to be mixed because it integrated factors with two types. The first was a fixed effect in the case of the treatment effect because treatments were defined previously. The second was a random effect in the case of the plot effect because, in theory, I could study other plots belonging to the same treatment. Therefore, I address some statistically random samples among a population.

Consequently, I used a univariate approach based on generalized linear mixed models for hierarchical and data analyzes (Bolker *et al.*, 2009; Pinheiro and Bates, 2000) to study the differences between treatments for each observed variable (bulk density, total organic carbon (TOC) and total nitrogen (N) contents, available phosphorus (P), potassium (K) and copper (Cu) content, cation exchange capacity (CEC), soil microbial biomass (MB), nematode trophic group and nematode taxa density, ecological indexes based on nematofauna and the density and biomass of endogeic and anecic earthworms. Prior to the analysis, when necessary, the distribution of the observed variables was adjusted to a Gaussian distribution using appropriate transformations (square root or logarithmic). The variables describing density data for nematode trophic groups, nematode taxa and endogeic, anecic and total earthworms were not normalized because they instead followed a fish distribution. The Mel and glmer functions from the lme4 library of R 2.11.1 software (R Development Core Team, 2011) were used to compute mixed models from variables exhibiting Gaussian and fish distributions, respectively. The two models used were the following:

(1) model = Mel (DATA1 [, i] ~ + Treatment (1|))(Treatment/plot), data = DATA1)

(2) model = glmer (DATA2 [, i] ~ + Treatment (1|))(Treatment/plot), data = DATA2, family = fish (link = "log"))

where * DATA1 is the dataset containing measurement or weighing data; and

* DATA2 is the dataset with data from counts.

Multiple comparisons of the means among treatments were then tested using Markov Chain Monte Carlo samples.

7.2.2. MULTIVARIATE ANALYSIS

LINEAR DISCRIMINANT ANALYSIS

Based on the results of the univariate approach, a linear discriminant analysis was conducted to discriminate among observations from the 4 treatments (Conventional, Organic7, Organic11 and Organic17). For this purpose, this multivariate analysis computed the best discriminating functions to differentiate among objects in the treatments while minimizing the variability within a treatment(Legendre and Legendre, 1998). The bulk density, total organic carbon (TOC) and total nitrogen (N) contents, microbial soil biomass carbon (MB), available phosphorus (P), potassium (K) and copper (Cu) contents, effective CEC (CEC), plant-feeding (PF), bacterial feeding (Ba), fungal-feeding (Fu), combined omnivorous and predator (Om + Pr) nematode densities and endogeic earthworm density and biomass were the variables in the integrated in the discriminant analysis. This analysis was performed using XL-Stat software for Windows ®. The results were presented in the form of a correlations circle of variables, the distribution of the 96 observations along the two discriminating axes and a confusion matrix (real) comparing the a priori and a posteriori (calculated) classification of the observations using the cross-validation technique.

PERMANOVA AND MULTI-DIMENSIONAL SCALING (MDS)

For the 24 plots, I calculated the mean density of the 40 identified nematode taxa in the 4 replicates. Then a Bray Curtis similarity matrix was calculated using PRIMER-E Ltd. software (Plymouth, United Kingdom) based on standardized data and square root transformed. A PERMANOVA test was used to statistically evaluate whether the 4 treatments led to different nematode communities. An MDS representation was generated to illustrate the similarities of the nematode communities between plots.

8. SOCIAL STUDY

8.1. SAMPLING

Four of the 9 areas of the "*Referential Network*" were studied: Montagnac, Aigues-Mortes, Vergèze and Saint-Hippolyte du Fort. All of the winegrowers who agreed to have their plot sampled also agreed to answer the questions, with one exception. The panel of winegrowers presented diverse vineyard management systems in conventional farming or in organic farming. Thus, 29 winegrowers were surveyed: 8 for Montagnac, 5 for Aigues-Mortes, 8 for Vergèze and 8 for Saint-Hippolyte du Fort. This is therefore a oriented sample (Table II- 4) built based on preliminary research questions, as opposed to a sample generated randomly from a list of winegrowers in Languedoc-Roussillon. This choice was justified, especially because the goal was not to conduct a quantitative questionnaire survey among a large number of individuals, but to engage in comprehensive interviews.

8.2. THE SURVEY

A comprehensive interview survey, as practiced in sociology, is used to determine the practices of actors and the meaning they attach to their practices (Kaufman, 1996). The objective of the investigator is then to speak with the interviewees about a series of predefined themes, allowing them to express themselves as freely as possible and inviting them using constant reminders to clarify their thinking. The subjects to be addressed with the winemakers had been previously defined:

Table II- 4: Number of investigated winegrowers by type of wine (conventional or organic) for each area.

ZONE	VITICULTURE	NUMBER OF WINEMAKERS SURVEYED
Aigues-Mortes	conventional	3
	organic	2
Montagnac	conventional	7
	organic	1
Fort Saint-Hippolyte	conventional	4
	organic	4
Vergèze	conventional	2
	organic	6
	TOTAL	**29**

1- What are the vineyard practices of the winegrowers? Why have they made these choices? What are the main limitations to their activities?

2- How do the winegrowers decide what types and doses of fertilizer or amendments to apply and how to manage their soil (chemical weeding, tillage or sodding)?

3- What do the winemakers know about the soil? What is a "good" soil according to them? Do they work to improve or maintain the quality of their soil?

4- What indicators do the winegrowers use to distinguish among different types of soil? Do they rate the quality of the soil before changing agricultural practice?

The interviews, lasting an average of 45 minutes, were conducted between June and October 2010 at the homes of the winegrowers by Montpellier SupAgro students . Latter on the interviews were transcribed and coded manually by the students. Recurrences in the interviews identified information of a general nature beyond the individual experience of any particular winemaker.

CHAPTER III

A LARGE FIELD STUDY TO CONSTITUTE A BASELINE FOR THE EVALUATION OF VINEYARD SOIL QUALITY

In the following chapter, I present my dataset of physical, chemical and biological indicators of soil quality in the context of the Languedoc-Roussillon region. To attain with this goal, a large field study has been carried out on 164 vineyard plots. They were carefully selected in order to maximize the diversity of soil types and to take into account most of vineyard management practices.

A LARGE FIELD STUDY TO CONSTITUTE A BASELINE FOR THE EVALUATION OF VINEYARD SOIL QUALITY

1. INTRODUCTION

This study evaluated the effects of vineyard management system on soil quality on a broad range of soil types. A network of 164 plots located in 9 different pedo-landscaped areas of Languedoc-Roussillon (South of France) were studied. In each area, plots with different management systems were selected.

The different vineyard management systems and soil types were grouped into homogeneous groups using a classification methodology. These groups were used as a framework to interpret the dynamic soil quality defined which was linked to the land use and management (Chapter I). The classification was then used to test the following hypotheses:

1. the types of soil affected the physical and chemical properties and biological indicators of dynamic soil quality,
2. the vineyard management systems affected the physical and chemical properties and biological indicators of dynamic soil quality.

2. MATERIAL AND METHODS

2.1. SITE DESCRIPTION, MANAGEMENT AND FIELD PLOT DESIGN

The study was conducted in spring 2009 using the "*Referential Network*" (Chapter II) consisting of 9 areas in the Languedoc-Roussillon region of France. Different plots were sampled in each area, giving a total of 164 plots. All were commercial vineyard plots. Details of the plots in each area and the denomination of soil for each area (IUSS Working Group WRB, 2006a) are given in Table III- 1. The climate in the 9 areas is typically Mediterranean with 14.7 ± 0.6 °C mean annual temperature, 694 ± 58 mm annual rainfall and 1,323 ± 26 mm annual ETP Penman-Monteith (averages based on data collected from 2000 to 2010 by Météo-France).

Table III- 1 : Location and name of soil in the 9 areas

Town	Longitude	Latitude	Altitude (m)	Soil denomination	Number of plots
Terrats	42°36'27'' N	2°46'14'' E	135	Luvisol and Cambisol	11
Lesquerde	42°48'01'' N	2°31'47'' E	358	Arenosol	19
Montagnac	43°28'50'' N	3°29'02'' E	54	Calcisol	21
Faugères	43°33'57'' N	3°11'19'' E	284	Cambisol	21
Aigues-Mortes	43°34'02'' N	4°11'33'' E	5	Arenosol	18
Vergèze	43°44'37'' N	4°13'14'' E	32	Cambisol	17
Jonquières Saint-Vincent	43°49'38''N	4°33'48'' E	37	Rhodic Luvisol	19
Saint-Hyppolyte du Fort	43°57'56'' N	3°51'28'' E	170	Calcisol	15
Saint-Victor la Coste	44°03'38'' N	4°38'29'' E	143	Calcisol	23

In each area, soil samples were taken from plots under different vineyard management systems. A vineyard management system was defined as the combination of different viticultural practices. Based on interviews with winegrowers for each plot, the following viticultural practices were selected:

- Use of pesticides. A distinction was drawn between non-synthetic and synthetic pesticides. The term pesticides included fungicides, insecticides and acaricides but not herbicides. The main non-synthetic pesticides were:
    - Bordeaux mixture containing copper sulfate (20% content of copper) to fight against Downy Mildew (*Plasmopara viticola*),
    - sulphur-based fungicides to fight against Powdery Mildew (*Erysiphe necator*),
    - insecticides using the bacteria *Bacillus thuringiensis* which is able to synthetize and excrete toxic crystals to Eudemis (*Lobesia botrana*) and Cochylis (*Eupoecilia ambiguella*).
- Use of fertilizers. A distinction was drawn between fertilization with organic fertilizers only and "other" fertilization strategies which included, (i) no fertilization, (ii) mineral fertilizers with broadcast or foliar application and (iii) fertilization strategies including the occasional application of organic matter or combined organic and mineral fertilization. In this latter case, the quantity of organic carbon applied was always less than that on plots where organic fertilizers were used.
- Inter-row weeding. A distinction was drawn between no weeding, mechanical weeding and chemical weeding. In this article, no weeding is termed permanent grass cover and mechanical weeding is termed tillage. It should be noted that tillage was considered to be solely for weeding although tillage has many other purposes such as soil aeration, reducing compaction and burying the grass cover residues and fertilizers. Chemical weeding was

considered to be the use of herbicides, mainly glyphosate, which were generally applied once or twice per year. Many winegrowers weeded within the rows chemically but weeded mechanically between the rows. In this case, the plots were considered to be mechanically weeded.

- Grass cover. Three different cases were distinguished for the duration of the grass cover, (i) there was permanent grass cover (corresponding to no weeding), (ii) there was temporary grass cover (4-8 months) and (iii) no grass cover (bare soil all year round).

2.2. SAMPLING PROCEDURE

Soil samples were taken between March 5 and May 22, 2009 (Table III- 2). All samples were taken from the 0-15 cm topsoil in the center of the inter-row. Ten soil subsamples were taken on each plot using a gouge auger and carefully homogenized to form a single representative soil sample. This soil sample was sieved using a 1 cm mesh before biological analyzes and sieved using a 2 mm mesh before physical and chemical analyzes. For bulk density measurements, 3 samples per plot were taken using a cylindrical core sampler.

Because of the large number of plots included in the "*Referential Network*", earthworms were only sampled in 13 plots in the Saint-Victor la Coste area on February 17, 2011. The soil water content was 20.1 ± 0.4% (w/w). Five plots were managed with permanent grass cover cut 4-5 times per year. Five others were weeded mechanically (3-4 times per year) but grass cover was temporarily maintained during autumn and winter. The remaining 3 plots were chemically weeded once per year and there was temporary grass cover during autumn and winter. In each of these 13 plots, earthworms were sampled in 4 representative subplots in the center of the inter-row. Each subplot was watered with an irritant solution of mustard (Amora®Fine and Strong Mustard at a concentration of 15 g per liter of water (Pelosi *et al.*, 2009)). Three applications of 10 liters of the solution were applied in a 1 m x 1 m quadrat, with 10 minutes between applications. Earthworms were collected as they rose to the surface. Ten minutes after the third application, a 25 cm x 25 cm block of soil 15 cm thick was excavated and the earthworms were extracted by hand. The earthworms were then placed in a solution of 75% ethanol for storage. They were classified into epigeic, endogeic and anecic ecological categories. Adults were distinguished from juveniles by the presence of the clitellum (sexual organ). The earthworms were gently dried on paper towels to remove all traces of ethanol. The earthworms in each ecological category were counted and weighed, distinguishing adults from juveniles.

Table III- 2 : Soil water content on the sampling dates in the 9 areas

Area	Date of soil sampling	Water content (%)	Water holding capacity (%)	Water content / water holding capacity (%)
Aigues-Mortes	March 5 and 6, 2010	10.7 ± 0.5	6.9 ± 0.4	155*
Montagnac	March 12 and 13, 2010	19.1 ± 0.6	28.2 ± 0.8	68
Vergèze	March 15 and 16, 2010	20.4 ± 0.5	28.8 ± 0.6	71
Jonquières Saint-Vincent	March 17 and 18, 2010	17.0 ± 1.0	23.9 ± 1.3	71
Saint-Victor la Coste	March 19 and 20, 2010	16.8 ± 0.6	23.1 ± 1.0	73
Lesquerde	March 30 and 31, 2010	6.7 ± 0.5	11.2 ± 0.6	60
Terrats	April 1 and 2, 2010	12.1 ± 0.5	22.8 ± 0.6	53
Faugères	April 12 and 13, 2010	11.5 ± 0.4	22.5 ± 0.6	51
Saint-Hippolyte du Fort	May 21 and 22, 2010	14.8 ± 0.5	23.9 ± 0.5	62

* soil was sampled just after rain.

2.3. PHYSICAL AND CHEMICAL ANALYZES

The proportion of soil particles which were coarser than 1 cm (SP_1 cm) and 2 mm (SP_2 mm) was determined. The soil texture was measured after decarbonation. The bulk density (BD) was measured by drying soil samples at 105 °C for 1 week and weighing the samples rapidly (NF ISO 11272, 1998). However, the bulk density could not be measured on very stony soils (21 plots which were located mainly in Jonquières Saint-Vincent). The soil particle density (SPD) was determined using a modification of the method described (Musy and Soutter, 1991) with a 50 ml volumetric flask in place of a pycnometer. The bulk density (BD) and soil particle density (SPD) were used to calculate the soil total porosity (Tp) (Equation III-1):

$$Tp = 1 - \frac{BD}{SPD} \times 100$$

Equation III-1

The water holding capacity (WHC) was measured using the pressure plate extractor method (ISO 11274, 1998) after a pressure of 0.2 bar for 24 h. The Mean Weight Diameter (MWD) was calculated (Chapter II) as an aggregate stability index. Five grams of aggregates between 3 and 5 mm in diameter was moistened by quick immersion in water (NF X 31-515, (in preparation)). The fraction of aggregates between 3 and 5 mm was measured to determine the representativeness of the aggregate stability tests. The aggregate stability was not measured on very sandy soils (> 80% of sand *i.e.* Lesquerde and Aigues-Mortes) because these soils are, by definition, not structured, nor on very stony soils (> 90% of soil particles coarser than 1 cm *i.e.* Jonquières Saint-Vincent) because the measurement would not have been realistic. The aggregate stability was measured both taking account of and excluding gravel.

The chemical properties relevant to the understanding of soil functioning were also determined. The total and active calcareous contents were measured according to ISO 106963 (1995) and NF X 31-106 (1982) respectively. The total organic carbon (TOC) and total nitrogen (N) contents were measured by dry combustion according to ISO 10694 (1995) and ISO 13878 (1998) respectively. The effective cation exchange capacity (CEC) was determined using the cobaltihexamine chloride method (NF ISO 23470, 2007). A single water extract (soil : extractant ratio 1 : 10 and 2 h of contact) was used to determine the pH and the available phosphorus (P), potassium (K) and copper (Cu) contents. The solution was centrifuged (2000 × g during 20 min at 20 °C) and filtered at 0.2 µm. The P content was then determined using the green malachite method (Ohno and Zibilske, 1991) and the K and Cu contents were measured by flame atomic absorption spectrometry (Varian A600).

2.4. BIOLOGICAL ANALYZES

The soil microbial biomass carbon (MB) was determined using fumigation-extraction (Wu *et al.*, 1990). The organic carbon from fumigated and non-fumigated soils was measured with a total organic carbon analyzer TOC-V CSH (Shimadzu). The soil respiration was measured according to ISO 14239 (1997). 10 g of dry soil was wetted to 100% of the WHC and then incubated for 28 days at 28 °C. The CO_2 emitted was absorbed in 20 ml of 0.5M-NaOH solution. The excess NaOH was titrated using a Titrino plus 848 titrator with HCl at 1 N. The quantities of soil carbon respired by the soil microorganisms was deduced by comparison with controls without soils. As described by Probst *et al.* (2008), the metabolic quotient (qCO_2) was calculated by dividing quantities of C-CO_2 by C-MB. The MB/TOC and C-CO_2/TOC ratios were also calculated.

Soil nematodes were extracted from 200 g of wet soil using the Oostenbrink elutriation method, together with sieving and cottonwood extraction (ISO 23611-4, 2007). Nematodes were fixed in a 4% formaldehyde solution and a representative sub-sample was mounted on mass slides for identification at high magnification (×400). An average of 150 nematodes per sample was identified to family level and grouped into 6 trophic groups: obligate plant-feeders (OPF), facultative plant-feeders (FPF), bacterial-feeders (Ba), fungal-feeders (Fu), omnivores (Om) and predators (Pr). The combination of trophic group and cp-value was used to classify each nematode taxon a functional guild. Six nematode ecological indices were then calculated: maturity Index (MI), plant parasitic index

(PPI) (Bongers, 1990), enrichment index (EI), structure Index (SI), channel index (CI) (Ferris et al., 2001) and nematode channel ratio (NCR) (Yeates, 2003).

Earthworms were gently dried before being weighed and counted. Adult and juvenile earthworms were distinguished and distributed into endogeics and anecics.

2.5. STATISTICAL ANALYZES

Vineyard management systems and soil types were grouped into homogeneous types using a classification methodology. Basic physical and chemical properties such as content of soil particles coarser than 1 cm and 2 mm, soil texture, soil particle density, pH and calcareous (total and active) content were used for soil type classification as they generally do not change over a short time scale (<10 years). The type of pesticide used (2 categories: with non-synthetic and synthetic pesticides), the type of fertilization (2 categories: with organic fertilizers only and other strategies), the type of weeding in the inter-row (3 categories: non-weeding, mechanical weeding and chemical weeding) were used to classify the vineyard management systems. The soil types and vineyard management systems were classified using the "hclust" function from the "ade4" library of the R.2.11.1 (R Development Core Team, 2011) software using the "ward" method. Before clustering, all data were centered and scaled. Principal component analysis (PCA) was applied for each classification with the same library. The soil and vineyard types were then used as factors in a two-way ANOVA to determine the significant differences in dynamic soil quality indicators. Before analysis if necessary, the distribution of the observed variables was adjusted to Gaussian distribution by logarithmic transformation. The variables describing the density for nematode trophic groups were not normalized because they followed a Poisson distribution. The functions "lm" and "glm" from the "lme4" library of the R 2.11.1 software (R Development Core Team, 2011) were used for variables with Gaussian and Poisson distributions respectively. When there were significant differences between variables at a threshold level of $p>0.05$, pairwise testing was applied for soil types and/or vineyard management systems without significant interactions. In these cases, separate box plots were constructed for the 7 soil types and 9 vineyard management systems. However, when variables showed significant interaction between soil type and vineyard management system, pairwise testing was carried out for vineyard management systems within each soil type. A single box plot combining soil types and vineyard management systems was constructed. Combinations were not considered if they were represented by a single plot. 30 combinations were analyzed. The pairwise test based on Tukey test ($p< 0.05$) was used for non-count variables and the pairwise test based on Bonferonni test

($p<0.05$) was used for count variables corresponding to nematode density. The XLstat 2008.6.01 software was used for these pairwise tests and R 2.11.1 software (R Development Core Team, 2011) was used to construct box plots.

A different model was used for variables relating to earthworms, considering the various plot designs in comparison with soil sampling. A univariate approach using generalized and linear mixed models for hierarchical data (Bolker *et al.*, 2009; Pinheiro and Bates, 2000) was used to study the effects of types of weeding on density and biomass of total, endogeic and anecic earthworms. Before analysis, the biomass data distribution was adjusted to Gaussian distribution using logarithmic transformations. The earthworm density variables were not normalized because they followed Poisson distribution. The “lmer” and “glmer” functions from the “lme4” library of the R 2.11.1 software (R Development Core Team, 2011) were used to calculate mixed models from variables with Gaussian and Poisson distribution, respectively. Multiple comparisons between the means of the treatments were tested using Markov Chain Monte Carlo samples.

3. RESULTS

3.1. CLASSIFICATION OF SOIL TYPES AND VINEYARD MANAGEMENT SYSTEMS

3.1.1. CLASSIFICATION OF SOIL TYPES

Seven types of soil were discriminated which were represented on the plan of Principal Component Analysis (PCA) (Figure III- 1). These results were summarized by the classification tree of the Figure I-2. The total calcareous content, the texture and the content of soil particles coarser than 1 cm were the main properties used to discriminate the soil types (Table III- 3). The first branching was due to the total calcareous content. Very calcareous soils (> 400 g of total calcareous kg^{-1}) were considered as a single group (type B). For less calcareous soils, type A was separated from the others because soils were very sandy (> 80% of sand). The third group including moderately sandy soils was divided into 2 types depending on the clay content. Type C soils were less clayey than soils in type D (15-20% of clay versus 30-40 %). Low or non-calcareous soils were discriminated according to stoniness. Very stony soils (90% stones) were grouped into type E whereas other plots were discriminated according to their sand content. The sandiest soils were grouped into type G and less sandy soils were grouped into type F (>80% of sand versus 45-55%).

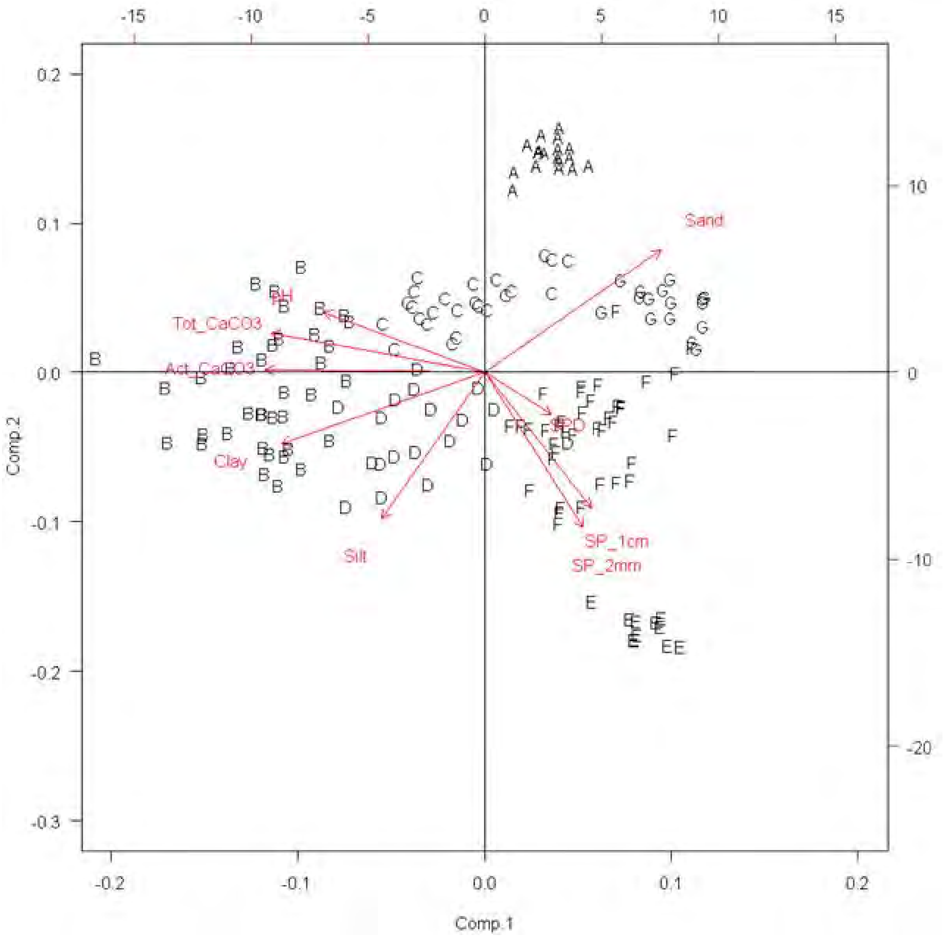


Figure III- 1 : Principal component analysis performed on basic soil properties: soil particles coarser than 1 cm (SP_1cm) and coarser than 2 mm (SP_2mm), texture (Sand, Silt and Clay), soil particle density (SPD), pH, total (Tot_CaCO3) and active

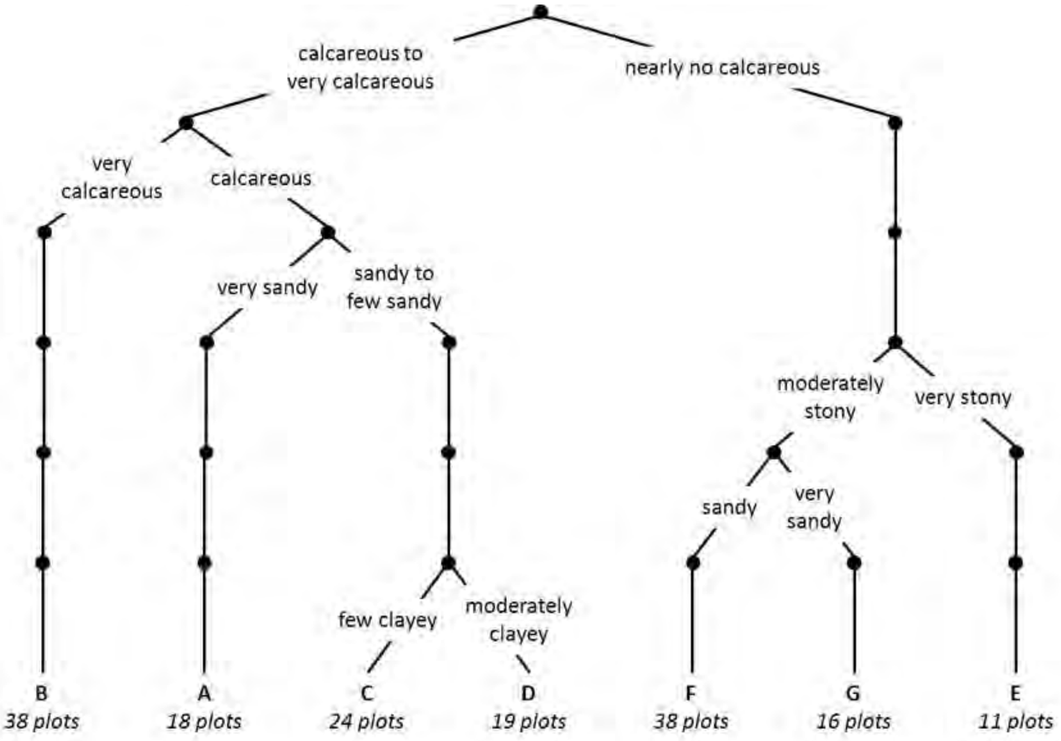


Figure III- 2 : soil classification tree

Table III- 3 : the 7 soil types based on physical and chemical properties

Soil Type	Description	Number of plots	Particles coarser than 1 cm (% w/w)	Clay (% w/w)	Sand (% w/w)	pH	Total $CaCO_3$ ($g\ kg^{-1}$)
A	very sandy & calcareous	18	< 5	< 10	> 80	> 8.4	150 - 200
B	clayey & very calcareous	38	< 5	> 40	< 30	8.0 – 8.3	> 400
C	sandy & calcareous	24	< 5	15 - 20	45 - 55	8.0 – 8.3	150 - 200
D	intermediate texture & calcareous	19	10 - 20	30 - 40	< 30	8.0 – 8.3	90 - 100
E	sandy, very stony	11	90	15 - 20	45 - 55	7.0	< 5
F	sandy acid	38	10 - 20	15 - 20	45 - 55	< 7.0	< 5
G	very sandy acid	16	10 - 20	< 10	> 80	< 7.0	< 5

Table III- 4 showed the assignment of the plots in the 9 geographical areas to the 7 soil types. Plots in Aigues-Mortes, Montagnac, Saint-Victor la Coste, Faugères, Terrats and Lesquerde had homogeneous basic properties and nearly all the plots in each area were had the same type of soil (A, B, C, F or G). However, Terrats and Faugères were grouped together. The basic soil properties of plots in Vergèze, Jonquières Saint-Vincent and Saint-Hippolyte du Fort varied, plots in Vergèze being clearly separated into types B and D. In Jonquières Saint-Vincent and Saint-Hippolyte du Fort, plots were separated into types D, E and F and B, C and D respectively.

Table III- 4 : Geographical distribution of soil types

		Soil types							**TOTAL**
		A	**B**	**C**	**D**	**E**	**F**	**G**	
Areas of study	**Aigues-Mortes**	18	0	0	0	0	0	0	18
	Montagnac	0	20	1	0	0	0	0	21
	Vergèze	0	8	0	9	0	0	0	17
	Jonquières Saint-Vincent	0	0	0	2	11	6	0	19
	Saint-Victor la Coste	0	1	22	0	0	0	0	23
	Lesquerde	0	0	0	0	0	3	16	19
	Terrats	0	0	0	2	0	9	0	11
	Faugères	0	0	0	1	0	20	0	21
	Saint-Hippolyte du Fort	0	9	1	5	0	0	0	15
	TOTAL	18	38	24	19	11	38	16	164

3.1.2. CLASSIFICATION OF VINEYARD MANAGEMENT SYSTEMS

Nine classes of vineyard management system were distinguished on the first PCA plane (Figure III- 3). These were represented as a classification tree (Figure III- 4). The first branching was due to the type of fertilizer used (non-synthetic or synthetic). Within the second branching, for plots treated with synthetic pesticides, there were two additional groups corresponding to bare soils and soils covered with grass. Plots with grass cover were discriminated according to the type of fertilization (only organic versus other). The plots managed with grass cover and organic fertilizers were grouped together as class 3. Grass covered plots with ”other” fertilization practices were further subdivided. Plots managed with permanent grass cover were grouped into class 6 and plots with temporary grass cover were divided in 2 further classes to allow discrimination of tilled plots (class 1) and chemically weeded plots (class 8). Plots with bare soil were divided into those with tillage and those with chemical weeding. Chemically weeded plots were not subdivided and were placed in class 5. Plots with bare soil maintained by tillage were divided according to the type of fertilization which was organic only (class 7) and others (class 4). The plots treated with non-synthetic pesticides were also divided according to the type of fertilization which was organic only (class 2) and others (class 9).

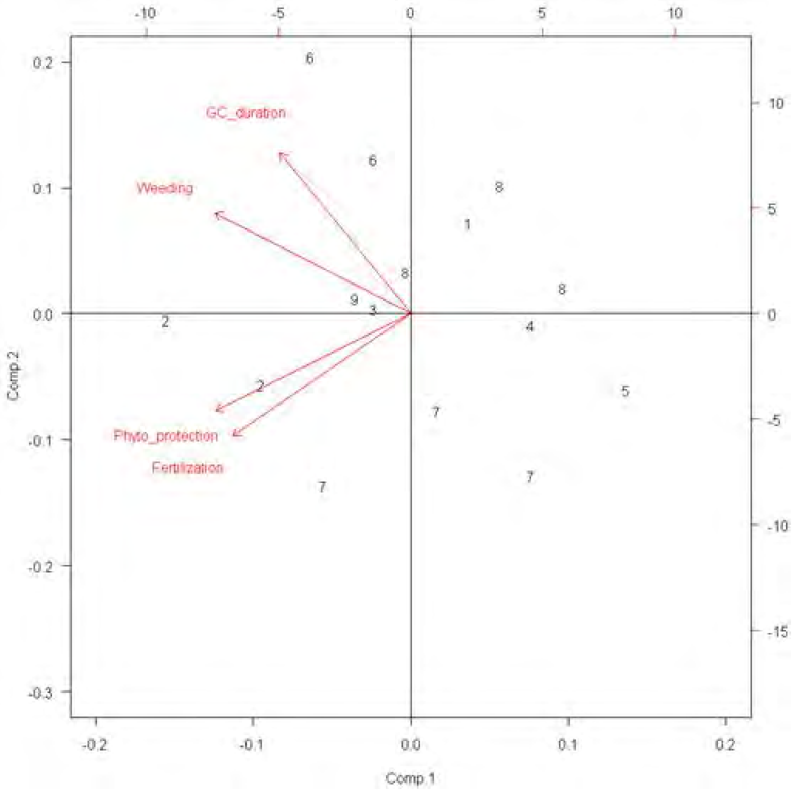


Figure III- 3 : Principal component analysis performed on vineyard management systems using type of pesticides (Phyto_protection), type of fertilization (Fertilization), type of weeding (Weeding) and duration of grass cover (GC_duration)

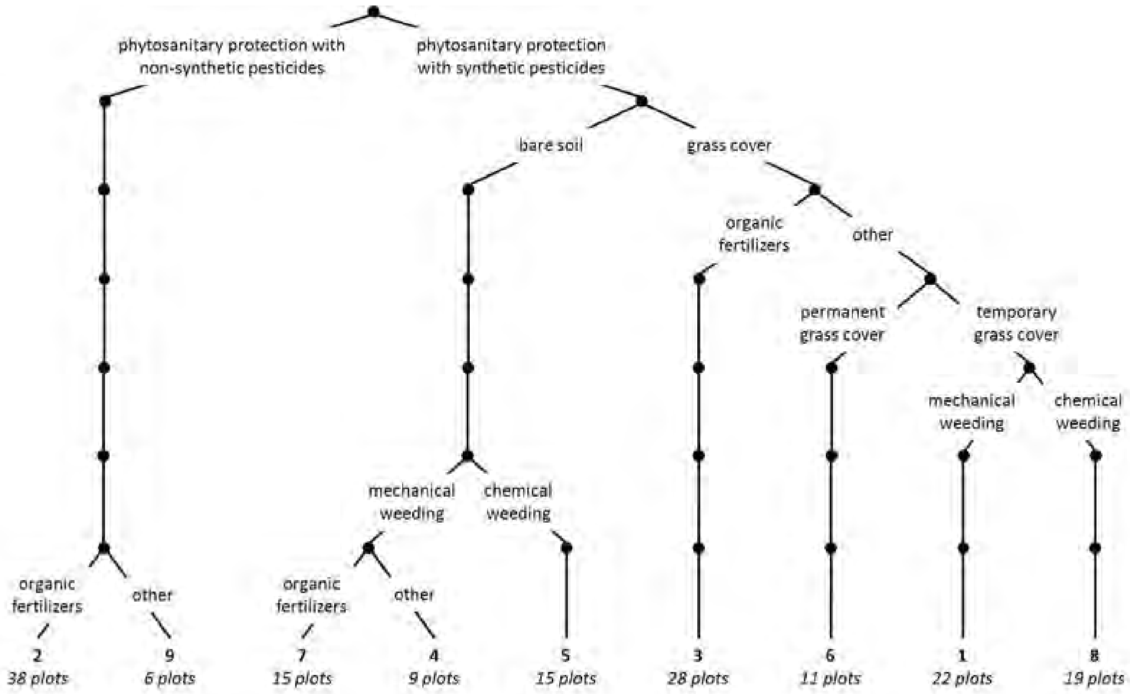


Figure III- 4 : vineyard management system classification tree

Table III- 5 shows a different view of the vineyard management systems from that in the classification tree (Figure III- 4). For classes 2 and 9 (non-synthetic pesticides), plots were always managed by tillage and grass cover was temporary. In class 3, all plots were tilled and grass cover was temporary. All plots in class 5 were fertilized using non-organic fertilizers. There was some classification bias in classes 7 and 8. In class 7, there were differences in the type of pesticide used (33% of plots treated with non-synthetic pesticides and the others treated with synthetic pesticides) and the type of weeding (67% of plots were mechanically weeded whereas the others were chemically weeded). For class 8, although all plots were chemically weeded (frequently, once or twice per year, or occasionally, once every two years) there were plots with temporary grass cover (79%) or plots with permanent grass cover (21%). 5% of plots were treated with organic fertilizer.

Table III- 6 shows the geographical distribution of the various vineyard management systems in the 9 areas. There were more plots in classes 1, 2 and 3 and fewer in classes 4, 6 and 9. An analysis of the geographical distribution of vineyard management systems showed that class 2 was present in 9 areas, class 3 in 7 areas and class 5 in 6 areas whereas classes 6, 8 and 9 were only present in 4 areas. No geographical area contained all vineyard management systems. The Aigues-Mortes and Saint-Hippolyte du Fort areas contained few different types of vineyard management system (3 and 4 respectively) whereas in the Faugères and Montagnac areas, there were 7 classes of vineyard management system.

Table III- 5 : Geographical distribution of the viticultural practices for each type of vineyard management system

Vineyard manage-ments	Number of plots	Pesticides		Fertilization		Weeding			Grass cover (month year^{-1})		
		non-synthetic	synthetic	only organic	other	no	mecha-nical	che-mical	12	4-8	0
1	22		■		■		■			■	
2	38	■		■		5%	95%		5%	95%	
3	28		■	■			■			■	
4	9		■		■		■				■
5	15		■		■			■			■
6	11		■		■	■			■		
7	15	33%	67%	■			67%	33%			■
8	19		■	5%	95%			■	21%	79%	
9	6	■			■		■			■	

Black boxes indicate that 100% of plots had the corresponding type of vineyard practices.

Dark grey boxes indicate that more than 50% of plots had the corresponding type of vineyard practices and the exact percentages are given.

Light grey boxes indicate that less than 50% of plots had the corresponding type of vineyard practices and the exact percentages are given.

Table III- 6 : Geographical distribution of the different vineyard management systems in the 9 areas

		Classification of vineyard management system									**TOTAL**
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
Areas of study	**Aigues-Mortes**	6	6	6	0	0	0	0	0	0	18
	Montagnac	6	6	1	1	2	3	2	0	0	21
	Vergèze	0	5	0	0	2	4	2	3	1	17
	Jonquières Saint-Vincent	0	3	4	0	3	3	0	5	1	19
	Saint-Victor la Coste	0	1	6	0	1	2	0	10	3	23
	Lesquerde	3	5	0	4	6	0	0	0	1	19
	Terrats	2	4	1	1	0	0	3	0	0	11
	Faugères	5	2	7	2	1	0	3	1	0	21
	Saint-Hippolyte du Fort	0	6	3	1	0	0	5	0	0	15
TOTAL		22	38	28	9	15	12	15	19	6	164

3.1.3. COMBINATIONS OF SOIL TYPES AND VINEYARD MANAGEMENT SYSTEMS

Table III- 7 showed all 63 possible combinations of soil types and vineyard management systems. Of these, 20 did not occur and, for 13, there was only 1 plot. Soil types B and F had all vineyard management systems whereas other soil types had only some systems. Type A had 3 vineyard management systems, Type C did not have vineyard management systems 1, 4 and 7 and type E did not have vineyard management systems 1, 4, 7 and 9. Type D did not have vineyard management systems 1 and 4 and type G had only vineyard management systems 1, 2, 4 and 5.

Table III- 7 : Matrix of all combinations of soil type and vineyard management system

		Vineyard management system									TOTAL
		1	2	3	4	5	6	7	8	9	
Soil type	A	6	6	6	0	0	0	0	0	0	18
	B	6	11	1	2	2	7	7	1	1	38
	C	0	1	6	0	2	2	0	10	3	24
	D	0	7	4	0	1	1	2	3	1	19
	E	0	2	1	0	3	1	0	4	0	11
	F	7	8	10	3	1	1	6	1	1	38
	G	3	3	0	4	6	0	0	0	0	16
	TOTAL	**22**	**38**	**28**	**9**	**15**	**12**	**15**	**19**	**6**	**164**

3.2. EFFECTS OF SOIL TYPE AND VINEYARD MANAGEMENT SYSTEM ON SOIL INDICATORS

3.2.1. EFFECTS OF SOIL TYPE AND VINEYARD MANAGEMENT SYSTEM ON PHYSICAL INDICATORS

Table III- 8 showed that the bulk density, water holding capacity, total porosity and MWD with and without gravel were significantly affected by both soil type and vineyard management system at $p<0.05$. The water holding capacity and MWD with and without gravel were also significantly affected by the interaction between the soil type and vineyard management system at $p<0.05$. As a consequence, 2 box plots were constructed (1 for soil type and 1 for vineyard management systems) for bulk density and total porosity and a single box plot combining soil type and vineyard management system for water holding capacity and MWD with and without gravel.

Table III- 8 : Probability levels of the two-way ANOVA (soil type, vineyard management system and soil type x vineyard management system) for physical indicators

Probability levels of the two-ways ANOVA	**Bulk density** (g cm^{-3})	**Water holding capacity** (% w/w)	**Total porosity** (%)	**MWD without gravels** (mm)	**MWD with gravels** (mm)
Soil type	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Vineyard management	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Soil type x Vineyard management	0.100	0.005	0.145	0.009	0.004

Figure III- 5 showed that the lowest bulk density was measured for the soil B (1.31 g cm^{-3}) and the highest was for soil G (1.54 g cm^{-3}), the difference being significant. For vineyard management systems, the lowest values were measured for systems 1, 2, 7 and 9 with a mean of 1.34 g cm^{-3}. Vineyard management system 5 had the highest bulk density (1.55 g cm^{-3}) which was significant.

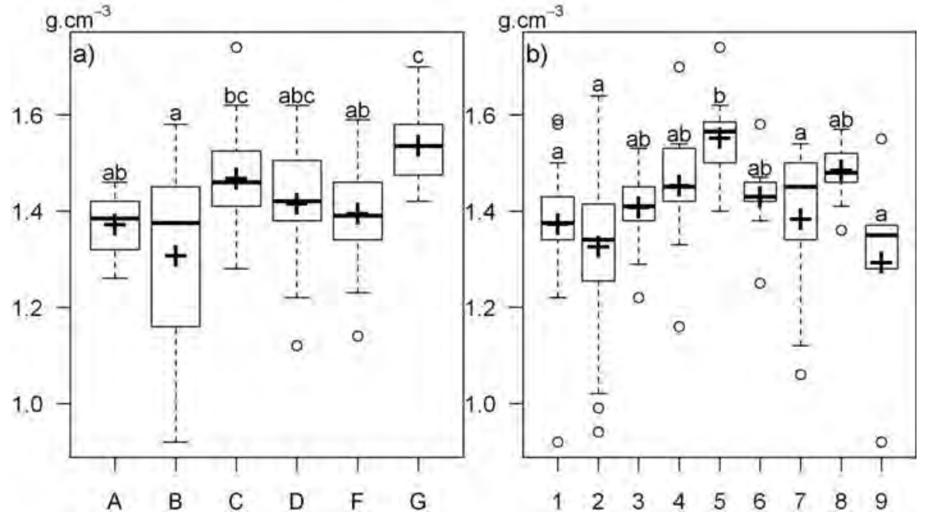


Figure III- 5 : Bulk density (g cm^{-3}) depending on (a) soil type A to G and (b) vineyard management system 1 to 9

The WHC of soils A and G were significantly lower than the other soil types with a WHC of 6.9% and 10.5% respectively (Figure III- 6). For soil A, vineyard management system 1 had a significantly higher WHC in comparison with system 3 (8.4% versus 5.8%). For soil G, vineyard management system 2 had a significantly higher WHC compared to other vineyard management systems (14.3% versus 9.64%). The other vineyard management systems did not have any significant effect on the WHC within a soil type(Figure III- 6).

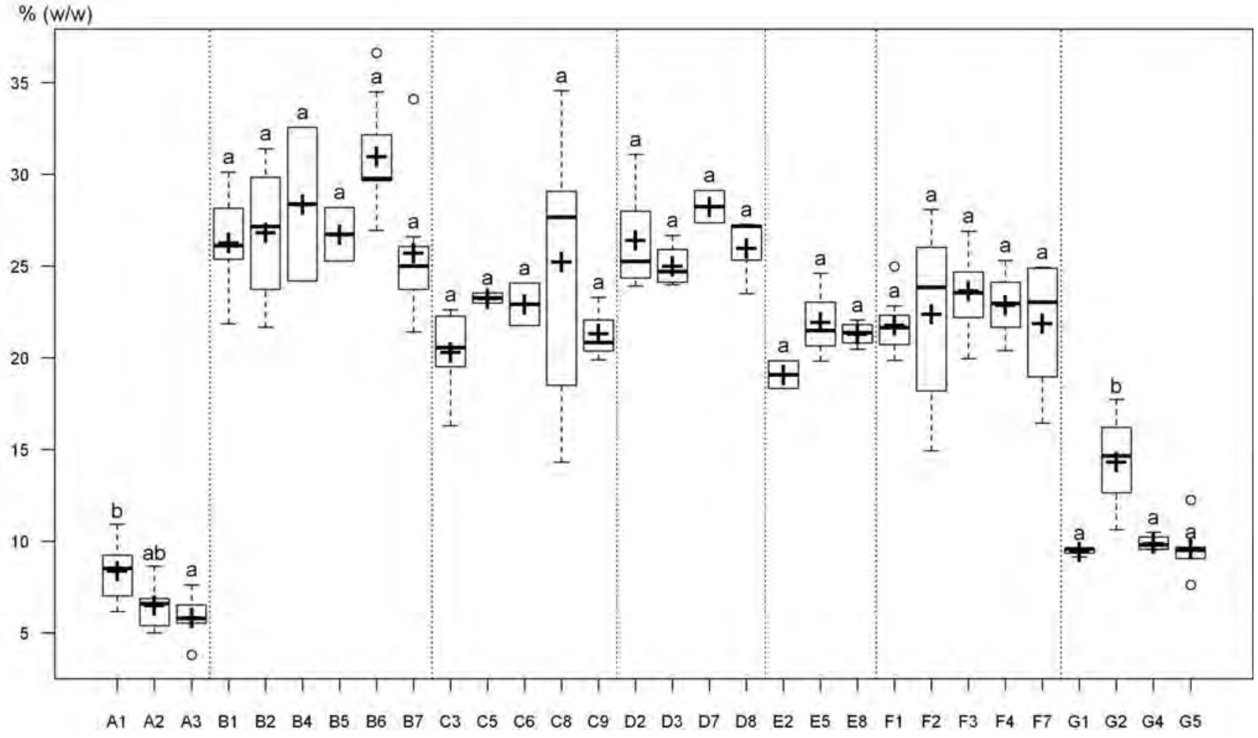


Figure III- 6 : Water holding capacity (WHC) (%) of vineyard management systems (1 to 9) x soil type (A to G)

Soil G had a significantly lower total porosity (44.0%) than the soil B (57.6%) (Figure III- 7). Other soil types ranged between 50.9% and 54.8%. Statistical analysis discriminated 3 different groups of vineyard management system. The first group comprised systems 1, 3 and 4 (mean of 49.4%), the second only vineyard management system 6 (58.8%) and the third group comprised the remaining vineyard management systems (2, 5 7 8 and 9 with a mean of 53.9%)(Figure III- 7).

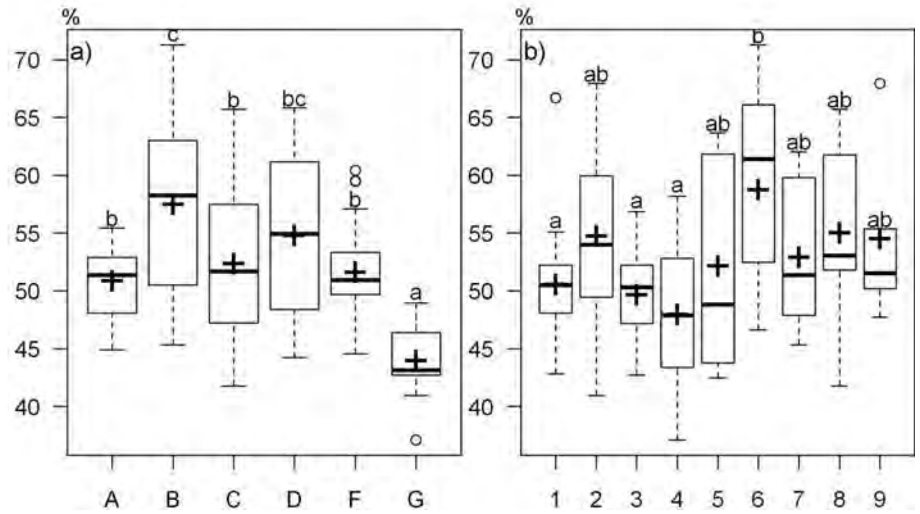


Figure III- 7 : Total porosity (%) depending on (a) soil types A to G and (b) vineyard management systems 1 to 9

Aggregate stability was measured with and without gravel (Figure III- 8and Figure III- 9, respectively). The lowest MWD values were recorded for soils B, C and D compared to soil F. The vineyard management system only had a significant effect for the soil B. With a mean MWD of 0.53 mm, vineyard management systems 1, 2 and 4 had a significant higher MWD than system 6 (0.30 mm). Management systems 5 and 7 had intermediate values. For the MWD without gravel, there was a significant difference only for soil D. Vineyard management system 3 had a significantly lower MWD (1.49 mm versus 0.67 for the mean of MWD for D2, D7 and D8).

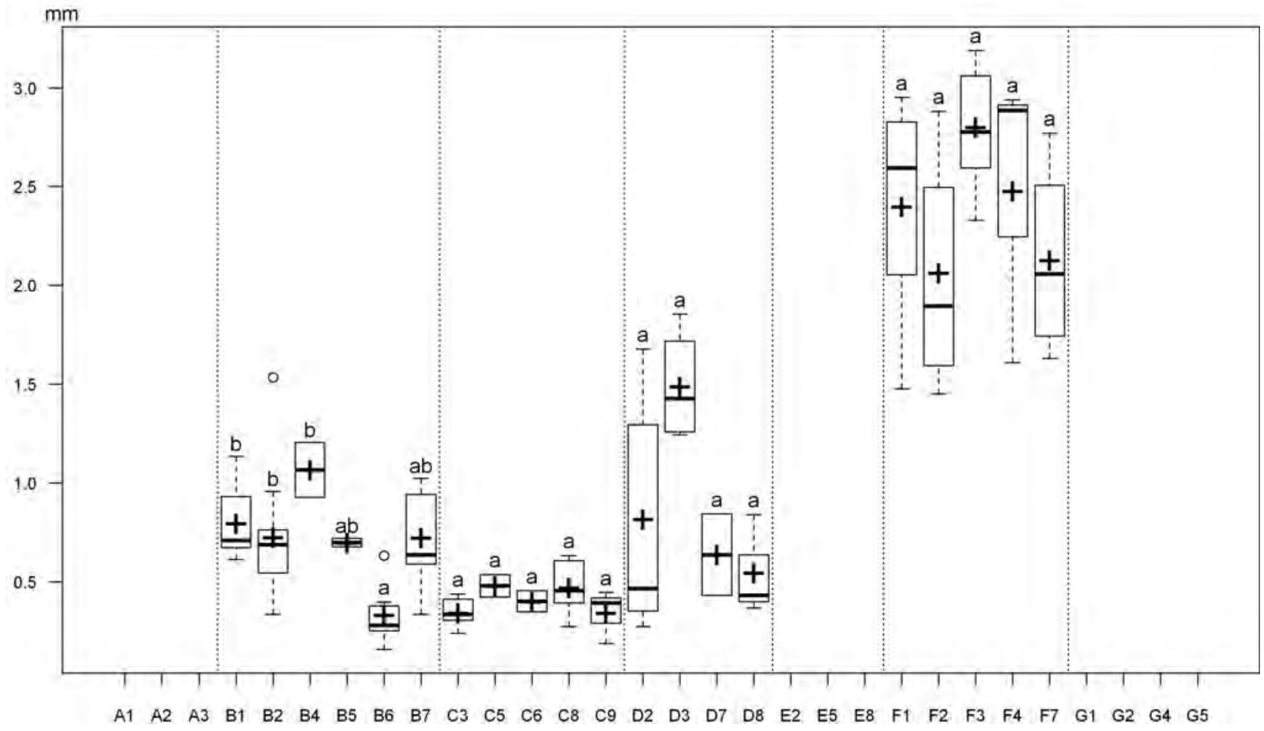


Figure III- 8 : MWD (mm) with gravel for vineyard management systems (1 to 9) x soil type (A to G)

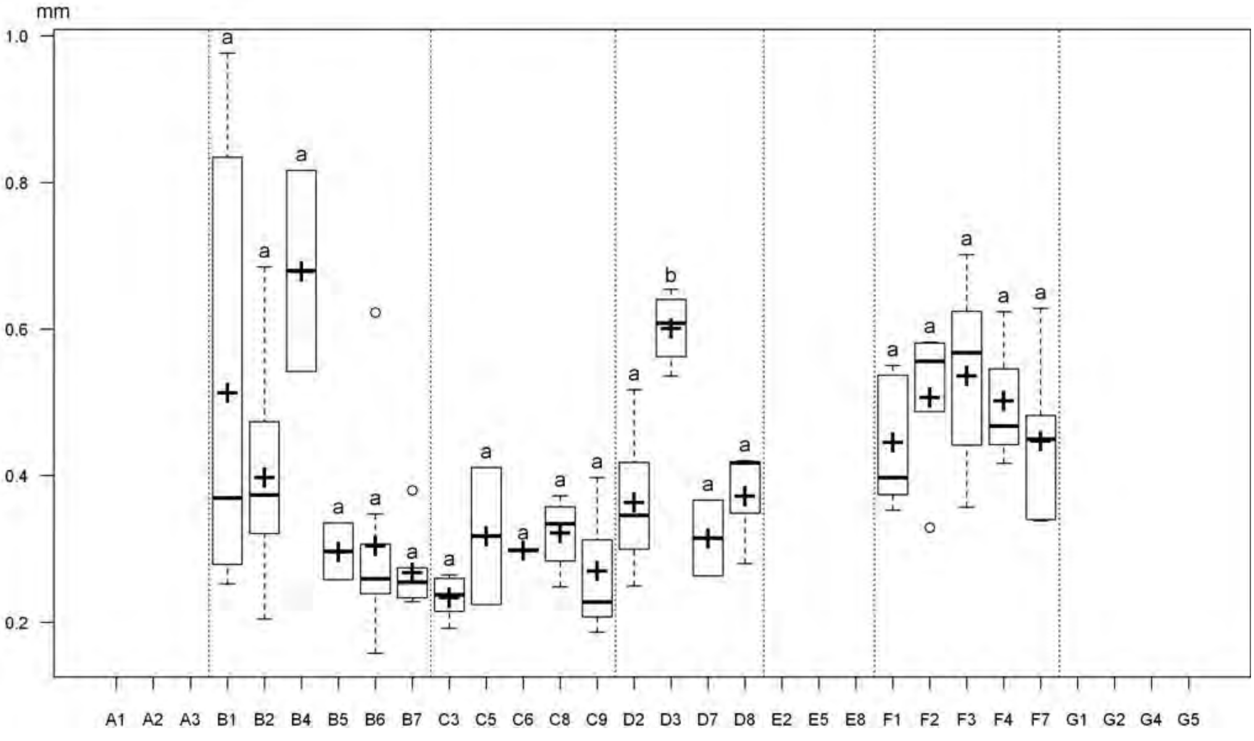


Figure III- 9 : MWD (mm) without gravel for vineyard management systems (1 to 9) x soil type (A to G)

3.2.2. EFFECTS OF SOIL TYPES AND VINEYARD MANAGEMENT SYSTEMS ON CHEMICAL INDICATORS

Table III- 9 shows that the C/N ratio, P, K, Cu contents and CEC were significantly influenced by both soil type and vineyard management system without any significant effect of their interaction at $p<0.05$. However, TOC and total N contents were significantly influenced by the interaction between soil types and vineyard management systems at $p<0.05$.

Table III- 9 : : Probability levels of the two-way ANOVA (soil type, vineyard management system and soil type x vineyard management system) for chemical indicators

Probability levels of the two- way ANOVA	TOC (mg g^{-1})	Total N (mg g^{-1})	C/N	P (mg kg^{-1})	K (mg kg^{-1})	Cu (mg kg^{-1})	CEC (cmol^{+} kg^{-1})
Soil type	< 0.001	< 0.001	< 0.001	< 0.001	0.113	< 0.001	< 0.001
Vineyard management	< 0.001	< 0.001	< 0.001	0.406	0.029	< 0.001	< 0.001
Soil type x Vineyard management	0.021	0.014	0.062	0.897	0.168	0.082	0.124

Figure III- 10 showed that the vineyard management systems significantly affected TOC content only for soils C and G. For soil C, vineyard management systems 3 and 9 had a significant lower TOC content (a mean of 10.3 mg g^{-1}) than system 8 (16.8 mg g^{-1}). For soil G, vineyard management system 2 significantly increased the TOC in comparison with the other systems (12.1 mg g^{-1} versus 6.2 mg g^{-1}).

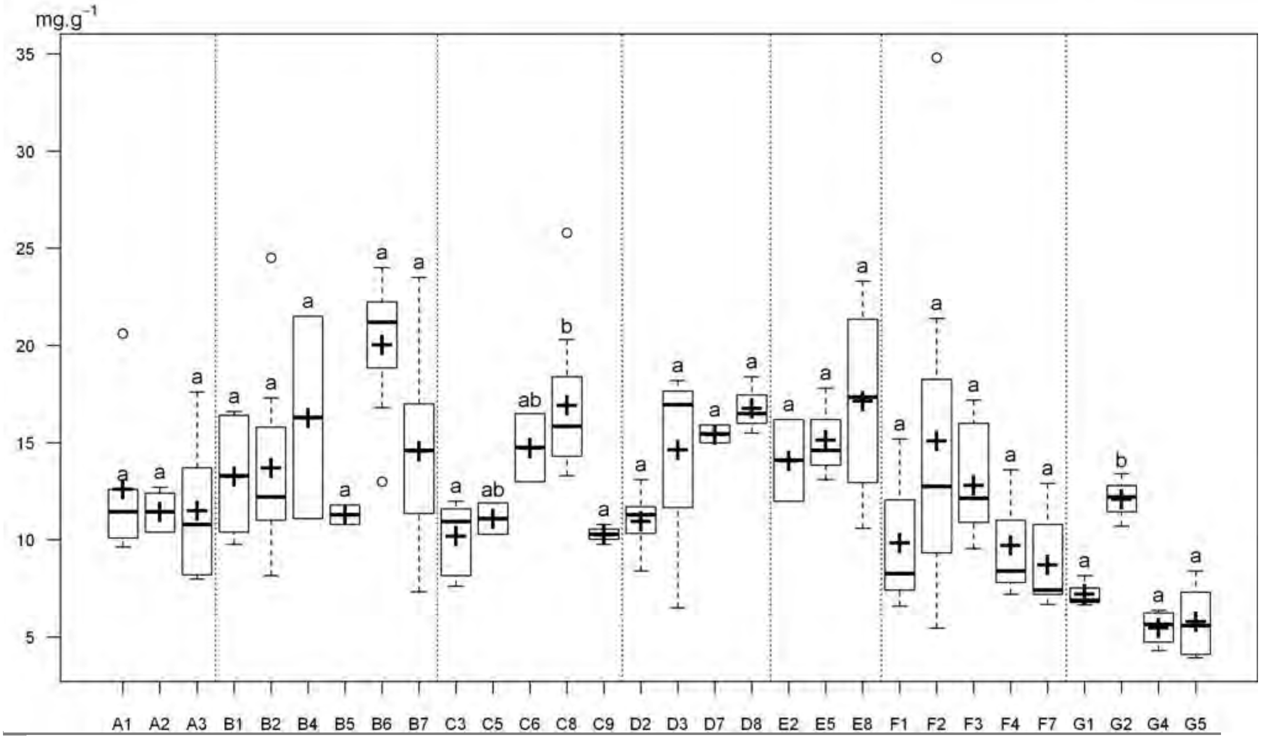


Figure III- 10 : Total organic carbon content (mg g^{-1}) of vineyard management systems (1 to 9) x soil type (A to G)

Similar to TOC content, the total N content was significantly affected by the vineyard management system for soils C and G (Figure III- 11). However, the vineyard management system also affected the total N content in soil D where the total N content was higher than for soils C and G. Furthermore, the vineyard management system 3 gave a significantly higher total N content than vineyard management system 2 (1.40 mg g^{-1} versus 0.99 mg g^{-1}) in the three soils C, D and G.

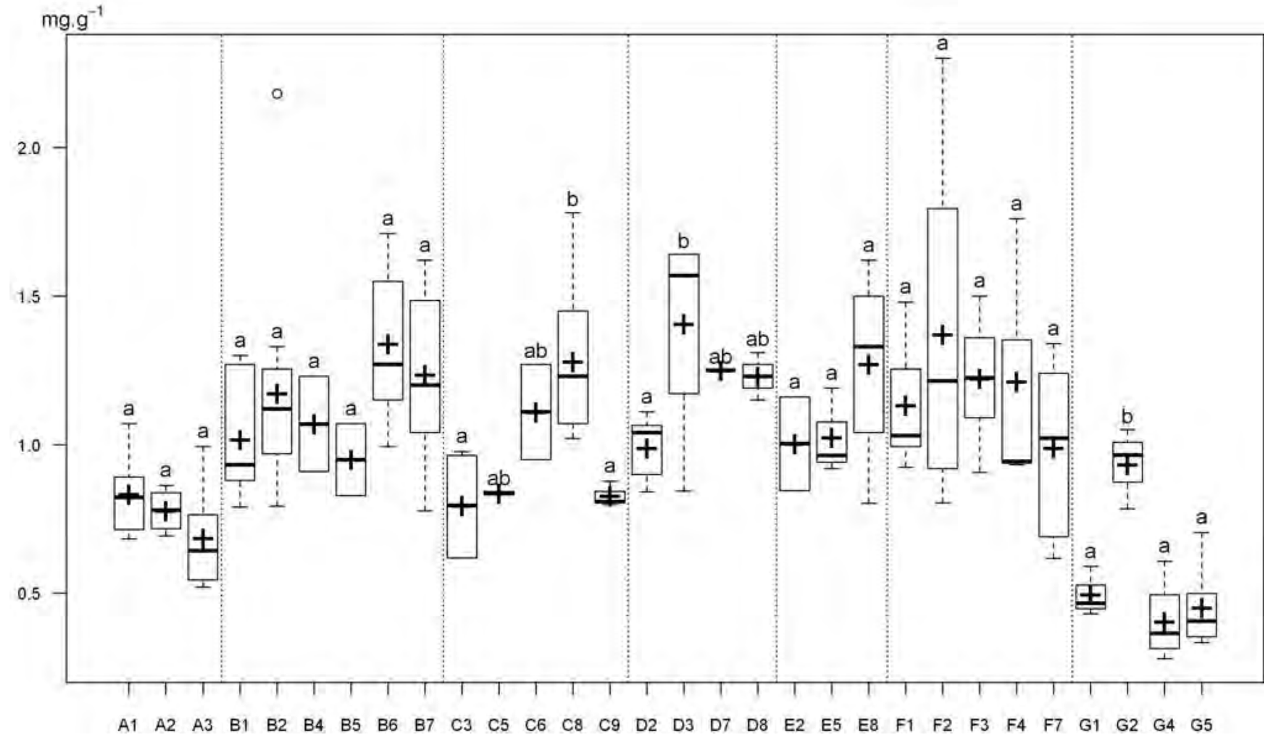


Figure III- 11: Total nitrogen (Total N) content (mg g^{-1}) of vineyard management system (1 to 9) x soil type (A to G)

The mean C/N ratio varied from 9.8 to 15.6 C/N ratio ranging from 10.0 to 15.0 (Figure III- 12). The C/N was significantly affected by the soil type. The lowest variability was measured for soil E and the highest for soil B where values ranged from 8.8 to 19.2. Soil F had a mean of 9.8, a significantly lower C/N than the other soils. Soil A had the highest mean C/N of 15.6, which was significantly higher than the other soils (Figure III- 12). However, soil A was found only in one particular plot. The C/N ratios of soils E and G were significantly higher than the C/N of soil F (13.8 and 13.6 respectively). The vineyard management system had also a significant effect on the C/N ratio. The lowest mean C/N (10.7) was calculated for vineyard management system 7 and the highest mean C/N was for system 6 (14.4) (Figure III- 12).

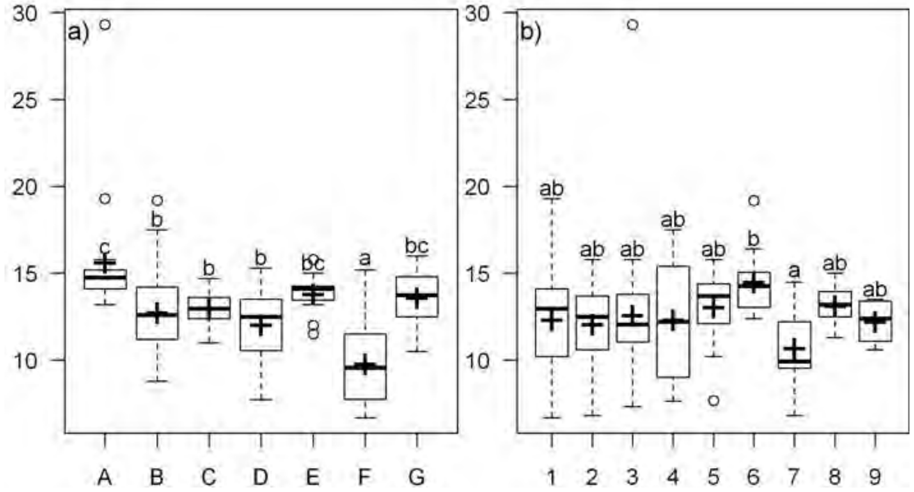


Figure III- 12 : C/N depending on (a) soil types A to G and (b) vineyard management system from 1 to 9

The P content differed significantly only with soil type (Figure III- 13). The P content of soil B (2.0 mg kg^{-1}) was significantly lower than that of soils A, E, F and G. The highest P contents were measured for soils E and F, 6.3 mg kg^{-1} and 5.1 mg kg^{-1} respectively. The variability of the P content was high for soil F.

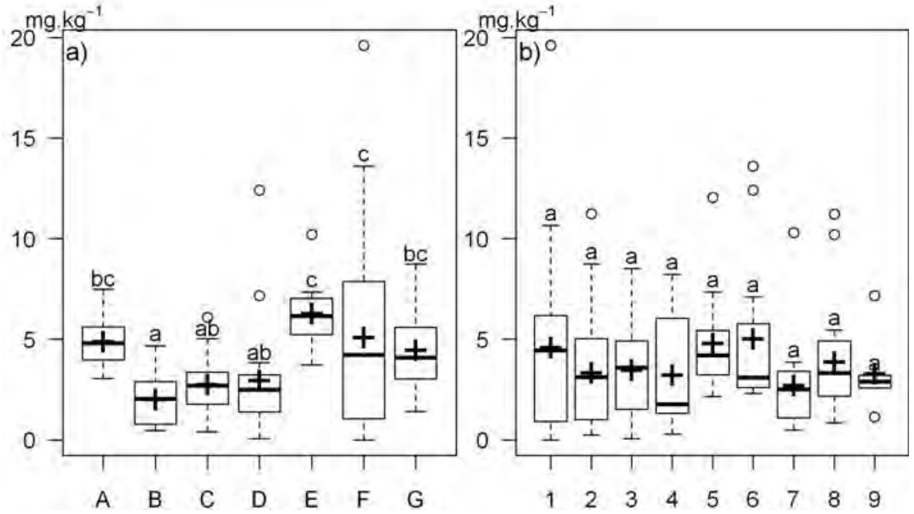


Figure III- 13 : Available phosphorus (P) content (mg kg^{-1}) depending on (a) soil type A to G and (b) vineyard management system 1 to 9

Only the vineyard management system had a significant effect on the K content (Figure III- 14). The highest mean value was measured for vineyard management system 6 (68.6 mg kg^{-1}). Vineyard management systems 2, 3, 4 and 7 had the lowest K contents with 38.6 mg kg^{-1}, 40.6 mg kg^{-1}, 33.4 mg kg^{-1} and 38.8 mg kg^{-1} respectively. It should be noted that there were many outliers in vineyard management systems 1, 3, 5 and 6(Figure III- 14).

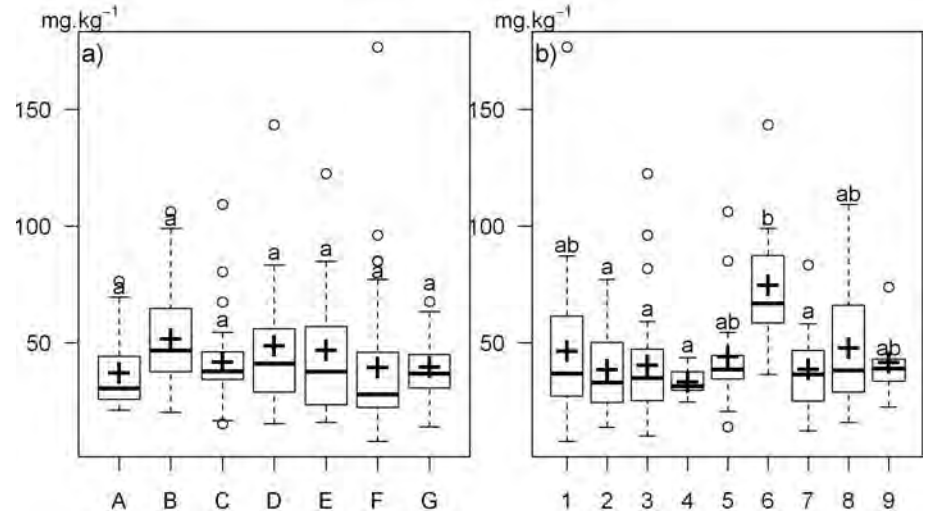


Figure III- 14 : Available potassium (K) content (mg kg^{-1}) depending on (a) soil types A to G and (b) vineyard management systems 1 to 9

The Cu content varied considerably between plots (Figure III- 15). The soil type and vineyard management systems had significant effects on the Cu content. For the soil types, soils A and E had a significantly higher Cu content (0.69 mg kg^{-1}) and soil G the lowest Cu content (0.22 mg Cu kg^{-1}). Soils B, C, D and F had intermediate values. For vineyard management systems, system 6 had a significantly higher Cu content of 0.80 mg kg^{-1}. Vineyard management systems 3 and 4 had the lowest Cu content with 0.28 mg kg^{-1} and 0.19 mg kg^{-1} respectively (Figure III- 15).

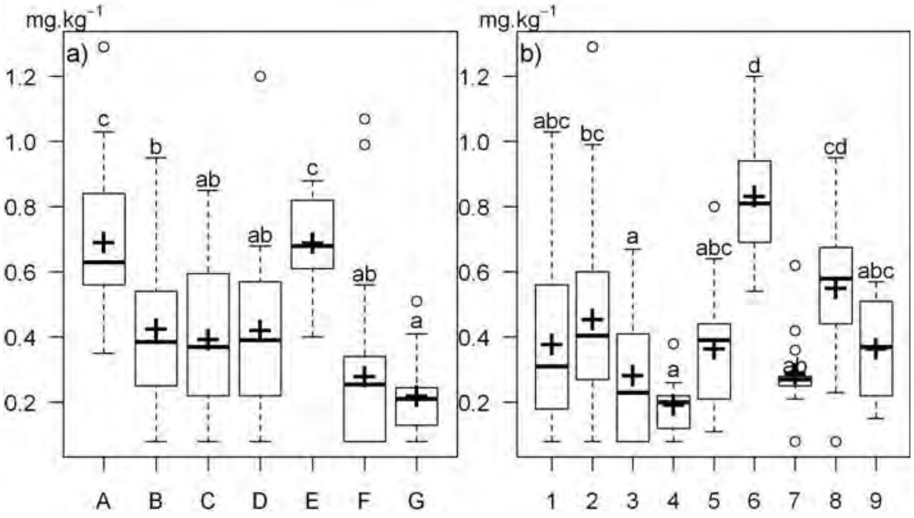


Figure III- 15 : Available copper (Cu) content (mg kg^{-1}) depending on (a) soil types A to G and (b) vineyard management systems 1 to 9

The CEC ranged between 3.4 cmol$^+$ kg^{-1} and 15.8 cmol$^+$ kg^{-1} (Figure III- 16). Only the soil type had a significant effect on CEC. There were 3 distinct groups of soil. The first comprised soils B and D with the highest CEC (16.0 cmol$^+$ kg^{-1} and 15.8 cmol$^+$ kg^{-1} respectively). The second comprised soils C and F which had intermediate CEC (10.2 cmol$^+$ kg^{-1} and 8.8 cmol$^+$ kg^{-1} respectively). The third group comprised soils A and G with the lowest CEC (4.3 cmol$^+$ kg^{-1} and 3.4 cmol$^+$ kg^{-1}respectively). The mean CECs of these 3 groups were significantly different. The CEC of soil E (7.2 cmol$^+$ kg^{-1}), was not significantly different from the CEC of either groups A+G or C+F. Although no significant effect of vineyard management system was found, the highest CEC was measured for vineyard management system 6 (12.8 cmol$^+$ kg^{-1}) and the lowest CEC was for vineyard management system 5 (7.2 cmol$^+$ kg^{-1}) (Figure III- 16).

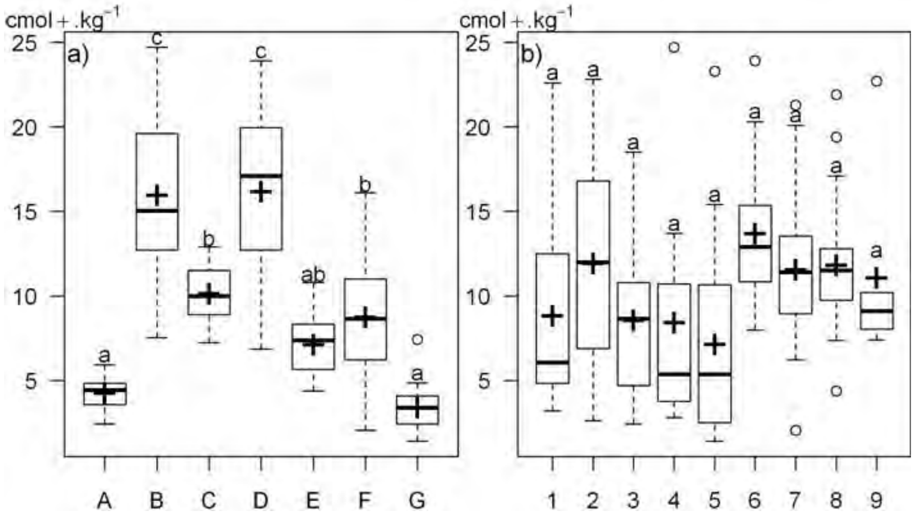


Figure III- 16 : Cation exchange capacity (CEC) (cmol$^+$ kg^{-1}) depending on (a) soil types A to G and (b) vineyard management systems 1 to 9

3.2.3. EFFECTS OF SOIL TYPES AND VINEYARD MANAGEMENT SYSTEMS ON MICROBIAL INDICATORS

Table III- 10 showed that respiration, metabolic quotient and MB/TOC were significantly affected by both soil types and vineyard management systems without any significant effect on their interaction at $p < 0.05$. However, MB was significantly affected by the interaction between soil type and vineyard management system at $p<0.05$. No significant effect on CO_2/TOC was found.

Table III- 10: Probability levels of the two-way ANOVA (soil type, vineyard management system and soil type x vineyard management system) for microbiological indicators

Probability levels of the two-way ANOVA	MB (µg C g^{-1})	Respiration (µg C g^{-1})	qCO_2	MB/TOC	CO_2/TOC
Soil type	< 0.001	0.001	0.003	< 0.001	0.062
Vineyard management	< 0.001	0.084	0.007	< 0.001	0.475
Soil type x Vineyard management	0.001	0.603	0.116	0.142	0.463

Within each soil type, MB did not vary depending on the different vineyard management systems (Figure III- 17) except for soil G where there were significant effects of vineyard management systems. For soil G, vineyard management system 2 produced higher MB (53.6 µg C g^{-1}) than vineyard management systems 4 and 5 (34.6 µg C g^{-1} mean).

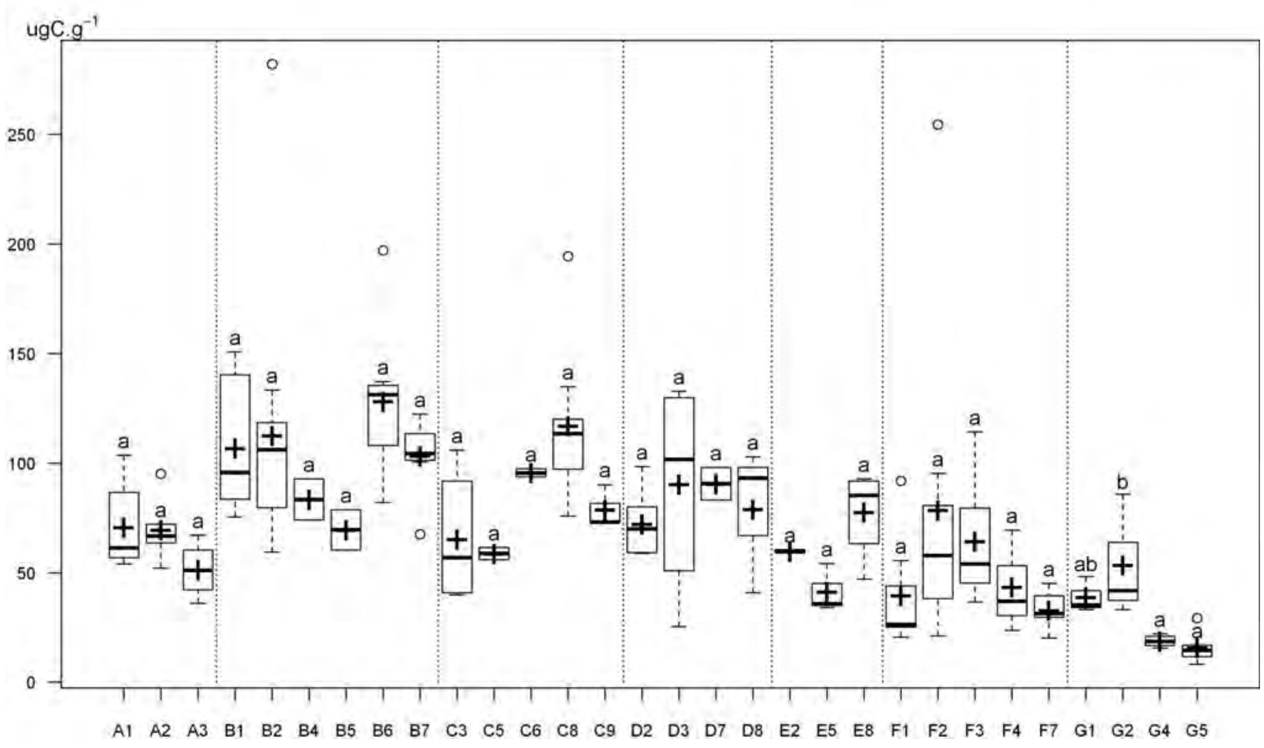


Figure III- 17: Microbial biomass (MB) (µg C g^{-1}) of vineyard management systems (1 to 9) x soil type (A to G)

The soil respiration ranged from 0.5 mg C g^{-1} to 1.37 mg C g^{-1} (Figure III- 18). Only the soil type had a significant effect. The highest soil respiration was measured for soil D with 0.45 g C g^{-1} which was significantly higher than soil respiration for soils A and C (0.22 g C g^{-1} and 0.24 g C g^{-1} respectively,).

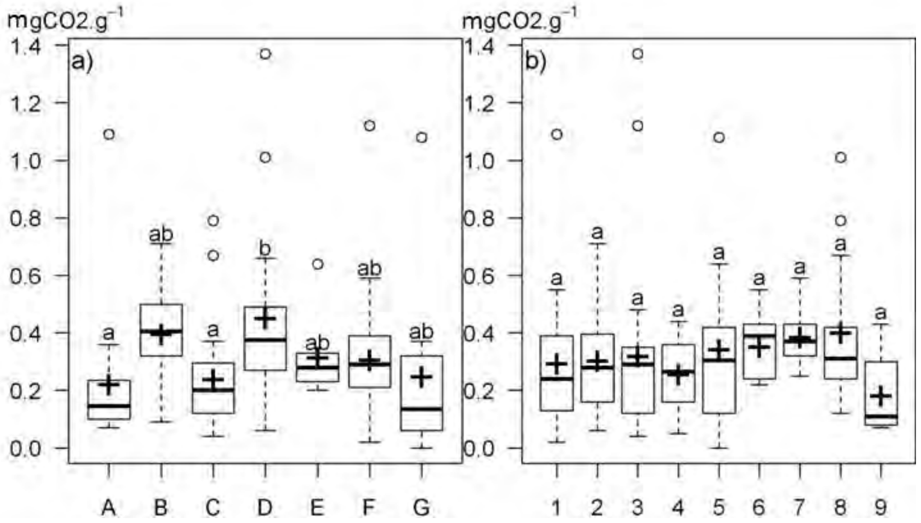


Figure III- 18: Emitted CO_2 (g C-CO2 g^{-1}) depending on (a) soil types A to G and (b) vineyard management systems 1 to 9

The overall metabolic quotient (*qCO2*) varied from 0.04 to 6.52 but most plots had a qCO_2 of less than 1.00 (Figure III- 19). The qCO_2 was significantly affected by soil type and vineyard management system. The qCO_2 of soil G was significantly higher than that of soils A, B and C. However, the 2 outliers of soil G induced a bias and increased the mean qCO_2 significantly. Disregarding these 2 points, no significant effect of soil type and vineyard management system was observed (data not shown). Only vineyard management system 5 had a significant effect on qCO_2 (Figure III- 19*).*

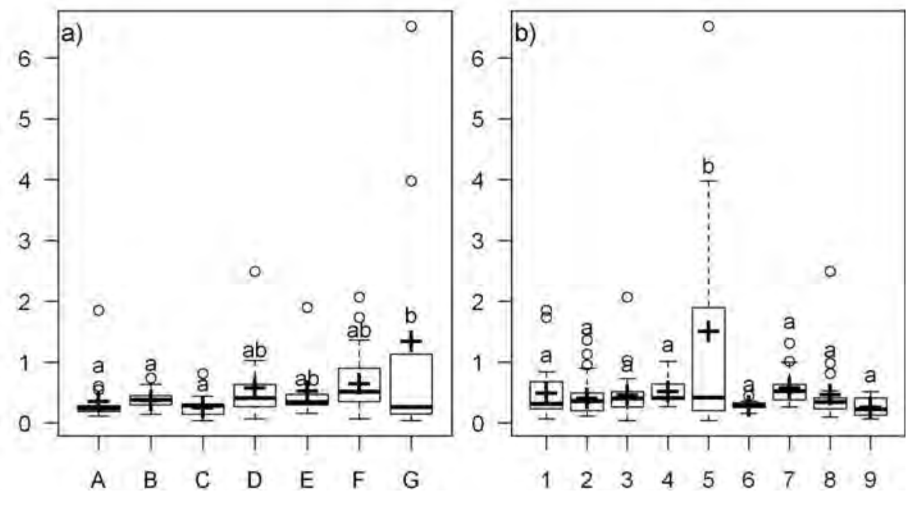


Figure III- 19: Metabolic quotient (*qCO_2*) depending on (a) soil types A to G and (b) vineyard management system 1 to 9

MB/TOC was significantly affected by soil type (Figure III- 20). The highest value was calculated for soil B (0.74) which was significantly higher than the mean value for soils A, D, E, F and G. The lowest MB/TOC was for soil G (0.37) which was significantly lower than for soils A, B, C and D. Soils A and D had intermediate values (0.57). The vineyard management system also had a significant effect on MB/TOC. Vineyard management systems 1, 2, 6, 7, 8 and 9 had the highest MB/TOC values with an overall mean of 0.63. These values were significantly higher than for vineyard management system 5 (0.37).

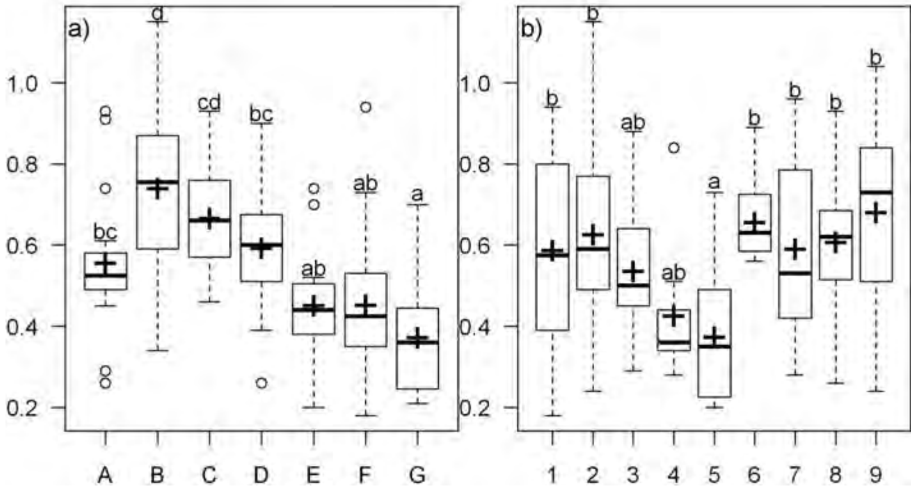


Figure III- 20: MB/TOC depending on (a) soil types A to G and (b) vineyard management systems 1 to 9

The CO_2:TOC index varied from 0.07 to 26.24 (Figure III- 21) and was below 5.00 for most plots. The soil type and vineyard management system did not appear to have any significant effect.

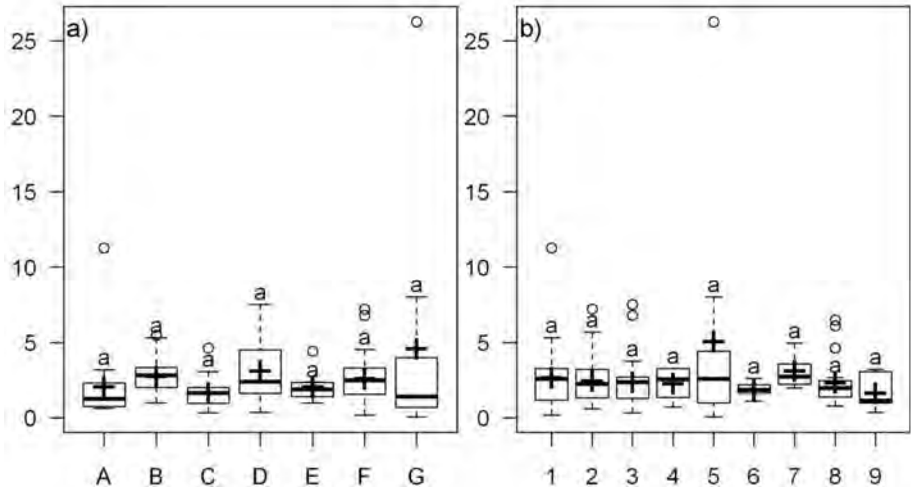


Figure III- 21: CO_2/TOC depending on (a) soil types A to G and (b) vineyard management systems 1 to 9

3.2.4. EFFECTS OF SOIL TYPE AND VINEYARD MANAGEMENT SYSTEM ON NEMATODE TROPHIC GROUP DENSITIES

Table III- 11 showed the density of total nematodes, total plant-feeders, obligate plant feeders, facultative plant feeders, bacterial feeders and fungal feeders were significantly affected by both soil type and vineyard management system and that their interaction had no significant effect at $p<0.05$. However, the density of free-living and omnivore nematodes was significantly affected by the interaction between soil type and vineyard management system at $p<0.05$. Predator density was affected only by the soil type.

Table III- 11 : Probability levels of the two-way ANOVA (soil type, vineyard management system and soil type x vineyard management system) for nematode trophic group density (TPF: total plant-feeders, FLN: free-living nematodes, OPF: obligate plant-feeders, FPF: facultative plant-feeders, Ba: bacterial-feeders, Fu: Fungal-feeders, Om: omnivores and Pr: predators)

Probability levels of the two-way ANOVA	Total	TPF	FLN	OPF	FPF	Ba	Fu	Om	Pr
	(ind. (100 g dry soil)$^{-1}$)								
Soil type	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.039
Vineyard management	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.081
Soil type x Vineyard management	0.163	0.349	0.022	0.529	0.621	0.293	0.144	< 0.001	0.555

The total nematode density varied considerably, ranging from 35 to 3,638 ind. 100 g^{-1}. It was significantly affected by soil type and vineyard management system (Figure III- 22). There were two groups of soil type: the first comprised soils A, B and C and the second soils D, E, F and G. The density of total nematodes in the first group (1,232 ind. 100 g^{-1} in mean) was significantly higher than that in the second group (486 ind. 100 g^{-1}). Vineyard management systems 4 and 5 had the lowest density of total nematodes (mean of 339 ind. 100 g^{-1}) which was significantly lower than for vineyard management systems 6, 8 and 9. Vineyard management system 6 had a total nematode density of 1,720 ind. 100 g^{-1}, which was significantly higher than for systems 1, 3, 4, 5 and 7.

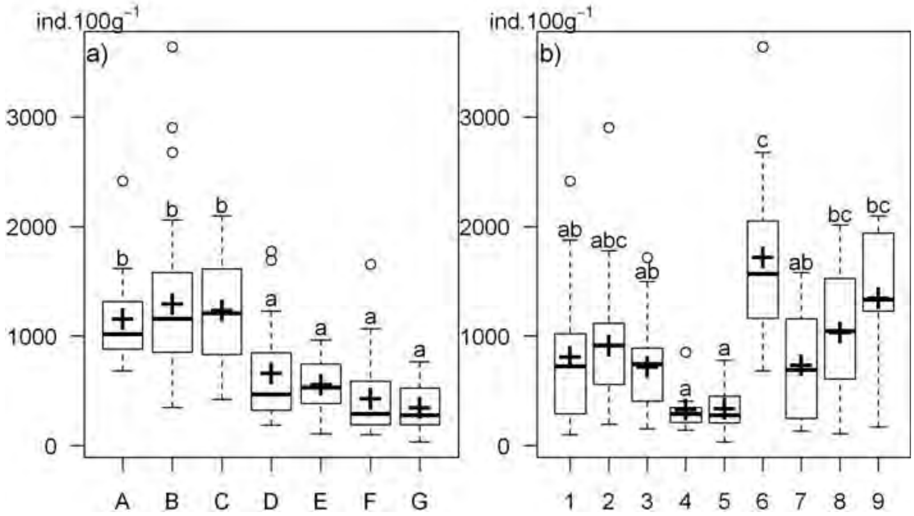


Figure III- 22: Density of total nematodes (ind. 100 g^{-1}) depending on (a) soil types A to G and (b) vineyard management systems 1 to 9

The total plant feeder density also fluctuated in a wide range from 6 to 2,666 ind. 100 g^{-1} (Figure III-23). The soil type and vineyard management system had significant effects on the density of these nematodes. Soils B and C, with a mean of 610 ind. 100 g^{-1}, had a significantly higher density than soils D, E, F and G (a mean of 147 ind. 100 g^{-1}). Soil A had significantly higher density than soils F and G. Vineyard management systems 4 and 5 had the lowest density of total plant feeders (71 and 106 ind. 100 g^{-1} respectively). These were significantly lower than for vineyard management systems 2, 6, 8 and 9. The highest density was measured for vineyard management system 6 (923 ind 100 g^{-1}) which was significantly higher than for vineyard management systems 1, 3, 4 and 5.

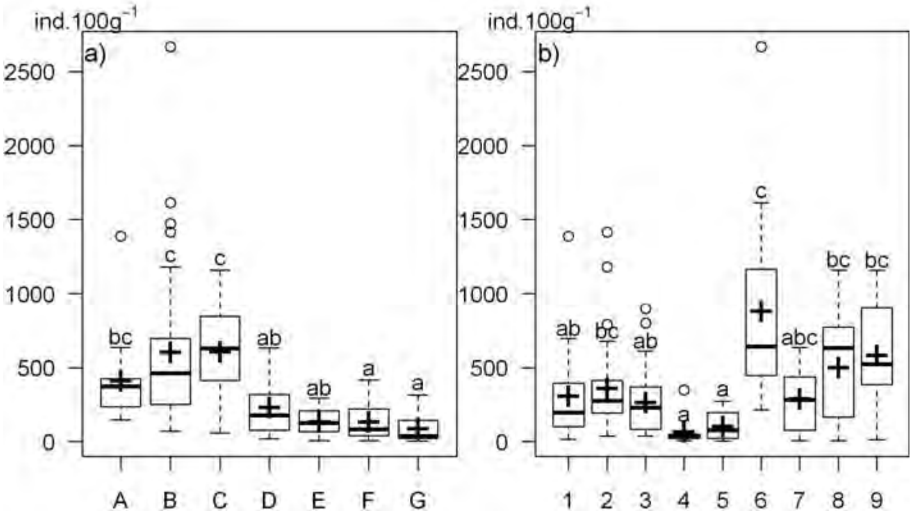


Figure III- 23 : : Density of total plant-feeding (TPF) nematodes (ind. 100 g^{-1}) depending on (a) soil types A to G and (b) vineyard management systems 1 to 9

The density of free-living nematodes was significantly affected by soil type, vineyard management system and the interaction between them (Figure III- 24). For soils, the lowest values were measured for soils F and G which were lower than the densities found in soil B. Free-living nematode density tended to vary with the vineyard management system. However, no significant differences between vineyard management systems were found within a soil type except for soil G where vineyard management system 1 had a significantly higher density (547 ind. 100 g^{-1}) than system 5 (145 ind. 100 g^{-1}).

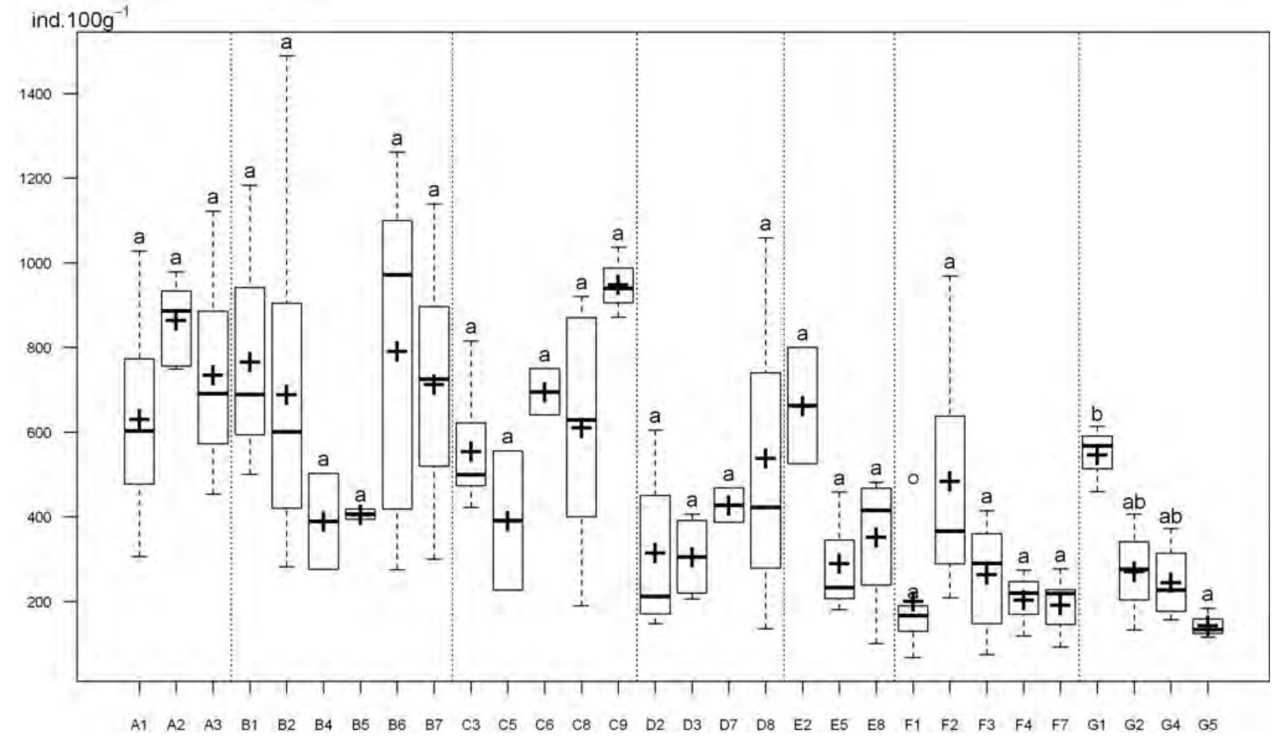


Figure III- 24: Density of total free-living nematodes (ind. 100 g^{-1}) for vineyard management systems (1 to 9) x soil type (A to G)

The density of obligate plant feeders varied from 0 to 2,268 ind. 100 g^{-1} (Figure III- 25). Soil type and vineyard management system had a significant effect. Soils A, B and C had significantly higher density of total plant feeders than soils D, E, F and G (mean of 313 versus 48 ind. 100 g^{-1}). For vineyard management systems, the lowest values were found for vineyard management systems 1, 4, 5 and 7 (mean of 87 ind. 100 g^{-1}) which were significantly lower than for vineyard management systems 2, 3, 6, 8 and 9. The highest mean density was found for vineyard management system 6 (588 ind. 100 g^{-1}) which was significantly higher than for vineyard management systems 1, 2, 3, 4, 5 and 7 (112 ind. 100 g^{-1}) (Figure III- 25).

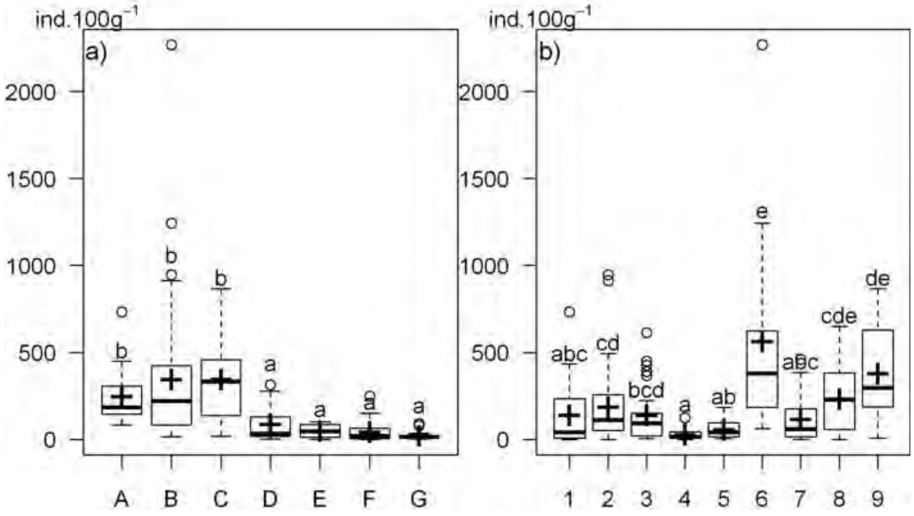


Figure III- 25: Density of obligate plant-feeding (OPF) nematodes (ind. 100 g^{-1}) depending on (a) soil types A to G and (b) vineyard management systems 1 to 9

The density of facultative plant feeders varied from 1 to 837 ind. 100 g^{-1} (Figure III- 26). The soil type had a significant effect on the density of facultative plant-feeders. There were 3 groups. The first, comprising soils B and C, had the highest densities (mean of 264 ind. 100 g^{-1}). This group was significantly different from soils E, F and G in the second group which had the lowest density (mean of 83 ind. 100 g^{-1}). The third group with soils A and D had intermediate densities (mean of 156 ind. 100 g^{-1}). For the vineyard management system, the density of facultative plant feeders was the lowest for vineyard management systems 4 and 5 (mean of 45 ind. 100 g^{-1}) which was significantly lower than for vineyard management systems 2, 6, 8 and 9. The highest density was measured for vineyard management system 6 (335 ind. 100 g^{-1}) which was significantly lower than for vineyard management systems 3, 4 and 5.

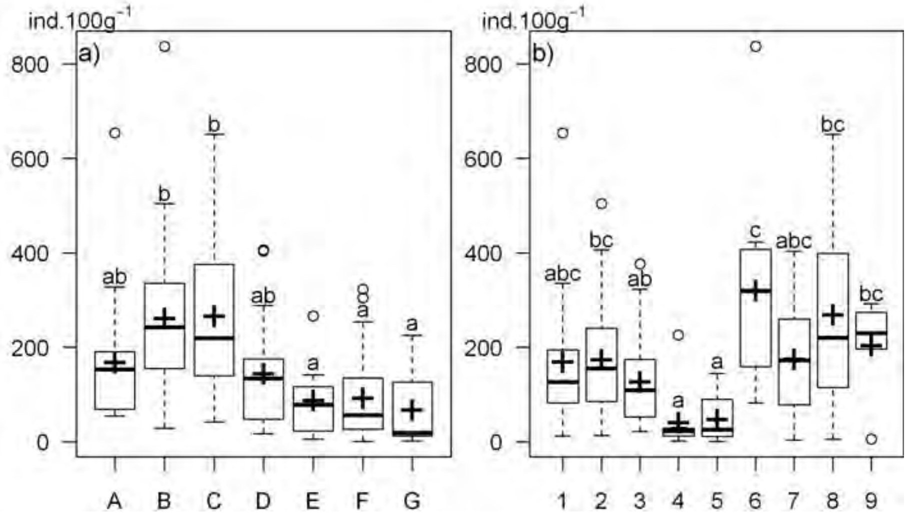


Figure III- 26: Density of facultative plant-feeding (FPF) nematodes (ind. 100 g^{-1}) depending on (a) soil types A to G and (b) vineyard management systems 1 to 9

For bacterial feeders, densities ranged from 17 to 874 ind. 100 g^{-1} (Figure III- 27). The soil type and vineyard management system had a significant effect on bacterial feeder density. Soils D, F and G had a lower density (139 ind. 100 g^{-1}) than soils B and C (mean of 303 ind. 100 g^{-1}) and soil A (476 ind. 100 g^{-1}). Soil E had a density of 183 ind. 100 g^{-1}, which was significantly different from soil C only. For vineyard management systems, bacterial-feeders had the lowest density for system 4 (90 ind. 100 g^{-1}). This density was significant lower than those of the vineyard management systems 6 and 9 (349 ind. 100 g^{-1}).

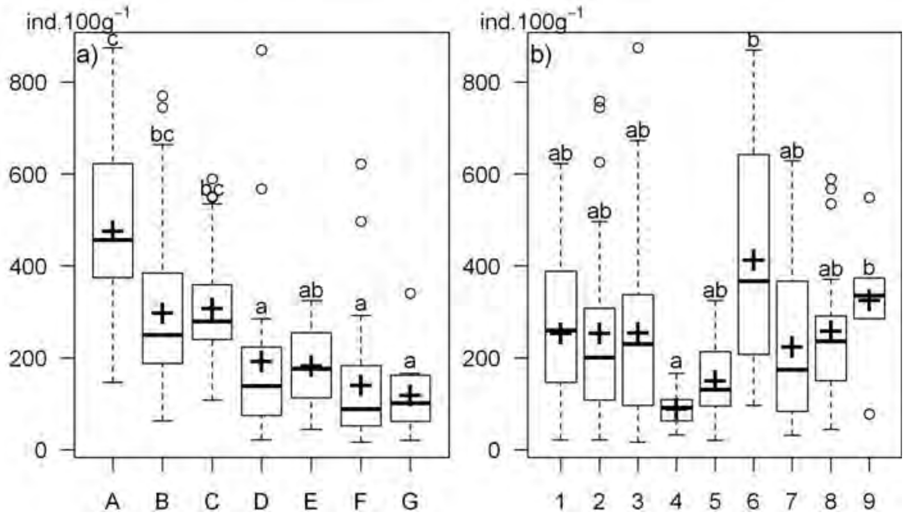


Figure III- 27 : : Density of bacterial-feeding (Ba) nematodes (ind. 100 g^{-1}) depending on (a) soil types A to G and (b) vineyard management systems 1 to 9

The density of fungal feeders varied from 26 to 644 ind. 100 g^{-1} (Figure III- 28). It was significantly influenced by soil type and vineyard management system. Soils D, F and G had a mean density of 144 ind. 100 g^{-1}, which was significantly lower than for soil B (309 ind. 100 g^{-1}). Soils A, C and E had intermediate values (188 ind. 100 g^{-1}). There was no significant difference between vineyard management systems 1, 2, 6, 7 and 9. Their mean density (263 ind. 100 g^{-1}) was significantly higher than for vineyard management system 5 (80 ind. 100 g^{-1}). Vineyard management systems 3, 4 and 8 had a mean density of fungal-feeders of 334 ind. 100 g^{-1}.

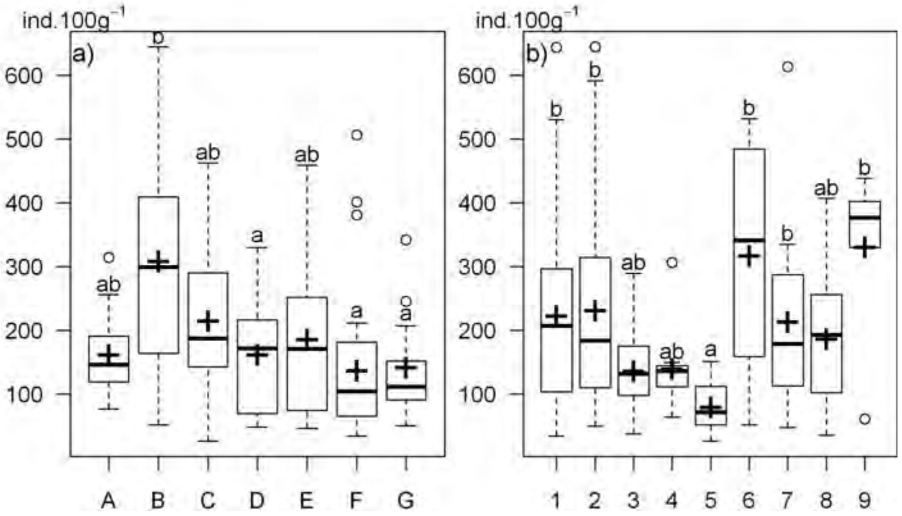


Figure III- 28 : : Density of fungal-feeding (Fu) nematodes (ind. 100 g^{-1}) depending on (a) soil types A to G and (b) vineyard management systems 1 to 9

Omnivore density was significantly affected by the interaction between soil type and vineyard management system (Figure III- 29). The vineyard management system had a significant effect only for soil F. Vineyard management system 2 (64 ind. 100 g^{-1}) had significantly higher omnivore density than vineyard management systems 1, 4 and 7 (12 ind. 100 g^{-1}).

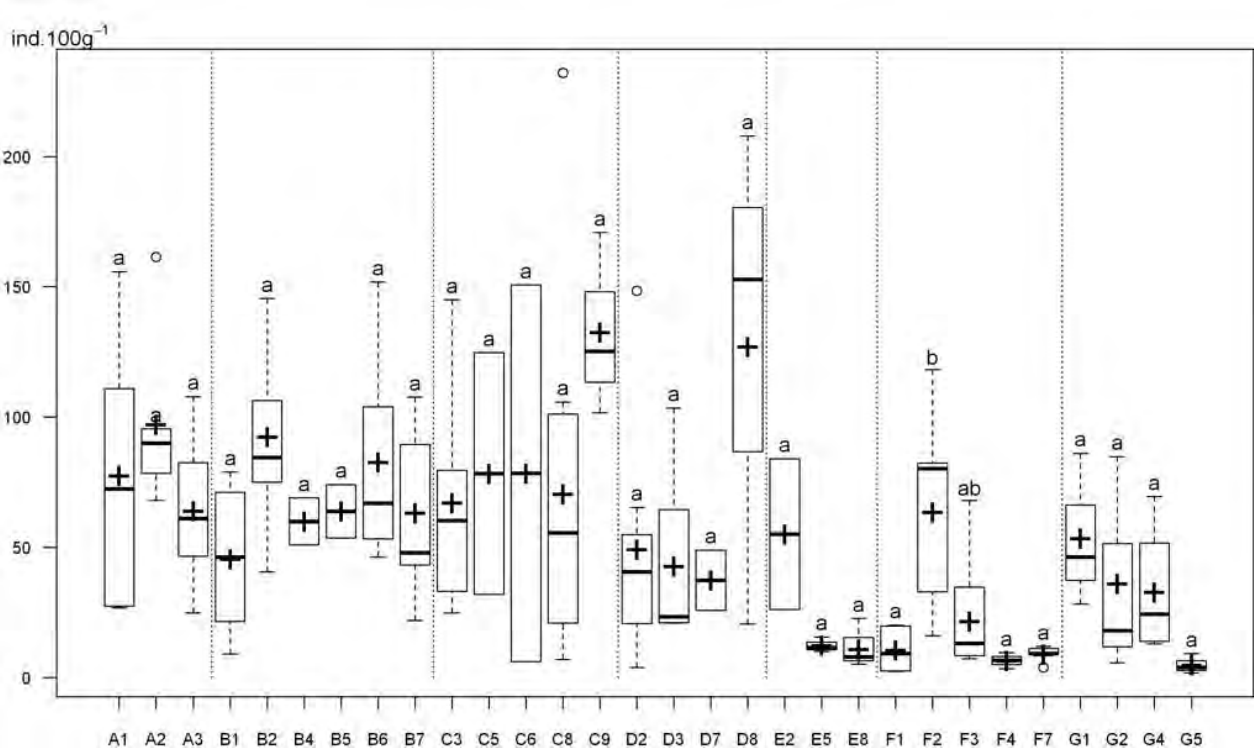


Figure III- 29: Density of omnivores (Om) (ind. 100 g^{-1}) in vineyard management systems (1 to 9) x soil type (A to G)

The density of predators ranged from 0 to 91 ind. 100 g^{-1} (Figure III- 30) and was affected only by soil type. Soils B and G (6 ind. 100 g^{-1}) had a significantly lower predator density than soils A, C and E (24 ind. 100 g^{-1}).

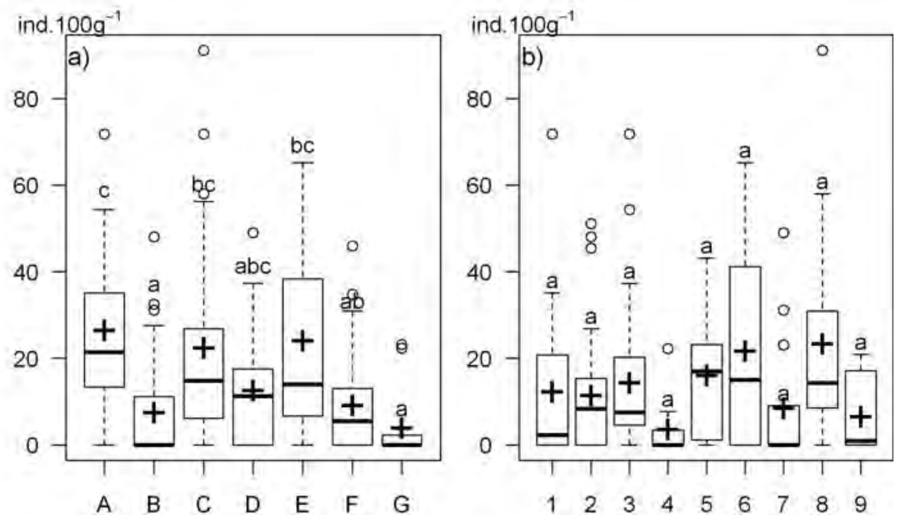


Figure III- 30 : : Density of predator (Pr) nematodes (ind. 100 g^{-1}) depending on (a) soil types A to G and (b) vineyard management systems 1 to 9

3.2.5. EFFECTS OF SOIL TYPE AND VINEYARD MANAGEMENT SYSTEM ON NEMATODE INDICES

Table III- 12 shows that MI, EI, SI and NCR were significantly affected by both soil type and vineyard management system and that their interaction had no significant effect at $p<0.05$. PPI and CI were significantly affected only by the soil type.

Table III- 12: Probability levels of the two-way ANOVA (soil type, vineyard management system and soil type x vineyard management) for nematode indices

Probability levels of the two-way ANOVA	MI	PPI	EI	SI	CI	NCR
Soil type	0.017	< 0.001	< 0.001	0.010	0.052	< 0.001
Vineyard management	0.011	0.056	0.011	0.008	0.083	0.002
Soil type x Vineyard management	0.153	0.195	0.062	0.099	0.490	0.596

MI varied from 1.8 to 3.6 and was significantly affected by soil type and vineyard management system (Figure III- 31). There was high variability of MI within soil D in comparison with the other soils, in particular, soil A. Soil C had the highest MI (2.6 in mean) which was significantly higher than the MI for soils A, B F and G (2.4, 2.3, 2.3 and 2.2, respectively). For the effect of vineyard management systems on MI, the highest value was calculated for soil A (2.6) which was significantly higher than for soils 1, 3, 4 and 7 (mean of 2.3).

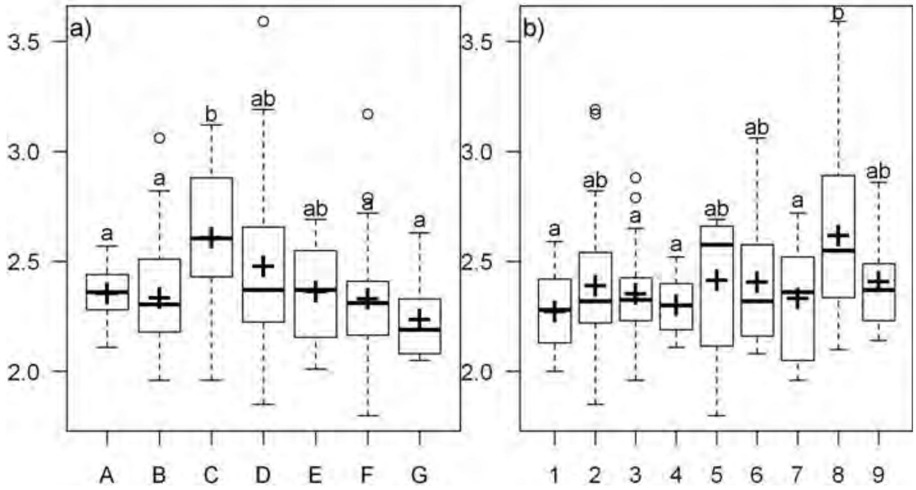


Figure III- 31: Maturity index (MI) depending on (a) soil types A to G and (b) vineyard management systems 1 to 9

PPI ranged from 2.0 to 3.0. Only the soil type had a significant effect on PPI (Figure III- 32). Soil A had the highest mean value (2.6) which was significantly higher than for all the other soils (mean of 2.3).

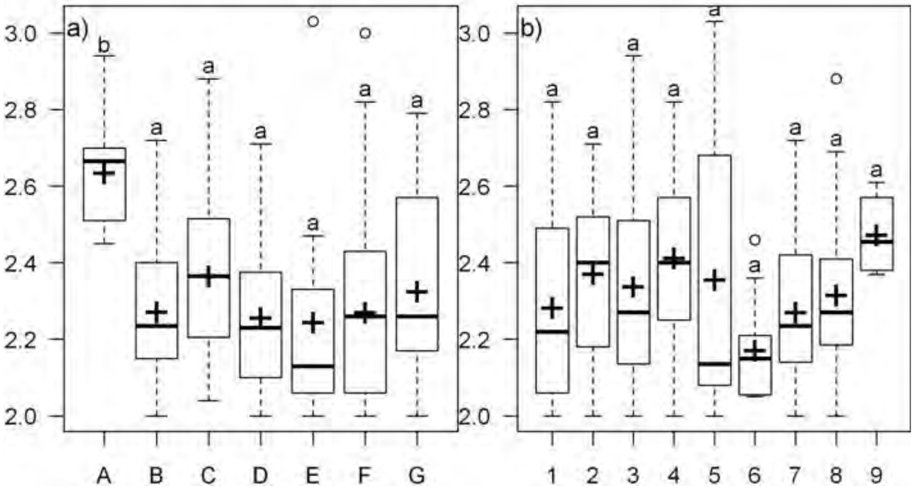


Figure III- 32: Plant-parasitic index (PPI) depending on (a) soil types A to G and (b) vineyard management systems 1 to 9

EI covered a wide range, from 6.3 to 76.0 (Figure III- 33). However, most plots had values between 30 and 50. EI was significantly affected by soil type and vineyard management system. It was significantly lower in soil A (29.6) than all the other soils which had a mean value of 41.8. Although the vineyard management system had an overall effect, a mean comparison test did not reveal any significant pairwise differences. However, EI tended to be higher for vineyard management systems 6 and 7 than for system 5.

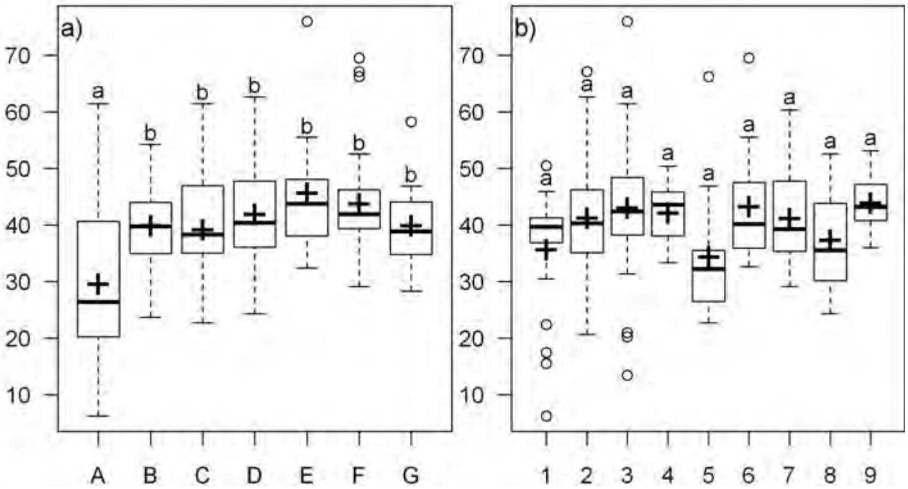


Figure III- 33: Enrichment index (EI) depending on (a) soil types A to G and (b) vineyard management systems 1 to 9

SI covered a wide, ranged from 5.9 to 88.7 (Figure III- 34). It was significantly affected by both soil type and vineyard management system. For soil types, the SI of soil C was significantly higher (64.6) than for soils B, F and G (42.6) which had the lowest values. For vineyard management systems, system 1 had a significantly lower SI (39.2) than system 8 (61.9).

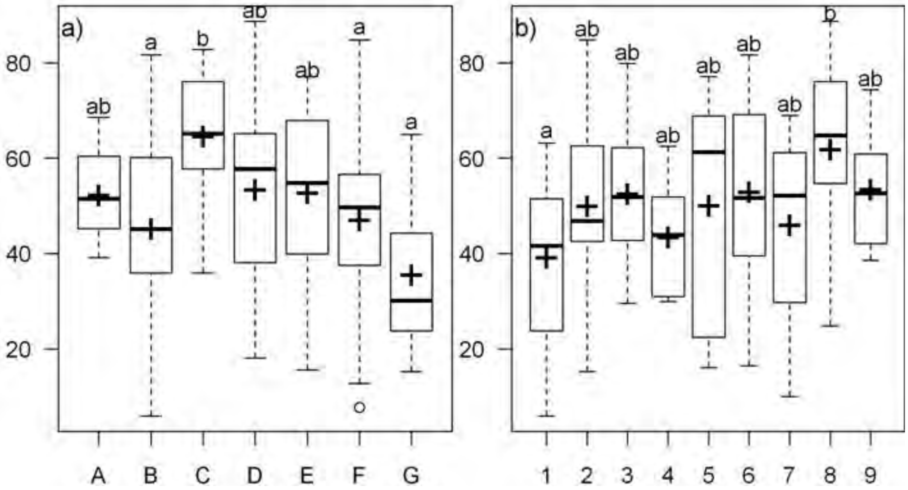


Figure III- 34: Structure index (SI) depending on (a) soil types A to G and (b) vineyard management systems 1 to 9

CI covered the full range from 0 to 100 (Figure III- 35). Only significant effects of soil type are shown. Soils B and G had significantly higher CI (84.7) than soil C (62.0).

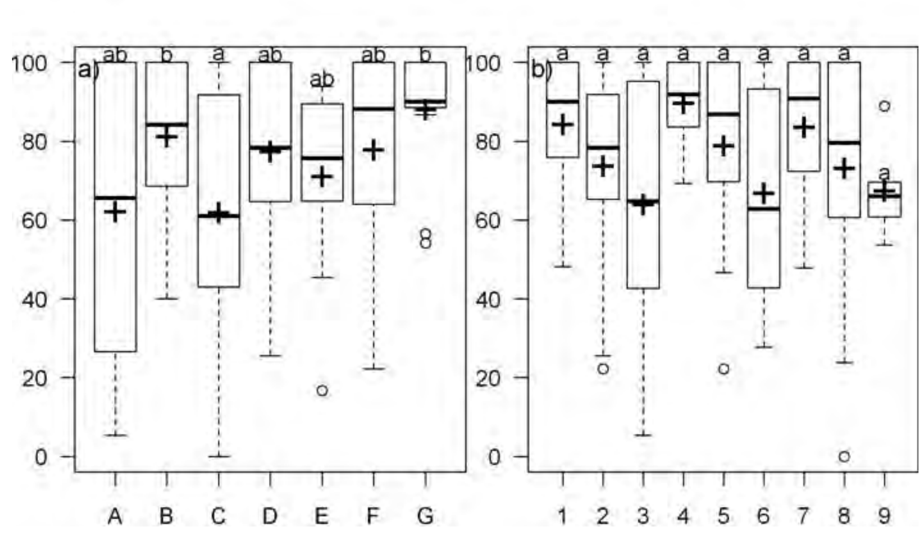


Figure III- 35: Channel index (CI) depending on (a) soil types A to G and (b) vineyard management systems 1 to 9

NCR covered nearly the whole range from 0.15 to 0.88 (Figure 38). Significant effects of soil type and vineyard management system were evident. Soils A and C had NCRs of 0.74 and 0.61, respectively which were significant higher than for soils B, D, F and G (mean of 0.47). The NCR of soil E (0.52) was significantly lower than for soil A only. Vineyard management systems 2 and 3 had very high variability while vineyard management systems 5 and 9 had low variability. The NCR for soil 4 was significantly lower than for soils 3 and 5 (mean of 0.39 versus 0.61).

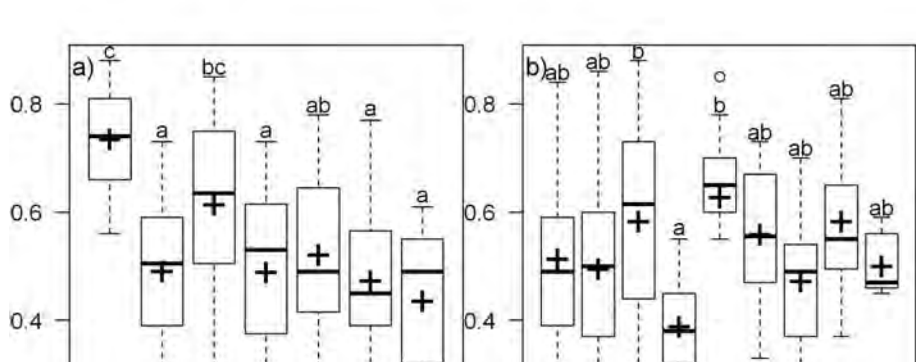


Figure III- 36: Nematode channel ratio (NCR) depending on (a) soil types A to G and (b) vineyard management systems 1 to 9

3.2.6. EFFECTS OF SOIL TYPES AND VINEYARD MANAGEMENTS ON EARTHWORMS

Table III- 13 showed that the density of anecic earthworms and the biomass of total and anecic earthworms were significantly affected by the type of grass cover management. Chemically weeded plots had the highest values whereas tilled plots had the lowest values. The results for permanent grass cover were intermediate. The density of anecic earthworms was 41.4 ind m^{-2} under chemical weeding, 12.6 ind m^{-2} under permanent grass cover and 1.6 ind m^{-2} under tillage (Figure III- 37). The biomass of total earthworms was 48.4 g m^{-2} under chemical weeding, 25.3 g m^{-2} under permanent grass cover and 2.2 g m^{-2} under tillage. The biomass of anecic earthworms was 42.7 ind m^{-2} under chemical weeding, 21.2 ind m^{-2} under permanent grass cover and 0.8 ind m^{-2} under tillage (Figure III-37)

Table III- 13: Probability levels of the two-way ANOVA (soil type, vineyard management system and soil type x vineyard management system) for earthworm ecological category density and biomass

Probability levels of the one-way ANOVA	**Juveniles** (%)	**Density** (ind. m^{-2})			**Biomass** (g m^{-2})		
		Endogeics	**Anecics**	**Total**	**Endogeics**	**Anecics**	**Total**
Vineyard management	0.285	0.374	0.043	0.166	0.348	0.039	0.031

4. DISCUSSION

4.1. VINEYARD MANAGEMENT SYSTEMS AND PHYSICAL INDICATORS OF SOIL QUALITY

The physical description of soils is an important feature of soil functioning because soil structure regulates water and soluble elements as nitrate and gaz transport but also penetration resistance to root development (Hakansson and Lipiec, 2000). In our study, we described the soil structure with different indicators. First, we measured bulk density and total porosity as indicators of soil compaction. Even if they are correlated to a lot of inherent soil properties, many authors used it to study the crop managements (Bouwman and Arts, 2000; Bulluck *et al.*, 2002b). Generally, the sandy soils presented lower density than clayey ones. However, in our study, we measured the lowest mean bulk density for the most clayey soil (B) soils whereas the soil G with more than 80% of sand presented the highest bulk density. The porosity results confirmed this trend in those two soils.

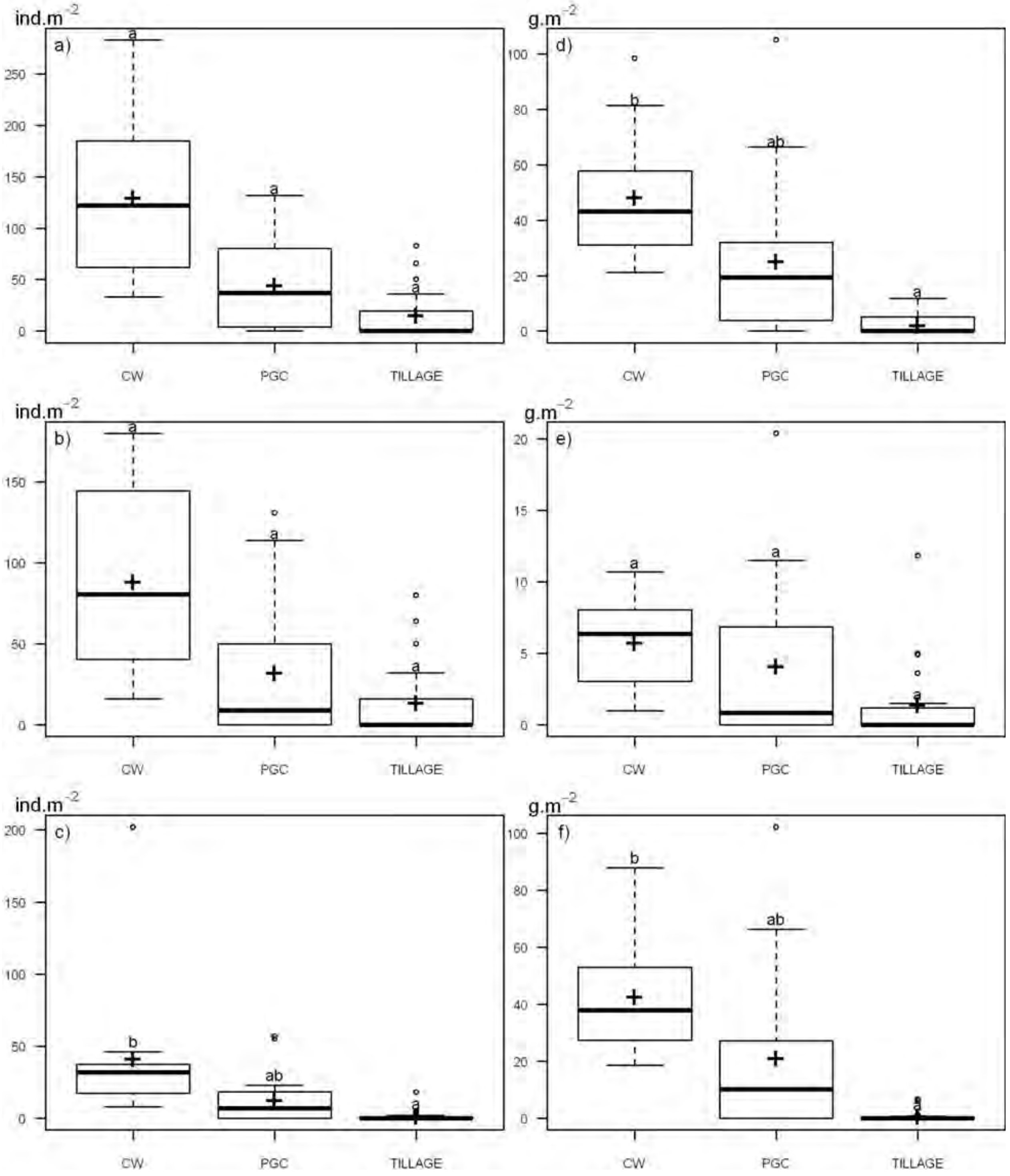


Figure III- 37: Density (ind. m^{-2}) of a) total, b) endogeic and c) anecic and biomass (g m^{-2}) of d) total, e) endogeic and f) anecic earthworms under chemical weeding (CW), permanent grass cover (PGC) and tillage (TILLAGE)

From our farmer's survey, we noticed that inside the class B, a lot of plots were recently tilled before soil sampling which can explained the lower bulk density observed in soil B. Lipiec et al. (2006) pointed out that the effect of one practice, the tillage, improve soil infiltration and water storage compared to no-till or reduced-tillage.Besides, if we considered all the vineyard management systems, we observed that whatever the type of soil, the plots with bare soil maintained by chemical weeding (vineyard management system 5) had the highest bulk density. Moreover, the earthworm sampling in Saint-Victor la Coste showed that biomass and density of earthworms was greater in permanent grass cover and chemical weeding than in tillage. According to Decaëns et al. (2001) and Capowiez et al. (2009), these soil organisms can increase the macroporosity which in turn decrease the bulk density. Thus, concerning the compaction, a vineyard management system including a high tractor traffic in the field should increase the bulk density even in sandy soils or where earthworm density and biomass are high. We can conclude from our results that the tillage is not the worse practice if isolated. Interestingly, we did not observe a net influence of organic fertilizers application although some authors pointed out its beneficial effects on bulk density (Bulluck *et al.*, 2002b; Celik *et al.*, 2010). Concerning the water holding capacity, we observed a net effect of soil type. Indeed, the lowest water holding capacity was observed for the sandiest soils (A and G). Interestingly, we showed that the vineyard management systems for the latter soils affected the water holding capacity. Precisely, the soil G exhibited a low TOC content but an application of organic matter (vineyard management system 2) have increased the WHC as shown by several authors (Jones *et al.*, 2010; Teixeira *et al.*, 2011). Explanation of the effects of vineyard management system 1 on soil A is less obvious. Indeed, we can only hypothesize that because of a greater TOC content of these plots, the organic matter application induces less effects. One should note that the vineyard management system 1 is characterized by mechanical weeding and with a grass cover of 4-8 months. Those two agricultural practices can increase the organic matter status of soils. From our results we can state that the water holding capacity is a sensitive indicator but only for the sandy soils. The aggregate stability is another physical indicator of soil quality because it provides information about the infiltrability of water in the soil and the erodibility of Mediterranean vineyard soils (Le Bissonnais *et al.*, 2007). However, in our case, both soil types and vineyard practices have an effect with significant interaction. The aggregation process is controlled by different mechanisms according to soil types. The soil texture, CEC, pH, calcareous content influenced the aggregation process. Moreover, the soil carbon is considered as an aggregation factors. Inside soil class B and D, the vineyard management systems 1, 2, 3 and 4 can influence the aggregate stability. However, any obvious trend can be identified among practices defining the vineyard management system above mentioned. For, these reasons, we cannot recommend the aggregate stability as a sensitive indicator of soil dynamic quality in our case.

4.2. VINEYARD MANAGEMENT SYSTEMS AND CHEMICAL INDICATORS OF SOIL QUALITY

The maintenance or the increase of soil organic matter is relevant in sustainable agriculture (Eswaran *et al.*, 1993) because soil organic matter is involved in many processes. One should note that all sampled plots have a very low TOC as measured by Jones et al. (2005) and Sanchez-Maranon et al. (2002). Whatever the vineyard management system, we observed the lowest organic matter content under soil types A, F and G corresponding to sandy soils. From our farmer's survey, we analyzed that the application of compost can increase the total organic content for the sandy soil G. Furthermore, for the soil G nearly all winegrowers using management 1, 4 and 5 burned vine-pruning outside the plots instead crushed them and restitute into the soils, so these practices led to any increase of soil organic matter. The grass cover which were permanent (vineyard management system 6) or temporary managed by chemical weeding (vineyard management system 8) tended to increase organic matter content in the soils B, C, D and E as indicated by Potthoff et al. (2006) and Morlat and Jacquet (2003). However we could hypothesize that the soils where permanent grass cover was implanted was initially rich in organic matter. Indeed, in Mediterranean vineyards, winegrowers keep permanent grass cover when vines are too vigorous. The soil organic matter can greatly influence the CEC (Bulluck *et al.*, 2002b). However, the highest CEC was for the most clayey soils (B and D) and the lowest for the sandiest soils (A and G) although TOC contents in these soils were nearly similar. More details on the type of exogenous organic matter which were applied are necessary to analyze the absence of effects of application (vineyard management systems 2 and 3). One should note that for soil A and G have very low CEC < 5 $\text{cmol}^+ \text{kg}^{-1}$. As a consequence, application of soluble fertilizers can be harmful for the environment and non efficient for vines because cations are not retained. About the C/N ratio, we observed a net effect of soil types especially for the soil A corresponding to the sandiest soil. In this area, winegrowers had to sow, every year, a dense annual grass cover with different type of plants to protect soil to wind erosion during the winter. The C/N ratio could have been influenced by the different plant sowed after decomposition (Abiven and Recous, 2007). In the same idea, the highest C/N was measured under permanent grass cover. The main macroelements absorbed by plants are N, P and K. As TOC, the total N content (organic and inorganic) was both influenced by soil types and vineyard management systems. In soil G (sandy and acid), only vineyard management system 2 can improve the total N content. The N cycle in vineyard is not well documented. However, as pointed out by Steenwerth and Belina (2008) and later by Garland et al. (2011), the vineyard management systems can have major impacts on seasonal N_2O emissions. As vineyard represents a large proportion of agricultural lands in Languedoc Roussillon, we suggest that our analysis of the vineyard management system on total soil nitrogen can contribute to improve the models or inventories of greenhouse gases. The phosphorus is involved in plant vegetative growth, number of clusters per vine stock and sugar content (Coga *et al.*, 2008). In our study, any effect of vineyard management system was observed. However, strong effects of the calcareous content were observed. Indeed, the lowest values were observed under the soils with the highest calcareous contents and the opposite. Some authors as Lindsay et al. (1989) showed that P precipitated in presence of calcareous and then became insoluble. Other chemical processes related to soil mineralogy can also explain the results observed in soil class A, B, C and D as studied by Devau et al. (2009). The potassium is always a very important nutriment for vine regulation of water stress (Manning, 2010). In our study, the potassium content was affected by the vineyard management system. Permanent grass cover presented the highest content of K.

Our results about Cu were comparable to other studies led in vineyards. We observed a significant effect of soil type on Cu content. We showed that the lowest value was for very sandy soils with low pH (soils F and G), and the highest in clayey soils with high pH. The TOC content was not very different among soil types, we suggested then that the Cu should be associated with clay only when pH is high as showed by (Michaud *et al.*, 2007). According to vineyard management systems, the permanent grass cover (vineyard management system 6) tended to increased Cu content in soils. Here, we hypothesized two effects of grass cover on Cu contents. First the grass cover increased the organic matter content at the soil surface and then promotes the retention of Cu. Indeed, Brun et al. (2001) showed that Cu accumulates in the upper layers of soils. Secondly, the grass cover limited the Cu-contaminated vine leaves in autumn increasing so the quantity of Cu in soils after leave decomposition. However, more fungicides were applied on plots with permanent grass cover because this vineyard management system was used under very vigorous vineyard, leading to a favorable microclimate to the development of cryptogamic diseases as Downy Mildew (*Plasmopara viticola*). To fight against this pest, fungicides were used more frequently (Michaud *et al.*, 2007). At the opposite the low content of soil organic matter at soil surface in bare soils (vineyard management system 4, 5 and 7) could explain why Cu contents are so low. For tilled soils corresponding to vineyard management systems 1, 2 and 9), Cu content was not very high so we suggest a dilution trough the upper soil layers. We needed to precise that we measured copper on a water extract. This methodological point is important because Michaud et al. (2007) showed that in calcareous soils contaminated by Cu fungicides, water-extractable Cu varied little, compared to total soil Cu, or EDTA-extractable C.

4.3. VINEYARD MANAGEMENT SYSTEMS AND BIOLOGICAL INDICATORS OF SOIL QUALITY

Globally, the microbial biomass (MB) was low under the vineyards and comparable to the value obtained by Dequiedt et al. (2011) studying vineyards. Over the 5 measurements on the microbial compartment (MB, CO_2, *qCO_2*, MB/TOC, CO_2/TOC), the ratio MB/TOC was the most efficient to discriminate the effects of the vineyard management systems whatever the soil type. For microbial biomass, we observed globally an effect of soil types. The trends for MB were nearly the same that for TOC content. Indeed, several authors showed a good correlation between TOC and MB. In other hand, the lowest microbial biomass was measured under sandy soils (A, F and G) whereas the highest was for the most clayey soil (B).

Whatever the soil type and the viticultural management considered, nematological indices revealed that vineyard soils were generally poor in available resources (EI varied mainly from 35 to 45), perturbed and with a low structured food-web (for the majority of plots, SI was comprised between 40 and 60). The MI was in accordance with other results on vineyards (Coll *et al.*, 2011; Manachini, 2001). Globally, nematodes were more abundant under calcareous soils than under non-calcareous soil; this was particularly true for bacterial-feeders. Predators were less abundant under clayey soil (soil B) than under sandy soils. The earthworm community was characterized under the soil C, in Saint-Victor la Coste. High difference between vineyard management systems were measured, the highest density and biomass of anecics were found under bare soil with chemical weeding than under bare soil with tillage. Intermediate values were found for temporary grass cover.

The vineyard management systems leading to bare soil during all the year presented the more marked negative effects on the density of nematodes belonging to most of the trophic groups and on the MB/TOC. This was true above all for the management systems with chemical weeding (5) and with tillage without organic fertilizers (4). Indeed, these 2 vineyard management systems presented globally the lowest density of total nematodes, total plant-feeders, total free-living nematodes, obligate and facultative plant-feeders, bacterial-feeders, fungal-feeders and omnivores. The lowest plant-feeders density indicated that the weed control was very efficient for these two vineyard management systems. From these results, we saw clearly that the biological activity was very low when soil was bare. Herbicide effects of soil fauna were difficult to identify. We can hypothesize that it could be a toxicity effect or an absence of grass cover effect to explain such results. Indirect effects linked to the disappearance of the rhizosphere were often shown (Bengtsson *et al.*, 2005; Bunemann *et al.*, 2006). The detrimental effect of soil tillage has already been shown by some authors (Coll *et al.*, 2011; Villenave *et al.*, 2009a). Usually when direct sowing replaces tillage, control of weeds is realized by applications of herbicide which do not affect soil organisms as much as tillage. The low density of microbivorous nematodes (bacterial-feeders and fungal-feeders) measured for these vineyard management systems (4 and 5) had to be related to the low microbial compartment measured by the microbial biomass/total organic carbon. These indicators (soil nematofauna and microbial compartment) are concordant. Furthermore, soils were compacted with these vineyard management systems and Bouwman and Arts (2000) highlighted the negative effect of soil compaction on some nematode trophic groups, such as the bacterial-feeders and the omnivores; such negative effects of soil compaction on soil microorganisms have also been observed (Bouwman and Arts, 2000). MI and SI were lower for the bare soils with tillage than for those of the chemical weeding, the soil food web was shorter and less structured under tilled soils. Physical perturbations due to tillage have more negative effects on sensitive nematodes belonging to the colonizer-persistent class of 4 and 5 than other viticultural practices used to control grass cover (chemical weeding particularly). So, for bare soil, the chemical weeding was less detrimental to sensitive nematodes than tillage. Maybe, the absence of physical perturbations, as tillage, for chemical weeding appeared as a positive effect.

The same results are obtained for anecic earthworms in Saint-Victor la Coste which are drastically reduced by tillage whereas bare soil and chemical weeding appear to be the most favorable situation for earthworms. Under annual crops same results on persistent nematodes and earthworm have been measured by (Djibril *et al.*, 2011) when comparing tillage to direct seeding with chemical weeding of the plant cover. The Enrichment Index (EI) showed a richer environment with more available resources under tilled soils. Maybe the soil aeration due to tillage increased the mineralization of organic matter as we can see the increase trend of the CO_2/TOC ratio for the vineyard management system 5. These two vineyard management systems led to different bacteria/fungi ratio. Indeed, the NCR was the lowest for the vineyard management system 4 whereas it was the highest for the vineyard management system 5. So, for the vineyard management system 4, the decomposition pathway was more fungal than for the vineyard management system 5. Tillage should be more detrimental to fungus than chemical weeding.

For the vineyard management system 7, characterized by bare soil, both tillage and chemical weeding and apply of organic matter had biological parameters indicating a higher soil biological activity (MB/TOC, emitted CO_2 and densities of most trophic group higher than in vineyard management system 4 and vineyard management system 5 except for the predators). The higher density of plant-feeders for the vineyard management system 7 in comparison with those than vineyard management system 4 and vineyard management system 5 seemed to indicate a more important rhizosphere activity and a lower control of weed through the year. Concerning the nematological indices, they presented intermediate results for vineyard management system 7 in comparison with the vineyard management systems 4 and 5, as if this vineyard management system with apply of organic matter compensated a little the physical perturbations due to tillage.

Two vineyard management systems presented approximately the same trends in nematode density and community structure: vineyard management system 6 with permanent grass cover and use of non-organic compost too and vineyard management system 8 characterized by temporary grass cover managed with chemical weeding and application of non-organic compost. They presented high soil nematode activity in comparison with other vineyard management systems. Indeed, vineyard management system 6 had the highest nematode density for most of the trophic groups and MB/TOC (even if non significant) and vineyard management system 8 had high density of total nematodes, plant-feeders, predators and medium density of bacterial-feeders, fungal-feeders and omnivores. No physical perturbation, due to tillage and correct rhizospheric activity explain these good results. Even if vineyard management system 6 presented higher nematode activity than vineyard management system 8, it was vineyard management system 8 which presented the more structured and more complex soil micro-food web with the highest MI and SI. We hypothesized that one herbicide application per year was less perturbing for nematode communities than the 3-4 passes to mow grass. Manachini (2001) found also no effect of glyphosate on soil nematode density in an American vineyard. Bare soils with chemical weeding constituted bad environment for the development of microorganisms; on the contrary, the stimulation effects of root-exudates on the microbial growth (Bouwman and Arts, 2000; Whitelaw-Weckert *et al.*, 2007) attributed to the grass cover can explain the high microbial activity under vineyard management system 6. Concerning the availability in resources, the vineyard management system 6 presented the most enriched environment with the highest EI (even if not significantly different). The same values of NCR (a mean of 0.56) for these two vineyard management systems showed a pathway decomposition relatively equilibrate between fungi and bacteria. A particularity for vineyard management system 6 had to be mentioned: the PPI that is the lowest (even if difference not significant). This result meant that the upper layers of the soil functioned as a meadow in this system. It was not the case for the vineyard management system 8 because grass cover was destroyed each year. The total plant-feeders (923 ind. 100 g^{-1}, data not shown) under this vineyard management system were dominated by *Paratylenchus sp.* (470 ind. 100 g^{-1}, data not shown) and Tylenchidae (335 ind. 100 g^{-1}, data not shown) as it is often the case under meadows (Villenave *et al.*, in press). As these nematodes are belonging to the colonizer-persistent class 2, they led to a low PPI.

To finish, we compared the vineyard management systems 1, 2, 3 and 9, all characterized by mechanical weeding and temporary grass cover. They presented intermediate values for the microbiological and nematological parameters as well as earthworm parameters. It is not easy to distinguish between them those with use of non-synthetic and synthetic and those with fertilization type: only organic and other fertilization. The vineyard management systems 2 and 3 with application of organic matter did not have very specific characteristics. The quantity of organic matter applied is maybe too low to significantly affect the biological component of the soil. However, vineyard management system 2 presented a lot of omnivores for the soils A, B, E and F in comparison with the other vineyard management systems. Among the four vineyard management systems 1, 2, 3 and 9 (only 6 plots, for 9), the 9 presented higher density of total nematodes, total plant-feeders, total free-living nematodes (for the class C only), obligate plant-feeders, fungal-feeders, omnivores (for the class C only). Concerning nematological indices, the same MI and EI were calculated. The only differences were for the vineyard management system 1, with a lower SI and for the vineyard management system 3 with a higher NCR.

Other agricultural practices are known to influence microbial biomass. Normally, apply of organic fertilizers increases microbial biomass (Briar *et al.*, 2007; Vestberg *et al.*, 2009) and fungicide treatments containing copper presented negative effects on microbial biomass (Diaz-Ravina *et al.*, 2007; Marzaioli *et al.*, 2010a). However, we did not find these trends in our study. No positive effect of vineyard management systems with organic fertilizers (2, 3 and 7) on microbial biomass was observed. And yet, the highest MB was measured on soils with the highest Cu content.

As a conclusion, we obtained a unique dataset which compare the different vineyard management on the dynamic soil quality. We identified several indicators as bulk density, and nematodes indices and earthworms and in lesser extent chemical parameters sensitive to describe the effects of soil managements.

CHAPTER IV

ORGANIC VITICULTURE & SOIL QUALITY

More and more winegrowers decide to convert their vineyard from conventional to organic viticulture. As a consequence, major modifications of practices, such as the substitution of mineral fertilizers by organic ones, can drastically modify soil quality. Thus, I aimed to monitor the rate of such changes on soil quality. For this reason, I decided to study the long-term modification of soil quality after conversion into organic viticulture. This following chapter is divided in two sub-chapters. First, I present an overview of soil quality after the organic conversion at different times (0, 7, 11 and 17 years after conversion), based on the combination of physical, chemical and biological indicators. Second, I focus on the effects of the organic farming on nematode communities.

CHAPTER IV-1:

ORGANIC VITICULTURE AND SOIL QUALITY: A LONG-TERM STUDY IN SOUTHERN FRANCE

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2011, *Applied Soil Ecology,* Accepted.

Abstract: The rate of conversion of conventional vineyards into organic farming is currently increasing. This results in modifications of agricultural practices such as the application of organic manure, the use of tillage or grass-cutting to control weeds and the application of natural pesticides with preventive action. One of the aims of organic farming is to preserve the environment. In this context, the objective of our work was to evaluate the long-term effects of organic viticulture on soil quality. The study was conducted in a commercial vineyard where plots which had been organically managed for 7 (Organic7), 11 (Organic11) and 17 years (Organic17) were compared to conventionally managed plots (Conventional). Soil physical and chemical parameters (bulk density, organic matter, available phosphorus, potassium and copper contents) and biological parameters (soil microbial biomass, density of nematode trophic groups and density and biomass of earthworm ecological categories) were measured. The organic farming led to an increase in soil organic matter, potassium content, soil microbial biomass, plant-feeding and fungal-feeding nematode densities. However, organic farming increased soil compaction, decreased endogeic earthworm density and did not modify the soil micro-food web evaluated by nematofauna analysis. Our study highlights the difficulty to show the benefits of organic farming on global soil quality in this particular pedoclimatic area and set of farming practices.

Key words: conventional viticulture, bioindicators, organic matter, microbial biomass, nematodes, earthworms.

1. INTRODUCTION

Food and beverage safety issues, environmental considerations, but also economic interests are prompting more and more winegrowers to convert conventionally managed vineyards into organic farming. From 2001 to 2008, the area of organically managed French vineyards increased by 110% : 13426 ha in 2001 (AgenceBIO, 2002) and 28190 ha in 2008 (Agence BIO, 2009). Conventional viticulture uses agrochemicals such as manufactured inorganic fertilizers and synthetic chemical pesticides. In contrast, these are banned in organic farming, while only organic fertilizers, crushed rocks and a few non synthetic pesticides are allowed (Briar *et al.*, 2007). Instead of applying herbicides, weeds are managed by tillage or grass-cutting in organic farming. As a consequence, organic farming claims to reduce disturbance intensity of agricultural practices on the environment (Reganold *et al.*, 1987), and especially on soil. Indeed, soil is a non-renewable resource and most vineyard soils are considered as highly degraded in terms of loss of organic carbon as a result increasing erosion and diminution of nutrient contents (Le Bissonnais *et al.*, 2007; Martinez-Casasnovas and Ramos, 2009), accumulation of metals and organic pollutants (Chaignon *et al.*, 2003; Komarek *et al.*, 2010) or compaction due to tractor traffics (Coulouma *et al.*, 2006). One of the main objectives of organic farming is to give more importance to soil biological functioning in order to improve its physical (affecting the circulation of water, aeration), chemical (affecting the availability of nutrients) and biological (affecting the biodiversity and fate of organic matter) properties (Van Bruggen and Semenov, 2000). Furthermore, in wine production, the soil is considered, together with climate, as a key component of Terroir (Van Leeuwen *et al.*, 2004) which can influence the wine quality (Van Leeuwen and Seguin, 2006).

As defined by Doran and Parkin (1994) “the soil quality is the ability of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health”. Soil quality is generally evaluated by the interpretation of physical, chemical or biological indicators. Among physical and chemical indicators, those most used by winegrowers are soil bulk density, pH, availability of major nutrients (N, P, K, Ca, Mg), organic matter content which is known to increase soil water holding capacity (Teixeira *et al.*, 2011), to promote soil aggregation (Le Bissonnais *et al.*, 2007; Morlat and Chaussod, 2008) and to constitute a pool of available nutrients (Haynes, 1999). Biological indicators or bioindicators are considered to give an evaluation of soil functioning because soil organisms have intimate relationships with their surroundings (Franzle, 2006), and then can give information about soil degration or improvement (Bispo *et al.*, 2011). The most widely studied are microorganisms and soil fauna (Bispo *et al.*, 2011; Huber *et al.*, 2008). Microorganisms are involved in different key processes in the ecosystems, such as the decomposition of organic matter, humus formation, soil aggregation, retention and cycling of nutrients, and various symbiotic and parasitic relationships with plants (Paul and Clark, 1996). Other useful bioindicators are nematodes and earthworms. To evaluate the soil food web, the soil nematodes are pertinent bioindicators because they present an important diversity of trophic groups such as plant-feeders, bacterial-feeders, fungal-feeders, omnivores and predators (Villenave *et al.*, 2004; Yeates *et al.*, 1993). Indeed, they are implicated in soil organic matter mineralization processes (Neher, 2001). In addition, they are ubiquitous and thus present in all pedo-climatic situations including habitats that vary from pristine to extremely degraded (Bongers and Ferris, 1999). Other representatives of soil fauna are earthworms. They are described as bioindicators of soil quality as they modify soil physical properties. In particular they maintain soil structure and modify soil hydrodynamic functioning (Eijsackers *et al.*, 2005). They provide additional information about the fate of organic matter. As a consequence both nematodes and earthworms give different and therefore complementary data on soil functioning.

Several authors compared vineyard soil characteristics after inorganic and organic fertilizer application (Bustamante *et al.*, 2011; Morlat and Chaussod, 2008) and under different grass management practices (Monteiro and Lopes, 2007; Smith *et al.*, 2008; Steenwerth and Belina, 2008). Until now, scientific knowledge concerning the effects of organic viticulture on soil functioning is scarce, except the studies of Reeve et al. (2005), Probst et al. (2008) and Reinecke et al. (2008). There is thus a great need to evaluate if soil quality is altered by changing practices during the conversion of vineyards into organic farming. Former studies have focused on earthworms and microbial biomass (Ingels *et al.*, 2005; Reuter and Kubiak, 2003; Whitelaw-Weckert *et al.*, 2007), but fewer studies were conducted on nematodes as bioindicators of vineyard soil quality (Rahman *et al.*, 2009; Sanchez-Moreno and Ferris, 2007). To our knowledge, none of this research combined several physical, chemical and biological indicators to give a complete overview of soil quality of vineyards.

In this work, we measured the long-term effects of organic viticulture by physical and chemical indicators (organic matter content, availability of major nutrients and contaminant (Cu), bulk density) as well as by bioindicators (microbial biomass, nematodes and earthworms). With our methodology, we can then evaluate if intensive practices denoted as conventional are more damaging to soil quality and biological functions than are arguably organic practices. The present study was conducted on 24 vineyard plots: 10 were conventionally managed, while the others had different ages of conversion into organic farming (7, 11 and 17 years).

2. MATERIAL AND METHODS

2.1. SITE DESCRIPTION, MANAGEMENT AND FIELD PLOT DESIGN

This study was conducted in May 2009 in Cruscades, which is located in the South of France, in the Languedoc-Roussillon region (43°11'29.13"N, 2°49'1.78"E; 26 - 50 m elevation). The climate is typically Mediterranean with 14.7 °C mean annual temperature, 600 mm of annual rainfall and 1380 mm of annual ETP Penman-Monteith (average value based on data collected from 2000 to 2010 by Météo-France). The plots did not present any slope. The soil was silty-clay, with 42 ± 2% of silt, 36 ± 1% of clay and 22 ± 2% of sand. It was calcareous (208 ± 7 g of total CaCO3 kg^{-1}), yielding a pH in water of 8.3. The soil water-holding capacity was 20.6 ± 0.5% (w/w).

The study was conducted on 24 commercial wine grape vineyard plots whose mean area was around 1.5 ha. They presented different varieties of grape (*Vitis vinifera* L.) such as Cabernet-Sauvignon, Carignan N, Chardonnay, Cinsault, Grenache N, Merlot, Mourvèdre, Pinot N and Syrah. The rootstocks were mainly R110 and R140, but Riparia and 410a were also present. The year of plantation varied from 1932 to 2003. The plantation density was comprised between 3300 and 5000 vines per hectare. Ten plots were managed according to conventional farming (Conventional) and the others according to organic farming (Organic). Five plots have been organically managed since September 2001, officially certified in 2004 (Organic7). Four plots have been organically managed since September 1997 (Organic11) and the last 5 plots since September 1991 (Organic17). These 4 sets of plots will be referred to as treatments here below. Conventional agricultural practices were identical for each treatment before the organic conversion as well as organic agricultural practices after the conversion (Table IV- 1). Four representative subplots (5 vines x 4 inter-rows) per plot were sampled. Consequently, 96 subplots were studied.

Table IV- 1 : Agricultural practices in conventional farming and organic farming.

	Soil management		**Fertilisation** (N-P-K)	**Vine phytosanitary protection**	**Tractor frequency per year** (year^{-1})
	Rows	**Inter-rows**			
Conventional	Chemical weeding (glyphosate, 700 g ha^{-1}, 1 year^{-1})	Tillage with tined tools (15 cm depth, 2 year^{-1})	Mineral (10-10-20, 200 kg ha^{-1}, 1 year^{-1})	Synthesis and natural (6 treatments year^{-1})	14
Organic	Tillage (10 cm of depth, 1 year^{-1})	Mouldboard ploughing (25 cm depth, 4 year^{-1})	Compost (90% of OM; 9-5-0, 500 kg ha^{-1}, 1 year^{-1})	Natural (8 treatments year^{-1})	18

2.2. SAMPLING PROCEDURE

The sampling was conducted in springtime, a few days after mild raining events and could be considered to occur within the same time frame (from 4th to 15th May for earthworms and from 22nd to 28th May 2009 for soil). The soil water content was 14.7 ± 0.3% (w/w) for earthworm sampling and 11.2 ± 0.2% (w/w) for soil sampling. Soil and earthworms were sampled in the 0-15 cm topsoil in the center of the inter-row. There were one soil and one earthworm sample per subplot. Each soil sample consisted of a composite of four subsamples, one per inter-row, taken with a gouge auger. Soil used to measure bulk density was sampled according to the cylinder method. Soil samples were sieved at 1 cm before biological analyzes and at 2 mm before physical and chemical analyzes. To sample earthworms, a monolith of soil of 45 cm x 45 cm on 15 cm depth was extracted per subplot. Earthworms were sampled by the hand-sorting method and placed in alcohol solution at 75%, then transferred into a 4% formaldehyde solution to be stored.

2.3. PHYSICAL AND CHEMICAL ANALYZES

Soil used to measure bulk density was dried at 105 °C for 1 week and weighed rapidly thereafter (NF ISO 11272, 1998). Total organic carbon (TOC) and total nitrogen (N) contents were measured by dry combustion according to the NF ISO 10694 (1995) norm for TOC and the ISO 13878 (1998) norm for N. The effective cation exchange capacity (CEC) was determined according to the cobaltihexamine chloride method (NF X 31-130, 1999). A water extract (soil:extractant ratio 1:10 and 2 hours of contact) was used to determine the contents of available phosphorus (P), potassium (K) and copper (Cu). The solution was centrifuged (2000 g during 20 minutes at 20°C) and filtered at 0.2 µm. The P content was determined by the green malachite method (Ohno and Zibilske, 1991). The K and Cu contents were measured by flame atomic absorption spectrometry (Varian A600).

2.4. BIOLOGICAL ANALYZES

Soil microbial biomass carbon (MB) was determined following the fumigation-extraction method (Wu *et al.*, 1990). The organic carbon from fumigated and non-fumigated soils was measured with a total organic carbon analyzer TOC-V CSH (Shimadzu). Nematodes were extracted from 200 g of wet soil using the Oostenbrink elutriation technique, complemented with sieving and cottonwood extraction (ISO 23611-4, 2007). Nematodes were fixed in a 4% formaldehyde solution and a representative subsample was mounted on glass slides for identification at high magnification (x400). An average of 150 nematodes per sample was identified to family level and grouped into 5 trophic groups: plant-feeders (PF), bacterial-feeders (Ba), fungal-feeders (Fu), omnivores (Om) and predators (Pr). Earthworms were gently dried before being weighed and counted. Adult and juvenile earthworms were distinguished and distributed into 2 ecological categories: endogeics and anecics.

2.5. STATISTICAL ANALYZES

An univariate approach using generalized and linear mixed models for hierarchical data (Bolker *et al.*, 2009; Pinheiro and Bates, 2000) was used to study the differences between treatments for each observed variable. Prior to the analysis and when necessary, the distribution of observed variables were adjusted to Gaussian distribution using proper transformations (square root or logarithmic). The variables describing density data belonging to nematode trophic groups and earthworm ecological categories were not normalized because they rather followed Poisson distribution. The functions *lmer* and *glmer* from the library lme4 of the R 2.11.1 software (R Development Core Team, 2011) were used to compute mixed models from variables having, respectively, Gaussian and Poisson distributions. The multiple comparisons of mean among treatments were then tested using Markov Chain Monte Carlo samples.

Based on the results of the univariate approach, a linear discriminant analysis was conducted to discriminate observations among the 4 treatments (Conventional, Organic7, Organic11 and Organic17). In order to do this, this multivariate analysis computed the best discriminant functions to differentiate objects among treatments, while minimizing variability within a treatment (Legendre and Legendre, 1998). Bulk density, total organic carbon (TOC) and total nitrogen (N) contents, soil microbial biomass carbon (MB), available phosphorus (P), potassium (K) and copper (Cu) contents, effective CEC (CEC), plant-feeding (PF), bacterial-feeding (Ba), fungal-feeding (Fu), combined omnivore and predator (Om+Pr) nematode densities and endogeic earthworm density and biomass were the variables integrated in the discriminant analysis. This analysis was performed using the XL-Stat software for Windows®. The results were presented in the form of correlations circle of variables, distribution of the 96 observations along the two discriminant axes and confusion matrix comparing *a priori* (real) and *a posteriori* (calculated) classification of observations using the cross-validation technique.

3. RESULTS

3.1. PHYSICAL AND CHEMICAL PARAMETERS

The Organic plots tended to have a higher bulk density than the Conventional plots but only bulk density of Organic11 was significantly higher than that of Conventional plots (Table IV- 2). The TOC content significantly increased from Conventional to Organic17 (+32%). A marked rise was measured between Organic7 and Organic11 (+15%). Concerning the total N content, 2 different groups were identified. Conventional and Organic7 had significantly lower N content than Organic11 and Organic17. A steep decrease in available P content was measured between Conventional and Organic7 (-58%) but, thereafter, a continuous increase of available P content was noticed between Organic7 to Organic11 (+43%) and Organic11 to Organic17 (+65%). The available K content significantly increased from Conventional to Organic17 (+81%). No significant difference was measured for available Cu content between treatments but one should note that the highest values were measured in Organic plots. The highest values of effective CEC were measured for Organic7 and Organic11. In these treatments, effective CEC was significantly higher (+27%) in comparison with Conventional and Organic17.

Table IV- 2 : Physical and chemical parameters : bulk density, total organic carbon (TOC), total nitrogen (N), available phosphorus (P), potassium (K) and copper (Cu) contents and effective cation exchange capacity (CEC) in conventional farming (Conventional) and organic farming for 7 years (Organic7), 11 years (Organic11) and 17 years (Organic17).

	Bulk density ($g\ cm^{-3}$)	**TOC** ($mg\ g^{-1}$)	**N** ($mg\ g^{-1}$)	**P** ($mg\ kg^{-1}$)	**K** ($mg\ kg^{-1}$)	**Cu** ($mg\ kg^{-1}$)	**CEC** ($cmol^{+}\ kg^{-1}$)
Conventional	1.21 ± 0.03 b	10.2 ± 0.3 c	1.00 ± 0.02 b	1.06 ± 0.12 a	27 ± 3 c	0.22 ± 0.03 a	16.3 ± 0.5 b
Organic7	1.31 ± 0.01 ab	10.8 ± 0.4 bc	1.01 ± 0.03 b	0.45 ± 0.04 b	30 ± 3 bc	0.35 ± 0.07 a	19.9 ± 0.7 a
Organic11	1.41 ± 0.02 a	12.4 ± 0.4 ab	1.25 ± 0.05 a	0.64 ± 0.04 ab	45 ± 5 ab	0.34 ± 0.06 a	20.7 ± 0.8 a
Organic17	1.29 ± 0.01 ab	13.5 ± 0.5 a	1.36 ± 0.04 a	1.05 ± 0.06 a	49 ± 5 a	0.39 ± 0.07 a	15.7 ± 0.4 b
	*	*	*	*	¥	ns	*

Means ± standards errors are presented. Means differing significantly are denoted with different lowercase letters and the threshold of significance is specified: * for significant at 95%, ¥ for significant at 90 % and ns for not significant.

3.2. BIOLOGICAL PARAMETERS

Organic11 and Organic 17 had significantly higher soil MB than Conventional and Organic7 (+34%) (Table IV- 3). The lowest total nematode density was measured for Conventional plots (Table IV- 3). The total nematode density was significantly higher in Organic7 (+45%) and in Organic17 (+79%) than in Conventional plots. The plant-feeder density was significantly higher in Organic7 (+126%) and in

Organic17 (+187%) than in Conventional plots. Plant-feeding nematodes were dominated by facultative plant-feeders with Tylenchidae family (data not shown). Among obligate plant-feeders, Paratylenchus sp. and Tylenchorynchus sp. dominated and almost no Xiphinema sp. were found whatever the treatment, just 7.5 and 12.1 ind. (100 g dry soil)-1 for 2 samples (data not shown). No significant difference was measured for bacterial-feeder densities between treatments. However, the lowest density was observed for Conventional plots. The fungal-feeder density increased from Conventional to Organic17. It was significantly higher in Organic7 (+43%) and in Organic17 (+97%) than in Conventional plots. The combined density of omnivores and predators was significantly higher (+44%) in Organic7 than in other treatments.

Table IV- 3 : Soil microbial biomass (MB) and nematode trophic group density in conventional farming (Conventional) and organic farming for 7 years (Organic7), 11 years (Organic11) and 17 years (Organic17).

	Microorganisms	**Nematofauna** (ind. (100 g dry soil)$^{-1}$)				
	MB (µg C g^{-1})	**Plant-feeders**	**Bacterial-feeders**	**Fungal-feeders**	**Omnivores-Predators**	**Total**
Conventional	77 ± 7 b	210 ± 17 c	402 ± 29 a	212 ± 15 b	112 ± 12 b	936 ± 49 c
Organic7	73 ± 3 b	474 ± 62 ab	422 ± 36 a	303 ± 38 a	156 ± 20 a	1355 ± 115 ab
Organic11	100 ± 5 a	403 ± 69 b	440 ± 55 a	303 ± 37 a	101 ± 17 b	1248 ± 137 bc
Organic17	101 ± 4 a	603 ± 62 a	541 ± 60 a	417 ± 51 a	113 ± 13 b	1672 ± 143 a
	¥	*	ns	¥	¥	¥

Means ± standards errors are presented. Means differing significantly are denoted with different lowercase letters and the threshold of significance is specified: * for significant at 95%, ¥ for significant at 90% and ns for not significant.

There were many samples without earthworms in all the treatments, and especially in the Organic plots (Table IV- 4). The total earthworm density was significantly higher in Conventional than in Organic plots (-44% between Conventional and Organic7 and -55% between Conventional and Organic17). Endogeics were the most represented (more than 85% of total density) compared to the anecics in both Conventional and Organic plots. The anecic density was low whatever the treatment and not significantly different between treatments. The highest biomass of earthworms was observed in the Conventional plots. Contrary to the density, the biomass was mainly represented by the anecics.

Table IV- 4 : Proportion of samples without earthworm, density and biomass of endogeic and anecic earthworms in conventional farming (Conventional) and organic farming for 7 years (Organic7), 11 years (Organic11) and 17 years (Organic17).

	Samples without earthworm (%)	Density (ind m^{-2})			Biomass (g m^{-2})		
		Endogeics	Anecics	Total	Endogeics	Anecics	Total
Conventional	45	12.5 ± 2.6 a	1.1 ± 0.5 a	13.6 ± 2.6 a	4.5 ± 1.1 a	15.5 ± 8.9 a	19.9 ± 9.1 a
Organic7	75	6.9 ± 5.5 b	0.7 ± 0.7 a	7.6 ± 5.5 b	0.6 ± 0.6 a	1.1 ± 1.1 a	1.8 ± 1.3 a
Organic11	75	6.1 ± 4.0 b	0.6 ± 0.6 a	6.7 ± 4.0 b	1.0 ± 0.9 a	8.1 ± 8.1 a	9.0 ± 8.1 a
Organic17	60	4.4 ± 2.0 b	1.7 ± 0.9 a	6.1 ± 2.1 b	0.3 ± 0.1 a	11.3 ± 7.0 a	11.7 ± 7.0 a
	-	¥	ns	¥	ns	ns	ns

Means ± standards errors are presented. Means differing significantly are denoted with different lowercase letters and the threshold of significance is specified: ¥ for significant at 90% and ns for not significant.

3.3. DISCRIMINANT ANALYSIS

The discriminant analysis (Figure IV- 1 and Table IV- 5) was significant at $\alpha = 0.001$ according to the Wilks test and each discriminant axis explained a significant portion of the overall variance of the database ($p < 0.01$). The first two discriminant functions explained 93% of the dataset variability (Figure IV- 1A). The first axis explained 68% of the dataset variability and was mainly defined by total N and TOC contents, plant-feeding nematode density, available K content and fungal-feeding nematode density. The axis 2 contributed 25% of the dataset variability and was correlated to effective CEC and available P content. The distribution of observations along the 2 axes showed a clear discrimination of the 4 treatments (Figure IV- 1B). The first axis clearly discriminated the 4 treatments and therefore, a gradient starting from Conventional to Organic17 was found along this axis. On the other hand, the second axis was less discriminant as it only discriminated Conventional and Organic17 from Organic7 and Organic11. Some overlaps were observed between treatments and were associated to the variability of observations in a given treatment. The confusion matrix (Table IV- 5) compared the classification of plots predicted by the model of discriminant analysis and the real classification constituted from experimental plot design. The confusion matrix showed that the discriminant analysis successfully classified 79% of the 96 observations. The *a posteriori* classification of Conventional and Organic17 plots were respectively correct at a rate of 88 and 90% whereas, Organic7 and Organic11 plots were correctly classified, respectively at a rate of 75 and 55%.

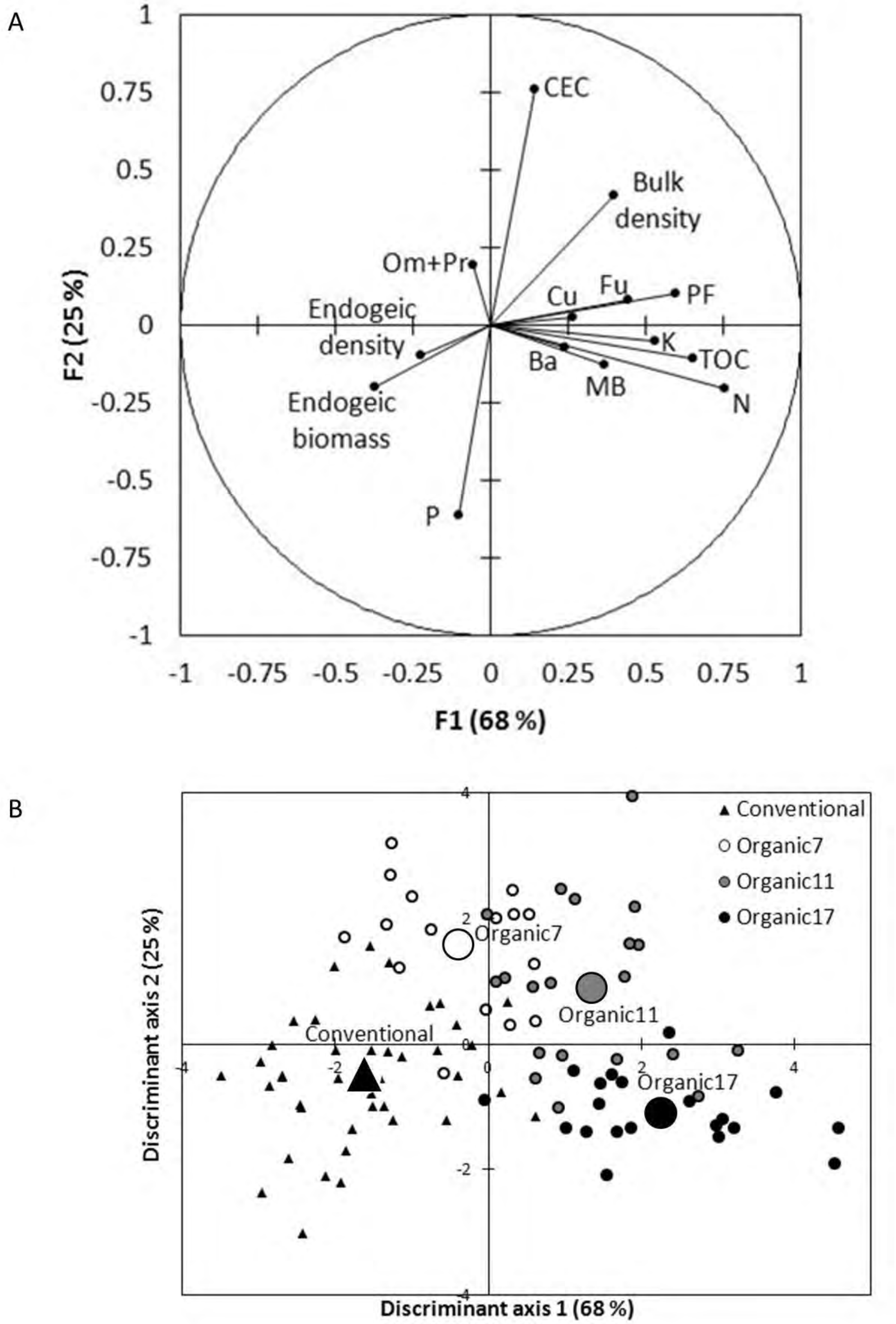

Figure IV- 1 : Discriminant analysis performed on physical, chemical and biological parameters for conventional farming (Conventional) and organic farming for 7 years (Organic7), 11 years (Organic11) and 17 years (Organic17).

(A): Correlations circle of variables: bulk density, total organic carbon (TOC), total nitrogen (N), available phosphorus (P), potassium (K) and copper (Cu) contents, effective cation exchange capacity (CEC), soil microbial biomass (MB), density of plant-feeding (PF), bacterial-feeding (Ba), fungal-feeding (Fu), omnivore and predator (Om+Pr) nematodes and density and biomass of endogeic earthworms

(B): Distribution of the 96 observations and of the centroids (prominent symbols) of each treatment along the 2 discriminant axes.

Table IV- 5 : Confusion matrix comparing *a priori* (real) and *a posteriori* (calculated) classification of observations using the cross-validation technique.

		A posteriori classification				Correct classifications (%)
		Conventional	Organic7	Organic11	Organic17	
A priori classification	Conventional	35	3	2	0	88
	Organic7	3	12	1	0	75
	Organic11	0	3	11	6	55
	Organic17	1	0	1	18	90

4. DISCUSSION

4.1. SOIL QUALITY INDICATORS TO STUDY THE TRANSITION TO ORGANIC FARMING

This study was conducted on commercial vineyards. Fourteen plots which have been organically managed for 7, 11 and 17 years were compared to 10 conventionally managed plots. We analyzed the long-term effects of organic management on vineyard soil quality determined by physical, chemical and also biological indicators. Measurements on grape production were not included to define soil quality because the diversity of plant material would not have given reliable data to compare the different treatments. As reviewed by Bastida *et al.* (2008), the multiparametric indices are a promising tool to objectively describe the changes of soil quality but the weighting of different functions is subjective and does not depend on statistical (objective) method. In this study, our statistical approach was different because we used a combination of statistical tools that clearly distinguish the four treatments which organized themselves along the first axis, defining a gradient starting from Conventional to Organic17. Indeed, no significant difference appeared before 11 years of organic farming for total organic carbon (TOC), total nitrogen (N) and available potassium (K) contents, soil microbial biomass (MB) and fungal-feeding nematode density (Fu). However, other soil indicators, such as available P content rapidly decreased after conversion. Some authors such as Martin *et al*. (2007), explained such a trend as an exhaustion of available P pools built up from successive mineral P fertilizers. Afterwards, we observed an increase of available P content as reported by Garcia-Ruiz *et al.* (2009) and Liu *et al*. (2007) on different crops. Conversely, available K content increased progressively from Conventional to Organic17 whereas Gosling and Shepherd (2005) observed K was significantly higher in the conventional fields than in the low fertility organic fields. One should note that the quantity of compost applied was too low to explain the observed trends for P and K (25 kg P ha^{-1} yr^{-1} and no K, Table IV- 1). Previous studies have shown that microorganisms release organic acids which can increase the availability of P (Arcand and Schneider,

2006) and K (Basak and Biswas, 2009). Phosphatases excreted by microorganisms, and more particularly fungi, have also the ability to mineralize organic P (Rodriguez and Fraga, 1999). Thus, the increase of microbial biomass after organic conversion and activities of some microorganisms could explain why after 7 years of organic farming, the available P and K contents increased. The total nematode density, especially plant-feeders (PF) and total earthworm density, especially endogeic density responded more sharply and quickly to the organic conversion. Garcia-Ruiz et al. (2009) did the same observation for the plant-feeder density in one site of olive groves after 7-8 years of organic practices. In our case, plant-feeders that increased in density were mainly the facultative plant-feeders Tylenchidae and phytoparasitics *Tylenchorynchus* sp.. *Xiphinema* sp., grapevine fanleaf virus vector (GFLV) were almost absent in each treatment. However, it is known that the highest density of *Xiphinema* sp. occurred at 40 to 110 cm depth and yet we sampled it in the 0-15 cm topsoil (Villate *et al.*, 2008). For earthworm density, Scullion *et al.* (2007) observed some positive effects after 10 years of organic farming on grass-arable rotations. Gradual changes of soil properties in converting plots into organic farming have been measured by several authors and discussed by Martini *et al.* (2004). The other studied indicators did not present any change and should be considered as not sensitive enough to monitor the conversion to organic viticulture in these pedo-climatic conditions. So, organic matter, available P and K, microbial biomass, nematodes and earthworms could be considered as a basis to a guideline to best transition strategies in vineyards.

4.2. EFFECTS OF ORGANIC FARMING ON SOIL ORGANISMS

In organic farming, plant nutrition is based on the mineralization of organic matter by soil organisms. Several authors reported negative effects of Cu on soil organisms (Wightwick *et al.*, 2010). We observed, as Beni and Rossi (2009), trends of higher available Cu contents in Organic treatments than in Conventional ones. As a matter of facts, Cu salts are the only efficient fungicides against downy mildew, allowed in organic farming. Furthermore, Brun *et al.* (2001) showed Cu accumulates in the upper layers of soils. However in our study, we did not observe significant increase of available Cu after organic conversion. This might be related to the method that we used for measuring Cu availability. Michaud *et al.* (2007) have shown that in calcareous soils contaminated by Cu fungicides, water-extractable Cu varied little, compared to total soil Cu, or EDTA-extractable Cu.

Generally, grass cover and applications of organic matter have positive effects on earthworms in vineyards (Eisenhauer *et al.*, 2009; Paoletti, 1999; Pérès *et al.*, 1998). However, we measured the lowest density and biomass of earthworms in Organic plots. The density of anecics was very low in all treatments but it was certainly underestimated. Actually, the hand-sorting method without prior application of an expellant (such as mustard or formaldehyde solution) did not allow to sample larger earthworms, such as anecics, which can rapidly escape into deeper soil layers (Pelosi *et al.*, 2009). However, the hand-sorting is appropriate for endogeic and their density strongly decreased between Conventional and Organic7. The tillage which was more frequent to control weeds under organic management could also explain these observations. Several authors highlighted negative effects of tillage on earthworm density and biomass (Emmerling (2001) and Paoletti (1999) on different crops). Furthermore, with the organic conversion, the shallow tillage was replaced by a deeper mouldboard ploughing. Short-term studies (3 and 6 years) of Metzke *et al.* (2007) and Peigné *et al.* (2009) on different tillage systems under organic annual crop farming did not observe higher earthworm density or biomass under shallow tillage in comparison with mouldboard ploughing. However, we could hypothesize that mouldboard ploughing has long-term negative effect on earthworms. Villenave *et al.* (2009a) demonstrated that tillage also tends to disturb omnivore and predator nematodes. In the same way, we did not measure any modification of the densities of these nematodes with organic farming and their low densities in every plot indicated a simple and short soil micro-food web in all these vineyards (Ferris *et al.*, 2001). Soil compaction, as evaluated by the measure of bulk density, was higher in Organic plots. This was the consequence of the increase of the traffic for tillage and phytosanitary treatments in organic management. (Bouwman and Arts, 2000) observed a decrease of free-living nematode density in a heavily compacted soil compared with a slightly compacted soil. They explained that nematodes reacted negatively to the decreased pore space habitats due to soil compaction. In our case, bacterial and fungal-feeding nematode density was globally higher in Organic plots despite an increased bulk density. Hansen (1996) and Hansen and Engelstad (1999) showed that soil compaction had negative effects on earthworms. So, soil compaction could explain, with ploughing, the decrease of earthworm density that we observed in organic viticulture. More globally, agricultural practices in organic conversion cause some damage on soil organisms.

4.3. ORGANIC MATTER, MICROBIAL BIOMASS AND NEMATODES

The soil organic matter plays essential roles in soil functioning and it can be considered as the keystone of soil management under organic farming. Under Organic plots, we measured higher TOC contents. Many authors observed the same positive effect of organic farming as Briar *et al.* (2007) on different annual crops and Vestberg *et al.* (2009) on strawberry crops. The sole application of compost (261 kg of organic carbon ha^{-1} year^{-1}) would lead to a content of 11.2 mg of TOC g^{-1} of soil after 17 years of organic farming whereas we measured it at 13.5 mg g^{-1}. Thus, the more abundant grass cover in Organic treatments contributed certainly in the increase of TOC contents and microbial biomass as observed by (Potthoff *et al.*, 2006). Organic matter constitutes a source of nutrients for microorganisms (Calbrix *et al.*, 2007) which increased after the conversion into organic farming and root-exudates are known too to stimulate microbial growth (Bouwman and Arts, 2000; Whitelaw-Weckert *et al.*, 2007). In the same way, Rahman *et al.* (2009) showed positive effects of grass cover on the density of plant-feeding and microbivorous nematodes which agreed with our results. An increase of plant-feeding nematodes intensifies root C fluxes activating microbial biomass from the rhizosphere and microbivorous nematodes stimulate microorganisms (Denton *et al.*, 1999). Conversely, as there were more microorganisms in Organic plots, we consistently found more fungal-feeding nematode density in organic plots, which is in line with Ferris *et al.* (1996), Villenave *et al.* (2004) and Villenave *et al.* (2010). However, only an increasing trend was observed for bacterial-feeding nematode density in Organic plots. The nematodes are good indicators of soil decomposition pathway (Ferris *et al.*, 2004). The bacterial-feeders/fungal-feeders ratio decreased with organic farming, as observed by (McSorley and Frederick, 1999). So, the decomposition pathway becomes dominated by fungi under Organic plots in comparison with Conventional plots. The increase of fungi after organic conversion was also observed by different authors as (Gryndler *et al.*, 2006) for arbuscular mycorrhizal fungi. Thus, the application of compost and the presence of a grass cover on Organic plots led to increase soil organic matter, microbial biomass and nematode density, especially plant-feeders and fungal-feeders whereas ratio bacteria/fungi decreased.

5. CONCLUSION

Through our experimental design, we studied long-term effects of different changes of agricultural practices inherent to organic viticulture on soil quality. In this study, we have demonstrated that a transition period of 7 to 11 years, depending on the considered indicator, was needed to clearly separate Conventional and Organic farming practices in Southern French vineyards. Apart from classical sensitive indicators used to study organic transition like organic matter content, soil microbial biomass, or bulk density, the easy-to-use chemical available P and K contents should also be considered as sensitive indicators. Moreover, our results address the important question of P and K mining with organic practices during transition period. However afterwards, the increase of soil organic matter and related biological activities could partly counteract the observed decrease during the transition period. According to our results, the utilization of soil nematodes as bioindicators of soil quality shall be promoted. Indeed, the study of microbivorous provided some information about microbial biomass and bacteria/fungi ratio. As for omnivore and predator nematodes, they were reliable indicators of environmental perturbations. Despite the diversity of indicators, we have highlighted the difficulty to show the benefits of organic farming on global soil quality in this particular pedoclimatic area, and for the set of farming practices that were investigated.

Acknowledgements

We thank Louis Fabre, Xavier Sabouraud, Regis Loevenbruck, Jean-Jacques Loze and Gérard Pélissa for allowing us to analyze their vineyards. We also thank Hervé Aholoukpé, Hubert Alcin, Didier Arnal, Didier Blavet, Georg Carlsson, Benoît Cloutier-Hurteau, Cathy Coll, Gabrielle Daudin, Fan Deng, Marney Isaac, Sylvia Julien, Siham Khoulassa, Ernest Kouakoua, Rym Maougal, Aurélie Metay and Emilie Russello for their help in earthworm sampling. Special thanks go to Jean-Pierre Barthès for his expert advice on soils, Inès Sneessens and Malalatiana Razafindrakoto for her help in the laboratory analyzes, and Julien Papaïx, Philippe Deleporte and Benoît Cloutier-Hurteau for assistance with statistics. We gratefully acknowledge Terri Andon for carefully reading the manuscript and English revision.

Patrice Coll’s PhD grant was provided by the Agence de l'Environnement et de la Maîtrise de l'Energie (ADEME, France) and by Montpellier SupAgro (France). This work was financially supported by the INRA AIDY project (Analyze Intégrée de la DYnamique des systèmes biophysiques, techniques et de décision lors de la conversion à la viticulture biologique).

CHAPTER IV-2:

HOW ARE NEMATODE COMMUNITIES AFFECTED DURING A CONVERSION FROM CONVENTIONAL TO ORGANIC FARMING IN SOUTHERN FRENCH VINEYARDS?

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2011, *Nematology,* Submited.

Abstract: The rate of conversion from conventional vineyards to organic farming practices is increasing. Organic farming improves some soil properties, although some organic practices have negative effects on soils. The objective of this work was to complete the first study on the long-term effects of organic-farming through the use of soil nematodes as bioindicators of the soil functioning. Our experimentation was conducted in a commercial vineyard where plots that had been organically managed for 7 (Organic7), 11 (Organic11) and 17 years (Organic17) were compared to conventionally managed plots (Conventional). The nematode community structure and nematode indices were determined. As a main result, the organic practices increased the soil nematode density. An increase in the available resources, as measured by a higher enrichment index (EI), led to an increase in the microbial-feeder density and mainly opportunistic fungal-feeding nematodes. A greater density of plant-feeding nematodes was attributed to the presence of a grass cover. The soil functioning was shifted; the decomposition channel of the soil organic matter became more fungal than bacterial. Even though changes were observed in the nematode community structure following the conversion, the maturity index (MI), the plant-parasitic index (PPI) and the structure index (SI) remained constant. Consequently, the organic practices did not improve the soil food web length or complexity even though the biological activity, as measured by the microbial biomass and total nematode abundance, increased.

Key words: bioindicator, community structure, soil food web, ecological indices, tillage

1. INTRODUCTION

Ecosystems perform services for humankind (MEA, 2005), but in turn, human activities can alter ecosystem functioning through soil perturbations. Dominati *et al.* (2010) summarized the different perturbations that alter soils. Among them, chemical pollution in industrial areas or soil sealing due to urbanisation are the most obvious (Citeau *et al.*, 2008). However, agriculture, and more precisely viticulture, can have also negative effects on soil, such as compaction (Coulouma *et al.*, 2006), erosion (Le Bissonnais *et al.*, 2007) and pesticide pollution (Komarek *et al.*, 2010). An increasing number of winegrowers care about the environment and are beginning to adopt more sustainable agricultural practices. Indeed, the area of organically managed French vineyards increased by 110% from 13,426 ha in 2001 (Agence BIO, 2002) to 28,190 ha in 2008 (Agence BIO, 2009).

Organic farming is thought to produce healthier food or fibres while reducing the detrimental effects of agriculture on the environment and more particularly on soils (Reganold *et al.*, 1987). However, the conversion to organic farming requires substantial modification of grower practices. Indeed, organic growers ban mineral fertilizers in favour of organic ones and replace synthetic pesticides with natural pesticides and chemical weeding with tillage or grass cover (Briar *et al.*, 2007). Despite some recognised improvements of soil properties by these alternative practices, such as the increase of organic matter (Briar *et al.*, 2007; Vestberg *et al.*, 2009) or soil microbial biomass (Potthoff *et al.*, 2006), some deleterious side effects have also been noted. First, copper, which replaces synthesised fungicides, accumulates in soils (Besnard *et al.*, 2001; Brun *et al.*, 2001), and its toxicity damages the soil microbial community (Diaz-Ravina *et al.*, 2007; Marzaioli *et al.*, 2010a) and earthworms (Eijsackers *et al.*, 2005; Paoletti *et al.*, 1998). Furthermore, the pesticides allowed in organic farming are preventive and less efficient than synthetic pesticides. Thus, more pesticide applications are required, leading to increased soil compaction (Hamza and Anderson, 2005). Several authors (Emmerling, 2001; Paoletti, 1999) have shown a decrease of the density of earthworms with an increase in tillage frequency, which is used to reduce the weeds competing with the vines.

Thus, there is impetus to evaluate the effects of organic practices on soil functioning with a holistic approach. Some recent studies have evaluated soil quality using nematodes as bioindicators of vineyard soil quality (Ferris and McKenry, 1976; Rahman *et al.*, 2009; Sanchez-Moreno and Ferris, 2007; Zolda and Hanel, 2007). Free-living nematodes can be used for this type of assessment. First, they are present under all pedoclimatic situations, including habitats that vary from pristine to extremely degraded (Bongers and Ferris, 1999). Nematodes play key roles in soil organic matter decomposition and nutrient cycling (Ferris and Matute, 2003; Neher, 2001). Furthermore, they are pertinent bioindicators because they present an important diversity of trophic groups (plant-feeders, bacterial-feeders, fungal-feeders, omnivores and predators (Villenave *et al.*, 2004; Yeates *et al.*, 1993)) and of characteristic demographic groups such as colonizers, persistent species and intermediaries (Bongers, 1990). As a consequence, nematode indices can be used to evaluate changes of soil ecology in agricultural systems (Ferris *et al.*, 2001). Many studies have focused on the effects of agricultural practices on soil nematodes, such as different soil managements (Lopez-Fando and Bello, 1995; Overstreet *et al.*, 2010; Villenave *et al.*, 2001) or different kinds of mineral versus organic fertilisation (Liang *et al.*, 2009; Neher and Olson, 1999; Porazinska *et al.*, 1999; Villenave *et al.*, 2010). However, very few researchers have studied nematode communities after organic conversion, and the available studies only report findings after less than 10 years of organic management (Briar *et al.*, 2007; Neher, 1999; Tsiafouli *et al.*, 2006; Van Diepeningen *et al.*, 2006).

The present study analyzed how organic practices modify the nematode community in comparison with non organic practices and completed a global analysis of soil quality on the same plots that were used by (Coll *et al.*, 2011). We worked on 24 vineyard plots, of which 10 were conventionally managed, while the others had different ages of conversion into organic farming (7, 11 and 17 years). We presented the density of the different nematode taxa arranged by trophic group along with ecological indices, including the maturity index, plant-parasitic index, enrichment index, structure index, channel index and nematode channel ratio.

2. MATERIALS AND METHODS

2.1. SITE DESCRIPTION, MANAGEMENT AND FIELD PLOT DESIGN

The site description, management and field plot design is fully described by Coll *et al.* (2011). Briefly, the study occurred in May 2009 in Cruscades, which is located in the South of France in the Languedoc-Roussillon region (43°11'29.13"N, 2°49'1.78"E; 26 - 50 m elevation). The soil was silty clay, with 42 ± 2% silt, 36 ± 1% clay and 22 ± 2% sand. The soil was calcareous, with 208 ± 7 g of total $CaCO_3$ kg^{-1}, yielding a pH in water of 8.3. The soil water-holding capacity was 20.6 ± 0.5% (w/w). The study was conducted on 24 commercial vineyard plots with a mean area of approximately 1.5 ha. The year of plantation varied from 1932 to 2003. The plantation density ranged between 3,300 and 5,000 vines per hectare. Ten plots were managed according to non organic or conventional farming (Conventional), and the others were managed according to organic farming (Organic). Four plots have been organically managed since September 2001 (Organic7). Five plots have been organically managed since September 1997 (Organic11), and the last 5 plots have been organically managed since September 1991 (Organic17). These 4 sets of plots will be referred to as treatments here. The conventional agricultural practices were identical for each treatment before the organic conversion, and the organic agricultural practices after the conversion were also identical (Table IV- 6). Four representative subplots of 5 vines x 4 inter-rows per plot were sampled. Consequently, 96 subplots were studied.

Table IV- 6 : Agricultural practices in conventional farming and organic farming.

	Soil management		**Fertilisation** (N-P-K)	**Vine phytosanitary protection**	**Tractor frequency per year** (year^{-1})
	Rows	**Inter-rows**			
Conventional	Chemical weeding (glyphosate, 700 g ha^{-1}, 1 year^{-1})	Tillage with tined tools (15 cm depth, 2 year^{-1})	Mineral (10-10-20, 200 kg ha^{-1}, 1 year^{-1})	Synthesis and natural (6 treatments year^{-1})	14
Organic	Tillage (10 cm of depth, 1 year^{-1})	Mouldboard ploughing (25 cm depth, 4 year^{-1})	Compost (90% of OM; 9-5-0, 500 kg ha^{-1}, 1 year^{-1})	Natural (8 treatments year^{-1})	18

The total organic carbon (ISO 10694, 1995) significantly increased from 10.2 mg g^{-1} in the Conventional plot to 13.5 mg g^{-1} in Organic17, with 10.8 mg g^{-1} in Organic7 and 12.4 mg g^{-1} in Organic11 (Coll *et al.*, 2011). An increase was also measured in the total nitrogen (ISO 13878, 1998) and microbial biomass (Wu *et al.*, 1990). The microbial biomass significantly increased from the Conventional (77 µg C g^{-1}) to the Organic17 (101 µg C g^{-1}) plot (Coll *et al.*, 2011).

2.2. SAMPLING PROCEDURE

The sampling was conducted in spring, a few days after mild raining events (May 2009, from the 22nd to the 28th). The soil water content was 11.2 ± 0.2% (w/w) during the soil sampling. The soil was sampled in the 0-15 cm of topsoil in the center of the inter-row space. One soil sample was taken per subplot. Each soil sample consisted of a composite of 4 subsamples, 1 composite per inter-row, taken with a gouge auger. The soil samples were sieved through a 1-cm mesh before biological analyzes and through a 2-mm mesh before chemical analyzes. All 96 of the soil samples were analyzed.

2.3. NEMATODE ANALYZES

Nematodes were extracted from 200 g of wet soil using the Oostenbrink elutriation technique, complemented with sieving and a cottonwood extraction (ISO 23611-4, 2007). The nematodes were fixed in a 4% formaldehyde solution, and a representative sub-sample was mounted on mass slides for identification at high magnification (x 400). An average of 150 nematodes per sample was identified to the genus or family level. Each nematode taxa was assigned to one of 6 trophic groups: obligate plant-feeders (OPF), facultative plant-feeders (FPF), bacterial-feeders (Ba), fungal-feeders (Fu), omnivores (Om) and predators (Pr) (Yeates *et al.*, 1993). Furthermore, each taxa was also associated to a cp-value from 1 to 5 on a colonizer-persistency (cp) scale according to its demographic characteristics, such as size, longevity, fecundity and sensibility to perturbations (Bongers, 1990). The combination between the trophic group and cp-value was used to classify each nematode taxa into a functional guild. For example, a fungal-feeding nematode with a cp-value of 3 is categorised in the Fu3 functional guild. Then, 6 nematode ecological indices were calculated: the maturity Index (MI), plant-parasitic index (PPI) (Bongers, 1990), enrichment index (EI), structure Index (SI), channel index (CI) (Ferris *et al.*, 2001) and nematode channel ratio (NCR) (Yeates, 2003). We also proposed another nematode channel ratio including Tylenchidae as fungal-feeders (NCR_Tyl).

2.4. STATISTICAL ANALYZES

A univariate approach using generalised and linear mixed models for hierarchical data (Bolker *et al.*, 2009; Pinheiro and Bates, 2000) was used to study the differences between treatments of the nematode taxa densities and ecological indices based on the nematofauna. All of the variables describing the density data of the nematode taxa and trophic groups followed a Poisson distribution. The functions *lmer* and *glmer* from the library lme4 of the R 2.11.1 software environment (R Development Core Team, 2011) were used. The multiple comparisons of means among treatments were then tested using Markov Chain Monte Carlo methods. Finally, a multivariate approach was also conducted to discriminate the nematode community structure based on the average density of 40 nematode taxa (at a genus or family level) in the 24 plots. A Bray-Curtis similarity matrix was calculated with PRIMER-E Ltd software (Plymouth, United-Kingdom) on data that had been standardised and square-root transformed. A Permanova test was used to statistically evaluate if the 4 treatments led to different nematode communities. A multi-dimensional scaling (MDS) representation was completed to illustrate the similarities in the nematode community between the plots.

Table IV- 7 Nematode taxon density (individuals 100 g^{-1} dry soil) in conventional farming (Conventional) and organic farming for 7 years (Organic7), 11 years (Organic11) and 17 years (Organic17).

Family	Genus[a]	Cp-value	Conventional	Organic7	Organic11	Organic17	
Tylenchulidae	*Paratylenchus*	2	14 ± 5 b	86 ± 40 a	20 ± 6 a	9 ± 3 b	*
Belonolaimidae	ND	3	37 ± 6 b	102 ± 25 ab	62 ± 25 b	172 ± 35 a	*
Hoplolaimidae	*Helicotylenchus*	3	9 ± 2 b	21 ± 7 a	32 ± 9 a	4 ± 3 c	¥
Pratylenchidae	*Pratylenchus*	3	1 ± 1 c	13 ± 4 ab	47 ± 16 a	10 ± 5 b	*
Total obligate plant-feeders			61 ± 9 b	223 ± 43 a	161 ± 37 a	196 ± 36 ab	¥
Tylenchidae	ND	2	149 ± 16 c	251 ± 40 b	241 ± 39 b	406 ± 48 a	¥
Total facultative plant-feeders			149 ± 16 c	251 ± 40 b	242 ± 39 b	408 ± 47 a	¥
Panagrolaimidae	*Panagrolaimus*	1	27 ± 5 c	40 ± 9 bc	184 ± 49 a	108 ± 26 ab	*
Rhabditidae	ND	1	11 ± 2 a	19 ± 10 a	15 ± 4 a	19 ± 6 a	ns
Cephalobidae	*Acrobeles*	2	17 ± 4 a	19 ± 9 ab	22 ± 7 a	5 ± 2 b	*
Cephalobidae	*Acrobeloides*	2	25 ± 5 b	49 ± 10 a	18 ± 5 b	47 ± 11 ab	¥
Cephalobidae	*Cephalobus*	2	77 ± 13 b	106 ± 27 a	61 ± 9 b	103 ± 16 b	¥
Cephalobidae	*Cervidellus*	2	14 ± 2 a	15 ± 6 a	9 ± 3 a	16 ± 5 a	ns
Cephalobidae	*Eucephalobus*	2	4 ± 1 b	25 ± 17 b	30 ± 8 a	16 ± 8 b	*
Cephalobidae	*Heterocephalobus*	2	75 ± 13 a	47 ± 17 b	34 ± 8 b	117 ± 21 a	¥
Monhysteridae	ND	2	112 ± 12 a	48 ± 13 b	30 ± 8 c	73 ± 14 a	¥
Osstellidae	*Drilocephalobus*	2	7 ± 3 a	5 ± 2 ab	1 ± 1 b	5 ± 3 ab	**
Plectidae	*Plectus, Wilsonema*	2	3 ± 1 b	17 ± 6 a	6 ± 2 b	8 ± 5 b	¥
Prismatolaimidae	*Prismatolaimus*	3	21 ± 4 b	24 ± 10 b	27 ± 10 b	8 ± 4 a	¥
Alaimidae	*Alaimus*	4	2 ± 1 a	4 ± 3 a	0 ± 0 b	7 ± 3 a	**
Total bacterial-feeders			402 ± 29 a	422 ± 36 a	440 ± 55 a	541 ± 60 a	ns
Anguinidae	*Ditylenchus*	2	50 ± 7 b	102 ± 25 a	78 ± 16 a	74 ± 15 ab	¥
Aphelenchidae	*Aphelenchus*	2	32 ± 7 b	31 ± 6 b	84 ± 18 a	95 ± 15 a	*
Aphelenchoididae	*Aphelenchoides, Aprutides*	2	126 ± 10 b	143 ± 20 b	139 ± 15 b	248 ± 36 a	¥
Diphterophoridae	*Diphterophora*	3	3 ± 1 b	26 ± 10 a	1 ± 1 c	0 ± 0 d	¥
Total fungal-feeders			212 ± 15 b	303 ± 38 a	303 ± 37 a	417 ± 51 a	¥
Qudsianematidae	ND	4	100 ± 12 ab	133 ± 20 a	59 ± 11 c	98 ± 13 bc	¥
Aporcelaimidae	ND	5	10 ± 2 b	11 ± 3 b	39 ± 9 a	10 ± 4 b	¥
Total omnivores			109 ± 12 b	145 ± 19 a	100 ± 17 ab	109 ± 13 b	¥
Mononchidae	ND	4	2 ± 1 a	9 ± 4 a	1 ± 1 a	2 ± 1 a	ns
Total predators			3 ± 1 a	11 ± 5 a	2 ± 1 a	4 ± 2 a	ns
Others[b]			5 ± 2	5 ± 2	5 ± 3	2 ± 1	
Total nematodes			936 ± 49 c	1355 ± 115 ab	1248 ± 137 bc	1672 ± 143 a	¥

The means ± standard errors are presented. The means that differ significantly are denoted with different lowercase letters, and the threshold of significance is specified: ** for significant at 99%, * for significant at 95%, ¥ for significant at 90% and ns for not significant.

[a] ND: Not defined.

[b] Others: *Trichodorus* sp., *Xiphinema* sp., Ecphyadophoridae, *Psilenchus* sp., *Boleodorus* sp., *Acrobelophis* sp., *Acrolobus* sp., *Chiloplacus* sp., Leptolaimidae, Leptonchidae, Belondiridae, *Tripyla* sp. and *Discolaimus* sp.

3. RESULTS

3.1. NEMATODE COMMUNITY COMPOSITION IN THE DIFFERENT PLOTS

In total, 29 families of nematodes were found. Among them, 9 had a very low absolute abundance and a relative density of less than 0.5% of the total nematodes in each treatment: Trichodoridae, Longidoridae, Ecphyadophoridae, Psilenchidae, Leptolaimidae, Leptonchidae, Belondiridae, Tripylidae and Discolaimidae. Their densities are not presented in Table IV- 7. Among the other 20 families, 7 were not identified further to the genus level (Belonolaimidae, Tylenchidae, Rhabditidae, Monhysteridae, Qudsianematidae, Aporcelaimidae and Mononchidae). The lowest total nematode density was measured in the Conventional plots (Table IV- 7). The total nematode density was significantly higher in Organic7 (+45%) and in Organic17 (+79%) than in the Conventional plots. In all of the treatments, facultative plant-feeders and bacterial-feeders were the most abundant trophic groups.

3.2. EFFECTS OF ORGANIC FARMING ON NEMATODE COMMUNITY STRUCTURE

The Permanova analysis showed a significant effect of treatment (p = 0.001; data not shown) on the composition of the nematode community. As shown in Table IV- 8, the nematode community structure was significantly different between the different treatments, except between Organic11 and Organic7 (p-value>0.05). These results are illustrated in Figure IV- 2, which represents the MDS analysis. The Kruskal stress value was 0.18, giving a correct 2D representation (Clarke and Warwick, 2001). The plots were well aggregated for Conventional, Organic11 and Organic17. However, for Organic7, the plots were separated.

Table IV- 8 : Results, presented as P-values, of the Permanova analysis for the comparison of the soil nematode community structure (density of 40 taxa) of the 24 plots among the 4 treatments: conventional farming (Conventional) and organic farming for 7 years (Organic7), 11 years (Organic11) and 17 years (Organic17).

	Conventional	**Organic7**	**Organic11**	**Organic17**
Conventional	-			
Organic7	0.010	-		
Organic11	0.002	0.087	-	
Organic17	0.001	0.016	0.007	-

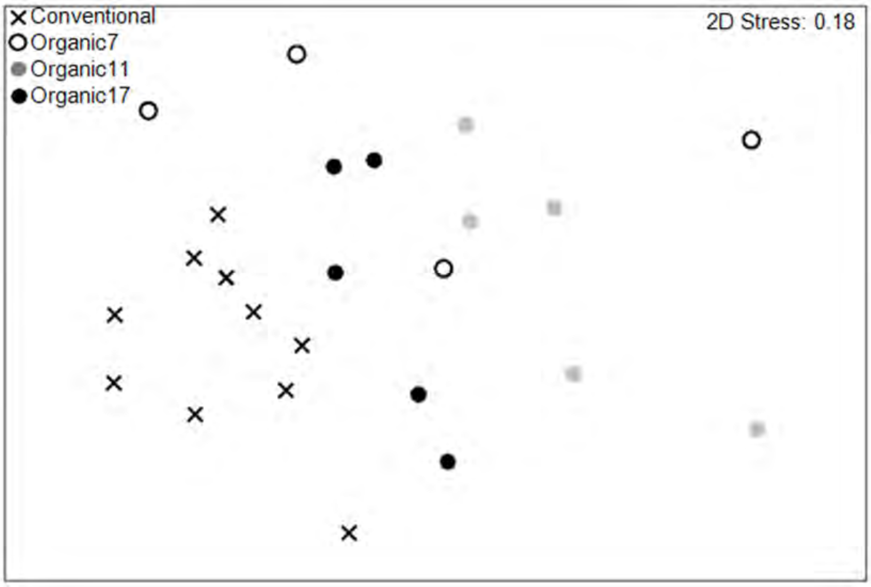

Figure IV- 2 : Representation of the multi-dimensional scaling of the soil nematode community structure (density of 40 taxa) of the 24 plots after conventional farming (Conventional) and organic farming for 7 years (Organic7), 11 years (Organic11) and 17 years (Organic17).

3.3. EFFECTS OF ORGANIC FARMING ON NEMATODE INDICES

No significant difference was observed in the MI, PPI, SI and NCR among the treatments (Table IV- 9). Organic11 and Organic17 had a significantly higher EI than Conventional (+47%), and the highest value of EI was calculated for Organic11. Concerning the CI, Organic11 had a significantly lower value than Conventional and Organic7 (-39%). The NCR_Tyl was significantly lower in Organic17 than in Conventional (-23%).

Table IV- 9 : Nematode indices (maturity index (MI), plant-parasitic index (PPI), enrichment index (EI), structure index (SI), channel index (CI), nematode channel ratio (NCR), nematode channel ratio including Tylenchidae (NCR_Tyl)) in conventional farming (Conventional) and organic farming for 7 years (Organic7), 11 years (Organic11) and 17 years (Organic17).

	MI	PPI	EI	SI	CI	NCR	NCR_Tyl
Conventional	2.33 ± 0.03 a	2.24 ± 0.03 a	37.4 ± 1.8 c	47.6 ± 2.4 a	69.2 ± 3.7 a	0.65 ± 0.02 a	0.52 ± 0.02 a
Organic7	2.37 ± 0.06 a	2.31 ± 0.05 a	44.3 ± 3.3 bc	53.9 ± 4.4 a	60.4 ± 6.5 a	0.59 ± 0.03 a	0.45 ± 0.03 a
Organic11	2.18 ± 0.08 a	2.32 ± 0.04 a	59.9 ± 3.2 a	50.1 ± 3.5 a	39.6 ± 3.8 b	0.58 ± 0.02 a	0.44 ± 0.02 a
Organic17	2.19 ± 0.05 a	2.30 ± 0.04 a	49.9 ± 2.7 ab	41.6 ± 4.0 a	53.8 ± 5.4 ab	0.57 ± 0.03 a	0.40 ± 0.02 b
	ns	ns	¥	ns	¥	ns	¥

The means ± standard errors are presented. The means that differ significantly are denoted with different lowercase letters, and the threshold of significance is specified: ¥ for significant at 90% and ns for not significant.

3.4. EFFECTS OF ORGANIC FARMING ON OBLIGATE AND FACULTATIVE PLANT-FEEDERS

The organic plots had a higher obligate plant-feeder density than the conventional plots (+217%), but no significant difference was found among the organic treatments. In all of the treatments, *Paratylenchus* sp. and Belonolaimidae (mainly *Tylenchorynchus* sp.) dominated, forming 84% of the community in Conventional and Organic7, 51% in Organic11 and 92% in Organic17. The *Paratylenchus* sp. density was significantly higher in Organic7 (+514%) than in Conventional, whereas no significant difference was observed between Conventional and Organic17. For Belonolaimidae, the highest densities were found in Organic7 and Organic17. Organic17 had a significantly higher Belonolaimidae density than Conventional and Organic11. *Helicotylenchus* sp. were significantly more abundant in Organic7 and Organic11 than in Conventional and Organic17. The organic plots had a significantly higher density of *Pratylenchus* sp. than the conventional plots. The highest density of *Pratylenchus* sp. was measured in Organic11 (+309% in comparison with Organic7 and Organic17). Almost no *Xiphinema* sp. were found in any of the treatments, with only 7.5 and 12.1 individuals 100 g^{-1} dry soil for 2 samples (data not shown).

The facultative plant-feeders were nearly all Tylenchidae, which composed more than 99.5% of that community in each treatment. The organic plots had a significantly higher density than the conventional plots, with +65% in Organic7 and Organic11 and +173% in Organic17.

3.5. EFFECTS OF ORGANIC FARMING ON FREE-LIVING NEMATODES

Concerning total bacterial-feeders, no significant difference was measured among the treatments. However, the lowest density was observed in the conventional plots. In Conventional and Organic7, Cephalobidae and Monhysteridae were very dominant (81% and 73%, respectively), whereas in Organic11 and Organic17, the dominant groups were Panagrolaimidae and Cephalobidae (81% and 76%, respectively). In more detail, the density of *Panagrolaimus* sp. was significantly higher in Organic11 than in Conventional and Organic7 (+449%). Organic17 had a significantly higher density of *Panagrolaimus* sp. than Conventional (+300%). For Cephalobidae, we observed a high diversity of the genus in comparison with the other families. *Cephalobus* sp. and *Heterocephalobus* sp. were the most abundant genera in all of the treatments. *Acrobeles* sp. were the least abundant in Organic17. The density of *Acrobeloides* sp. and *Cephalobus* sp. evolved in the same ways after organic conversion: their highest values were observed in Organic7 and Organic17. Organic11 had a significantly higher density of *Eucephalobus* sp. than the other treatments (+100%). Organic17 contained a significantly higher density of *Heterocephalobus* sp. than Organic7 and Organic11. Conventional had the highest Monhysteridae density. After 11 years of organic farming, the density of Monhysteridae increased, and no significant difference was shown between Conventional and Organic17. Organic7 had a significantly higher density of Plectidae (*Plectus* sp. and *Wilsonema* sp.) than the other treatments (+200%). The density of *Prismatolaimus* sp. was significantly lower in Organic17 than in the other treatments (-67%).

The fungal-feeder density increased from Conventional to Organic17. It was significantly higher in Organic7 (+43%) and in Organic17 (+97%) than in the Conventional plots. Organic7 and Organic11 had a significantly higher *Ditylenchus* sp. density than Conventional (+80%). For *Aphelenchus* sp., 2 different groups were identified. Conventional and Organic7 had a significantly lower *Aphelenchus* sp. density than Organic11 and Organic17. For Aphelenchoididae (*Aphelenchoides* sp. and *Aprutides* sp.), Organic17 had a significantly higher Aphelenchoididae density than the other treatments (+82%). A steep increase was observed for the *Diphterophora* sp. density in Organic7. No *Diphterophora* sp. were found in Organic17.

The density of omnivores was significantly higher in Organic7 than in Conventional and Organic17 (+33%). Among the omnivores, Qudsianematidae were the dominant family in each treatment (more than 90% in Conventional, Organic7 and Organic17 and 59% in Organic11). The density of Qudsianematidae was significantly lower in Organic11 than in Conventional and Organic7 (-49%). However, Organic11 had significantly the highest density of Aporcelaimidae (+277% in comparison with the other treatments).

The predators were mainly represented by Mononchidae. No significant difference was observed for the density of Mononchidae, even though the highest value was observed in Organic7.

4. DISCUSSION

4.1. ORGANIC PRACTICES AND NEMATODE COMMUNITY STRUCTURE

This study was conducted on commercial vineyards. Fourteen plots that have been organically managed for 7, 11 and 17 years were compared to 10 conventionally managed plots. We focused on the long-term effects of organic management on nematode community structure. The MDS representation allowed us to clearly distinguish 3 groups: Conventional, Organic11 and Organic17. The Permanova analysis statistically confirmed this observation. The plots of Organic7 could be associated either with Conventional or Organic11. This trend is typical of a transition period, as we discussed in a previous work (Coll *et al.*, 2011). After more than 7 years of organic farming, the nematode community structure was changed by the increase of plant-feeders, particularly facultative plant-feeders, along with fungal-feeders and omnivores. Such differences could be attributed to the greater grass cover development in this vineyard because tillage was the only way of controlling grass instead of chemical weeding. Neher (1999) also observed an increase of plant-feeder density on annual crops (wheat, soybean and corn) that were organically managed for 8 years. The application of compost also explained the increase of fungal-feeder density, as shown by Bulluck *et al.* (2002a) after fertilisation with different kinds of organic matter.

The evolution of the fungal-feeding proportion within microbivorous nematodes was evaluated using the NCR. Even though no significant difference was observed among the 4 treatments for this index, the NCR trended to decrease after the organic conversion (-9% between Conventional and Organic7). The soil organic matter decomposition pathway tended to become more fungal than bacterial after organic conversion (Yeates, 2003), in accordance with the development of a more complex soil organic matter. However, the study of the CI led us to the opposite interpretation because the most predominant fungal-fed trophic channels of the soil decomposer food web were observed in the Conventional plots (Ferris *et al.*, 2001). This opposite information about the soil food web can be explained because the calculation of the CI takes into account only the Ba1- and Fu2-density CI, whereas the NCR considers all of the bacterial and fungal-feeders. Because all of the plots had a low density of Ba1 nematodes, the CI might not be a very pertinent indicator for these vineyard soils. Villenave *et al.* (2010) came to the same conclusion for agricultural soils in Burkina Faso.

4.2. ORGANIC FARMING STIMULATED NEMATODE COMMUNITIES

The increase of plant-feeding and microbial-feeding nematode densities can be related to the significant increase of total organic carbon content after 11 years of organic management (Coll *et al.*, 2011). Indeed, plant-feeders stimulate microbial growth, increasing root-exudation (Bouwman and Arts, 2000; Whitelaw-Weckert *et al.*, 2007), and microbial-feeders stimulate microorganisms by grazing them (Denton *et al.*, 1999; Djigal *et al.*, 2004).

The increase of plant-feeders could be attributed to the development of grass cover in organic plots (Rahman *et al.*, 2009). The PPI did not change among the treatments, whereas Neher (1999) observed a significantly higher PPI value in plots organically managed for 8 years than in plots conventionally managed. In all of the treatments, Tylenchidae dominated the plant-feeder community (66% for Conventional, 51% for Organic7, 59% for Organic11 and 66% for Organic17) and increased significantly in abundance under organic agriculture. Several authors (Okada *et al.*, 2005; Okada and Kadota, 2003; Sohlenius *et al.*, 1977; Todd, 1996; Yeates *et al.*, 1993) showed that Tylenchidae were “root hair-feeding and fungal-feeding nematodes”. In this study, Tylenchidae were classed in a facultative plant-feeder group to isolate them from strict phytoparasitic nematodes. According to the definition of the nematode indices, they were not included in the NCR index, which did not significantly vary between treatments. In contrast, the NCR including Tylenchidae, NCR_Tyl, was significantly lower after 11 and 17 years of organic farming. As a matter of fact, both the facultative fungal-feeders Tylenchidae and strict fungal-feeders increased in abundance with organic farming, whereas the bacterial-feeders remained more or less constant after the conversion.

Concerning the obligate plant-feeders, the 4 main ones, *Helicotylenchus* sp., *Pratylenchus* sp., Belonolaimidae and *Paratylenchus* sp., were consistently more abundant in the Organic plots than in the Conventional plots. Addison and Fourie (2008) assessed the taxa of plant-parasitic nematodes for a vineyard in South Africa as *Meloidogyne* sp., *Xiphinema* sp., *Pratylenchus* sp., *Paratrichodorus* sp., *Longidorus* sp., *Tylenchulus* sp., *Criconematinae* sp., *Rotylenchus* sp., *Helicotylenchus* sp. and *Scutellonema* sp.. These nematodes are also the most abundant in vineyards in other places (Aballay *et al.*, 2009; AlBanna and Gardner, 1996; Zolda and Hanel, 2007). In France, as in many other countries, the most dangerous nematode for adult vineyards is *Xiphinema* sp., which transfers the grape fanleaf virus (GFLV). In our case, this nematode was almost absent in each treatment. However, the *Xiphinema* sp. are mainly located deep in the soil where roots of vines are localised, i.e., at 40–110 cm depth, (Villate *et al.*, 2008), while we sampled at 0–15 cm depth.

Fungal and bacterial-feeders play a role in the composition of soil microorganisms and in the turnover of soil matter and availability of nutrients (Lopez-Fando and Bello, 1995). We observed that fungal-feeder density increased with organic farming, whereas bacterial-feeders did not follow the same pattern. The EI was higher in Organic plots than in Conventional plots even though a significant difference was only observed between Conventional and Organic11. Therefore, there was an enrichment of microbivorous nematodes in Organic plots, as Liang *et al.* (2009) observed after 20 years of organic manure application on maize. In contrast, van Diepeningen *et al.* (2006) observed that mechanical weeding in combination with ploughing enhanced the fungal-feeding nematode populations. Therefore, the replacement of shallow tillage by mouldboard ploughing could promote the development of fungal-feeding nematodes.

We mentioned that the density of bacterial-feeders was not sharply increased with organic farming, even after 17 years of organic management. However, the analysis of taxa revealed some differences in the bacterial-feeding community. Indeed, some taxa reacted positively to organic farming, such as *Panagrolaimus* sp. in Organic11 and *Heterocephalobus* sp. in Organic17. For other bacterial-feeders, we observed positive effects of organic farming during the first years and negative effects after, as was the case of *Eucephalobus* sp. and Plectidae. Concerning the fungal-feeders, the density of *Ditylenchus* sp. and *Diphterophora* sp. increased quickly, i.e., after 7 years, whereas their density decreased after that time. However, *Aphelenchus* sp. and Aphelenchoididae were significantly higher in Organic11 and in Oragnic17, respectively, than in Conventional.

4.3. ORGANIC FARMING DID NOT IMPROVE THE LENGTH AND THE COMPLEXITY OF THE SOIL FOOD WEB

The MI and SI presented no significant difference between Conventional and Organic treatments. Van Diepeningen *et al.* (2006) also found no significant differences in the SI between conventionally and organically managed plots. However, usually, stable environments without perturbation have a high MI (Bongers, 1990) and a high SI (Ferris *et al.*, 2001). The stagnation of the MI and SI after organic conversion revealed no increase in the proportion of persistent free-living nematodes, mainly including omnivores and predators but also fungal-feeders and bacterial-feeders. Thus, the organic practices are not less perturbing for soil nematodes than conventional ones. Tillage is probably the worst organic practice affecting soil organisms, as found by Villenave *et al.* (2009a) and Villenave *et al.* (2009b). Lopez-Fando and Bello (1995) also observed a decrease in the total number and diversity of soil nematodes in cereal agro-ecosystems with tillage. In our study, the organic farming was characterised by mouldboard ploughing, which is associated with soil compaction due to more intensive traffic, and the accumulation of copper from fungicides (Coll *et al.*, 2011). These modifications were important enough to prevent an improvement of soil stability. We specifically highlighted the negative effects of organic farming on Monhysteridae after 7 years of organic farming, on Qudsianematidae and *Diphterophora* sp. after 11 years, and on *Acrobeles* sp. and *Prismatolaimus* sp. as observed in Organic17. Korthals *et al.* (1996) and Villenave *et al.* (2001) also showed that *Acrobeles* sp. are sensitive to perturbations.

For *Acrobeles* sp. and *Prismatolaimus* sp., there was no difference between Conventional, Organic7 and Organic11, but there was a significant decrease in their population density after 17 years of organic farming. We hypothesise that copper accumulated in soil and reached a toxic level for these nematodes, as previously mentioned by Bakonyi *et al.* (2003). Indeed, Georgieva *et al.* (2002) showed a negative effect of Cu on *Acrobeles* sp. Furthermore, we expected to observe a higher diversity under organic plots. In our case, we did not confirm this hypothesis because nearly all of the genera or families were observed in each of the treatments. Except for the very rare nematodes classed as "others", only *Alaimus* sp. and *Diphterophora* sp. were absent in Organic11 and Organic17, respectively.

5. CONCLUSION

We demonstrated that organic farming tends to increase the density of microbial-feeding and particularly opportunistic fungal-feeding nematodes, indicating an increase in nutrient resource availability. The presence of a grass cover increased the density of plant-feeding nematodes. The fungal decomposition channel increased relative to the bacterial decomposition channel, revealing a change in the soil organic matter quality. Although we observed a change in the nematode community structure, the MI, PPI and SI indices remained constant, therefore organic farming did not clearly lead to a functional modification or an improvement of the soil food web length or complexity.

Acknowledgements

We thank Louis Fabre, Xavier Sabouraud, Regis Loevenbruck, Jean-Jacques Loze and Gérard Pélissa for allowing us to analyze their vineyards. Special thanks go to Jean-Pierre Barthès for his expert advice on soils, Inès Sneessens for her help with the laboratory analyzes, Edith Le Cadre for her advice on the manuscript, and Julien Papaïx and Philippe Deleporte for assistance with statistics.

Patrice Coll's PhD grant was provided by the Agence de l'Environnement et de la Maîtrise de l'Energie (ADEME, France) and by Montpellier SupAgro (France). This study was financially supported by the INRA AIDY project (Analyze Intégrée de la DYnamique des systèmes biophysiques, techniques et de décision lors de la conversion à la viticulture biologique).

CHAPTER V

RELATIONSHIPS BETWEEN EARTHWORMS AND ELECTROMAGNETIC INDUCTION (EMI) MEASUREMENTS EN VINEYARDS

In the two previous chapters, I showed the interest of earthworms as sensitive indicators of agricultural practices. However, the classic methods of sampling (spraying soil with an expellant and hand sorting) need a lot of means, above all manpower, that can limit the study of earthworms. So, it is necessary to develop simpler methods to estimate earthworm presence. Through a fruitful collaboration between the Joint Unit Research Eco&Sols and the University of Basilicata in Italy, we studied a relationship between abundance and biomass of earthworms and electromagnetic induction measurements.

RELATIONSHIPS BETWEEN EARTHWORMS AND ELECTROMAGNETIC INDUCTION (EMI) MEASUREMENTS EN VINEYARDS

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2011, article in preparation.

Abstract: Non-invasive geophysical methods, such as EMI (Electromagnetic Induction), are innovative instruments to study soil biological parameters. This work was carried out to assess correlations between soil earthworm abundance and biomass and soil apparent electrical conductivity (EC_a) measured by means of a Profiler GSSI EMP-400. The trial was performed in a 9 commercial vineyards located in South of France. Mustard and hand-sorting method was used to sample earthworms. Earthworm abundance and biomass were correlated to EC_a also under different soil management conditions. EMI technique seems to be a very efficient tool to locate representative soil sampling areas and spatialize earthworm parameters at the field level.

1. INTRODUCTION

In agro-ecosystems, earthworms play a key role in promoting soil fertility (Cenci and Jones, 2009). Furthermore, because of their strong interaction with soil, earthworm communities are also profoundly affected by agricultural practices, such as soil tillage, crop residues restitution, use of fertilizers and organic and mineral pesticides (Chan, 2001; Eijsackers et al., 2005). Moreover, they are sensitive to both chemical and physical soil parameters (Coll *et al.*, 2011; Paoletti, 1999). Earthworm presence, abundance and diversity are often considered, alone or integrated with other indicators, as indexes of soil quality status (Bispo *et al.*, 2011; Franzle, 2006). Earthworm abundance increase in soil managed with grass cover but still more in soil managed with chemical weeding practices (Vrsic, 2011). About soil tillage, it showed a negative effect on earthworms (Paoletti et al., 1998; Pérès et al., 2010).

Even if earthworms are very interesting to study, their sampling is not easy whatever the sampling method. There are different methods of sampling, by physical process (Bouché, 1969), with chemical products such as formaline (Raw, 1959) or by electroshocking (Osterholz, 2006), but all show many difficulties and some are toxic for operators (Eichinger et al., 2007). Moreover, all these methods are labor intensive and time consuming, especially in wet and heavy soils (Bouché and Aliaga, 1986) and also in stony soils. They also need a sophisticated logistic. Recently, innovative and no harmful extracting substance as mustard was used (Chan and Munro, 2001), with positive results (Lawrence and Bowers, 2002; Pelosi et al., 2009). Mustard suspension shows no phytotoxic effects contrary to formalin and is safe for men and environment (Valckx *et al.*, 2011).

The non-invasive biogeophysical techniques, such as ElectroMagnetic Induction (EMI), can be an useful tool to study the soil distribution of the physical and chemical characters strongly conditioning earthworm vital cycle. Indeed, the measurement of apparent soil electrical conductivity (EC_a) by EMI has become an invaluable tool for identifying the spatial variation of the soil physical and chemical properties (Corwin and Lesch, 2003; Davies, 2004; Doolittle *et al.*, 2001; Morari *et al.*, 2009; Tromp-van Meerveld and McDonnell, 2009). Several factors influence the apparent electrical conductivity (EC_a) like soil water content and conductivity, soil texture, skeleton, temperature, clay content, mineralogy, cation exchange capacity, organic matter content and bulk density (Bronson *et al.*, 2005; Chen *et al.*, 2004; Corwin and Lesch, 2003; Domsch and Giebel, 2004; Friedman, 2005; Rhoades *et al.*, 1999). Soil EC_a is an integrated value of the soil properties (Valckx *et al.*, 2011; Vitharana *et al.*, 2006).

Through geophysic methods, innovative and rapid instrumentations, potential habitats for biota in soils may be characterized and identified. EC_a mapping has successfully been applied in soil-microbiological studies in agricultural soils and the potential of the EC_a approach becomes to be used for to reference to soil-biota distribution and activity (Joschko et al., 2010). Recent study showed that species spatial distribution can be evaluated by EC_a measurements (Valckx *et al.*, 2011).

EC_a signals can be used firstly to identify areas with a homogeneous physical-chemical basis where earthworm abundance and biomass measurements can be made.

In this work, we searched relationships between soil ECa and earthworm density and biomass on different earthworm ecological categories (anecics and endogeics) evaluating soil properties (water content, pH and skeleton) and different soil management effects on earthworms. The present study was conducted on 9 vineyard plots: 3 with grass cover (GC), 3 with chemical weed control (CW) and 3 with soil tillage (T).

2. MATERIALS AND METHODS

2.1. STUDY SITES, MANAGEMENT AND FIELDS PLOT DESIGN

The experimentation was conducted in 9 commercial vineyards located in Saint-Victor la Coste, South of France, in the Languedoc-Roussillon Region 44° 04’ 44.65’’ N, 4° 38’ 47,12’’ E, 85-100 m elevation. The climate is typically Mediterranean with 14.8°C mean annual temperature, 776 mm of annual rainfall and 1418 mm of annual ETP Penman-Monteith (average value based on data collected from 2000 to 20010 by Météo-France). The commercial wine grape vineyard plots studied are around 1 ha large. They presented different varieties of grape (*Vitis vinifera* L.) such as Cabernet-Sauvignon, Carignan N, Grenache N, Merlot Mourvèdre and Syrah. The rootstocks were mainly R110 and SO4. The year of plantation varied from 1950 to 1999 and the vine density was comprised between 4,000 and 5,000 vines per hectare.

So, we sampled plots with contrasted management (Table 1): 3 with permanent grass cover (GC), 3 were chemically weeded (CW) and the last 3 were tilled (T). Tilled plots have been organically managed since September 2006. Soils are calcisols (IUSS Working Group WRB, 2006b), Soil practices were identical for each treatment before the conversion as well as tilled agricultural practices after the conversion. Some plots present minimal slope. Skeleton in all plots was 55.9 ± 36.6 g kg^{-1}. The soils were Sandy Clay Loam, with 15.1 ± 2.5 % of clay, 33.2 ± 5.3% of silt and 51.7 ± 6.9% of sand. Organic C and total N were respectively 14.2 ± 4.7 and 1.05 ± 0.30 g kg^{-1}. Soil was calcareous (total $CaCO3$, 220 ± 70.9 g kg^{-1}), yielding a pH in water of 8.28 ± 0.17. The soil water-holding capacity was

12.6 ± 0.4% (w/w) and total porosity 0.46 ± 0.01 (v/v). In Table 1 are resumed principal soil management information for plots.

Table V- 1 : General soil management characteristics for typologies.

Typology	Grass-cover (GC)	Chemical weeding (CW)	Tillage (T)
Plots	3	3	3
Soil Management	Conventional	Conventional	Organic
Dominant treatment	Grass cover	Chemical weeded	Tillage
Fertilization	No	No	Organic (guano, 1.5 t y^{-1})
Number of soil tillage / year	0	0	7
Tillage depth (m)	-	-	0.15
Cover crops	Spontaneous permanent	Spontaneous temporary	Spontaneous temporary
Chemical Weeding treatment	1 (glyphosate)	2-3 (glyphosate)	-
Conversion date	-	-	2006
Plant Residues management	Mulching	Mulching	Burying

2.2. ELECTROMAGNETIC INDUCTION MEASUREMENTS

Electromagnetic induction (EMI) measurements were carried out on February 15-16th, 2011 in each plot with a multi-frequency EMI sensor (GSSI Profiler EMP-400). The Profiler is a multifrequency Electro-Magnetic Induction (EMI) sensor, which can operate to measure simultaneously up to 3 frequencies between 1 kHz and 16 kHz, with intercoil spacing of 1.2 m. For this study, we operated at 3, 8 and 15 kHz to have information about different soil layers. The instrument was used in vertical dipole mode (VDP). The depths of the magnetic field penetration were about 1.5 m for VDP modes (Allen *et al.*, 2007; Geonics Limited, 1998). The instrument sensitivity varies as a non-linear function of depth (McNeill, 1990). EC_a value outputs (apparent electric conductivity, mS m^{-1}) of the Profiler were used. The instrument was calibrated according to its technical standards. The acquisition modality was each 0.75 second in continuous mode data collection. ECa measurement was made walking along each inter-row at a speed of about 4-5 km h^{-1}. All EC_a points acquisition were georeferenced using the Tripod Data System Recon PDA with integrated Bluetooth service and Holux™ WAAS-GPS with differential correction HDOP allows one to estimate the accuracy of GPS horizontal (latitude/longitude) position fixes by adjusting the error estimates according to the geometry of the satellites used. For each plot measurements were hooked never less ten satellites.

To product EMI map, survey data collected were processed by kriging method – singular cell 1x1 meter, using MagMap2000© and Surfer Golden©.

EC_a measurement was effected in the same conditions for all plots. The spatial variability of soil EC_a measurements from the profiler EMP-400 systems was evaluated through both classical statistics and geostatistical techniques for each frequency. In elaboration phase of the EC_a data anomalous or values acquired near the vineyard metallic tutor were erased.

2.3. EARTHWORM SORTING

Two days after EMI surveys, earthworms were sampled on four sub-plot per plots, in the center of the inter-row. In all plots, the average distance between earthworm sampling areas was 56.3±29.1 meters (range from 19.6 to 172.4 meters). Sampling was undertaken using a frame (1 m x 1 m) which was placed on the soil (Pelosi et al., 2009). Ten liters of mustard solution, used as expellant (Amora® commercial mustard “fine et forte” was thoroughly mixed with water to obtain a solution at a concentration of 15 g l^{-1}) were applied three times at 10-min intervals. Emerging earthworms were sampled manually after every mustard solution application. Then, a 25x25x15 cm deep block of soil was excavated at the middle of each place and earthworms in the sampled soil were sorted by hand. Earthworms were placed in 75% alcohol solution, then transferred into a 4% formaldehyde solution to be stored.

2.4. SOIL SAMPLING IN SELECTED PLOTS

Two days after earthworm sampling, soil samples were taken in a grass cover (1GC), a chemical wedded (1CW) and a tilled (1T) plots, each of these plots being representative of the different vineyards management. Boreholes were identified for each plot: 18 ones for plot 1GC according to a grid pattern of 25x15 m, 24 ones for plot 1CW according to a grid pattern of 15x10 m and 20 ones for plot 1T according to a grid pattern of 20x15 m. On each borehole, soil was sampled in the center of the inter-row with a gauge auger at 0-15 cm, 15-30 cm and 30-45 cm depth. Consequently, 186 samples were collected in total.

2.5. SOIL SAMPLE ANALYZES

Soil used to measure gravimetric water content was dried at 105°C for 1 week and weighted rapidly thereafter. Soil volumetric water content (θv, mm mm^{-1}) was obtained multiplying the gravimetric water content (θw, g g−1) by the soil bulk density (Gardner, 1986). Electrical conductivity (water:soil sample, 1:2.5) was measured in the laboratory according to (Rhoades, 1982) by a Crison 525 conductivimeter (Crison, Barcelona) on a thoroughly shaken mix of soil (1.0 g dry weight) and distilled water (2.5 ml).

Earthworms were gently dried before being weighed and counted after being separated in two ecological categories: endogeics and anecics. Earthworm abundance and biomass were calculated per m^2 of the soil surface.

2.6. STATISTICAL ANALYSIS

Descriptive statistics of measured parameters were calculated. ANOVA on earthworm abundance and biomass were performed.

Interpolation of measured EC_a and soil water content were carried out using kriging method with 1 m^2 cell dimensions (Surfer Golden Software). In order to identify univariate relationships between EC_a, soil volumetric water content, earthworm abundance and biomass, and other soil parameters, linear regression were calculated.

In order to identify univariate association between EC_a and soil volumetric water content, different statistical models were tested for each data group. Statistical regression analysis, showing minimization of the sum of square residuals, normal distribution of the data residues, and the highest statistical significant relationship was selected.

Stepwise linear regression (forward method) was performed to analyze multivariate relationships between EC_a, earthworm and soil parameters.

Statistical analysis was performed using STATISTICA® 6.0 (Stat-Soft, Inc.; www.statsoft.com).

3 RESULTS

3.1. EC_A IN THE THREE REPRESENTATIVE PLOTS

Figure V- 1 shows EC_a spatial variation in selected plots 1GC at 15, 8 and 3 kHz frequencies used. These maps indicate that electrical conductivity increases with soil depth, but that this increase varies from area to area.

In CW, EC_a ranged from 0.1 to 75.1 mS m^{-1} with mean at 20.5 ± 8.3 mS m^{-1}. EC_a values in GC floating from 0.1 to 33.4 mS m^{-1} with mean at 16.54 ± 3.4 mS m^{-1}. Finally, in T, EC_a ranged from 4.3 to 44.7 mS m^{-1} with mean 21.5 ± 5.1 mS m^{-1}. Between soil management groups no significant difference were found in EC_a values.

In the plot 1GC, we can identify a central area more conductive; 1383 EC_a values ranged from 14.6 to 24 mS m^{-1} at 15 kHz frequency, with average at 20.8 ± 1.1 mS m^{-1}. In the plot 1CW (maps not showed) there was high resistivity (EC_a about 0-15 mS m^{-1}) along the east margin. The EC_a values increased steadily along the transverse axis of the field, following soil volumetric water content increase (map not shown); 1326 EC_a values ranged from 0.1 to 34.5 mS m^{-1} at 15 kHz frequency with average close to 14.6 ± 9.4 mS $m^{-1}$and coefficient of variation at 1.5 (%).

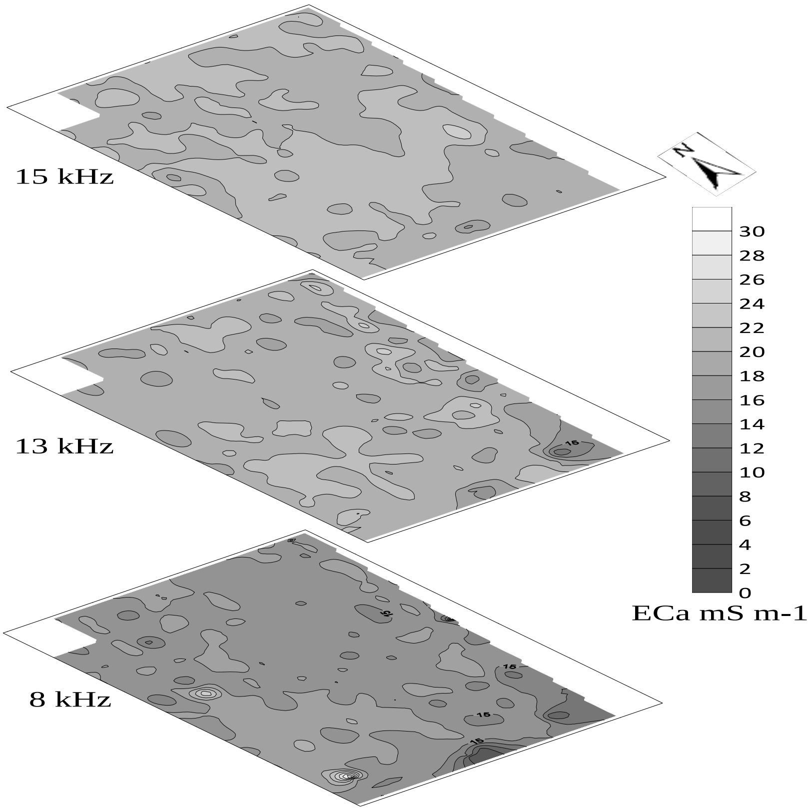

Figure V- 1 : EC_a maps at 1GC plot.

In the field tilled 1T (maps not showed) an increase of apparent electrical conductivity was seen towards the south, where the slope of the ground was slightly higher. Within the range of breweries and more longitudinal conductive areas which have stored a greater amount of water as a result of repeated mechanical workings of the soil, from the outside inwards to the central zone. In this last selected plot, at 15 kHz frequency studied, EC_a values ranged from 4.8 to 35.7 mS m^{-1} with average 26.0 ± 3.3 mS m^{-1} .

3.2 CHARACTERISTICS OF THE SAMPLED SOILS

Data of the measured soil parameters are reported in Table 2. Analysis showed that the skeleton represented less than 1% of the total soil mass in the three studied plots. Generally, skeleton, slightly increase in sampling depth. With an average pH of 8.1, soils are tending to alkaline class. No significant difference in pH between soil depths (± 0.5) was measured. The conductivity of the soil, determined in the laboratory, was higher in 1GC than in the other two. A sharp reduction in the value of conductivity was measured in 1CW with increasing soil depth. Soil volumetric water content tended to increase with depth in all three fields.

Table V- 2 : Soil characteristics of 1GC, 1CW and 1T plots. Capital letters indicate soil depth (A = 0-15 cm ; B = 15-30 cm ; C = 30-45 cm).

		pH			**Conductivity** mS m^{-1}			**Humidity** (v/v)			**Skeleton**			**EC_a frequencies** (kHz)		
		A	B	C	A	B	C	A	B	C	A	B	C	15	8	3
1GC	ū	8.4	8.4	8.4	180	178	183	17.0	19.4	21.4	0.4	0.5	0.7	21.0	20.2	16.7
	RSD	0.04	0.04	0.05	0.22	0.20	0.19	0.09	0.09	0.10	0.39	0.28	0.63	0.03	0.04	0.05
1CW	ū	8.0	8.0	8.0	182	154	135	9.4	14.2	18.8	0.5	0.5	1.0	1.9	10.2	16.3
	RSD	0.01	0.01	0.02	0.30	0.24	0.16	0.25	0.33	0.16	1.64	1.78	1.34	3.69	0.61	0.42
1T	ū	7.9	7.9	7.9	180	175	178	16.7	19.3	23.5	0.3	0.6	0.8	28.4	28.8	31.5
	RSD	0.03	0.02	0.05	0.29	0.21	0.21	0.13	0.12	0.10	0.41	0.74	0.62	0.16	0.17	0.18

3.3. RELATIONSHIPS BETWEEN SOIL APPARENT CONDUCTIVITY (EC_A) AND SOIL ABIOTIC CHARACTERISTICS.

3.3.1. SOIL WATER CONTENT (ΘV)

The best statistical model describing the relationship between EC_a and θ_v was the linear Eq. (3) $\theta_v = \beta_1 EC_a + \beta_2$.

In order to evaluate the error linked to the use of the founded linear relationship, all field EC_a values and soil volumetric water content laboratory data (n=62) were randomly splitted in two dataset by simple random sampling without replacement: a training dataset (dataset I, n=40) and a validation dataset (dataset II, n=22).

$\theta_{ve}= EC_a \beta_1 + \beta_2$ where the parameters named β_1 and β_2, coming from dataset I regression, had values of 0.89 and +1.9, respectively. The estimated θ_{ve} values were then regressed on θ_{vm} values and θ_{ve}–θ_{vm} pairs were compared by the Wilcoxon signed-rank test. The error linked to θ_v evaluation of dataset II samples by means of the relationship built on dataset I was very low and not statistically different according to the Wilcoxon signed-rank test. When applied to dataset II (n=22), the regression equation obtained from dataset I (n=40) yielded θ_{ve} values that were highly correlated ($p>0.001$, n=40) with θ_{vm} values, and were not significantly different according to the Wilcoxon signed-rank test. According to these evaluations, spatial and temporal variability of soil volumetric water content was estimated using the linear model equation resulting from the statistical relationship between all EC_a and all θ_v data (n=62).

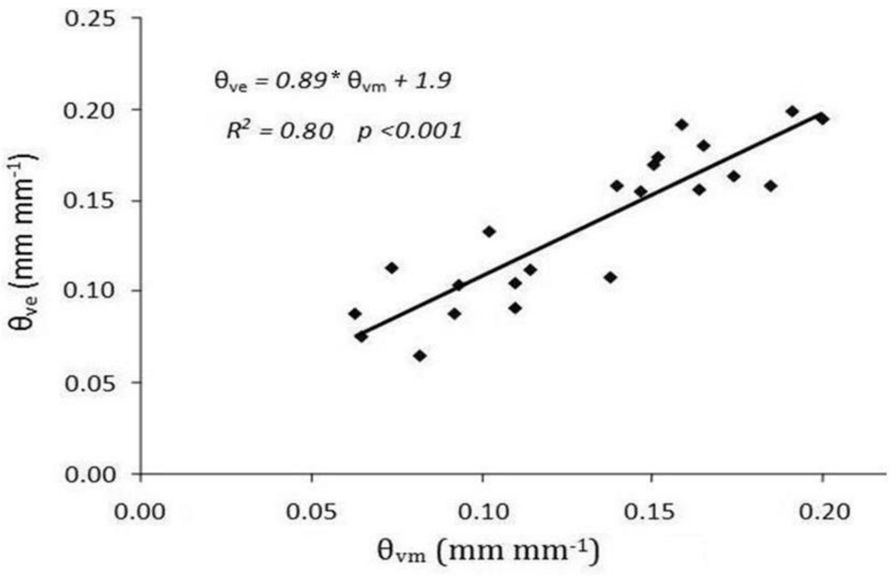

Figure V- 2 : Scatterplot of estimated versus measured volumetric water content values (θ_{ve} versus θ_{vm}).

3.4. RELATIONSHIPS BETWEEN SOIL APPARENT CONDUCTIVITY (EC_A) AND EARTHWORM ABUNDANCE.

Earthworm abundances in February 2011 in the vineyard sampled at Saint-Victor la Coste ranged between 0 and 283 individuals per m^{-2}. Earthworm biomass varied between 0 and 105.1 g m^{-2}.

Earthworms were more abundant under CW compared to T and GC (Table V- 3). In CW earthworm abundance was 129.9 ± 77.6 individuals m^{-2} and biomass was 48.4 ± 23.0 g fresh weight m^{-2}. In GC abundance was 71.3 ± 36.9 individuals m^{-2} and biomass was 38.6 ± 28.1 g fresh weight m^{-2}. Finally in T, abundance was 20.0 ± 28.2 individuals m^{-2} and biomass was 6.2 ± 3.3 g fresh weight m^{-2}.

Table V- 3 : Density and biomass of anecic, endogeic and total earthworms in plots managed by grass cover (GC), chemical weeding (CW) and tillage (T).

	Density (ind m^{-2})			Biomass (g m^{-2})		
	Anecics	Endogeics	Total	Anecics	Endogeics	Total
GC	17 ab	54 ab	71 b	31.8 a	6.8 a	38.6 a
CW	41 a	88 a	129 a	42.7 a	5.7 ab	48.4 a
T	3 b	21 b	24 c	1.3 b	2.3 b	3.6 b

Means are represented. Means differing significantly are denoted with different letters at $p<0.05$

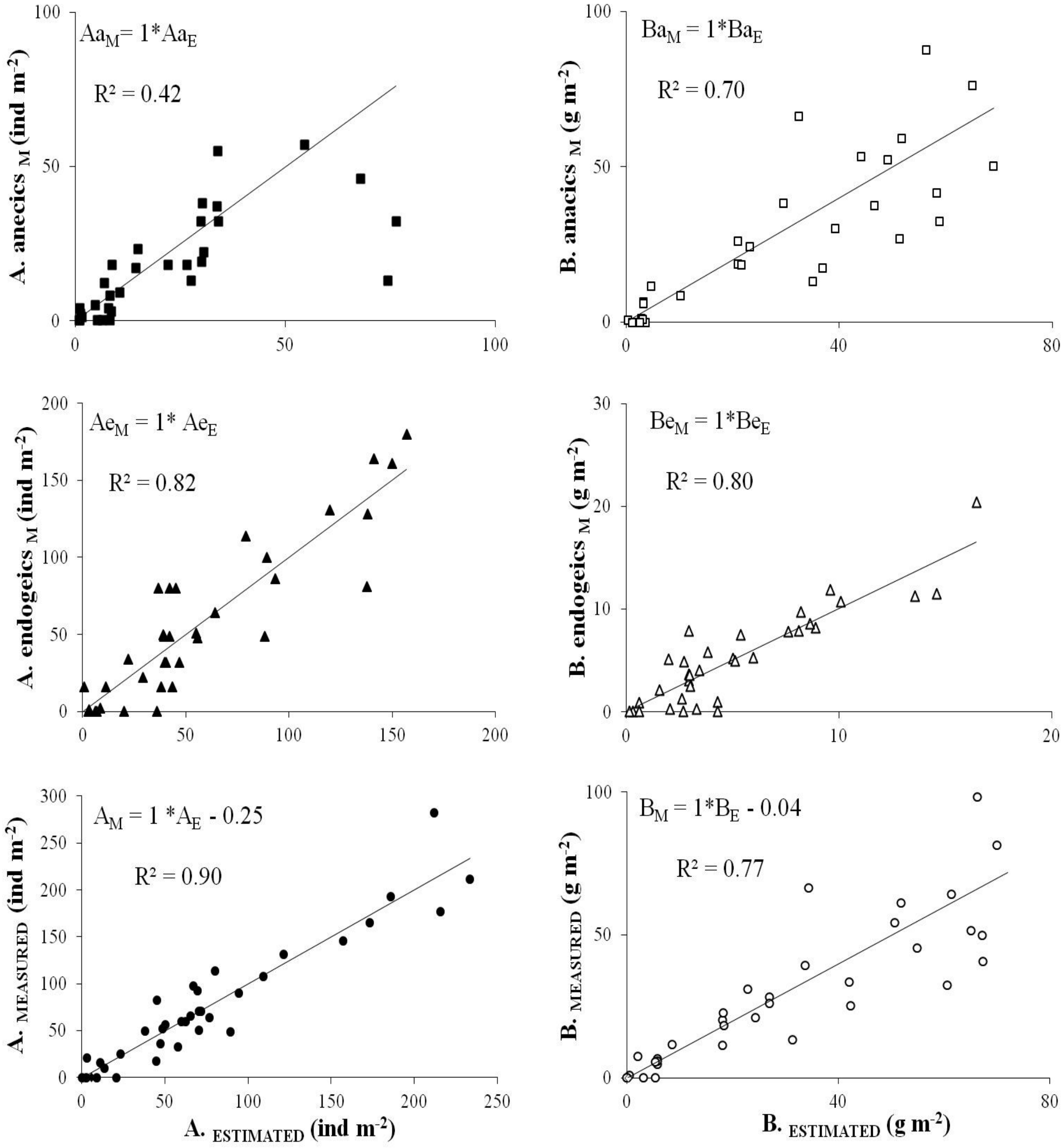

Figure V- 3 : Relationships between EC_a and biomass and abundance in anecics and endogeics earthworm categories.

In CW, EC_a ranged from 0.1 to 75.1 mS m^{-1} with mean at 20.5 ± 8.3 mS m^{-1}. EC_a values in GC floating from 0.1 to 33.4 mS m^{-1} with mean at 16.54 ± 3.4 mS m^{-1}. Finally, in T, EC_a ranged from 4.3 to 44.7 mS m^{-1} with mean 21.5 ± 5.1 mS m^{-1}. Between soil management groups no significant difference were found in EC_a values.

All estimate values (n=36) obtained using plot site-specific relationships (EC_a versus biomass abundance) were plotted against measured values (Figure V- 3). Coefficient of determination (R^2) results higher for abundance then for biomass values. Between earthworm categories, endogeics showed R^2 values higher than anecics.

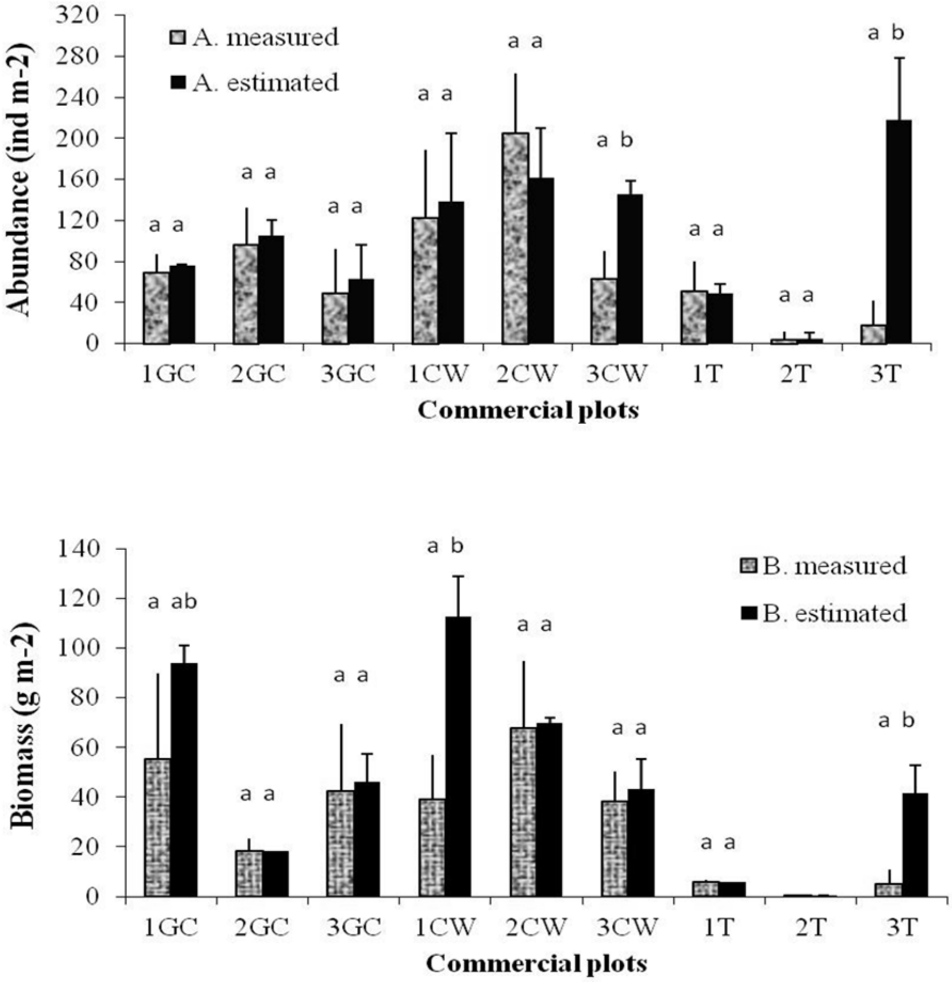

Figure V- 4 : Estimated accuracy in each vineyard plots.

4 DISCUSSION

This study demonstrated the interaction and relationships of EC_a with physical chemical soil properties, and with earthworm abundance and biomass under different vineyard management: in grass cover, chemical weeded and tilled vineyard.

EC_a values, measured in this situation, were typical of a resistively soil (Celano *et al.*, 2011; Hagrey al *et al.*, 2004). They rose as the used wavelengths decreased and soil depth exploration increased. In spite of this, in all plots, EC_a distributions were very similar for all the frequencies used.

The significance of within-field spatial variability of soil properties has been scientifically acknowledged and documented (Corwin and Lesch, 2003; Davies, 2004; Doolittle *et al.*, 2001; Morari *et al.*, 2009; Tromp-van Meerveld and McDonnell, 2009). The electrical conductivity is a function of a number of soil properties namely texture, water content and salinity (Samouëlian et al., 2005). The use of the EMI technique allows to investigate the spatial variability of soil and to relate to its chemical - physical properties. In our case of study, these relationships of measured parameters have been biased by elevated water content of soils.

Relationships between EC_a values and skeleton, pH and electrical conductivity in laboratory, showed different interaction but not significant correlations in all 3 plots. Values of pH, conductivity, and skeleton showed more close relation with EC_a at 8 kHz, respectively with 0.18, 0.16 and 0.41 (R^2).

Sandy soil of studied plots are relatively not evolved and with a scarce content of soluble salts attested by the low electrical conductivity measured. Soil water content results the dominant variable of the ECa in this pedoclimatic conditions.

Stronger relation was found between soil water content and EC_a values. In fact, soil conductivity increases when the water content increases (Celano *et al.*, 2011; Hagrey al *et al.*, 2004; Lazzari *et al.*, 2008; Samouëlian *et al.*, 2005). In particular, the conduction of electrical current in sandy soils is mainly electrolytic, based on the displacement of ions in the solution circulating in the pores of the soil, and therefore it is higher with the presence of dissolved salts. Thus, the electrical current in soils depends both on the amount of water in the pores and on water quality (Celano et al., 2011). High relationship reliability between soil water content and EC_a, allows us to benefit from field measurements. Through the use of EMI technique is possible to spatialize water distribution at field scale. This is an important parameter for growth and development of earthworms (Dominguez and Edwards, 1997; Gunadi *et al.*, 2003; Reinecke and Venter, 1987).

Our study focus, also, on strong relationships found between EC_a measurements and earthworm abundance and biomass for anecics and endogeics.

The estimated values of the earthworms total biomass and abundance align very well to the respective values measured (Figure 3). According to the different categories of earthworms, the strongest relationships are found for endogeic groups (Figure 3). This could be attributed to the lesser sensitivity of this earthworm group to soil management practices with respect to anecics (Wyss and Glasstetter, 1992). Therefore, the relation between anecic earthworm group with EMI signal, as an integrated value of soil physical-chemical conditions, is attenuated.

The relationship between EC_a and earthworm abundance and biomass, however, was not constant across the sequence of observations, but was influenced by the soil management practices. Such finding confirms that disturbance factor, such as tillage significantly affected earthworm biology (Chan and Munro, 2001; Pommeresche and Loes, 2009; Rasmussen, 1999). In grass cover and chemical weeded plot, these correlations can be using as to spatialize earthworms in the soil (Figure V- 4). These, are equilibrating soil systems, where, earthworm population search and found best life condition (good moisture range, high porosity, medium pH, proper salinity, substrate availability, etc) seating and performing their biological functions.

5 CONCLUSION

This finding suggests to verify the possibility of defining an integrated procedure (classical sampling methods combined with geophysical measurements) for earthworm community assessment under different pedoclimatic conditions. According to this innovative procedure, EC_a signals should be used firstly to identify areas with a homogeneous physical basis where earthworm abundance and biomass measurements could be studied. Once defined the relation EC_a *versus* earthworm parameters and its significance, it could be possible to spatialize such parameters at whole field level. Besides the substantial reduction of soil samplings number, the integrated procedure could give back a better picture of soil biological status by mean of earthworm parameters. Obviously, in order to verify the efficiency of this innovative method, the obtained data should be compared with values coming from the application of the classical assessment techniques (random sampling, mesh sampling) characterized by high statistical basis.

Acknowledgments

We thank “Victor Contis” Association for allowing us to analyze their vineyards in Saint Victor la Coste. We also thank Abid Hussain, Zeeshan Majeed and Yulia Kiryakova for their help in soil sampling. This work was financially supported by the Doctoral school “Crop Science and Environmental Science” of University of Basilicata.

CHAPTER VI

LA QUALITE DES SOLS : ASSOCIER PERCEPTIONS ET ANALYSES DES SCIENTIFIQUES ET DES VITICULTEURS

One of the long-term objectives of my PhD is to propose to winegrowers an operational set of physical, chemical and biological indicators of soil quality in order to adopt more sustainable agricultural practices. Thus, in order to facilitate the communication between scientists and winegrowers, I analyzed the winegrower perception of soil quality and their knowledge about soil functioning. This subject is developed in the following chapter.

LA QUALITE DES SOLS : ASSOCIER PERCEPTIONS ET ANALYSES DES SCIENTIFIQUES ET DES VITICULTEURS

Patrice Coll, Ronan Le Velly, Edith Le Cadre et Cécile Villenave

2011, *Etude et gestion des sols,* Soumis.

Résumé : Ce travail s'inscrit dans un projet de recherche visant à proposer aux viticulteurs un outil d'évaluation de la qualité de leurs sols, afin qu'ils puissent adopter des itinéraires culturaux plus respectueux de l'environnement. Afin d'accroître la transférabilité de cet outil, il est nécessaire de mieux connaître quelle(s) définition(s) les viticulteurs donnent de la qualité des sols et quels moyens ils utilisent pour l'évaluer. Pour répondre à ces questions, une enquête par entretien compréhensif a été réalisée auprès de 29 viticulteurs de 4 zones différentes du Languedoc-Roussillon (sud de la France). L'enquête a montré que les registres de la qualité des sols évoqués par les viticulteurs rappellent en de nombreux points les définitions proposées par les scientifiques, mais qu'ils ne s'y superposent pas. L'étude des indicateurs utilisés par les viticulteurs a également révélé le besoin d'outils diversifiés, performants et opérationnels pour évaluer la qualité des sols.

Mots-clés : vigne, perception, définition, indicateurs, facteurs explicatifs.

SOIL QUALITY : ASSOCIATE PERCEPTIONS AND ANALYZES OF SCIENTISTS AND WINEGROWERS

Summary : This work is included in a research project whose the objective is to suggest to wine-growers an evaluation tool of the soil quality to adopt agricultural practices more respectful to the environment. To increase the transferability of this tool towards wine-growers, it is necessary to best know what definition(s) of soil quality can give the wine-growers and what mean(s) they use to evaluate it. To answer to these questions, an investigation by understanding interview was realised on 29 wine-growers from 4 different areas of Languedoc-Roussillon (South of France). This study showed that registers of soil quality given by wine-growers remind in numerous points the definitions proposed by scientists. The study of indicators which were used by winegrowers revealed too the need of diversified, efficient and operational tools to evaluate soil quality.

Key words : vineyard, perception, definition, indicators, explicative factors.

1. INTRODUCTION

En France, la vigne est conduite en grande majorité selon des pratiques conventionnelles qui ont parfois un effet défavorable sur le sol favorisant le tassement (Coulouma *et al.*, 2006), l'érosion (Le Bissonnais *et al.*, 2007), l'accumulation du cuivre (Saby *et al.*, 2011), la diminution de la biomasse microbienne (Dequiedt *et al.*, 2011). Or, le sol joue des rôles importants pour les agroécosystèmes, notamment pour les cultures pérennes comme la vigne. Il constitue le support physique des cultures et intervient dans la nutrition hydrique et minérale des plantes. Le sol constitue aussi l'habitat d'une grande quantité d'organismes qui jouent des rôles importants dans la structuration du sol et la dynamique de la matière organique et des éléments nutritifs. De plus, le sol est une composante essentielle du Terroir (Van Leeuwen and Seguin, 2006), notion chère à la filière vigne et vin.

Dans ce contexte, un projet de recherche a été conduit pour évaluer la qualité des sols viticoles à partir d'indicateurs physico-chimiques et biologiques potentiellement modifiés par les pratiques culturales. Les deux principaux objectifs de ce travail étaient (1) d'étudier les effets des pratiques culturales sur la qualité des sols et (2) de définir des gammes de variation pour ces indicateurs dans le contexte de la viticulture en Languedoc-Roussillon. L'enjeu finalisé est de proposer aux professionnels de la filière viticole un outil d'évaluation de la qualité des sols, afin qu'ils puissent en analyser la durabilité et adopter des itinéraires culturaux plus respectueux de l'environnement. Ainsi, il est nécessaire de mieux connaître les relations qu'entretiennent les viticulteurs avec leurs sols : y apportent-ils une attention particulière ? Quels sont, selon eux, les facteurs de qualité d'un sol ? Ont-ils déjà des outils d'évaluation de la qualité des sols ? A l'instar de nombreux travaux (Ali, 2003; Andrews *et al.*, 2003; Barrios *et al.*, 2006; Ericksen and Ardón, 2003; Mairura *et al.*, 2007) menés dans différents pays du monde (Bangladesh, Etats-Unis, Honduras, Nicaragua, Colombie, Pérou, Venezuela et Kenya) et sur des productions agricoles très diverses (riz, tomate, coton, maïs et pois), nous pensons que la conception d'outils d'évaluation de la qualité des sols sera d'autant plus pertinente qu'elle associera les savoirs pratiques et les préoccupations des agriculteurs aux connaissances apportées par la recherche scientifique. A notre connaissance, peu de travaux ont cherché à établir ce lien, dans le cadre de la viticulture. Même si des travaux (Carey *et al.*, 2007; Goulet and Morlat, 2011) ont étudié la perception des Terroirs chez les viticulteurs, elles ne traitent pas directement de la qualité des sols.

Pour cela, une enquête a été réalisée par entretiens compréhensifs auprès de 29 viticulteurs originaires de 4 zones du Languedoc-Roussillon. Le contenu de ces entretiens a ensuite été comparé à celui des publications scientifiques sur la qualité des sols. Cette confrontation nous a permis d'identifier les proximités et les écarts existants entre ces deux ensembles de discours, en ce qui concerne d’une part, la définition de la qualité des sols et d’autre part, la nature des indicateurs permettant de l’évaluer. Enfin, des pistes de recherche complémentaires qui permettraient de mieux comprendre les facteurs déterminant les perceptions de qualité des sols chez les viticulteurs ont été identifiées.

2. METHODE

2.1. ECHANTILLONNAGE

Cette étude a été conduite dans le Languedoc-Roussillon (sud de la France). Quatre zones ont été étudiées : Montagnac (Hérault), Aigues-Mortes (Gard), Vergèze (Gard) et Saint-Hippolyte du Fort (Gard). La localisation des zones d’études et le détail de leurs principales caractéristiques pédologiques sont présentés en Figure VI- 1. Les zones sont soumises au même type de climat méditerranéen avec 14,8 ± 0,5 °C de température annuelle moyenne, 728 ± 232 mm de précipitations annuelles et 1 310 ± 70 mm d’ETP Penman-Monteith annuelle (valeur moyenne basée sur des données collectées de 2000 à 2010 par Météo-France). Au total, 29 viticulteurs ont été enquêtés : 8 pour Montagnac, 5 pour Aigues-Mortes, 8 pour Vergèze et 8 pour Saint-Hippolyte du Fort. Le choix de travailler sur 4 zones déterminées a été motivé par le souhait de comprendre si le contexte, au sens large (pédoclimatique, économique, social, culturel…) pouvait expliquer les différences observées. Nous avons aussi tenu à enquêter un panel de viticulteurs aux pratiques culturales variées (mode de gestion du sol et de fertilisation principalement) en mode conventionnel ou biologique afin de déterminer si les pratiques culturales étaient liées aux différentes définitions et évaluations de la qualité des sols. Nous avons donc constitué un échantillon raisonné (Table VI- 1), construit en fonction des questions de recherche préalables, et non pas à un échantillonnage généré par un tirage au sort au sein d’une liste des viticulteurs du Languedoc-Roussillon. Ce choix se justifiait d’autant plus que l’objectif n’était pas de mener une enquête quantitative, par questionnaire sur un grand nombre d’individus, mais d’engager des entretiens compréhensifs.

Table VI- 1 : Nombre de viticulteurs enquêtés par type de viticulture (conventionnel ou biologique) pour chaque zone.

ZONE	VITICULTURE	NOMBRE DE VITICULTEURS ENQUETES
Aigues-Mortes	conventionnelle	3
	biologique	2
Montagnac	conventionnelle	7
	biologique	1
Saint-Hippolyte du Fort	conventionnelle	4
	biologique	4
Vergèze	conventionnelle	2
	biologique	6
	TOTAL	**29**

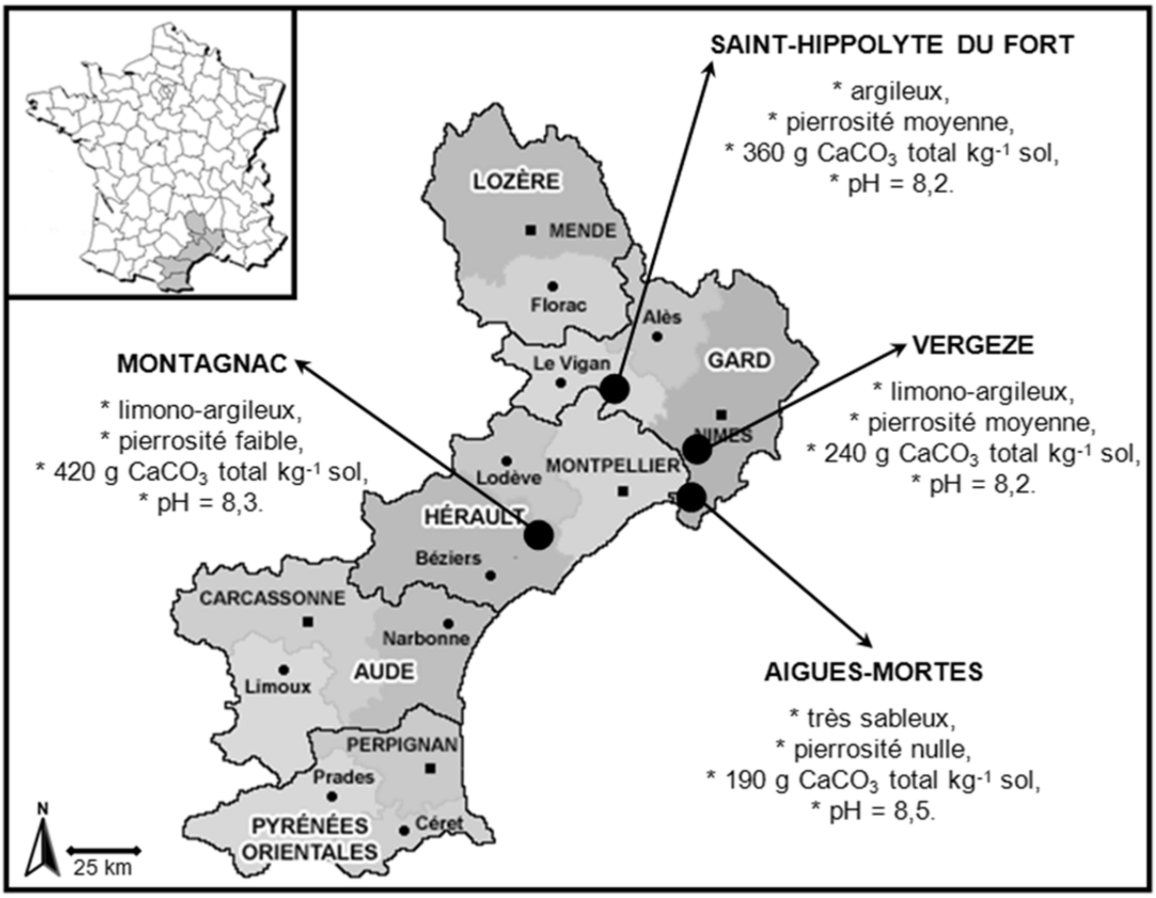

Figure VI- 1 : Localisation des 4 zones d'étude avec leurs principales propriétés pédologiques (texture, pierrosité, teneur en calcaire ($CaCO_3$) total et pH).

2.2. ENQUETE

L’enquête par entretien compréhensif, telle qu’elle est pratiquée en sociologie, vise à connaître les pratiques des acteurs et le sens qu’ils attachent à leurs pratiques (Kaufman, 1996). L’objectif de l’enquêteur est alors de faire parler les interviewés sur une série de thèmes prédéfinis, en les laissant s’exprimer le plus librement possible et en les invitant par des relances à préciser constamment leur pensée. Les thèmes à aborder avec les viticulteurs avaient été préalablement définis :

1- Quelles sont leurs pratiques culturales ? Pourquoi avoir fait ces choix ? Quelles sont leurs principales contraintes dans leur activité ?

2- Comment décident-ils des types et doses d’engrais ou d’amendements à apporter et de la façon de gérer leur sol (désherbage chimique, travail du sol et enherbement) ?

3- Que savent-ils sur le sol ? Qu’est-ce qu’un « bon » sol selon eux ? Agissent-ils pour améliorer ou conserver la qualité de leurs sols ?

4- Quels indicateurs utilisent-ils pour distinguer les différents types de sols ? Evaluent-ils la qualité des sols avant d’agir ?

Les entretiens, d’une durée moyenne de 45 minutes, ont été réalisés entre juin et octobre 2010 au domicile ou sur l’exploitation des viticulteurs. Ils ont ensuite été retranscrits et codés manuellement. Les récurrences dans les discours ont permis de dégager des enseignements de nature générale, allant au-delà de l’expérience individuelle de tel ou tel viticulteur.

3. RESULTATS ET DISCUSSION

3.1. QUELLE DEFINITION DE LA QUALITE DES SOLS ?

3.1.1. LA QUALITE DES SOLS DEFINIE PAR LES SCIENTIFIQUES

Beaucoup de définitions de la qualité des sols ont été proposées entre les années 1990 et 2000 (Arshad and Martin, 2002). La qualité des sols a été reliée uniquement à la production pour certains (Hornick, 1992; Karlen *et al.*, 1997) et uniquement à l’environnement pour d’autres (Johnson *et al.*, 1997; Warkentin, 1995). Ces deux composantes ont été intégrées par Doran et Parkin (1994) ; la qualité d’un sol est « *la capacité d’un sol à fonctionner en maintenant la productivité biologique, la* *qualité de l'environnement et maintenir la santé des plantes et des animaux* ». Cette définition est la plus citée aujourd'hui. D'autres précisions l'ont enrichies comme l'intégration de la notion de durabilité (Doran and Zeiss, 2000) et l'importance de considérer la qualité du sol dans un contexte donné (Doran and Safley, 1997) et pour une utilisation donnée (Martin *et al.*, 1999).

3.1.2. LES COMPOSANTES DE LA QUALITE DES SOLS IDENTIFIEES PAR LES VITICULTEURS

Dans les entretiens réalisés, les viticulteurs ont mobilisé une large gamme de caractéristiques pour s'exprimer sur la qualité de leurs sols. De leurs discours, 4 registres de perception ont été évoqués de façon exclusive ou combinée chez un même producteur : le sol en tant qu'outil de production, le sol comme réservoir avec des propriétés physico-chimiques, le sol est un système vivant à protéger et le sol, composante du Terroir (Table VI- 2).

Table VI- 2 : Présentation des 4 registres de la qualité des sols donnés par les viticulteurs (1) le sol en tant qu'outil de production (Production), (2) le sol comme réservoir avec des propriétés physico-chimiques (Physico-chimiques), (3) le sol en tant que système vivant à protéger (Vivant) et (4) le sol, composante du Terroir (Terroir).

ZONE	VITICULTURE	REGISTRES			
		PRODUCTION	PHYSICO-CHIMIQUE	SYSTEME VIVANT	TERROIR
Aigues-Mortes	conventionnelle	1	0	2	0
	biologique	0	2	1	1
Montagnac	conventionnelle	4	2	4	2
	biologique	0	0	1	0
Saint-Hippolyte du Fort	conventionnelle	1	2	3	2
	biologique	0	4	4	2
Vergèze	conventionnelle	0	1	0	0
	biologique	3	2	4	0
	TOTAL	**9**	**13**	**19**	**7**

Parmi les viticulteurs enquêtés, 9 évaluent la qualité des sols à partir de leur capacité de production. Qualité et fertilité des sols sont alors associées : « *un bon sol est un sol fertile* » (53 ans, Aigues-Mortes, viticulture conventionnelle), « *qui permet à la vigne de s'exprimer pleinement au niveau des récoltes* » (65 ans, Vergèze, viticulture biologique). Cette fertilité peut également être évaluée de façon différenciée, selon des objectifs de production. Ainsi, un viticulteur (49 ans, Vergèze, viticulture biologique) affirme « *tous les sols sont bons, cela dépend ce qu'on leur demande* ». Pour lui, « l*es sols* *limoneux sans cailloux ont de très bons rendements et sont parfaits pour la production de jus de raisins* ».

Selon un second registre, observable dans près de la moitié de notre échantillon (13 viticulteurs), la qualité des sols est définie par leurs caractéristiques physico-chimiques. Les viticulteurs ont alors évoqué la texture du sol. C'est tout particulièrement le cas à Aigues Mortes où les sols très sableux et à proximité de la mer génèrent deux problèmes majeurs : (1) l'érosion éolienne (par grand vent, « les parcelles volent » (53 ans, Aigues-Mortes, viticulture conventionnelle)) et (2) la faible rétention en eau et en nutriments (« Sur le sable, sans engrais, rien ne pousse. Ici, on ne peut faire que du conventionnel » (80 ans, Aigues-Mortes, viticulture conventionnelle)). La pierrosité a également été évoquée à plusieurs reprises. Les cailloux sont une contrainte pour certains ; « *un bon sol en est peu ou pas pourvu* » (50 ans, Montagnac, viticulture conventionnelle) car si les parcelles sont caillouteuses, certains outils comme les charrues et la herse rotative ne peuvent être utilisées. A l'inverse, d'autres ((51 ans, Montagnac, viticulture conventionnelle) et (49 ans, Vergèze, viticulture biologique)) ont dit que les cailloux constituent un critère de qualité et qu'ils sont à l'« *origine de très bons vins* ». La capacité de rétention en eau est une caractéristique qui a aussi été mentionnée ; les viticulteurs la reliant souvent à la profondeur du sol. Nombreux enfin sont les viticulteurs qui ont parlé de la teneur en macronutriments et en matière organique. « *Un bon sol est […] riche en matière organique* » (50 ans, Montagnac, viticulture conventionnelle). « *Les sols qui ont reçu des apports de matière organique sont plus stables, absorbent plus l'eau et ainsi les vignes résistent mieux à la sécheresse* » (35 ans, Saint-Hippolyte du Fort, viticulture biologique).

Dans un troisième registre plus présent que le précédent (19 viticulteurs), les professionnels perçoivent le sol comme un système vivant à protéger. Pour un viticulteur (52 ans, Saint-Hippolyte, viticulture conventionnelle) : *« Quand on est entomologiste et qu'on regarde un peu, on voit les bestioles qui [..] vivent, les vers qui commencent à faire des trous, les fourmis qui charrient, tout ça, tout ce qu'on voit, cette vie, cet équilibre, cette biodiversité !* ». Un autre (65 ans, Vergèze, viticulture biologique) a affirmé que dans un bon sol, « *il faut toujours qu'il y ait des vers de terre, de la vie, des petits trous dedans quand on regarde les mottes* ». Dans leur réflexion, ces agriculteurs ont considéré le sol comme une entité vivante à part entière. Plusieurs l'ont d'ailleurs personnifié en disant « *il faut que le sol vive et respire* » (53 ans, Saint-Hippolyte, viticulture biologique). D'autres (53 ans, Aigues-Mortes, viticulture conventionnelle) ont mis en garde, « *un sol c'est sûr qu'il ne faut pas le tuer* », et ont fait part de leur regret face au « *massacre* » du sol par les pratiques non respectueuses de l'environnement (51 ans, Montagnac, viticulture conventionnelle).

Une dernière notion est enfin ressortie des enquêtes : le Terroir. Sept viticulteurs ont spontanément évoqué cet aspect du sol et seulement 3 ont affirmé que le vin porte la marque du Terroir et qu'il influence le type de vin. Un d'entre eux (61 ans, Aigues-Mortes, viticulture biologique) a affirmé : « *Bien sûr qu'il y a un reflet sur le vin. [Les sols de sable] donnent des vins plus légers […]. Le Terroir a obligatoirement un effet sur le vin*. ».

3.1.3. COMPARAISON ENTRE LES PERCEPTIONS DES SCIENTIFIQUES ET CELLES DES PROFESSIONNELS SUR LA QUALITE DES SOLS

En comparant les deux types de définition, celle des scientifiques et celle des viticulteurs, nous avons remarqué des points communs. L'aspect production, présent chez les premiers, n'a bien évidemment pas été oublié par les seconds. D'ailleurs, plusieurs viticulteurs ont parlé de fertilité au lieu de qualité des sols. Bien que la définition du terme fertilité ait été aussi discutée par les scientifiques que le terme qualité, il est fort probable que les viticulteurs l'associent uniquement à la notion de production. Bien que plus restrictive, cette vision semble être plus facilement perceptible par les agriculteurs. Ainsi, pour assurer le transfert entre recherche et milieu professionnel, les scientifiques ont certainement intérêt à intégrer dans leurs discours le terme fertilité en plus de celui de qualité des sols. Les viticulteurs ont aussi intégré la part de l'environnement dans la définition de la qualité des sols. Même si la notion de durabilité n'a pas été directement mobilisée par les viticulteurs rencontrés, elle fait écho aux descriptions du sol comme un être vivant qu'il « *ne faut pas tuer* ». Sur ce point, les perceptions des viticulteurs ont cependant différé de celles des scientifiques car elles ont révélé une conception de la protection de l'environnement plus restreinte, plus locale. Les professionnels ont semblé prioritairement concernés par la durabilité de leur sol, de leurs parcelles, avant d'embrasser des problématiques environnementales plus larges (comme celles qui touchent à la dégradation des ressources en eau, par exemple). La définition d'un « *bon* » sol pour les viticulteurs est apparue comme directement associée à des caractéristiques pédologiques (profondeur, texture, pierrosité, capacité de rétention en eau, teneur en matière organique et en nutriments), alors que la littérature scientifique a développé des définitions plus générales. Les paramètres à mesurer sont décidés dans un second temps, après définition des utilisations du sol et des fonctions associées (Arshad and Martin, 2002; Bastida *et al.*, 2008). Enfin, soulignons la présence de références au Terroir dans les discours de certains viticulteurs car cette notion est absente des définitions proposée par les scientifiques (Ali, 2003; Barrios and Trejo, 2003; Ericksen and Ardón, 2003; Ingram *et al.*, 2010). Néanmoins, un tel écart est peut-être essentiellement le résultat de l'importance de cette notion en viticulture, et plus particulièrement en France.

3.2. COMMENT EVALUER LA QUALITE DES SOLS ?

3.2.1. LES INDICATEURS RECONNUS PAR LES SCIENTIFIQUES

Dans le cadre de notre projet de recherche, nous avons tout d'abord mesuré un set d'indicateurs physico-chimiques (Table VI- 3), en nous inspirant de ceux qui avaient été sélectionnés dans de précédents travaux (Arshad and Martin, 2002; Bastida *et al.*, 2008; Karlen *et al.*, 1997; Marzaioli *et al.*, 2010b; Wienhold *et al.*, 2004). Nous l'avons complété par des mesures de bio-indicateurs, car les organismes du sol vivent en étroites relations avec leur environnement et donnent ainsi une évaluation du fonctionnement du sol (Franzle, 2006). Nous avons ainsi étudié les microorganismes, les nématodes libres et les vers de terre (Table VI- 3).

3.2.2. LES INDICATEURS OBSERVES PAR LES VITICULTEURS

Dans les discours des viticulteurs, nous retrouvons de nombreux indicateurs physico-chimiques. Plusieurs viticulteurs ont dit observer la pierrosité et la texture de leurs sols pour en évaluer la qualité. De même, la couleur et l'odeur des sols ont été souvent données par les viticulteurs comme un indicateur de fertilité des sols. Un sol de couleur noire est « *riche en matière organique. Il suffit qu'on gratouille le sol pour s'en rendre compte* » (50 ans, Montagnac, viticulture conventionnelle). « *Une terre noire, foncée, retient mieux la chaleur et l'humidité et elle a une odeur de champignon. […] Tandis qu'une terre stérile possède une couleur blanche* » (65 ans, Vergèze, viticulture biologique). Enfin, nous avons également rencontré un viticulteur qui a réalisé une fosse pédologique pour évaluer la profondeur de son sol. Afin de valider leurs observations de terrain ou de les compléter, certains viticulteurs ont aussi demandé des analyses de laboratoire (texture, pH, teneur en matière organique et en éléments nutritifs majeurs (N, P et K)). Cependant, peu ont commandé des analyses de sol de façon régulière pour leur permettre d'évaluer l'impact de leurs pratiques culturales et/ou de piloter de façon plus fine, la gestion de leurs sols.

Table VI- 3 : Indicateurs physico-chimiques et biologiques étudiés avec le(s) processus associé(s).

INDICATEURS	PROCESSUS ASSOCIES
Physiques	
pierrosité	- érosion, - capacité de rétention en eau du sol…
texture	- érosion, - aération, - capacité de rétention en eau et en nutriments du sol…
densité apparente	- compaction du sol…
micro et macroporosité	- aération, - capacité de rétention en eau du sol…
humidité à la capacité au champ	- capacité de rétention en eau du sol…
stabilité structurale des agrégats	- érosion, - infiltration de l'eau dans l'eau…
Chimiques	
calcaire actif et total	- pH, - disponibilité des éléments...
pH	- disponibilité des éléments, - sélection d'organismes vivants...
carbone (C) organique et azote (N) total	- stabilité des agrégats, - capacité de rétention en eau et en nutriments du sol, - stock de nutriments minéralisables, - activités biologiques...
disponibilité des macronutriments (P et K)	- productivité des plantes…
capacité d'échange cationique (CEC)	- capacité de rétention en nutriments du sol…
disponibilité en cuivre (Cu)	- risque de toxicité pour les organismes du sol…
Biologiques	
microorganismes	- décomposition de la matière organique, - formation de l'humus, - agrégation du sol, - cycle et rétention des nutriments…
nématodes	- intensité de différents processus (décomposition de la matière organique), - structure du réseau trophique non nématologique (compartiments bactérien et fongique, prédation), - niveau de perturbations du système sol (longueur de la micro-chaîne trophique), - biodiversité…
vers de terre	- décomposition de la matière organique, - structuration du sol, - fonctionnement hydrodynamique du sol…

Les viticulteurs ont aussi fait référence à des bio-indicateurs. Un viticulteur a par exemple engagé une stagiaire pour faire l'inventaire de la biodiversité dans ses vignes. Parmi les bio-indicateurs, nous avons noté l'utilisation de la flore. « *Il y a de bonnes herbes et de mauvaises herbes. Les bonnes herbes sont les chénopodes. Les mauvaises herbes à cette saison commencent à jaunir, à sécher* » (53 ans, Aigues-Mortes, viticulture conventionnelle). D'autres, plus nombreux, ont observé la faune, surtout les vers de terre. A une autre échelle, certains ont parlé des renseignements que leur apportent la mégafaune tels que les oiseaux et sangliers. Un viticulteur (65 ans, Vergèze, viticulture biologique) explique : « *il y a plein d'oiseaux, quand vous labourez, qui vous suivent pour manger justement toutes les vermines qu'il y a dans le sol. Moi, j'ai l'impression que quand il y a beaucoup d'oiseaux derrière le tracteur, c'est qu'il y a beaucoup de choses à manger, sinon ils ne viendraient pas. C'est comme les pêcheurs. Derrière les bateaux de pêche, il y a beaucoup d'oiseaux parce qu'ils rejettent les petits poissons etc.* ». Un autre (45 ans, Saint-Hippolyte du Fort, viticulture biologique) a expliqué « *qu'en dessous [sous ses pieds], il y a des vers de terre, puisqu'il y a des sangliers qui passent* ».

Les viticulteurs interrogés ne se sont pas référés qu'à des indicateurs physico-chimiques et biologiques du sol. Beaucoup ont également évoqué les observations qu'ils réalisent sur la vigne (tolérance à la sécheresse, carences, rendements…), car elles les renseignent sur l'état de leur sol. Dans les termes d'un d'entre eux : « *La qualité [des sols] est surtout évaluée à la récolte du végétal qui y pousse* » (65 ans, Vergèze, viticulture biologique). Dans cette perspective, certains ont fait réaliser en laboratoire des analyses pétiolaires pour connaître les quantités de nutriments absorbées par la vigne et ainsi mieux gérer les fertilisations.

Enfin, nous avons aussi noté que les viticulteurs se basaient beaucoup sur leur propre expérience et/ou celle de leurs voisins ou prédécesseurs. Un viticulteur (53 ans, Saint-Hippolyte du Fort, viticulture biologique) a avoué « *essayer de se renseigner sur le passé des vignes, ses antécédents, les analyses chimiques et granulométriques du sol* ». A l'inverse, peu de viticulteurs ont reçu des conseils extérieurs (Chambres d'Agriculture, entreprises de conseil…) et beaucoup nous ont fait part de leur regret. Des viticulteurs ont ainsi souligné qu'ils n'étaient pas assez conseillés sur la gestion du sol et qu'ils manquaient de connaissances. Un viticulteur (32 ans, Montagnac, viticulture conventionnelle) a précisé : « *les vers de terre c'est une chose, mais bon on ne les connaît pas bien, donc on n'en parle pas* ».

3.2.3. QUE PEUVENT APPORTER LES SCIENTIFIQUES AUX VITICULTEURS ?

Les chercheurs et les viticulteurs partagent bon nombre d'indicateurs. Cependant, nous avons remarqué que ces indicateurs étaient souvent évalués par les seconds de façon empirique sur le terrain, sans recourir à une analyse de laboratoire. Les viticulteurs ont insisté sur l'utilisation des plantes bio-indicatrices et des vers de terre. Même si ces indicateurs présentent l'avantage d'être facilement observables, leur interprétation est plus difficile. D'après Diekmann (2003), l'utilisation des plantes bio-indicatrices pour évaluer la qualité des sols est un sujet de controverse. En effet, la bio-indication par les plantes porte souvent sur des mesures qualitatives, non reliées à des valeurs seuils et/ou ne tient pas compte de l'étendue des réponses des plantes à une modification donnée selon un gradient géographique ou pendant leur cycle de vie. A l'image de ce qu'Ali (2003) observait parmi les fermiers du Bangladesh, les données avancées par les viticulteurs languedociens restent relativement imprécises, non quantitatives (« *il y a des vers* », « *on voit des bestioles* »). De même, aucun viticulteur de notre échantillon n'a fait mention de protocole de mesure ou de fréquence d'observations. Ces méthodes d'évaluation ont soulevé aussi le problème des seuils. Par exemple, à partir de quel pourcentage de cailloux, un viticulteur juge-t-il qu'une parcelle est caillouteuse ? Les observations des producteurs leur permettent de distinguer de grandes classes de sol au sein d'une même zone, mais elles ne constituent pas un outil d'évaluation ou de pilotage suffisant.

Un autre constat est que les laboratoires d'analyses sollicités par les viticulteurs que nous avons enquêtés n'ont réalisées que des mesures physico-chimiques. Certains laboratoires proposent pourtant des analyses biologiques en routine mais ils sont peu nombreux et leurs analyses sont peu diversifiées (biomasse microbienne et respirométrie, principalement).

Enfin, les agriculteurs ont fait mention d'indicateurs que nous n'abordons pas dans notre projet de recherche. Il s'agit des indicateurs mesurés sur vigne comme les rendements, les carences… Ce point est important. Il rappelle le caractère pluridimensionnel des analyses menées par les professionnels, lorsque celles suggérées par les scientifiques sont généralement plus compartimentées. Pour autant, nous ne pensons pas qu'il remette en question la pertinence de notre projet. L'écophysiologie de la vigne a été davantage étudiée que le fonctionnement des sols dans les systèmes viticoles et les viticulteurs manquent encore d'indicateurs de la qualité des sols.

3.3. LES FACTEURS EXPLIQUANT LES DIFFERENCES DE PERCEPTIONS ?

Nous avons mis en évidence l’intérêt des viticulteurs pour la qualité des sols. Mais, qui sont les viticulteurs particulièrement attentifs à la qualité de leurs sols ? Les travaux classiques de sociologie ont montré que les agriculteurs qui étaient les premiers à adopter des innovations avaient souvent des caractéristiques particulières (plus éduqués, plus solides financièrement, disposant de réseaux sociaux plus hétérogènes…) (Padel, 2001; Ryan and Gross, 1943). Dans cette enquête, nous n’avons pas eu le sentiment que cela était véritablement confirmé. Ni l’âge, ni le niveau d’étude, ni la taille de l’exploitation, ni de façon peut-être plus inattendue le mode de production (conventionnel ou biologique, Table VI- 2) ne semblent avoir d’effets déterminants. D’autres recherches, quantitatives cette fois, permettraient de confirmer, nuancer ou invalider ces constats de façon statistique. Des études ethnographiques pourraient également aider à mieux saisir les raisons pour lesquelles les viticulteurs engagent effectivement des actions visant à mieux prendre en compte la qualité de leurs sols. Elles feraient alors vraisemblablement apparaitre le poids des dynamiques d’apprentissage qui se développent au sein des territoires et des organisations collectives (Darré *et al.*, 1989). D’ailleurs, nous avons pu constater sur Vergèze l’influence de la source d’eau minérale naturelle gazeuse Perrier® qui a conduit les viticulteurs de la commune à réduire l’utilisation de produits phytosanitaires de synthèse. Nous avons aussi noté les actions volontaristes menées au sein des caves coopératives (acquisition de matériel, réunions hebdomadaires avec un technicien de la Chambre d’Agriculture du Gard).

4. CONCLUSION

L’évaluation de la qualité des sols est un enjeu que partagent scientifiques et viticulteurs. Cependant, c’est une tâche complexe tant les fonctions à étudier sont nombreuses et différentes en fonction des individus. Les viticulteurs reconnaissent d’ailleurs que les indicateurs dont ils disposent sur la qualité de leurs sols sont, aujourd’hui, trop peu nombreux et peu opérationnels. L’enjeu de notre travail de recherche qui consiste à mettre au point des indicateurs de la qualité des sols prend donc tout son sens. Cependant, scientifiques et viticulteurs doivent interagir pour assurer la réussite d’un tel challenge. Des concessions devront être faites. Pour les scientifiques, il faudra accepter de travailler sur des indicateurs peut-être moins précis mais plus pertinents alors que nous pourrions conseiller aux professionnels de la filière d’engager des formations pour acquérir les connaissances nécessaires pour l’utilisation des outils.

Remerciements

Nous souhaitons remercier l'ensemble des viticulteurs qui ont bien voulu participer à cette enquête. Nous sommes également très reconnaissants pour le travail qu'ont fourni Boris Hiro, Mathilde Mellin, Charlotte Ngo-Dinh et Arwa Osseiran, étudiants à Montpellier SupAgro, dans la réalisation des entretiens et leur retranscription. Nous adressons enfin nos remerciements à l'ensemble des personnes impliquées dans le module « Projet d'Elèves Ingénieurs ».

CHAPITRE VII

DISCUSSION
&
CONCLUSION

The aim of my work was to evaluate vineyard soil quality focusing on the upper soil layer influenced by vineyard management practices. In the main results, I highlighted that vineyard soils in the Languedoc-Roussillon region are very particular agro-ecosystems. Indeed, the majority of plots had total soil organic carbon content lower than 15 mg g^{-1}. This confirmed the results by Jones et al. (2005) and Sanchez-Maranon et al. (2002) who showed that cultivated Mediterranean soils are relatively poor in organic matter. Furthermore, our soils generally have a very high degree of stoniness, as much as 90%. With regard to soil pH, it was very variable with an extreme alkaline value under very calcareous soils (more than 400 g kg^{-1}) which greatly influences soil functioning. Therefore the majority of sampled vineyard soils presented initially low inherent soil quality. As a consequence, vineyard management, generally intensive, has to be evaluated in terms of potential soil degradations. Among the different types of soil disturbance, the most frequent ones were soil compaction (Coulouma et al., 2006), erosion (Le Bissonnais et al., 2007), accumulation of copper (Saby et al., 2011) which is toxic to soil organisms (Diaz-Ravina et al., 2007; Marzaioli et al., 2010a) and decreases soil organic matter (Peregrina et al., 2010).

Despite of the above mentioned low inherent soil quality, in conjunction with intensive vineyard management, both dynamic soil quality and vineyard management have not been studied a review of the literature shows. However, the social study revealed a keen interest from winegrowers to evaluate the (i) quality of their soils and (ii) the impact of their vineyard practices on soil. Some studies are showing an interest in the perception of soil quality by farmers (Andrews *et al.*, 2003; Baillod *et al.*, 2010; Talawar and Rhoades, 1998). However, I only found 2 studies (Carey et al., 2007; Goulet and Morlat, 2011) relative to the perception of the Terroir by winegrowers but they did not establish a direct link with soil quality. As a consequence, my survey on farmers is a precious source of information. Indeed, I found that winegrowers have very heterogeneous level of knowledge about soil properties and its functioning. Our interviews showed generally that the perception of soil quality by winegrowers was equivalent to those of scientists even if they obviously emphasized the production function of soils the soil-production function already highlighted by several authors (Barrera-Bassols and Zinck, 2003; Ericksen and Ardón, 2003). Interestingly, some winegrowers introduced the Terroir concept never previously mentioned in the above mentioned studies concerning crops other than vine. Winegrowers declared that they recognize some parameters as simple indicators of soil quality: stoniness, texture, colour, giving information about organic matter content and earthworms. However, winegrowers expressed the restricted number of indicators they used and their lack of operationality. As a consequence, my study aimed at a closer scientific understanding of a particular ecosystem and winegrowers who require operational tools to manage their vineyards better. According to Romig et al. (1995) and Andrews et al. (2003), the use of simple indicators for soil quality that make sense for farmers and other land managers , would probably be the most fruitful link between them and scientific research.

The study of soil quality was conducted on carefully selected commercial vineyard plots. This interdisciplinary work associated field surveys, soil sampling, analytical laboratory analyses and the use of statistical tools for interpretation. In order to obtain a global view of soil functioning, I combined the use of physical, chemical and biological indicators as suggested by several authors so as to yield a minimum data set of indicators (Arshad and Martin, 2002; Bastida *et al.*, 2008; Cassman, 1999; Kinyangi, 2007; Marzaioli *et al.*, 2010b; Wienhold *et al.*, 2004). The choice of indicators studied was a compromise between their relevance concerning soil functions and known protocols of joint research unit Eco&Sols where I was localized or that of other persons, staff from others units in Montpellier (UMR LISAH) who I encountered. At this point, I have also to include in my decision logistic or economic factors as the cost and time my decisions needed to take into account such factors as logistics, as well as economic ones in terms of costs and time. It is worth noting that we focused on the first 15 cm of soil because this depth concentrated the main soil processes such as mineralization of organic matter and infiltrability. Moreover, these soil layers are those that are most influenced by soil practices. However, for perennial plant such as vine, deeper soil layers are of great importance for root anchoring and water circulation. Indeed, Van Leeuwen et al. (2004) highlighted the effects of deeper soil properties, such as texture and stoniness, on vine development defined as the phenologic stage, vine vigor and berry composition. Nevertheless, these latter soil properties influenced parameters that are not beyond the scope of our study.

As very few studies address the question of vineyard soil quality, the first study consisted in building a baseline of our indicators as specified by Arshad and Martin (2002) in the context of the Languedoc-Roussillon region. To attain with this goal, vineyards were carefully selected in order to maximize the diversity of soil types representative of the Languedoc-Roussillon area and to take into account most of vineyard management practices. The first asset in this experimentation was the high number of vineyards (164) studied which will helps in the development of a referential for the indicators measured. This large dataset gives way to a lot of research paths. Our main result was that nearly all chosen indicators were sensitive to soil types and/or vineyard management, except soil respiration. More precisely, soil types were found to influence bulk density, water-holding capacity, total organic carbon content, available phosphorus content, microbial biomass/total organic carbon, nematode trophic group densities and the 6 nematode indices.

Whatever the nematode trophic groups, their density was higher in calcareous soil with alkaline pH. Predatory nematodes seemed to be not well adapted for very clayey soils. With regard to vineyard management, practices leading to bare soil all year round, whatever the weeding type, revealed high bulk density, worst effects on soil quality with the lowest total organic matter content, microbial biomass/organic carbon and density of diverse nematode trophic groups. Tillage was found to be detrimental to sensitive soil organisms such as omnivore and predator nematodes and anecic earthworms. As a matter of fact, a special sampling of earthworms on a restricted number of plots within the "*Referential Network"* showed that tillage significantly decreased the density and the biomass of earthworms, anecics in particular. On the other hand, permanent grass cover or temporary grass cover managed on the basis of one application of chemical weeding led us to observe a highest level of biological activity. As a matter of fact microbial biomass/total amounts of organic carbon, the density of plant feeders and free-living nematodes and the density and biomass of earthworms were the highest under these conditions. Moreover vineyard management with chemical weeding presented more structured and a more complex soil micro-food web as revealed by nematode indices.

Lastly, other types management were characterized by a temporary grass cover managed by tillage with different types of fertilizers and pesticides used for phytosanitary protection. They presented comparable indicator values and presented medium biological activity in comparison with the first 2 groups. This global study did not allow us to distinguish easily the effects of organic farming on soil quality compared with conventional management.

As conversions from conventional vineyards to organic ones are more and more frequent and abundant, it appeared necessary to study the effects of such vineyard management on soil quality. Interestingly, the long-term effects are almost not addressed by the literature. This is the reason why this question "effects of organic farming, from conversion to 17 years after the conversion" was assessed using a specific experimental design. During this study, I demonstrated that a transition period of 7–11 years, depending on the indicator under consideration, was needed to clearly separate soils under conventional and organic farming practices in a southern French vineyard. Apart from the usual sensitive indicators used to study organic transition such as organic matter content, soil microbial biomass or bulk density, the easy-to use chemical available P and K contents should also be considered as sensitive indicators. However, once soil functioning has stabilized, the greater soil organic matter content and related biological activities could partly counteract the observed decrease during the transition period as phosphorus mining built up from the application of previous soluble fertilizer . A further in-depth study about nematode communities completed my view on soil biological functioning. Indeed, organic farming tends to increase the density of microbial-feeding and particularly opportunistic fungal-feeding nematodes, indicating an increase in nutrient resource availability. The presence of a grass cover increased the density of plant-feeding nematodes. The fungal decomposition channel relatively increased the bacterial decomposition channel, revealing a change in the quality of soil organic matter. A quantitative positive effect of organic practices on soil biological activity (increase of organism abundance except earthworms) was measured but organic farming did not clearly lead to a functional modification or an improvement in the soil food web length or complexity as shown by the nematode indices MI, PPI and SI, which remained constant. However, one should note that organic farming and their associated practices are diverse. Our study does not conclude about organic practices but about a set of organic practices in a localized area. In consequence, it would be useful in the future to compare different organic farming practices rather than conventional/organic farming. For example, it would be very interesting to study alternatives to tillage in organic farming as we demonstrated the negative effects on soil organisms. Indeed, we demonstrated that soil organisms are key stone for soil functioning for organic farming because it relies on biological activities in vineyard soils naturally low in terms of organic matter content. My proposals are to evaluate the effects of sowing of adequate mixtures of grass species which dry out at the beginning of the summer or the control of grass cover with the use of rolofaca. This is a simple machine composed of a roll which breaks and lays stems without cutting them. Consequently, weeds die and, constitute efficient mulch.

In the two networks, we used earthworms and found that they were sensitive to viticultural practices in St Victor. However, in both networks *("Referential"* and *"Organic"*), sampling was difficult. Indeed, in the case of Saint-Victor la Coste, we sampled earthworms on 13 plots with 4 replicates per plot which entails huge logistics. Indeed, 40 persons were present for 1 day with 1,560 l of water and 23.4 kg of commercial mustard. These data illustrate why people are discouraged by earthworm samplings. Consequently, a new method based on resistivity was tested to predict biomass and abundance of earthworms directly on the field, in plots which were manually sorted for earthworms. The first result of the study showed very interesting and encouraging results.

Using existing data from the "*Referential network*", we have to complete the global analysis by more precise interpretations on the different sets of data. Firstly, surveys on vineyard management undertaken for each 164 plots (more than 50 winegrowers were interviewed) will have to be analyzed more precisely because local vine advisers need these data to guide winegrower's towards more sustainable vineyard management practices (Nicolas Constant, viticultural adviser in the AIVB-LR (Association Interprofessionnelle des Vins Biologiques du Languedoc-Roussillon), personal communication). Second, with regard to data analysis, it will be very pertinent to focus on specific analyzes such as aggregate stability, nematofauna and microorganisms. Data can also be used by

NIRS/MIRS experts for an integrated approach to soil quality or to study alternatives to biological indicators.

It is already possible to benefit from our study with a practical point of view as the main characteristics in terms of information/time/cost comparison of each indicator I used for a comparison with the effects of vineyard management on soils are listed in the Table VII- 1. My work is a practical complement of the CASDAR project (Special Trust for Agricultural and Rural Development) which aims at validating and proposing easy to measure indicators used by professionals. This CASDAR project reached great success with winegrowers. However, in order to obtain operational tools for winegrowers, indicators should have a scientific basis but also should be easy to measure and to interpret by winegrowers and vine professionals. Indeed, some of the indicators are very sensitive but the interpretation of results needs to be done by specialists before they are given to winegrowers. Finally, we pointed out the need for training on indicators and soil functioning for winegrowers and advisors. This need can be fulfilled by simple communication flyers as students (on master degree courses) created for winegrowers after the earthworm sampling in St Victor Lacoste (Appendix 2).

Generally, winegrowers should be aware of the diverse ecosystem roles played by vineyards such as the beauty of the landscape, limiting fire spreading, the regulation of N_2O emission or pesticides fate. Based on my data, I also suggest that the INAO (Institut National des Appellations d’Origine), a French organization whose aim is to establish the Terroirs or boundaries of an area with leading products of high typicity should describe better the soil features. Indeed, at the time of writing, only inherent soil quality characteristics were considered. As soil is considered as a non-renewable resource, dynamic soil properties should also be considered in the Terroir concept for a global imprint towards the production of the best of wines.

Table VII- 1 : Main practic characteristics of some indicators of soil quality

	Sampling on the plot			Laboratory analyses		Interpretation	
	Easiness	Time	Containts	Price (€/sample)	Commercial supply	Relevance	Frequency
Physical indicators							
Coarser particles than 2 mm	+++	+		5-10	+++	+	1 / 50 years
Texture	+++	+		20-25	+++	+	1 / 20 years
Bulk density	+	++	specific material	?	0	++	1 / 5 years
Water holding capacity	+++	+		10-15	+++	++	1 / 5 years
Aggregate stability	+++	+		?	0	++	1 / 5 years
Chemical indicators							
pH	+++	+		5 - 10	+++	+	1 / 20 years
Total CaCO3	+++	+		5 - 10	+++	+	1 / 20 years
Active CaCO3	+++	+		5 - 10	+++	+	1 / 20 years
Total organic C	+++	+		10 - 15	+++	+++	1 / 5 years
Total N	+++	+		10 - 15	+++	+++	1 / 5 years
Available P	+++	+		5 - 10	+++	++	1 / 5 years
Available K	+++	+		5 - 10	+++	++	1 / 5 years
CEC	+++	+		5 - 10	+++	+++	1 / 5 years
Available Cu	+++	+		5 - 10	+++	++	1 / 5 years
Biological indicators							
Microbial biomass	+++	+	fresh soil	45	+	+++	1 / 2 years
Respirometry	+++	+	fresh soil	45	+	+	1 / 2 years
Soil nematofauna : abundance of plant-feeders	+++	+	fresh soil	200	+	+++	1 / 2 years
Soil nematofauna : bacterial- & fungal -feeders	+++	+	fresh soil	included	+	+++	1 / 2 years
Soil nematofauna : omnivores & predators	+++	+	fresh soil	included	+	+++	1 / 2 years
Soil nematofauna indices: EI, SI, NCR...	+++	+	fresh soil	included	+	+++	1 / 2 years
Earthworms: abundance of ecological categories	+++	+++	very long time	?	+	+++	1 / 2 years
Earthworms: biomass of ecological categories	+++	+++		?	+	+++	1 / 2 years

0: absent ; +: low ; ++: middle ; +++: high.

CHAPITRE VIII

RESUME LONG DE THESE

INTRODUCTION

L'importance du fonctionnement du sol dans les écosystèmes a été souligné par de nombreux scientifiques (Arshad and Martin, 2002; Cameron *et al.*, 1996; Costanza *et al.*, 1997; Dale and Polasky, 2007; de Groot *et al.*, 2002; Lavelle *et al.*, 2006; Millennium Ecosystem Assessment, 2005; Porter *et al.*, 2009; Sombroek and Sims, 1995; Straton, 2006). Ces travaux ont fait référence aux rôles que joue le sol pour les activités humaines et notamment l'agriculture (support pour les cultures, rétention de l'eau et des nutriments, minéralisation de la matière organique, régulation des pathogènes…). Contrairement à l'eau ou à l'air, le sol est souvent considéré comme une ressource non renouvelable (Kibblewhite *et al.*, 2008). Les caractères multifonctionnels et indispensables pour toutes les activités humaines font du sol une ressource surexploitée (directement ou indirectement, volontairement ou involontairement), soumise à de fortes dégradations (Cassman, 1999). Les perturbations des sols peuvent être d'origine naturelle ou anthropique (Dominati *et al.*, 2010). Parmi les différentes activités humaines à l'origine de ces perturbations, l'agriculture est responsable d'une grande partie d'entre elles (Millennium Ecosystem Assessment, 2005).

En particulier, la culture de la vigne est souvent jugée comme très intensive car elle nécessite de nombreuses interventions pour la protection phytosanitaire, la gestion de la partie végétative (taille, palissage, rognage) et l'entretien du sol. Certaines pratiques culturales comme le désherbage chimique, l'utilisation de produits phytosanitaires ainsi que l'apport d'engrais minéraux sont connues pour causer des dommages sur les sols : érosion, diminution de la teneur en matière organique, pollution et perte de biodiversité (Chaignon *et al.*, 2003; Chopin *et al.*, 2008; Coulouma *et al.*, 2006; Komarek *et al.*, 2010; Le Bissonnais *et al.*, 2007; Martinez-Casasnovas and Ramos, 2009; Raclot *et al.*, 2009). De plus, la vigne est une culture pérenne et dans ce contexte de longévité, il est indispensable de s'interroger sur la durabilité du système viticole. Les sols sont aussi une des composantes clés du Terroir (Van Leeuwen *et al.*, 2004), notion chère à la filière viti-vinicole en France qui est le deuxième producteur de vins au niveau mondial (Agreste, 2010XXX). Ainsi, il apparaît indispensable d'adopter une viticulture durable, caractérisée par de faibles niveaux d'intrants (pesticides et fertilisants, majoritairement) pour limiter les pollutions, garantir l'innocuité des vins et atteindre les objectifs économiques.

Il existe une très grande diversité de pratiques culturales en vigne, en terme de gestion du sol (désherbage chimique, travail du sol et enherbement), de durée d'enherbement, de fertilisation (minérale, organique ou nulle), de restitution ou non des bois de taille ou encore de stratégies de protection phytosanitaire. Cette dernière décennie a été marquée par le nombre croissant de conversion des vignobles français à l'agriculture biologique. En effet, leur superficie a été multipliée par 8, entre 2001 et 2008 : 3 426 ha en 2001 (Agence BIO, 2002) et 28 190 ha en 2008 (Agence BIO, 2009). La conversion à l'agriculture biologique se traduit par un changement des pratiques. Ainsi, les produits phytosanitaires de synthèse sont remplacés par des produits d'origine naturelle, les désherbants chimiques par de l'enherbement naturel maîtrisé par tonte ou par travail du sol et les engrais minéraux par des apports de matière organique.

Les effets de certaines pratiques viticoles ont été étudiées sur des propriétés physiques, chimiques et biologiques du sol (Goulet *et al.*, 2004; Ingels *et al.*, 2005; Parker and Kluepfel, 2007; Raclot *et al.*, 2009; Rahman *et al.*, 2009; Reuter and Kubiak, 2003; Smith *et al.*, 2008; Steenwerth and Belina, 2008; Vrsic, 2011; Whitelaw-Weckert *et al.*, 2007; Xi *et al.*, 2009). Or, très peu d'études ont été menées sur la qualité globale des sols (Probst et al, 2008), bien que de nombreux auteurs aient mis en évidence leur nécessité (Blavet *et al.*, 2009; Ripoche *et al.*, 2011; Steenwerth *et al.*, 2010b). Doran et Parkin (1994) définissent la qualité des sols comme « la capacité d'un sol à fonctionner en maintenant la productivité biologique, la qualité de l'environnement et la santé des plantes et des animaux ». Certains chercheurs (Doran, 2002; Doran and Zeiss, 2000; Karlen *et al.*, 2003; Karlen *et al.*, 1997; Wienhold *et al.*, 2004) distinguent deux qualités des sols, la « qualité inhérente » et la « qualité dynamique ». La qualité inhérente fait référence aux propriétés naturelles et originelles des sols influencées par la roche mère, la topographie, le climat, la végétation et l'âge du sol (Dominati *et al.*, 2010). L'interprétation de cette qualité inhérente est utilisée pour estimer un potentiel d'utilisation des terres. La qualité dynamique est liée à l'utilisation et la gestion du sol. Elle permet par exemple d'apprécier les effets des différentes pratiques de gestion de sol pour un même sol et une même utilisation. La compréhension et la gestion de la qualité inhérente et dynamique des sols ne sont pas indépendantes mais complémentaires (Karlen *et al.*, 2003).

Un grand nombre d'indicateurs de la qualité des sols est disponible (Bispo *et al.*, 2011; Karlen *et al.*, 1997; Warkentin and Fletcher, 1977). Les indicateurs physico-chimiques sont prépondérants pour une approche agronomique. Néanmoins, les différentes communautés d'organismes du sol peuvent fournir une approche plus intégrative de la qualité des sols (Nuria *et al.*, 2011; Villenave *et al.*, 2009a). Les aspects méthodologiques restreignent, tout de même, leur utilisation courante, spécialement dans le cas des petits organismes (Decaëns *et al.*, 2006; Parr *et al.*, 1994).

Dans un contexte de durabilité des agro-écosystèmes viticoles, le principal objectif de mon travail était d'évaluer l'influence des pratiques culturales sur la qualité des sols viticoles de la région du Languedoc-Roussillon mesurée par des indicateurs.

Pour répondre à cet objectif, je me suis posé les questions suivantes :

Question 1 : Quel est la gamme de variation des indicateurs étudiés, dans le contexte de la viticulture en Languedoc-Roussillon ?

Question 2 : Comment évolue la qualité des sols lors d'un changement de pratiques ?

Question 3 : La prédiction d'indicateurs directement sur le terrain est-elle possible pour faciliter leur utilisation ?

Question 4 : Quel intérêt portent les professionnels à la mise en place d'indicateurs de la qualité des sols viticoles ?

STRATEGIE DE RECHERCHE

Pour mener à bien ce projet, j'ai développé une approche originale combinant différentes disciplines. En effet, des enquêtes de terrain et des mesures d'indicateurs physiques, chimiques et biologiques ont été réalisées sur des échantillons de sol prélevés sur un large réseau de 188 parcelles de vigne commerciale de raisins de cuve directement sélectionnées dans des exploitations gérées par des viticulteurs. L'ensemble des résultats obtenus a alors été traité par des analyses statistiques univariées et multivariées. Dans une démarche participative avec les viticulteurs, j'ai aussi étudié leurs perceptions de la qualité des sols pour faciliter l'utilisation des indicateurs étudiés lors de ma thèse.

Pour répondre aux questions posées précédemment, 4 études ont été menées :

1. La première étape a été de construire un référentiel, dans le contexte du Languedoc-Roussillon en définissant la gamme de variation des différents indicateurs comme proposé par Arshad et Martin (2002). Pour atteindre cet objectif, 164 parcelles ont été soigneusement sélectionnées dans 9 zones du Languedoc-Roussillon. Cette approche a permis de maximiser la diversité des types de sol représentatifs de la région : Terrats et Lesquerde dans les Pyrénées-Orientales, Montagnac et Faugères dans l'Hérault, Aigues-Mortes, Vergèze, Jonquières Saint-Vincent, Saint-Hippolyte du Fort et Saint-Victor la Coste dans le Gard. Au sein de chacune des zones, une grande variabilité de pratiques culturales en terme de type de protection phytosanitaire (avec des pesticides naturels ou de synthèse), de désherbage (chimique, mécanique ou aucun), de fertilisation (minérale ou organique) et de durée du couvert végétal (nulle, temporaire ou permanente) ont été étudiées. Sur

les 164 parcelles sélectionnées des prélèvements de sol ont été réalisés. Un échantillon composite, issu de 10 prélèvements réalisés au milieu de l'interrang sur 0-15 cm par parcelle a été analysé par parcelle. Les vers de terre ont été échantillonnés sur une des neuf zones (4 répétitions par parcelle sur 13 parcelles de Saint-Victor la Coste). Ce réseau de parcelles sera dénommé *Réseau Référentiel* (**Question 1**).

2. La deuxième étude s'est focalisée sur l'évolution de la qualité des sols dans le cas d'une conversion de la viticulture conventionnelle à la viticulture biologique. Cette étude a été réalisée dans un vignoble situé dans le sud de la France à Cruscades (Aude). Le sol était limono-argileux et calcaire. L'étude a été menée sur 24 parcelles, réparties en 4 traitements:

- 10 parcelles conduites en agriculture conventionnelle (Conventionnel),
- 14 parcelles conduites en agriculture biologique (Bio),
    - 4 depuis septembre 2001 et certifiées officiellement depuis 2004 (Bio7),
    - 5 depuis septembre 1997 (Bio11),
    - 5 depuis septembre 1991 (Bio17).

Les prélèvements de sol et de vers de terre ont été réalisés au milieu de l'interrang sur 0-15 cm. Quatre répétitions par parcelle ont été réalisées. Ce réseau de parcelles sera dénommé *Réseau Biologique* (**Question 2**).

3. La troisième étude a eu pour objectif de faciliter l'acquisition des mesures d'indicateurs qui peut représenter un obstacle important tant les moyens techniques et humains nécessaires sont importants. Ainsi, nous avons comparé la réponse d'un outil de terrain (Géoprofiler) intégrant l'ensemble des propriétés du sol aux données relatives à l'étude des vers de terre mesurées sur 13 parcelles du *Réseau Référentiel* situées à Saint-Victor la Coste (**Question 3**)

4. Pour finir, une étude sociologique a été menée pour mieux connaître quelle(s) définition(s) les viticulteurs donnent de la qualité des sols et quels moyens ils utilisent pour l'évaluer afin d'accroître la transférabilité des indicateurs de la qualité des sols. Pour cela, des enquêtes par entretiens compréhensifs ont été réalisées auprès de 29 viticulteurs originaires de 4 zones du *Réseau*

Référentiel : Montagnac dans l'Hérault et Aigues-Mortes, Vergèze et Saint-Hippolyte du Fort dans le Gard. Les viticulteurs interviewés suivaient des itinéraires culturaux différents, principalement en terme de gestion du sol et de fertilisation, soit en mode conventionnel soit biologique (**Question 4**).

Le choix des indicateurs a constitué une étape clé de ma thèse. La méthode adoptée ici, a été inspirée de Bispo et al. (2011) et a consisté à déterminer en amont les usages et les fonctions que je souhaitais étudier. Le choix s'est donc porté, sur un ensemble d'indicateurs variés associant les composantes physique, chimique et biologique afin de tirer profit de leur complémentarité. Il a été confirmé par l'existence de méthodes de mesure standardisées. Les différents indicateurs utilisés pour la mesure de la qualité du sol sont répertoriés dans la table VIII-1.

Table VIII- 1 : Les différents indicateurs mesurés et leurs processus associés

Indicateurs	Processus associés
Physiques	
pierrosité	- érosion - capacité de rétention en eau du sol
texture	- érosion - aération - capacité de rétention en eau et en nutriments du sol
densité apparente	- compaction du sol
micro et macroporosité	- aération - capacité de rétention en eau du sol
humidité à la capacité au champ	- capacité de rétention en eau du sol
stabilité structurale des agrégats	- érosion - infiltration de l'eau dans l'eau
Chimiques	
calcaire actif et total	- pH - disponibilité des éléments
pH	- disponibilité des éléments - sélection d'organismes vivants
carbone (C) organique et azote (N) total	- stabilité des agrégats - capacité de rétention en eau et en nutriments du sol - stock d'éléments nutritifs minéralisables - activités biologiques
disponibilité des macronutriments (P et K)	- croissance et développement des plantes
capacité d'échange cationique (CEC)	- capacité de rétention en nutriments du sol
disponibilité en cuivre (Cu)	- risque de toxicité pour les organismes du sol
Biologiques	
microorganismes	- décomposition de la matière organique - formation de l'humus - agrégation du sol - cycle et rétention des nutriments
nématodes	- intensité de différents processus (décomposition de la matière organique) - structure du réseau trophique non nématologique (compartiments bactérien et fongique, prédation) - niveau de perturbations du système sol (longueur de la micro-chaîne trophique) - biodiversité
vers de terre	- décomposition de la matière organique - structuration du sol - fonctionnement hydrodynamique du sol

Connaître la gamme de variation des indicateurs pour évaluer la qualité des sols viticoles : le *Réseau Référentiel*

L'utilisation de méthodes statistiques a permis d'établir une typologie des différents sols et des différentes pratiques culturales. Ainsi, nous avons distingué 7 types de sol et 9 types de pratiques culturales dont les caractéristiques sont présentées dans les tables VIII- 2 et 3. La table VIII- 4 présente la répartition des différentes pratiques culturales au sein des différents sols.

Cette première étude a mis en évidence le fait que les sols viticoles du Languedoc-Roussillon étaient très particuliers et présentaient une très grande diversité. En effet, la majorité des sols avaient de faibles teneurs en carbone organique (< 15 mg g^{-1}), de fortes pierrosités (jusqu'à 90 % de cailloux) avec une grande amplitude de pH, des pH très hauts pour les sols très calcaires (jusqu'à 400 g de $CaCO_3$ kg^{-1}) ou des pH bas autour de 6,5. L'ensemble de ces caractéristiques font des sols viticoles du Languedoc-Roussillon des agro-écosystèmes particulièrement vulnérables.

Les résultats de chaque indicateur ont été représentés de façon graphique sous la forme de diagramme à moustaches, dans le but de renseigner sur la gamme de variation de chaque indicateur. Un exemple est donné en Figure VIII- 1 pour l'abondance totale des nématodes. Des analyses de variance (ANOVA) à 2 facteurs (sols et pratiques culturales) ont été réalisées pour identifier les différences significatives entre traitements pour les principaux indicateurs étudiés. Elles ont révélé que presque tous les indicateurs choisis étaient sensibles aux sols et/ou aux pratiques culturales, excepté la respiration du sol. L'analyse de la nématofaune a permis de mettre en évidence des états du sol différents en fonction des pratiques viticoles. L'abondance des nématodes bactérivores et fongivores a pu être relié à la taille et à l'activité du comportement microbien du sol. Les vers de terre ont révélé un comportement semblable à celui des nématodes omnivores et prédateurs.

Table VIII- 2 : Caractéristiques des 7 types de sol basés sur les indicateurs de qualité inhérente

Type de sol	Description	Nombre de parcelles	Refus 1 cm (%)	Argiles (%)	Sables (%)	pH	$CaCO_3$ total (g kg^{-1})
A	très sableux & calcaire	18	< 5	< 10	> 80	> 8.4	150 - 200
B	argileux & très calcaire	38	< 5	> 40	< 30	8,0 – 8,3	> 400
C	sableux & calcaire	24	< 5	15 - 20	45 - 55	8,0 – 8,3	150 - 200
D	texture moyenne & calcaire	19	10 - 20	30 - 40	< 30	8.0 – 8,3	90 - 100
E	sableux & très pierreux	11	90	15 - 20	45 - 55	7,0	< 5
F	sableux & acide	38	10 - 20	15 - 20	45 - 55	< 7,0	< 5
G	très sableux & acide	16	10 - 20	< 10	> 80	< 7,0	< 5

Table VIII- 3 : Caractéristiques des 9 types de pratiques culturales

Type de pratiques culturales	Nombre de parcelles	Pesticides		Fertilisation		Désherbage			Enherbement (mois an^{-1})		
		naturels	synthétiques	organique	autre	aucun	mécanique	chimique	12	4-8	0
1	22		■		■		■			■	
2	38	■		■		5%	95%		5%	95%	
3	28		■	■			■			■	
4	9		■		■		■				■
5	15		■		■			■			■
6	11		■		■	■			■		
7	15	33%	67%	■			67%	33%			■
8	19		■	5%	95%			■	21%	79%	
9	6	■			■		■			■	

Table VIII- 4 : Matrice de comparaison des différentes classifications des pratiques et sols viticoles

		Pratiques viticoles									TOTAL
		1	2	3	4	5	6	7	8	9	
Sols	A	6	6	6	■	■	■	■	■	■	18
	B	6	11	1	2	2	7	7	1	1	38
	C	■	1	6	■	2	2	■	10	3	24
	D	■	7	4	■	1	1	2	3	1	19
	E	■	2	1	■	3	1	■	4	■	11
	F	7	8	10	3	1	1	6	1	1	38
	G	3	3	■	4	6	■	■	■	■	16
	TOTAL	22	38	28	9	15	11	15	19	6	163

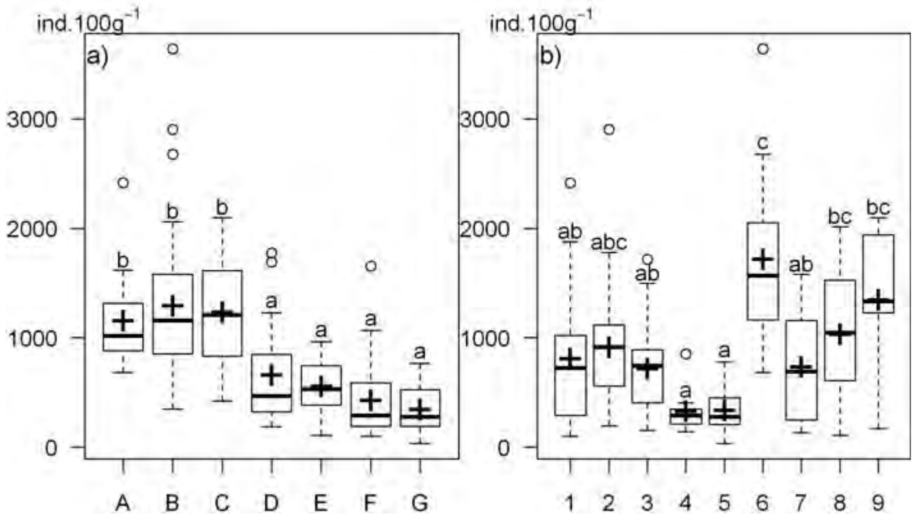

Figure VIII- 1 : Abondance totale des nématodes (ind. 100 g^{-1})

Plus précisément, les types de sol ont une influence sur la densité apparente, l'humidité à la capacité au champ, la teneur en matière organique, en phosphore disponible, le ratio biomasse microbienne/carbone organique, les densités des groupes trophiques de nématodes et les 6 indices nématofauniques. Quelques soient les groupes trophiques de nématodes, leur densité était plus importante en sols calcaires. En effet, 1 300 nématodes 100 g^{-1} de de sol, en moyenne, ont été comptés dans les sols les plus calcaires (A, B et C), alors pour les autres sols (D, E, F et G), ce ne sont que 500 nématodes 100 g^{-1} sol qui ont été comptés (Figure VIII- 1). En outre, les nématodes prédateurs ont paru ne pas être bien adaptés aux sols très argileux (B).

Concernant les pratiques viticoles, le désherbage chimique et le travail du sol conduisant à des sols nus toute l'année (4, 5 et 7) ont révélé les effets les plus négatifs sur la qualité des sols avec les plus fortes densités apparentes et les plus faibles teneurs en matière organique, ratios biomasse microbienne/carbone organique et densités des différents groupes trophiques de nématodes. Le maintien d'un sol nu en permanence est très défavorable pour la vie du sol (très peu d'organismes et très faible diversité fonctionnelle), encore plus si la destruction du couvert végétal est obtenu par travail du sol.

D'un autre côté, l'enherbement permanent (6) ou l'enherbement temporaire géré par désherbage chimique (8) ont révélé les plus hauts niveaux d'activité. Par exemple, la biomasse microbienne/carbone organique total, la densité des nématodes phytophages et des autres nématodes libres, ainsi que la densité et la biomasse des vers de terre ont été les plus élevées sous ces conditions. De plus, la gestion du vignoble avec le désherbage chimique a présenté une micro-chaîne trophique plus structurée et plus complexe, révélé par les indices nématologiques.

Pour finir, les autres pratiques (1, 2, 3 et 9) qui se caractérisaient par un enherbement temporaire géré par travail du sol, avec différentes fertilisations et protections phytosanitaires ont présentées des tendances comparables entre elles et un fonctionnement du sol intermédiaire entre les deux groupes identifiés précédemment. Le travail du sol a cependant montré des effets négatifs sur les organismes du sol comme les nématodes omnivores et prédateurs (indicateurs des perturbations) ainsi que la densité et la biomasse des vers de terre, surtout les vers de terre anéciques (vers utilisant des galeries et prélevant leur nourriture en surface du sol).

VITICULTURE BIOLOGIQUE ET QUALITE DES SOLS : LE *RESEAU BIOLOGIQUE*

Dans cette étude, la conversion de la viticulture conventionnelle en viticulture biologique a consisté en la substitution des fertilisants minéraux par l'application de matières organiques exogènes, l'implantation d'un couvert végétal, une augmentation de la fréquence du travail du sol mais aussi le remplacement de pesticides de synthèse par des pesticides naturels.

L'analyse discriminante (Figure VIII- 2B) basée sur les mesures des différents indicateurs (physiques, chimiques et biologiques) a montré une nette discrimination entre les 4 traitements (Conventionnel, Bio7, Bio11 et Bio17) et un gradient du Conventionnel vers le Bio17 indiqué par l'axe 1. Cet axe explique 68 % de la variabilité et est défini principalement par l'azote total, le carbone organique total, la densité des nématodes phytoparasites et fongivores ainsi que par la teneur en potassium disponible (Figure VIII- 2A). L'axe 2, contribuant à 25 % de la variabilité, est corrélé à la capacité d'échanges cationiques effective et la teneur en phosphore disponible (Figure VIII- 2A).

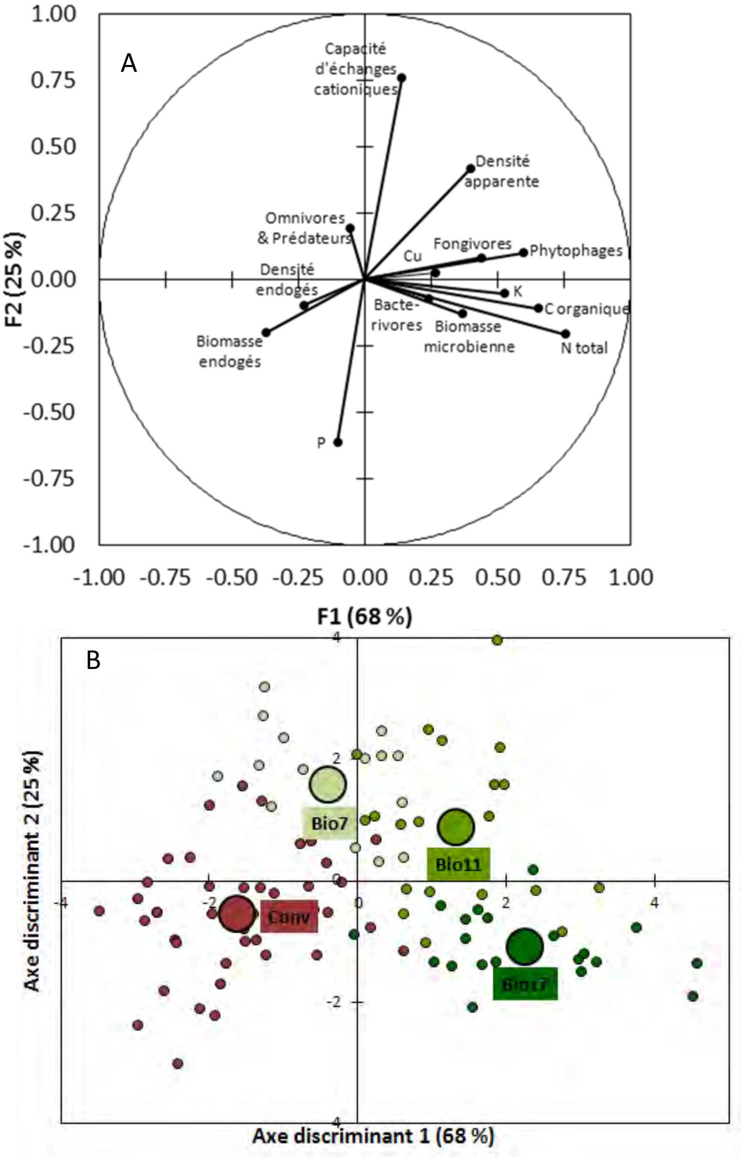

Figure VIII- 2 : Analyse discriminante basée sur 14 paramètres physiques, chimiques et biologiques pour les 4 traitements (Conventionnel, Bio7, Bio11 et Bio17).

Cercle de corrélations des différents indicateurs. (B) Distribution des 96 observations et de leur centroïde (symboles prédominants) pour chaque traitement le long des 2 axes discriminants.

Après 17 ans de viticulture biologique, la teneur en matière organique et la biomasse microbienne ont augmenté, respectivement + 32 % et + 34 %. Une augmentation des ressources disponibles est mesurée par un indice d'enrichissement (IE) plus élevé, elle a conduit à augmenter la densité des nématodes microbivores (+ 35 %, pour les bactérivores et + 97 %, pour les fongivores) et principalement les fongivores opportunistes. Le fonctionnement du sol a été modifié avec les voies de décomposition de la matière organique devenant plus fongique que bactérienne. Les transformations de la matière organique du sol ont conduit à l'augmentation de la teneur en phosphore (+ 133 % entre Bio7 et Bio17) et en potassium (+ 81 % entre Conventionnel et Bio17) disponibles. La conversion à l'agriculture biologique a également conduit à l'augmentation des nématodes phytophages, non nuisibles pour la vigne (+ 187 %, après 17 ans de viticulture biologique). Cette modification a été attribuée à la présence d'un couvert végétal plus dense, sur une plus longue période, pour les traitements Bio.

Même si des changements étaient observés dans la structure de la communauté de nématodes après conversion, l'indice de maturité (MI), l'indice des nématodes phytophages (PPI) et l'indice de structure (SI) sont restés constants. Par conséquent, les pratiques agricoles biologiques n'ont amélioré ni la longueur ni la complexité de la chaîne trophique du sol (bien que quantitativement l'activité biologique soit plus importante) ; le niveau de perturbations dans le sol n'a donc pas changé après conversion. La viticulture biologique a conduit à une diminution significative de l'abondance des vers de terre endogés (- 65 % en 17 ans). Il semblerait que le travail du sol réalisé en viticulture biologique, plus fréquent et plus profond qu'en viticulture conventionnelle, ait un effet négatif marqué sur le fonctionnement biologique du sol. Toutefois, l'augmentation de la compaction et de la teneur en cuivre disponible ont contribué à des modifications de l'état physique et chimique du sol, préjudiciables pour le fonctionnement du sol.

Dans cette étude, nous avons démontré que la période de transition 7-11 ans, dépendant des indicateurs considérés, étaient nécessaires pour séparer clairement les pratiques conventionnelles de celles organiques dans les vignobles du sud de la France. Malgré la diversité des indicateurs étudiés, nous avons souligné la difficulté de montrer les bénéfices de l'agriculture bio sur la qualité globale du sol dans une zone pédoclimatique particulière, et pour les types de pratiques culturales que nous avons étudiés.

Les résultats de cette étude dite *Réseau Biologique* ont été acceptés pour publication dans les deux revues Applied Soil Ecology (2011, vol. 50, pages 37-44) et Nematology (accepté le 25 décembre 2011).

DES MESURES ELECTROMAGNETIQUES POUR PREDIRE DES INDICATEURS RELATIFS AUX VERS DE TERRE

Dans les deux réseaux de parcelles *Référentiel* et *Biologique*, nous avons mesuré l'abondance et la biomasse des catégories écologiques de vers de terre. Ces indicateurs sont apparus sensibles aux différentes pratiques viticoles étudiées. Cependant, dans les deux cas, l'échantillonnage nécessité d'importants moyens techniques et humains (40 personnes pendant 1 journée, 1 560 l d'eau et 23,4 kg de moutarde commerciale pour échantillonner les vers de terre sur 13 parcelles à raison de 4 répétitions par parcelle). La logistique de ce type de prélèvements explique pourquoi de nombreuses personnes sont découragées par l'étude des vers de terre. Par conséquent, une nouvelle méthode basée sur la résistivité a été testé pour prédire la biomasse et l'abondance des vers de terre directement sur le champ. Les premiers résultats ont montré des résultats très intéressants et encourageants.

Les résultats de cette étude sont en cours de rédaction pour publication dans une revue scientifique.

LA QUALITE DES SOLS : ASSOCIER PERCEPTIONS ET ANALYSES DES SCIENTIFIQUES ET DES VITICULTEURS

Cette étude sociale a permis, dans un premier temps, d'identifier 4 registres de la qualité des sols. Les viticulteurs ont décrit leur sol comme (i) un outil de production, (ii) un réservoir avec des propriétés physico-chimiques, (iii) un système vivant à protéger et (iv) une composante du Terroir. La définition des registres de la qualité des sols rappellent en de nombreux points ceux proposées par les scientifiques. Cependant, les conceptions de la protection de l'environnement semblaient être plus limitées pour les viticulteurs et plus locales, restreintes à l'échelle de la parcelle ou de l'exploitation. Dans leur définition d'un « bon » sol, les viticulteurs ont donné aussi plus de précisions en terme de propriétés physico-chimiques tandis que les scientifiques sont plus généraux. Pour finir, les viticulteurs ont inclus dans la définition de la qualité des sols, la notion de Terroir.

Dans un second temps, les indicateurs physico-chimiques et biologiques mesurés sur le *Réseau Référentiel* et le *Réseau Biologique* ont été comparés à ceux utilisés par les viticulteurs. Les scientifiques et les professionnels partagent de nombreux indicateurs mais l'étude des indicateurs utilisés par les viticulteurs révèlent le besoin d'outils diversifiés, efficients et opérationnels pour évaluer la qualité des sols.

Pour finir, nous avons tenté de relier les perceptions des viticulteurs de la qualité des sols avec leurs caractéristiques socio-économiques. Cependant, ni l'âge, ni le niveau d'études, ni la taille de l'exploitation, ni le type de viticulture (conventionnel ou biologique) n'a semblé avoir d'effets déterminants.

Cette étude préliminaire, pourra inspirer des enquêtes réalisées, à partir de questionnaire, sur un grand nombre de viticulteurs conduisant à des données quantitatives, exploitables par des méthodes statistiques.

Les résultats de cette étude ont été acceptés pour publication dans la revue *Etude et Gestion des Sols*.

CONCLUSION ET PERSPECTIVES

Malgré des sols viticoles aux qualités inhérentes peu favorables et une gestion intensive des vignes, très peu d'études se sont intéressées à l'effet des pratiques viticoles sur la qualité dynamique des sols. Pourtant, l'enquête sociologique a révélé un intérêt motivé des viticulteurs pour évaluer la qualité de leurs sols. Mes travaux de recherche ont ainsi contribué à combler certaines lacunes à ce sujet. Ils ont permis de mieux comprendre la qualité dynamique des sols viticoles du Languedoc-Roussillon et les façons dont les pratiques culturales l'influencent. D'un point de vue opérationnel, ma recherche a aussi fourni un référentiel utilisable par les acteurs de la filière viticole. Il est à présent possible d'établir une liste d'indicateurs opérationnels pour évaluer la qualité des sols viticoles en y associant les principales caractéristiques pratiques en terme d'informations fournies, de temps et de coût d'acquisition (Table VIII- 5). Cependant, l'interprétation des résultats nécessitent d'être faite par des spécialistes. L'information et la sensibilisation de ces outils doivent passer par la formation des viticulteurs.

Le *Réseau Référentiel* devra, par la suite, faire l'objet d'autres analyses. Dans un premier temps, les résultats des enquêtes sur la gestion du vignoble réalisées sur l'ensemble des 164 parcelles (plus de 50 viticulteurs interviewés) devront être analysés pour permettre une interprétation plus fine sur les effets des pratiques viticoles sur les indicateurs. Deuxièmement, il serait très pertinent de se centrer sur des données spécifiques comme la stabilité structurale, la nématofaune et les microorganismes.

L'important jeu de données généré par cette étude pourra également servir de base pour des experts de la spectrométrie proche ou moyen infra rouge (NIRS ou MIRS) pour tenter de prédire les indicateurs biologiques souvent longs et coûteux à obtenir et aboutir à une approche intégrée de qualité du sol.

Le *Réseau Biologique* ne permet pas de généraliser les effets de la viticulture biologique sur la qualité des sols mais seulement de conclure les effets de certaines pratiques biologiques dans une zone donnée. Par conséquent, il pourrait être utile dans le futur de comparer différentes pratiques de l'agriculture biologique plutôt que de comparer agriculture conventionnelle et agriculture biologique. Par exemple, il pourrait être intéressant d'étudier des alternatives au travail du sol, ayant des effets négatifs sur les organismes du sol, comme le semis de mélanges d'espèces végétales qui meurent au début de l'été ou le contrôle de l'enherbement par utilisation d'un rolofaca (rouleau à lames horizontales cassant et couchant les tiges des adventices sans les couper).

Table VIII- 5 : Principales caractéristiques pratiques des indicateurs de qualité du sol étudiés

	Echantillonnage sur la parcelle			Analyses de laboratoire		Interprétation	
	Facilité	Temps	Contraintes	Coût (€/éch.)	Disponibilité	Pertinence	Fréquence (année)
Indicateurs physiques							
Pierrosité	+++	+		5-10	+++	+	1 / 50
Texture	+++	+		20-25	+++	+	1 / 20
Densité apparente	+	++	matériel	?	0	++	1 / 5
Humidité à la capacité au champ	+++	+		10-15	+++	++	1 / 5
Stabilité des agrégats	+++	+		?	0	++	1 / 5
Indicateurs chimiques							
pH	+++	+		5 - 10	+++	+	1 / 20
$CaCO_3$ total	+++	+		5 - 10	+++	+	1 / 20
$CaCO_3$ actif	+++	+		5 - 10	+++	+	1 / 20
Carbone organique total	+++	+		10 - 15	+++	+++	1 / 5
Azote total	+++	+		10 - 15	+++	+++	1 / 5
Phosphore disponible	+++	+		5 - 10	+++	++	1 / 5
Potassium disponible	+++	+		5 - 10	+++	++	1 / 5
Capacité d'échange cationique	+++	+		5 - 10	+++	+++	1 / 5
Cuivre disponible	+++	+		5 - 10	+++	++	1 / 5
Indicateurs biologiques							
Biomasse microbienne	+++	+	sol frais	45	+	+++	1 / 2
Respiration du sol	+++	+	sol frais	45	+	+	1 / 2
Nématofaune du sol : abondance des phytophages	+++	+	sol frais	200	+	+++	1 / 2
Nématofaune du sol : abondance des bactérivores & fongivores	+++	+	sol frais	inclus	+	+++	1 / 2
Nématofaune du sol : abondance des omnivores & prédateurs	+++	+	sol frais	Inclus	+	+++	1 / 2
Indices nématofaunique : EI, SI, NCR…	+++	+	sol frais	inclus	+	+++	1 / 2
Vers de terre : abondance des catégories écologiques	+++	+++	moyens	?	+	+++	1 / 2
Vers de terre : biomasse des catégories écologiques	+++	+++	moyens	?	+	+++	1 / 2

0: absent ; +: faible ; ++: moyen ; +++: élevé

CHAPITRE IX

NOUVEAU CHAPITRE DE LA THESE

Dans le cadre des formations proposées par la Maison des Ecoles Doctorales de Montpellier, j'ai eu l'opportunité de participer à une formation sur le thème de la « Valorisation des compétences des docteurs- Nouveau chapitre de la thèse ». Cette formation a eu pour but de m'aider à valoriser mon travail de thèse et à traduire en terme de compétences et savoir-faire mes acquis. Cette formation s'est conclue par une soutenance publique et a donné lieu à la rédaction d'une synthèse : celle-ci est présentée dans les pages qui suivent.

VALORISATION DES COMPETENCES DES DOCTEURS, NCT®

DES INDICATEURS PHYSICO-CHIMIQUES ET BIOLOGIQUES POUR EVALUER LA QUALITE DES SOLS VITICOLES

présenté par **Patrice COLL**

le 24 juin 2011

Sujet académique de la thèse : Caractérisation d'indicateurs physico-chimiques et biologiques pour déterminer la qualité des sols viticoles

Nom des co-directrices de thèse : Cécile VILLENAVE et Edith LE CADRE

Nom du « mentor » NCT : Nathalie CAMUS

Organisme de rattachement : Montpellier SupAgro

Ecole Doctorale : SIBAGHE (Systèmes Intégrés en Biologie, Agronomie, Géosciences, Hydrosciences, Environnement)

Date de soutenance de thèse : décembre 2011

1. CADRE GENERAL ET ENJEUX DE MA THESE

1.1. PRESENTATION DE MON PROJET

Les **sols viticoles** sont des **milieux complexes et fragiles**. Evaluer la qualité des sols s'avère donc indispensable pour optimiser leur fonctionnement et limiter leur dégradation. C'est dans ce contexte que je réalise une thèse de doctorat sur la « Caractérisation d'indicateurs physico-chimiques et biologiques pour déterminer la qualité des sols viticoles ». Ce travail est co-financé par Montpellier SupAgro[1] et l'ADEME[2] et il est réalisé au sein de l'UMR Eco&Sols[3]. Mon sujet porte sur une étude approfondie de paramètres physico-chimiques (teneur en matière organique et en éléments majeurs disponibles, porosité, stabilité structurale…) associés à des paramètres biologiques relatifs au compartiment microbien, à la nématofaune[4] et aux peuplements de vers de terre.

L'enjeu finalisé de ce projet est de proposer aux professionnels de la filière viticole un **outil de pilotage basé sur des indicateurs biologiques et physico-chimiques de qualité des sols** qui permettra d'analyser la **durabilité des sols** et d'inciter les viticulteurs à adopter des itinéraires culturaux plus **respectueux de l'environnement**, tout en prenant en compte les réalités économiques et sociales.

Dans ce cadre, **deux études de terrain** ont été menées. La première vise à évaluer les impacts de différentes pratiques culturales (désherbage chimique, travail du sol ou enherbement) sur la qualité des sols des neuf zones pédoclimatiques les plus représentatives du Languedoc-Roussillon. La deuxième est centrée sur l'évolution, à long terme, de la qualité des sols après la conversion d'un vignoble en agriculture biologique. Afin de mieux répondre aux attentes des professionnels, **une étude humaine et sociale** a permis de définir la perception de la qualité des sols chez les viticulteurs et leur préoccupation en terme de gestion du sol.

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[1] Ecole Nationale Supérieure d'Agronomie de Montpellier

[2] Agence De l'Environnement et de la Maîtrise de l'Energie

[3] Unité Mixte de Recherche : Ecologie Fonctionnelle et Biogéochimie des Sols et des Agroécosystèmes

[4] La nématofaune est l'ensemble d'une communauté de nématodes qui sont des vers microscopiques présents dans les sols.

1.2. MON SUJET DANS SON CONTEXTE

Mon projet de thèse s'inscrit dans un des trois thèmes étudiés par notre UMR. Il s'agit du thème : « Sol, activités et réseaux biologiques ». La conception de pratiques agronomiques capables de promouvoir les processus écologiques nécessite une **amélioration des connaissances actuelles du fonctionnement biologique du sol**, en particulier du rôle des organismes, des interactions trophiques ou non trophiques et de la biodiversité. L'originalité de nos travaux réside aussi dans la prise en compte des interactions (i) entre organismes dans les processus de symbiose, de prédation et de compétition (réseaux multi-trophiques), et (ii) entre organismes et leur environnement physico-chimique. Ces **systèmes de culture alternatifs, limitant l'utilisation d'intrants**, redonnent une place centrale aux processus écologiques fondés sur les fonctions des organismes du sol et des racines des végétaux. On parle alors d'intensification écologique, d'agriculture de conservation, d'agriculture biologique ou d'agro-écologie. Mon projet de recherche est **le seul dans l'UMR à s'intéresser aux systèmes viticoles**. Pourtant, les viticulteurs et organismes de conseils (Chambres d'Agriculture ou laboratoires privés) manifestent un intérêt croissant pour les questions relatives à la qualité des sols et aux cultures alternatives.

Mon travail de thèse est **très intégratif** puisqu'il cherche à étudier la qualité du sol dans son ensemble et à évaluer la complémentarité des différents indicateurs. L'ensemble des compétences nécessaires à la réalisation de mon travail est disponible dans notre laboratoire. Cependant, j'ai pris **contact avec une unité voisine**, l'UMR LISAH[5], auprès de laquelle j'ai pu obtenir de précieux conseils concernant les tests de stabilité structurale et les expertises de terrain (évaluation de la texture et du pH d'un sol, de l'hétérogénéité d'une parcelle…). Notre équipe de recherche est en relation avec d'autres unités avec lesquelles j'ai pu aussi collaborer comme les UMR System, LEPSE[6] et CEFE[7].

1.3. Moi dans ce contexte

Issu d'une famille de petits viticulteurs des Corbières (Aude), j'ai ressenti le lent et inexorable déclin de la viticulture dans mon pays. Vignerons en faillite, caves coopératives qui périclitent, vignes qui laissent place aux jachères, perte de notre patrimoine culturel local largement centré sur la vigne et le vin… tel est le paysage languedocien qui s'offre à nous aujourd'hui. Les difficultés que rencontrent ma famille et mes amis à vivre de leur métier auraient pu me décourager. Bien au contraire, elles ont fait naître en moi l'**envie de lutter**

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[5] Laboratoire d'étude des Interactions - Sol - Agrosystème - Hydrosystème
[6] Laboratoire d'Ecophysiologie des Plantes sous Stress Environnementaux
[7] Centre d'Ecologie Fonctionnelle et Evolutive

contre cette décadence, de mettre ma curiosité intellectuelle, ma force de travail, mon engagement professionnel au service d'une nouvelle viticulture inscrite dans les légitimes préoccupations du respect de l'environnement. Très jeune, je me suis orienté vers des **études tournées vers le monde agricole** : Baccalauréat Scientifique d'abord, puis IUT Génie Biologique – option Agronomie et enfin Ecole d'Ingénieur Agronome où tout naturellement j'ai choisi la spécialisation Viticulture-Œnologie. Sensible aux questions posées par le développement durable et la viticulture biologique, j'ai décidé de poursuivre mon cursus par une thèse de doctorat sur l'étude du fonctionnement biologique des sols. Mon engagement précoce dans ce projet de thèse m'a permis de **participer activement à l'élaboration du sujet**. A travers cette expérience, je souhaite apporter des éléments de réponse qui engageront la **filière viticole sur de nouvelles voies plus respectueuses de l'environnement**.

2. DEROULEMENT, GESTION ET COUT ESTIME DE MON PROJET

2.1. PRINCIPALES ETAPES

Le **cadrage du projet et la définition des expérimentations** ont constitué une **étape cruciale** pour le bon déroulement de mon projet. J'ai été épaulé dans cette tâche par mes **co-encadrantes** avec qui je me suis réuni fréquemment. Les membres du **comité de pilotage** ont aussi été d'une aide précieuse. La préparation des différentes réunions et la rédaction des synthèses correspondantes ont été indispensables pour que **je m'approprie le sujet**. Après validation des objectifs de recherche et des dispositifs expérimentaux, je me suis entièrement consacré aux travaux de terrain et aux analyses de sol. **Le comité de pilotage de 2ème année** a validé l'orientation que j'avais prise. En tant qu'agent contractuel de l'ADEME, **j'ai répondu aux exigences administratives demandées** : états d'avancement, fiche de congés…

2 .2. CHOIX DES PARTENAIRES

Un **grand nombre de partenaires** participe de près ou de loin à ce projet. Je distingue tout d'abord ceux du **secteur viti-vinicole** qui m'ont aidé dans la constitution du réseau de parcelles nécessaire à mes expérimentations. Je pense aux institutions suivantes : l'**AIVB-LR**[8], l'**IFV**[9], les **Chambres d'Agriculture de l'Hérault et des Pyrénées-Orientales**. Je n'oublie pas non plus l'ensemble des viticulteurs et les directeurs des caves coopératives qui m'ont accueilli sur leur vignoble.

J'ai su également m'entourer de **scientifiques compétents**, extérieurs à notre unité pour consolider certaines de mes compétences. Je fais référence ici aux chercheurs et techniciens des **UMR LISAH, System, Innovation et CEFE** ainsi qu'à l'**Université de Basilicata** (Italie).

J'ai également trouvé un **soutien précieux auprès des étudiants de Montpellier SupAgro** à travers des activités pédagogiques : stages, projet d'élève ingénieur et travaux pratiques.

2.3. FACTEUR DE SUCCES

Afin de valider la pertinence des indicateurs étudiés, j'ai analysé les sols de 188 parcelles réparties sur dix zones pédoclimatiques du Languedoc-Roussillon. La **constitution de ce réseau expérimental d'une telle envergure** et la rencontre d'un grand nombre de professionnels constituent à eux seuls le premier facteur de réussite de ma thèse.

L'intérêt de mon sujet pour le milieu professionnel est tel que j'ai été sollicité pour donner une **conférence orale au SITEVI**[10] en décembre 2009. J'ai été **interviewé pour le magazine Réussir Vigne** en tant qu'expert de la qualité des sols viticoles. Ces deux interventions m'ont permis de **diffuser mon travail** auprès du monde viticole et ont constitué d'excellents moyens de communication. J'ai aussi été **contacté par un consultant en agriculture écologique** pour des questions relatives à l'effet des désherbants chimiques sur les organismes du sol et par le responsable pédagogique de **l'École Supérieure d'Agriculture d'Angers** pour donner un cours sur la qualité des sols. Ces sollicitations témoignent du grand intérêt de mon sujet de recherche et de l'**efficacité de ma communication**. En plus d'être soutenues par le milieu viticole, mes recherches sont **reconnues par la communauté scientifique**. Ainsi, j'ai été sélectionné pour présenter mes résultats lors de conférences au 30ème Symposium International de l'ESN[11] et au 17ème Symposium International du GiESCO[12].

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[8] Association Interprofessionnelle des Vins Biologiques-Languedoc-Roussillon

[9] Institut Français de la Vigne et du Vin

[10] Salon International pour les filières VIgne-vin et fruits et légumes

[11] European Society of Nematologists

[12] Groupe International d'Experts en Systèmes vitivinicoles pour la CoOpération

2.4. FACTEURS DE RISQUES

En début de thèse, je ne disposais d'**aucun financement pour le fonctionnement du projet**. J'ai fait la démarche de **contacter moi-même des organismes** susceptibles de soutenir des activités de recherche comme les Fondations Gaz de France, EDF, Nicolas Hulot pour la Nature et l'Homme, Marcel Bleustein-Blanchet, Ensemble et la Fondation de France. Ces demandes se sont révélées infructueuses. C'est finalement en répondant aux appels d'offre interne de notre unité que j'ai obtenu un **budget conséquent** pour commencer mes recherches. Ce financement a été complété par une partie du budget alloué au projet AIDY[13] auquel mon travail de thèse a été associé. Le **projet AIDY** est construit autour d'une démarche de modélisation conceptuelle d'un système viticole converti en agriculture biologique. Il vise à formaliser les connaissances scientifiques pour identifier des indicateurs pertinents pour l'accompagnement des viticulteurs dans cette trajectoire.

Mon **projet de recherche est très ambitieux** et requiert un grand investissement sur le terrain et au laboratoire pour recueillir l'ensemble des données. Dans le but de **gérer au mieux la lourde charge de travail**, je me suis imposé un **planning très strict**. Je me suis aussi **entouré d'une stagiaire et d'un doctorant** avec qui j'ai collaboré pendant un an. Ces deux stratégies m'ont ainsi permis de me libérer du temps pour l'analyse et l'interprétation des résultats nécessaires à une **valorisation optimale** de mes travaux.

Compte-tenu du **nombre important des partenaires** associés à ce projet, il a parfois été **difficile de communiquer** auprès de chacun d'eux. Outre les appels téléphoniques et les envois d'e-mails, j'ai participé à **diverses manifestations** (SITEVI, Millésime Bio…) qui m'ont permis de **consolider les réseaux existants**.

2.5. ESTIMATION ET PRISE EN CHARGE DU COUT DU PROJET

J'ai souhaité dissocier dans la table IX-1 la valeur de ma thèse et son coût, c'est-à-dire le montant réel du budget qui a été utilisé pour financer ce projet. **La différence entre la valeur et le coût de ma thèse s'élève à 21 446,46 €**. Les trois postes sur lesquels des économies ont été faites sont :

- les ressources humaines,
- les infrastructures,
- les déplacements.

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[13] Analyse Intégrée de la DYnamique des systèmes biophysiques, techniques et de décision lors de la conversion à la viticulture biologique

Table IX- 1 : Valeur (€) et coût (€) de mon projet de thèse sur une période de 3 ans

	Nature de la dépense	Détails*		Valeur (€)	Coût (€)	Financeurs** avec part
1	**Ressources humaines**					
1.1	Doctorant	SB : 68071,54	CP : 29429,83	97501,40	97501,40	ADEME (50%), Montpellier SupAgro (50%)
1.2	Encadrante 1	SB : 15584,33	CP : 4675,30	20259,63	20259,63	IRD (100%)
1.3	Encadrante 2	SB : 10059,55	CP : 3017,87	13077,42	13077,42	Montpellier SupAgro (100%)
1.4	Techniciens	SB : 3241,20	CP : 634,52	3875,72	3875,72	INRA (90%), IRD (10%)
1.5	Pédologue-Expert			3000,00	0,00	-
1.6	Doctorant	SB : 18900,00	CP : 3780,00	22680,00	22680,00	Université Basilicata (100%)
1.7	Stagiaires			2502,54	1668,36	Annexe (100%)
1.8	Main d'œuvre occasionnelle	SB : 5420,16	CP : 1626,05	7046,21	0,00	-
1.9	Prestataire de services			9571,18	9571,18	Thème 1 (47%), AIDY (53%)
	Sous-total Ressources humaines			**179514,10**	**168633,71**	
2	Consommables					
2.1	Fournitures expérimentales			4008,86	4008,86	Thème 1 (63%), AIDY (37%)
2.2	Fournitures de bureau			300,00	300,00	UMR Eco&Sols (100%)
	Sous-total Consommables			**4308,86**	**4308,86**	
3	**Infrastructures**					
3.1	Entretien, gardiennage, secrétariat			700,00	700,00	UMR Eco&Sols (100%)
3.2	Loyers des locaux			7200,00	0,00	-
3.3	Electricité, eau, chauffage			100,00	100,00	UMR Eco&Sols (100%)
	Sous-total Infrastructures			**8000,00**	**900,00**	
4	**Matériel (amortissements)**					
4.1	Matériel d'expérimentation	Inclus dans 2.1		0,00	0,00	-
4.2	Ordinateur de bureau			946,63	946,63	UMR Eco&Sols (100%)
4.3	Logiciels de bureau			696,21	696,21	Montpellier SupAgro (100%)
	Sous-total Matériel			**1642,84**	**1642,84**	
5	**Déplacements**					
5.1	Missions en France			11655,05	8078,68	UMR Eco&Sols (39%), Thème 1 (23%), Université Basilicata (15%), AIDY (13%), Montpellier SupAgro (4%), ADEME (4%), P. Coll (2%)
5.2	Missions à l'étranger			0,00	0,00	-
5.3	Congrès en France			532,40	828,90	Thème 1 (59%), AIDY (28%), P. Coll (13%)
5.4	Congrès à l'étranger			3000,00	3000,00	Thème 1 (50%), Annexe (50%)
	Sous-total Déplacements			**15187,45**	**11907,58**	
6	**Formation**					
6.1	Formations			1390,00	1390,00	ED SIBAGHE (89%), UMR Eco&Sols (11%)
6.2	Inscription à Montpellier SupAgro			1051,00	1051,00	P. Coll (100%)
	Sous-total Formation			**2441,00**	**2441,00**	
7	**Documentation - communication**					
7.1	Affranchissements, Internet et téléphone			494,00	494,00	UMR Eco&Sols (100%)
7.2	Publicité, communication, impressions			672,69	586,49	Thème 1 (84%), P. Coll (16%)
7.3	Documentation (livres, bases de données)			508,90	508,90	Thème 1 (100%)
	Sous-total Documentation et communication			**1675,59**	**1589,39**	
8	**Charges financières (intérêts des emprunts)**			**0,00**	**0,00**	-
	Sous-total Charges financières			**0,00**	**0,00**	
9	**Charges exceptionnelles**			**0,00**	**0,00**	-
	Sous-total Charges exceptionnelles			**0,00**	**0,00**	
	TOTAL			**212669,84**	**191223,38**	

* Détail : SB = salaire brut, CP = charges patronales.

** Financeurs : Thème 1 = budget interne de l'UMR Eco&Sols, AIDY = projet de recherche, Annexe = projet annexe à ma thèse.

Un récapitulatif des différents organismes financeurs de mon projet de thèse sur une période de 3 ans est présenté dans la Table IX- 2.

Table IX- 2 : Financement de mon projet de thèse sur une période de 3 ans

Organismes financeurs*	Montant du financement (€)
Montpellier SupAgro	62847,49
ADEME	49073,85
Université Basilicata	23891,80
IRD	20647,18
Thème 1	11872,74
AIDY	7838,32
UMR Eco&Sols	5744,22
INRA	3488,15
Annexe	3168,36
P. Coll	1414,17
ED SIBAGHE	1237,10
TOTAL	**191223,38**

* Financeurs : Thème 1 = budget interne de l'UMR Eco&Sols, AIDY = projet de recherche, Annexe = projet annexe à ma thèse.

3. COMPETENCES, SAVOIR-FAIRE, QUALITES PROFESSIONNELLES ET PERSONNELLES

3.1. EXPERTISE TECHNIQUE ET SCIENTIFIQUE

- **appliqué, volontaire et intégratif**, j'ai développé de solides connaissances et compétences dans l'évaluation globale de la qualité des sols,
- **toujours attiré par les métiers de terrain**, je suis devenu un expert dans l'évaluation des principales caractéristiques d'un sol, la mise en place d'expérimentation et les méthodes de prélèvements des sols et de leur macrofaune,
- **motivé et soucieux de produire des connaissances**, je me suis formé sur de nombreux protocoles d'analyses physico-chimiques et biologiques,
- **tenace et doué d'une grande concentration**, je me suis **spécialisé** dans l'identification des nématodes qui est une discipline qui compte très peu d'experts,
- **soucieux de produire un travail de qualité**, je me suis référé aux personnes les plus compétentes pour m'assurer des formations de haut niveau,
- **curieux**, j'ai profité de mon immersion pendant trois ans dans le milieu de la recherche pour assister à des séminaires qui ont enrichi et élargi mes connaissances dans le domaine des sciences du sol.

3.2. CONNAISSANCES ET COMPETENCES TRANSVERSALES

- la rédaction d'articles scientifiques m'a permis de prendre plus de **recul** par rapport à mon sujet, d'améliorer mon **esprit critique** et d'être encore **plus rigoureux**,
- **soucieux d'augmenter mon efficacité et la qualité de mon travail**, je me suis formé à différents logiciels : EndNote pour la gestion des références bibliographiques, R pour les statistiques, Sphinx pour les questionnaires d'enquêtes, Google Earth et QGis pour la cartographie,
- j'ai également **amélioré mon niveau en Anglais**.

3.3. CONSTITUTION D'UN RESEAU

- **stratégique et efficace**, j'ai tissé un réseau de professionnels en peu de temps,
- **tenace**, j'ai continué à prospecter malgré les refus,
- **pédagogue et capable de vulgariser**, j'ai tenu des discours clairs et percutants qui m'ont permis de convaincre,
- **bon relationnel et sympathique**, je suis parvenu à créer une relation de confiance dès les premiers contacts,
- **diplomate, doué d'une grande adaptabilité et d'empathie**, j'ai tenu compte des préoccupations de chaque viticulteur pour adapter mon discours,
- **soucieux de ma réputation**, j'ai attaché beaucoup d'importance à entretenir le réseau que j'ai constitué.

3.4. ESPRIT PRATIQUE

- **ma très bonne forme physique** m'a permis de réaliser l'ensemble des prélèvements dans les temps prévus,
- **rigoureux et assidu**, j'ai respecté les objectifs fixés,
- **organisé et doué d'une grande anticipation**, j'ai veillé au bon déroulement des missions,
- **autonome, calme et doué d'une grande adaptabilité**, je suis parvenu à gérer les différents imprévus,
- **systématique et méthodique**, j'ai géré sans difficulté la traçabilité des nombreux échantillons que j'ai analysés.

3.5. TRANSFERT, COMMUNICATION ET ENSEIGNEMENT

- **attentif aux préoccupations des professionnels**, j'ai initié une étude sociologique portant sur la perception de la qualité des sols par les viticulteurs,
- **ouvert et communicant**, j'ai participé à des séminaires et colloques qui m'ont permis de présenter mes résultats scientifiques.
- **impliqué** au sein de notre unité, j'ai pris en charge pendant un an l'animation scientifique entre stagiaires, doctorants et post-doctorants,
- **altruiste**, j'ai mis mes connaissances au profit de notre unité en participant à la rédaction du protocole de la détermination de la biomasse microbienne adapté aux conditions de notre laboratoire,
- **pédagogue**, j'ai enseigné devant des étudiants de différentes formations.

3.6. MANAGEMENT ET ORGANISATION

- mon projet de thèse m'a appris que j'étais **capable de déléguer** une partie de mon travail à des stagiaires,
- **enthousiaste, convaincant et doué d'une capacité à mobiliser un grand nombre de personnes**, j'ai fait participer cinquante étudiants et scientifiques à une journée de prélèvements de vers de terre,
- **manager et logisticien**, j'ai relevé le défi de gérer cinquante personnes pendant une journée entière,
- **convivial et reconnaissant**, je n'ai pas oublié de remercier les personnes qui m'ont aidé autour d'un buffet.

3.7. GESTION DE BUDGET ET DE DOSSIERS ADMINISTRATIFS

- **autonome**, j'ai géré des budgets et les dossiers administratifs,
- soucieux de toujours **anticiper**, j'ai établi des budgets prévisionnels,
- **économe**, j'ai atteint mes objectifs malgré un budget très restreint,
- **précis et rigoureux**, j'ai suivi mes dépenses et réglé les problèmes avec les fournisseurs et les secrétaires au fur et à mesure,

- **droit et appliqué**, j'ai répondu le plus juste possible aux contraintes administratives (demande de mission…),
- je suis également **capable d'organiser un déplacement à l'étranger** (réservation d'hôtels, de billets d'avion, itinéraires…).

3.8. COMPETENCES TRANSFERABLES

Les emplois que je vise après la thèse sont tous en relation avec la vigne et/ou le sol. De ce fait, l'ensemble des compétences que j'ai acquises sont transférables aux postes que je vise après la thèse. Parmi les compétences transversales que j'ai acquises, la gestion des ressources, d'un budget et des contraintes administratives sont le quotidien de tout cadre en entreprise.

4. RESULTATS ET IMPACTS DE MA THESE

Pour la recherche en général et pour notre laboratoire en particulier :

- apporter des **connaissances supplémentaires** dans le fonctionnement biologique des sols,
- **publier** des articles dans des revues scientifiques,
- **communiquer** lors de congrès internationaux,
- **fédérer des chercheurs** de spécialités différentes ne travaillant pas habituellement ensemble,
- promouvoir une **meilleure visibilité de notre laboratoire** auprès du monde professionnel,
- constituer une **base de données importante** utilisable pour d'autres études,
- construire un **réseau de parcelles** susceptibles de supporter d'autres expérimentations.

Pour les partenaires du projet, les viticulteurs et l'ADEME principalement :

- **transférer** des connaissances de la recherche vers les professionnels,
- apporter des **informations précieuses** sur la qualité des sols,
- mettre au point un **outil d'évaluation de la qualité des sols**,
- adopter des **itinéraires culturaux plus respectueux des sols et de l'environnement**.

Pour moi :

- développer une **expertise scientifique**. L'identification des nématodes du sol est une discipline qui compte très peu de spécialistes,
- **gérer un projet de sa définition jusqu'à sa valorisation** en endossant les fonctions qui y sont associées,
- **tisser un réseau** varié indispensable dans le milieu professionnel.

5. IDENTIFICATIONS DES PISTES PROFESSIONNELLES

5.1. A COURT TERME

A la fin de la thèse, j'envisage de partir **vinifier 5 mois en Nouvelle-Zélande**. Tout d'abord, cette expérience me permettra de consolider mes compétences et mes connaissances relatives à l'œnologie. D'autre part, j'améliorerai mon niveau en Anglais. A mon retour, j'aurai l'opportunité de m'engager dans un contrat **post-doctoral sur l'impact du paillage biodégradable sur la vigne et le fonctionnement biologique du sol**. Ce post-doctorat sera un bon moyen pour me perfectionner dans la thématique étudiée en thèse. J'envisage aussi de continuer la publication d'articles scientifiques en relation avec ma thèse pendant ce poste.

5.2. A MOYEN TERME

La thèse a constitué pour moi un très bon moyen de **découvrir des métiers très différents** comme chercheur, enseignant, gestionnaire de projet, manager, conseiller… Ces expériences auraient pu me permettre de définir une orientation professionnelle. Or, toutes m'ont beaucoup intéressé et je ne sais vers quel poste me diriger. Ainsi, je profite du NCT pour étudier de façon plus approfondie les métiers :

- **d enseignant chercheur,**
- **de conseiller en viticulture-œnologie,**
- **de directeur d'un domaine viticole ou d'une cave coopérative.**

J'ai synthétisé dans la Table IX- 3, les avantages, les inconvénients ainsi que mes atouts pour chacun de ces postes. Les différents tests que j'ai réalisés dans le cadre du NCT® m'ont permis de prendre conscience que **j'ai besoin d'être actif et productif**. Mon sens pratique et mon besoin d'être sur le terrain m'amènent à rechercher l'efficacité. Les résultats chiffrables sont pour moi très importants, le résultat attendu doit être concret. Ainsi, il m'est pour le moment **plus facile de me projeter dans un poste de conseiller en viticulture-œnologie ou de directeur d'un domaine ou d'une cave coopérative**. En outre, une de mes grandes préoccupations est de **conserver ma double compétence viticulture et œnologie**, viticulture enrichie par mes connaissances en sciences du sol.

Table IX- 3 : Avantages, inconvénients et mes atouts par poste visé après la thèse

	Avantages	Inconvénients	Mes atouts pour le poste
Enseignant-chercheur	* deux métiers en un, * possibilité d'évolution, * grande souplesse de travail, * indépendance, * poste fixe, * salaire convenable.	* éloigné du monde professionnel, * peu de temps pour travail de terrain, * accès difficile à un poste, * trop d'inertie du système.	* expériences d'enseignements, * pédagogue, * organisé, * inventif pour coupler recherche et enseignement.
Conseiller en viticulture et œnologie	* travail de terrain, * contact avec la profession, * aide les viticulteurs, * problèmes concrets à résoudre, * métier très varié, * offres d'emploi existent.	* lourdes responsabilités, * poste très chronophage et peu de temps disponible par viticulteur, * secteur viticole en crise, * pic de travail pendant les vendanges, * beaucoup de déplacements.	* expert en qualité des sols, * bonne communication avec les professionnels, * bonne connaissance des problèmes liés à la profession, * soucieux d'offrir des conseils de qualité, * inspire la confiance, * capable de vulgariser.
Directeur d'un domaine ou d'une cave coopérative	* très axé production, * gestion d'entreprise, * management, * métier très varié, * vision d'ensemble de la filière, * salaire élevé, * offres d'emploi existent.	* lourdes responsabilités, * poste très chronophage, * secteur viticole en crise, * pic de travail pendant les vendanges, * difficultés de gérer des hommes.	* très attiré par la production, * prêt à endosser des responsabilités, * efficace, * organisé, * réactif, * calme.

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VALORISATION

Scientific publications

Celano G., Lardo E., Coll P., Le Cadre E., Palese A.M., Xiloyannis C., Villenave C., 2012. **Earthworm abundance prediction using electromagnetic induction (EMI) measurements on vineyards**. (in progress)

Lardo E., Coll P., Le Cadre E., Palese A.M., Xiloyannis C., Villenave C., Blanchart E., Ferrazzano G., Celano G., 2012. **L'uso della tecnica EMI in pescheto per lo studio della variabilità spaziale degli indicatori biologici di qualità del suolo**. Proceedings VII National Conference PESCHMED, Lamezia terme – Sibari (CS), Italy 26th-27th May, Italus Hortus (in progress).

Lardo E., Coll P., Le Cadre E., Palese A.M., Xiloyannis C., Villenave C., Blanchart E., Celano G., 2012. **Relationships between ECa measured by Electromagnetic Induction (EMI) and earthworms abundance and biomass in peach orchards**. Soil Biology and Biochemistry (submitted 17th October 2011).

Coll P., Le Cadre E. and Villenave C., 2011. **How are nematode communities affected during a conversion from conventional to organic farming in Southern French vineyards?** Nematology (submitted 12th October 2011).

Coll P., Le Velly R., Le Cadre E. and Villenave C., 2011. **La qualité des sols : associer perceptions et analyses des scientifiques et des viticulteurs**. Etude et Gestion des Sols (submitted 8th October 2011).

Coll P., Le Cadre E., Blanchart E., Hinsinger P. and Villenave C., 2011. Organic viticulture and soil quality: a long-term study in Southern France. Applied Soil Ecology 50, 37-44.

Coll P., Arnal D., Blanchart E., Hinsinger P., Le Cadre E., Souche G. and Villenave C., 2009. Viticultural soil quality : benefits of permanent grass cover on soil chemical characteristics and soil biological indicators, Progrès Agricole et Viticole 126, 527-531.

Scientific communications

Coll P., Lardo E., Le Cadre E. and Villenave C., 2011. Studying the soil quality is essential to evaluate the sustainability of a vineyard. Oral presentation in 17th Symposium International of the GiESCO (Groupe International d'Experts en Systèmes vitivinicoles pour la CoOpération), 29th August 2011 in Asti (Italy).

Lardo E., Coll P., Celano G., Le Cadre E., Villenave C. and Xiloyannis C., 2011. Soil organic matter, aggregate stability and respiration: integrated measures for the evaluation of the soil sustainability in the vineyards. Poster presentation in 17th Symposium International of the GiESCO (Groupe International d'Experts en Systèmes vitivinicoles pour la CoOpération), from 29th to 1st August 2011 in Asti (Italy).

Lardo E., Coll P., Palese A. M., Le Cadre E., Xiloyannis C., Villenave C., Ferrazzano G., Blanchard E. and Celano G., 2011. L'uso della tecnica EMI in pescheto per lo studio degli indicatori biologici di qualità del suolo. Poster presentation in the VVII PESCHMED (Convegno Nazionale sulla Peschicoltura Meridionale), 26th May 2011 in Lamezia Terme (Italy).

Coll P., Le Cadre E., Blanchart E., Arnal D., Hinsinger P. and Villenave C., 2010. Nematofauna, a sensitive bioindicator to characterize global soil quality during organic conversion of a vineyard. Oral presentation in the 30th Symposium International of the ESN (European Society of *NEMATOLOGISTS*), 21st September 2010 in Vienna (Autria).

Villenave C., Coll P. and Cortet J., 2010. Colonisation of a constructed Technosol by nematodes at the field scale in three years. Poster presentation in the 30th Symposium International of the ESN (European Society of *NEMATOLOGISTS*), 22nd September 2010 in Vienna (Autria).

Coll P., Arnal D., Blanchart E., Hinsinger P., Le Cadre E., Souche G. and Villenave C., 2009. Wine soil quality : benefits of grass cover on soil biological and physico-chemical indicators. Poster presentation in the 16th Symposium International of the GiESCO (*GROUPE INTERNATIONAL* d'Experts en Systèmes vitivinicoles pour la CoOpération), from 12th to 15th July 2009 in Davis (California, United-States).

Scientific communications for general public

Coll P., Le Cadre E., Blanchart E., Arnal D., Hinsinger P. and Cécile Villenave, 2011. Des indicateurs de qualité des sols. Cas de viticulture biologique. Oral presentation in the colloque of 2AD-ADEME (Agence De l'Environnement et la Maîtrise de l'Energie), 11th February 2011 in Paris (France). This presentation is available online on the adress http://www.colloque2adademe2011.fr.

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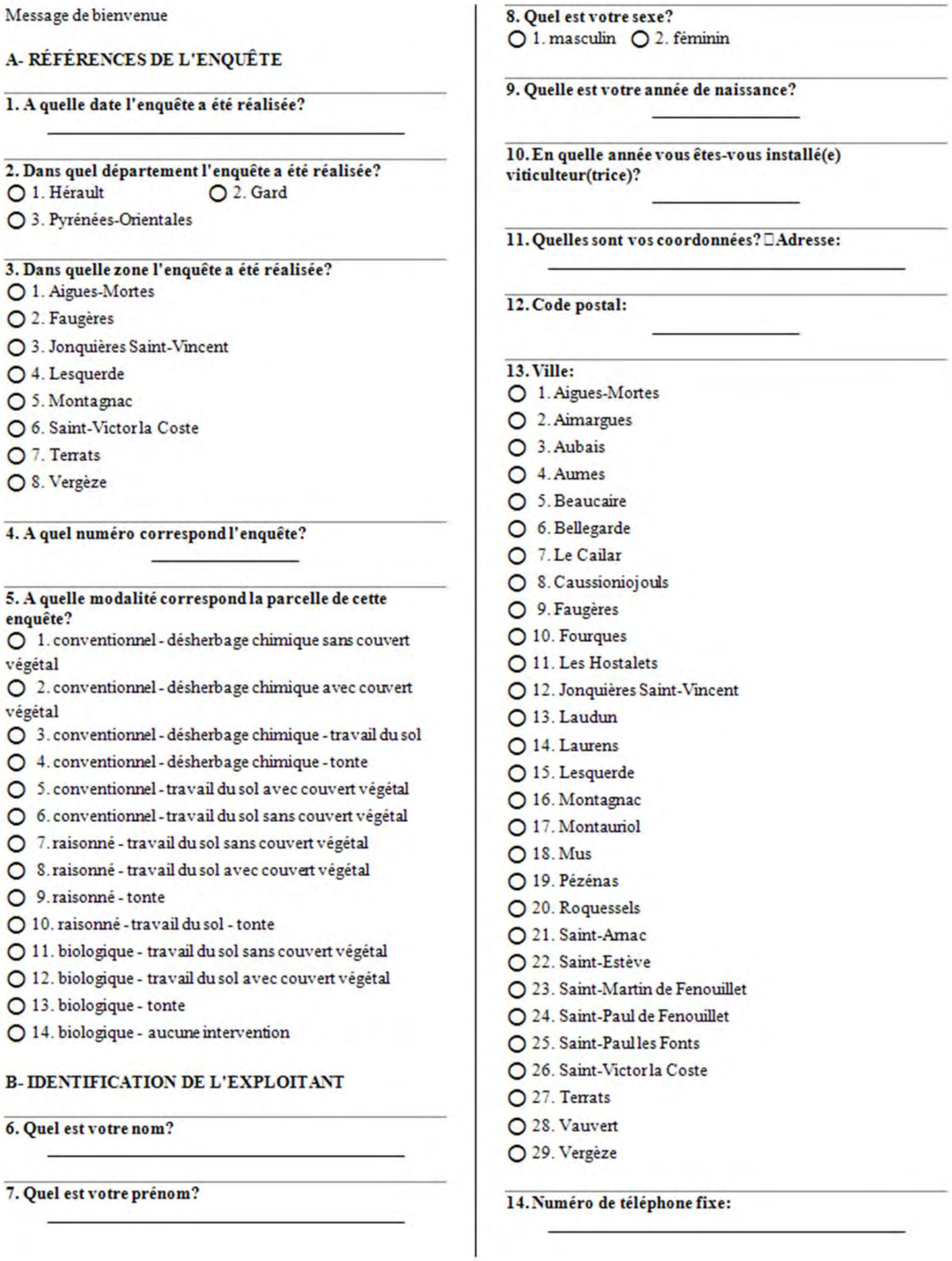
APPENDIX

APPENDIX 1 :

QUESTIONNAIRE ENQUETE-TERRAIN ITINERAIRE CULTURAL



Message de bienvenue

A- RÉFÉRENCES DE L'ENQUÊTE

1. A quelle date l'enquête a été réalisée?

____

2. Dans quel département l'enquête a été réalisée?
○ 1. Hérault ○ 2. Gard
○ 3. Pyrénées-Orientales

3. Dans quelle zone l'enquête a été réalisée?
○ 1. Aigues-Mortes
○ 2. Faugères
○ 3. Jonquières Saint-Vincent
○ 4. Lesquerde
○ 5. Montagnac
○ 6. Saint-Victor la Coste
○ 7. Terrats
○ 8. Vergèze

4. A quel numéro correspond l'enquête?

____

5. A quelle modalité correspond la parcelle de cette enquête?
○ 1. conventionnel - désherbage chimique sans couvert végétal
○ 2. conventionnel - désherbage chimique avec couvert végétal
○ 3. conventionnel - désherbage chimique - travail du sol
○ 4. conventionnel - désherbage chimique - tonte
○ 5. conventionnel - travail du sol avec couvert végétal
○ 6. conventionnel - travail du sol sans couvert végétal
○ 7. raisonné - travail du sol sans couvert végétal
○ 8. raisonné - travail du sol avec couvert végétal
○ 9. raisonné - tonte
○ 10. raisonné - travail du sol - tonte
○ 11. biologique - travail du sol sans couvert végétal
○ 12. biologique - travail du sol avec couvert végétal
○ 13. biologique - tonte
○ 14. biologique - aucune intervention

B- IDENTIFICATION DE L'EXPLOITANT

6. Quel est votre nom?

____

7. Quel est votre prénom?

____

8. Quel est votre sexe?
○ 1. masculin ○ 2. féminin

9. Quelle est votre année de naissance?

____

10. En quelle année vous êtes-vous installé(e) viticulteur(trice)?

____

11. Quelles sont vos coordonnées? □Adresse:

____

12. Code postal:

____

13. Ville:
○ 1. Aigues-Mortes
○ 2. Aimargues
○ 3. Aubais
○ 4. Aumes
○ 5. Beaucaire
○ 6. Bellegarde
○ 7. Le Cailar
○ 8. Caussiniojouls
○ 9. Faugères
○ 10. Fourques
○ 11. Les Hostalets
○ 12. Jonquières Saint-Vincent
○ 13. Laudun
○ 14. Laurens
○ 15. Lesquerde
○ 16. Montagnac
○ 17. Montauriol
○ 18. Mus
○ 19. Pézénas
○ 20. Roquessels
○ 21. Saint-Amac
○ 22. Saint-Estève
○ 23. Saint-Martin de Fenouillet
○ 24. Saint-Paul de Fenouillet
○ 25. Saint-Paul les Fonts
○ 26. Saint-Victor la Coste
○ 27. Terrats
○ 28. Vauvert
○ 29. Vergèze

14. Numéro de téléphone fixe:

____

15. Numéro de téléphone portable:

____

16. Adresse mail:

____

17. Êtes-vous coopérateur?

○ 1. oui ○ 2. non

18. Êtes-vous vigneron indépendant?

○ 1. oui ○ 2. non

19. Avez-vous d'autre(s) activité(s)?

○ 1. oui ○ 2. non

20. Si oui, laquelle (lesquelles)?

☐ 1. arboriculteur
☐ 2. céréalier
☐ 3. comptable
☐ 4. conseiller d'entreprise à la Chambre d'Agriculture du Gard
☐ 5. chauffeur poids lourd
☐ 6. directeur de cave coopérative viticole
☐ 7. disc jockey
☐ 8. éleveur équin
☐ 9. entrepreneur en travaux viticoles
☐ 10. loueur de gîtes ruraux
☐ 11. maraîcher
☐ 12. oléiculteur
☐ 13. retraité

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Autre_activité = "oui"

C- IDENTIFICATION DE L'EXPLOITATION

C-1- Description

21. Quelle est la surface agricole utile de votre exploitation, en hectares?

____

22. Quelle est la surface viticole de votre exploitation, en hectares?

____

23. Quelle est la surface moyenne de vos parcelles viticoles, en hectares?

____

24. Hormis les vignes à raisin de cuve, quelle(s) culture(s) est(sont) présente(s) sur votre exploitation?

☐ 1. arbres fruitiers
☐ 2. asperges
☐ 3. bois
☐ 4. céréales
☐ 5. chênes liège
☐ 6. colza
☐ 7. cultures maraîchères
☐ 8. landes
☐ 9. marais
☐ 10. oliviers
☐ 11. pinède
☐ 12. prairies
☐ 13. vignes à raisins de table

Vous pouvez cocher plusieurs cases.

25. Combien d'unités de travail humain sont attribuées à la composante viticole de votre exploitation?

____

26. Suivez-vous un (des) cahier(s) des charges de certification sur vos parcelles viticoles?

○ 1. oui ○ 2. non

27. Si non, pourquoi?

☐ 1. pas intéressé
☐ 2. pas d'intérêts économiques
☐ 3. pas d'obligations
☐ 4. procédures trop lourdes

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Cahier_charges = "non"

28-38. Si oui, quel(s) est(sont) ce(s) cahier(s) des charges?
1 : oui, 2 : non

	1	2
AB	○	○
Agriculture raisonnée	○	○
Ampelos	○	○
Biodyvin	○	○
Cahier des charges interne à la cave coopérative	○	○
Demeter	○	○
Euregap	○	○
Nature et Progrès	○	○

Simples	○	○
Terra Vitis	○	○
Typhlo	○	○

39. A quel type de viticulture correspond ce(s) cahier(s) des charges?

☐ 1. raisonnée ☐ 2. intégrée ☐ 3. biologique

☐ 4. biodynamique

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Cahier_charges = "oui"

40. Pourquoi avez-vous fait le choix de suivre ce(s) cahier(s) des charges?

☐ 1. bonne image
☐ 2. économique
☐ 3. gage de qualité
☐ 4. plus intéressant
☐ 5. nécessité par rapport au marché
☐ 6. respect de l'environnement
☐ 7. santé du viticulteur
☐ 8. technique
☐ 9. traçabilité
☐ 10. très bon compromis

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Cahier_charges = "oui"

41. Suivez-vous des stages, des formations, des conférences... qui vous aident à mieux gérer vos pratiques culturales?

○ 1. oui ○ 2. non

42. Si oui, quel(s) est(sont) l'(les) structure(s) qui les organise(nt)?

☐ 1. AIVB LR
☐ 2. cave coopérative
☐ 3. Chambre d'Agriculture
☐ 4. CIVAM Bio
☐ 5. entreprise d'engrais et de produits phytosanitaires

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Stages_formations = "oui"

C-2- Stratégie globale de gestion du sol sur l'ensemble des parcelles viticoles

43-51. Dans quelles proportions, en pourcentage, rencontre-t-on les modes de gestion du sol présentées ci-dessous?

Désherbage chimique (rang) - désherbage chimique (interrang)	________
Désherbage chimique (rang) - travail du sol (interrang)	________
Désherbage chimique (rang) - enherbement (interrang)	________
Désherbage chimique (rang) - désherbage chimique ET travail du sol (interrang)	________
Désherbage chimique (rang) - désherbage chimique ET enherbement (interrang)	________
Désherbage chimique (rang) - travail du sol ET enherbement (interrang)	________
Travail du sol (rang) - travail du sol (interrang)	________
Travail du sol (rang) - enherbement ET tonte (interrang)	________
Travail du sol (rang) - travail du sol ET enherbement (interrang)	________

52. Pourquoi pratiquez-vous le désherbage chimique sur le rang?

☐ 1. économique
☐ 2. efficace
☐ 3. nécessite peu de matériel
☐ 4. matériel de gestion du sol sur le rang peu adapté
☐ 5. parcelle trop pentue et/ou avec terrasses
☐ 6. pratique
☐ 7. rapide
☐ 8. sol trop caillouteux

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Désherbage_rg_désherbage_irg= Non réponse ou Désherbage_rg_travail_irg= Non réponse ou Désherbage_rg_enherbement_irg= Non réponse ou Désherbage_rg_désherbage+travail_irg= Non répo

53. Pourquoi pratiquez-vous le désherbage chimique sur l'interrang?

☐ 1. améliore la portance
☐ 2. écart entre les rangs trop étroits
☐ 3. économique
☐ 4. efficace
☐ 5. nécessite peu de matériel
☐ 6. pratique
☐ 7. rapide
☐ 8. sol trop caillouteux

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Désherbage_rg_désherbage_irg= Non réponse ou Désherbage_rg_désherbage+travail_irg= Non réponse ou Désherbage_rg_désherbage+enherbement_irg= Non réponse

54. Pourquoi pratiquez-vous le travail du sol sur le rang?

☐ 1. mode de gestion très intéressant à pratiquer
☐ 2. obligation par rapport au cahier des charges
☐ 3. pratique
☐ 4. rapide
☐ 5. respect de l'environnement

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Travail_rg_travail_irg= Non réponse ou Travail_rg_enherbement_irg= Non réponse ou Travail_rg_travail+enherbement_irg= Non réponse

55. Pourquoi pratiquez-vous le travail du sol sur l'interrang?

☐ 1. augmente l'infiltrabilité
☐ 2. décompacte
☐ 3. économique
☐ 4. efficace
☐ 5. favorable à un enracinement plus profond
☐ 6. favorable au fonctionnement biologique
☐ 7. en fonction du type de sol
☐ 8. limite les effets de la sécheresse
☐ 9. plus respectueux de l'environnement (pas d'herbicides)

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Désherbage_rg_travail_irg= Non réponse ou Désherbage_rg_désherbage+travail_irg= Non réponse ou Désherbage_rg_travail+enherbement_irg= Non réponse ou Travail_rg_travail_irg= Non ré

56. Pourquoi pratiquez-vous l'enherbement sur l'interrang?

☐ 1. améliore la portance
☐ 2. augmente la qualité
☐ 3. concurrence la vigne
☐ 4. économique
☐ 5. favorise le développement des outardes cannepetières
☐ 6. peu gourmand en temps de travail
☐ 7. limite l'érosion éolienne
☐ 8. obligation par rapport au cahier des charges
☐ 9. respect de l'environnement

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Désherbage_rg_enherbement_irg= Non réponse ou Désherbage_rg_désherbage+enherbement_irg= Non réponse ou Désherbage_rg_travail+enherbement_irg= Non réponse ou Travail_rg_enherbement

D- IDENTIFICATION DE LA PARCELLE

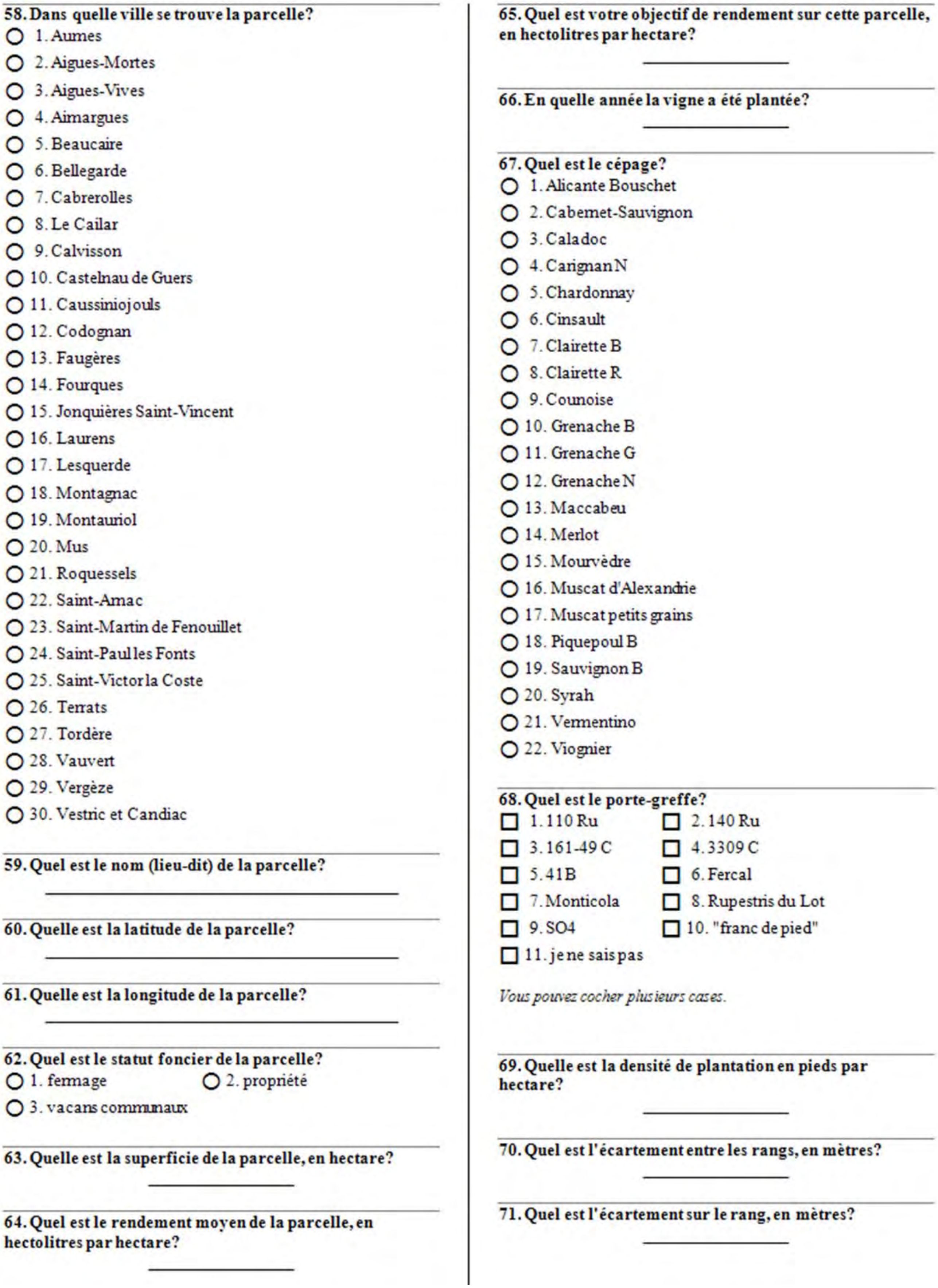
Les prochaines questions ne portent que sur la parcelle que vous avez choisie.

D-1 Description

57. Pour quelle(s) raison(s) avez-vous choisi cette parcelle?

☐ 1. pour avoir des informations complémentaires
☐ 2. au hasard
☐ 3. proche des autres parcelles
☐ 4. représentative d'un îlot de grande taille
☐ 5. la seule qui correspond aux critères de l'étude

Vous pouvez cocher plusieurs cases.



58. Dans quelle ville se trouve la parcelle?

○ 1. Aumes
○ 2. Aigues-Mortes
○ 3. Aigues-Vives
○ 4. Aimargues
○ 5. Beaucaire
○ 6. Bellegarde
○ 7. Cabrerolles
○ 8. Le Cailar
○ 9. Calvisson
○ 10. Castelnau de Guers
○ 11. Caussiniojouls
○ 12. Codognan
○ 13. Faugères
○ 14. Fourques
○ 15. Jonquières Saint-Vincent
○ 16. Laurens
○ 17. Lesquerde
○ 18. Montagnac
○ 19. Montauriol
○ 20. Mus
○ 21. Roquessels
○ 22. Saint-Arnac
○ 23. Saint-Martin de Fenouillet
○ 24. Saint-Paul les Fonts
○ 25. Saint-Victor la Coste
○ 26. Terrats
○ 27. Tordère
○ 28. Vauvert
○ 29. Vergèze
○ 30. Vestric et Candiac

59. Quel est le nom (lieu-dit) de la parcelle?

____

60. Quelle est la latitude de la parcelle?

____

61. Quelle est la longitude de la parcelle?

____

62. Quel est le statut foncier de la parcelle?

○ 1. fermage ○ 2. propriété
○ 3. vacans communaux

63. Quelle est la superficie de la parcelle, en hectare?

____

64. Quel est le rendement moyen de la parcelle, en hectolitres par hectare?

____

65. Quel est votre objectif de rendement sur cette parcelle, en hectolitres par hectare?

____

66. En quelle année la vigne a été plantée?

____

67. Quel est le cépage?

○ 1. Alicante Bouschet
○ 2. Cabernet-Sauvignon
○ 3. Caladoc
○ 4. Carignan N
○ 5. Chardonnay
○ 6. Cinsault
○ 7. Clairette B
○ 8. Clairette R
○ 9. Counoise
○ 10. Grenache B
○ 11. Grenache G
○ 12. Grenache N
○ 13. Maccabeu
○ 14. Merlot
○ 15. Mourvèdre
○ 16. Muscat d'Alexandrie
○ 17. Muscat petits grains
○ 18. Piquepoul B
○ 19. Sauvignon B
○ 20. Syrah
○ 21. Vermentino
○ 22. Viognier

68. Quel est le porte-greffe?

☐ 1. 110 Ru ☐ 2. 140 Ru
☐ 3. 161-49 C ☐ 4. 3309 C
☐ 5. 41B ☐ 6. Fercal
☐ 7. Monticola ☐ 8. Rupestris du Lot
☐ 9. SO4 ☐ 10. "franc de pied"
☐ 11. je ne sais pas

Vous pouvez cocher plusieurs cases.

69. Quelle est la densité de plantation en pieds par hectare?

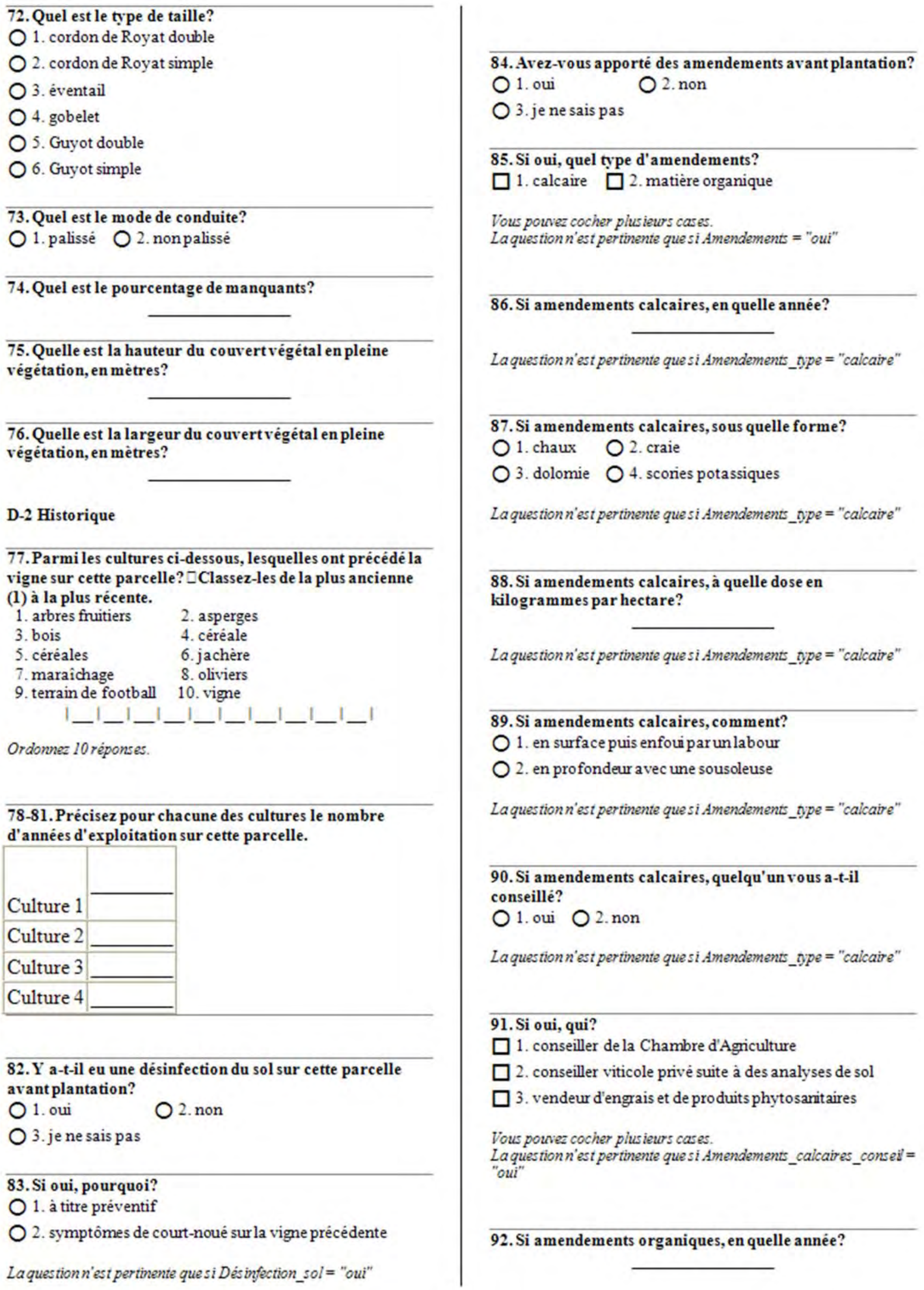
____

70. Quel est l'écartement entre les rangs, en mètres?

____

71. Quel est l'écartement sur le rang, en mètres?

____



72. Quel est le type de taille?

○ 1. cordon de Royat double

○ 2. cordon de Royat simple

○ 3. éventail

○ 4. gobelet

○ 5. Guyot double

○ 6. Guyot simple

73. Quel est le mode de conduite?

○ 1. palissé ○ 2. non palissé

74. Quel est le pourcentage de manquants?

____

75. Quelle est la hauteur du couvert végétal en pleine végétation, en mètres?

____

76. Quelle est la largeur du couvert végétal en pleine végétation, en mètres?

____

D-2 Historique

77. Parmi les cultures ci-dessous, lesquelles ont précédé la vigne sur cette parcelle? ▯Classez-les de la plus ancienne (1) à la plus récente.

1. arbres fruitiers 2. asperges
3. bois 4. céréale
5. céréales 6. jachère
7. maraîchage 8. oliviers
9. terrain de football 10. vigne

|__|__|__|__|__|__|__|__|__|__|

Ordonnez 10 réponses.

78-81. Précisez pour chacune des cultures le nombre d'années d'exploitation sur cette parcelle.

Culture 1	________
Culture 2	________
Culture 3	________
Culture 4	________

82. Y a-t-il eu une désinfection du sol sur cette parcelle avant plantation?

○ 1. oui ○ 2. non

○ 3. je ne sais pas

83. Si oui, pourquoi?

○ 1. à titre préventif

○ 2. symptômes de court-noué sur la vigne précédente

La question n'est pertinente que si Désinfection_sol = "oui"

84. Avez-vous apporté des amendements avant plantation?

○ 1. oui ○ 2. non

○ 3. je ne sais pas

85. Si oui, quel type d'amendements?

☐ 1. calcaire ☐ 2. matière organique

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Amendements = "oui"

86. Si amendements calcaires, en quelle année?

____

La question n'est pertinente que si Amendements_type = "calcaire"

87. Si amendements calcaires, sous quelle forme?

○ 1. chaux ○ 2. craie

○ 3. dolomie ○ 4. scories potassiques

La question n'est pertinente que si Amendements_type = "calcaire"

88. Si amendements calcaires, à quelle dose en kilogrammes par hectare?

____

La question n'est pertinente que si Amendements_type = "calcaire"

89. Si amendements calcaires, comment?

○ 1. en surface puis enfoui par un labour

○ 2. en profondeur avec une sousoleuse

La question n'est pertinente que si Amendements_type = "calcaire"

90. Si amendements calcaires, quelqu'un vous a-t-il conseillé?

○ 1. oui ○ 2. non

La question n'est pertinente que si Amendements_type = "calcaire"

91. Si oui, qui?

☐ 1. conseiller de la Chambre d'Agriculture

☐ 2. conseiller viticole privé suite à des analyses de sol

☐ 3. vendeur d'engrais et de produits phytosanitaires

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Amendements_calcaires_conseil = "oui"

92. Si amendements organiques, en quelle année?

____

La question n'est pertinente que si Amendements_type = "matière organique"

---

93. Si amendements organiques, sous quelle forme?

☐ 1. fumier
☐ 2. gadoues
☐ 3. guano de poisson (Angibaud)
☐ 4. marc de raisin composté
☐ 5. marc de raisin composté + compost urbain
☐ 6. marc de raisin composté + fumier
☐ 7. Végét'humus

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Amendements_type = "matière organique"

---

94. Si amendements organiques, à quelle dose en kilogrammes par hectare?

____

La question n'est pertinente que si Amendements_type = "matière organique"

---

95. Si amendements organiques, comment?

○ 1. en surface puis enfoui par un labour
○ 2. en profondeur avec une sousoleuse

La question n'est pertinente que si Amendements_type = "matière organique"

---

96. Si amendements organiques, quelqu'un vous a t-il conseillé?

○ 1. oui ○ 2. non

La question n'est pertinente que si Amendements_type = "matière organique"

---

97. Si oui, qui?

☐ 1. conseiller de la Chambre d'Agriculture
☐ 2. conseiller viticole privé suite à des analyses de sol
☐ 3. technicien de la zone
☐ 4. vendeur d'engrais et de produits phytosanitaires

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Amendements_organiques_conseil = "oui"

D-3 Itinéraire cultural

Nous nous intéressons à l'itinéraire cultural "moyen" suivi ces cinq dernières années.

---

98. Quel type de viticulture pratiquez-vous sur cette parcelle?

○ 1. conventionnelle ○ 2. raisonnée
○ 3. biologique

---

99. Depuis quelle année pratiquez-vous ce type de viticulture?

____

---

100. Depuis quelle année suivez-vous le même itinéraire cultural sur cette parcelle?

____

D-3-1 Traitement des bois de taille

---

101. Comment traitez-vous les bois de taille?

○ 1. broyage
○ 2. incinération
○ 3. ni broyage ni incinération

---

102. Y a-t-il restitution des bois sur la parcelle?

○ 1. oui ○ 2. non

---

103. Si oui, sur quel schéma?

○ 1. tous les rangs ○ 2. 1 rang sur 2
○ 3. 1 rang sur 3 ○ 4. 1 rang sur 4
○ 5. 1 rang sur 5 ○ 6. 1 rang sur 6

La question n'est pertinente que si Bois_taille_restitution = "oui"

D-3-2 Apports d'engrais et/ou d'amendements

---

104. Apportez-vous régulièrement de l'engrais?

○ 1. oui ○ 2. non

---

105. Si engrais, à quelle fréquence?

○ 1. tous les ans ○ 2. 1 an sur 2 ○ 3. 1 an sur 3
○ 4. 1 an sur 4 ○ 5. 1 an sur 5 ○ 6. 2 ans sur 3
○ 7. 2 ans sur 5 ○ 8. 3 ans sur 4 ○ 9. 3 ans sur 5

La question n'est pertinente que si Engrais = "oui"

---

106. Si engrais, quand?

○ 1. septembre ○ 2. octobre ○ 3. novembre
○ 4. décembre ○ 5. janvier ○ 6. février
○ 7. mars ○ 8. avril ○ 9. août

La question n'est pertinente que si Engrais = "oui"

---

107. Si engrais, quel type?

○ 1. minéral ○ 2. organique
○ 3. organo-minéral

La question n'est pertinente que si Engrais = "oui"

108. Si engrais, quelle est la formulation en azote, phosphore et potassium (NPK) de cet engrais?

____

La question n'est pertinente que si Engrais = "oui"

109. Si engrais, à quelle dose, en kilogrammes (ou en litres) par hectare et par an?

____

La question n'est pertinente que si Engrais = "oui"

110. Si engrais, comment?

○ 1. en profondeur (avec sousoleuse)
○ 2. en pulvérisation
○ 3. en surface (épandeur)

La question n'est pertinente que si Engrais = "oui"

111. Si engrais, sur quel schéma?

○ 1. tous les rangs ○ 2. 1 rang sur 2
○ 3. 1 rang sur 3 ○ 4. 1 rang sur 4

La question n'est pertinente que si Engrais = "oui"

112. Si engrais, quelqu'un vous conseille-t-il?

○ 1. oui ○ 2. non

La question n'est pertinente que si Engrais = "oui"

113. Si oui, qui?

☐ 1. conseiller de la Chambre d'Agriculture
☐ 2. conseiller viticole privé suite à des analyses de sol
☐ 3. technicien viticole de la zone
☐ 4. vendeur d'engrais et de produits phytosanitaires

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Engrais_conseil = "oui"

114. Apportez-vous régulièrement des amendements calcaires?

○ 1. oui ○ 2. non

115. Si amendements calcaires, à quelle fréquence?

○ 1. tous les ans ○ 2. 1 an sur 2 ○ 3. 1 an sur 3
○ 4. 1 an sur 4 ○ 5. 1 an sur 5 ○ 6. 3 ans sur 5

La question n'est pertinente que si Amendements_calcaires = "oui"

116. Si amendements calcaires, quand?

○ 1. octobre ○ 2. novembre ○ 3. décembre
○ 4. janvier ○ 5. février ○ 6. mars
○ 7. avril

La question n'est pertinente que si Amendements_calcaires = "oui"

117. Si amendements calcaires, sous quelle forme?

○ 1. craie ○ 2. chaux ○ 3. dolomie

La question n'est pertinente que si Amendements_calcaires = "oui"

118. Si amendements calcaires, à quelle dose, en kilogrammes par hectare et par an?

____

La question n'est pertinente que si Amendements_calcaires = "oui"

119. Si amendements calcaires, comment?

○ 1. en profondeur (avec sousoleuse)
○ 2. en surface (épandeur)

La question n'est pertinente que si Amendements_calcaires = "oui"

120. Si amendements calcaires, sur quel schéma?

○ 1. tous les rangs ○ 2. 1 rang sur 2
○ 3. 1 rang sur 3 ○ 4. 1 rang sur 4

La question n'est pertinente que si Amendements_calcaires = "oui"

121. Si amendements calcaires, quelqu'un vous conseille-t-il?

○ 1. oui ○ 2. non

La question n'est pertinente que si Amendements_calcaires = "oui"

122. Si oui, qui?

○ 1. conseiller de la Chambre d'Agriculture
○ 2. conseiller viticole privé suite à des analyses de sol
○ 3. technicien viticole de la zone
○ 4. vendeur d'engrais et de produits phytosanitaires

La question n'est pertinente que si Amendement_moyen_conseil = "oui"

D-3-3 Entretien du sol

123. Un couvert végétal est-il présent une partie de l'année?

○ 1. oui ○ 2. non

124. Si oui, pendant combien de mois?

____

La question n'est pertinente que si Couvert_végétal = "oui"

125. Si oui, quelles périodes sont concernées?

☐ 1. janvier ☐ 2. février ☐ 3. mars
☐ 4. avril ☐ 5. mai ☐ 6. juin
☐ 7. juillet ☐ 8. août ☐ 9. septembre
☐ 10. octobre ☐ 11. novembre ☐ 12. décembre

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Couvert_végétal = "oui"

D-3-3-1 Sur le rang

126. Avez-vous mis en place un paillage plastique?

○ 1. oui ○ 2. non

127. Si oui, est-il encore efficace?

○ 1. oui ○ 2. non

La question n'est pertinente que si Paillage_plastique = "oui"

128. Si non, l'avez-vous éliminé?

○ 1. oui ○ 2. non

La question n'est pertinente que si Paillage_plastique_efficace = "non"

129. Si oui, au bout de combien d'années après sa mise en place?

○ 1. 1 ○ 2. 2 ○ 3. 3 ○ 4. 4 ○ 5. 5
○ 6. 6 ○ 7. 7 ○ 8. 8

La question n'est pertinente que si Paillage_plastique_élimination = "oui"

130. Pratiquez-vous le désherbage chimique?

○ 1. oui ○ 2. non

131. Si désherbage chimique, combien de fois par an?

○ 1. 1 ○ 2. 2 ○ 3. 3 ○ 4. 4 ○ 5. 5

La question n'est pertinente que si Rang_désherbage = "oui"

132. Si désherbage chimique, quand?

☐ 1. février ☐ 2. mars ☐ 3. avril
☐ 4. mai ☐ 5. juin ☐ 6. juillet
☐ 7. août

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Rang_désherbage = "oui"

133. Si désherbage chimique, quel(s) herbicide(s) utilisés?

☐ 1. glyphosate ☐ 2. autre que glyphosate

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Rang_désherbage = "oui"

134. Si autre que glyphosate, préciser

____

La question n'est pertinente que si désherbage_chimique_rang_type = "autre que glyphosate"

135. Si désherbage chimique, à quelle dose utilisez-vous ce(ces) herbicide(s)? □Précisons qu'une dose homologuée sera noté 100 %.

○ 1. 100 % ○ 2. 90 % ○ 3. 80 % ○ 4. 75 %
○ 5. 70 % ○ 6. 60 ○ 7. 50 % ○ 8. 35 %

La question n'est pertinente que si Rang_désherbage = "oui"

136. Si désherbage chimique, comment?

☐ 1. atomiseur à dos
☐ 2. cuve portée par un quad
☐ 3. cuve portée par un tracteur
☐ 4. enjambeur
☐ 5. gyrojet

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Rang_désherbage = "oui"

137. Si désherbage chimique, sur quelle superficie, en pourcentage par rapport à l'ensemble de la parcelle?

○ 1. 10 % ○ 2. 15 % ○ 3. 20 % ○ 4. 25 %
○ 5. 30 % ○ 6. 35 % ○ 7. 40 % ○ 8. 45 %
○ 9. 50 %

La question n'est pertinente que si Rang_désherbage = "oui"

138. Si désherbage chimique, quelqu'un vous conseille-t-il?

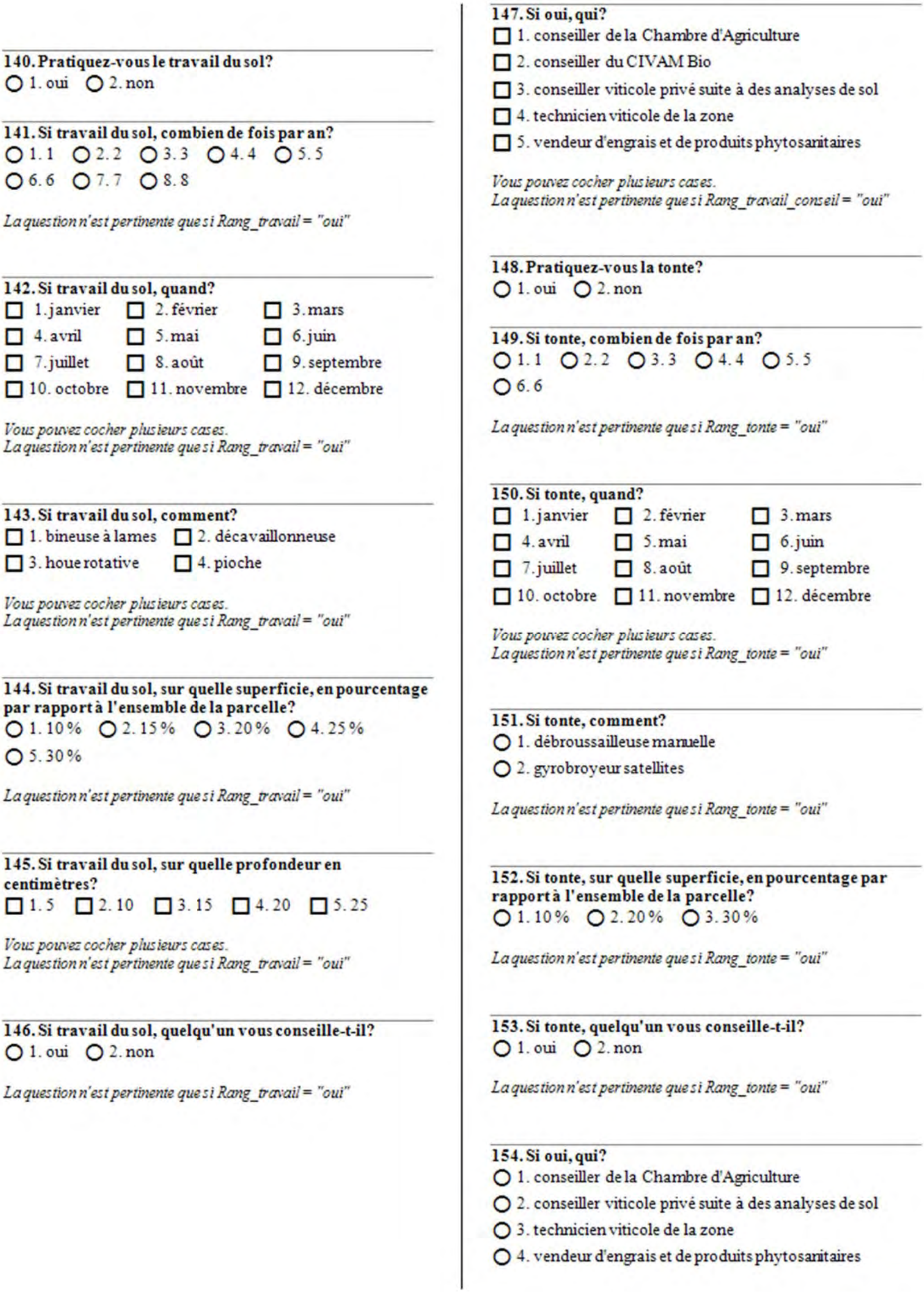
○ 1. oui ○ 2. non

La question n'est pertinente que si Rang_désherbage = "oui"

139. Si oui, qui?

☐ 1. conseiller de la Chambre d'Agriculture
☐ 2. conseiller viticole privé suite à des analyses de sol
☐ 3. technicien viticole de la zone
☐ 4. vendeur d'engrais et de produits phytosanitaires

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Rang_désherbage_conseil = "oui"



140. Pratiquez-vous le travail du sol?
○ 1. oui ○ 2. non

141. Si travail du sol, combien de fois par an?
○ 1. 1 ○ 2. 2 ○ 3. 3 ○ 4. 4 ○ 5. 5
○ 6. 6 ○ 7. 7 ○ 8. 8

La question n'est pertinente que si Rang_travail = "oui"

142. Si travail du sol, quand?
☐ 1. janvier ☐ 2. février ☐ 3. mars
☐ 4. avril ☐ 5. mai ☐ 6. juin
☐ 7. juillet ☐ 8. août ☐ 9. septembre
☐ 10. octobre ☐ 11. novembre ☐ 12. décembre

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Rang_travail = "oui"

143. Si travail du sol, comment?
☐ 1. bineuse à lames ☐ 2. décavaillonneuse
☐ 3. houe rotative ☐ 4. pioche

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Rang_travail = "oui"

144. Si travail du sol, sur quelle superficie, en pourcentage par rapport à l'ensemble de la parcelle?
○ 1. 10 % ○ 2. 15 % ○ 3. 20 % ○ 4. 25 %
○ 5. 30 %

La question n'est pertinente que si Rang_travail = "oui"

145. Si travail du sol, sur quelle profondeur en centimètres?
☐ 1. 5 ☐ 2. 10 ☐ 3. 15 ☐ 4. 20 ☐ 5. 25

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Rang_travail = "oui"

146. Si travail du sol, quelqu'un vous conseille-t-il?
○ 1. oui ○ 2. non

La question n'est pertinente que si Rang_travail = "oui"

147. Si oui, qui?
☐ 1. conseiller de la Chambre d'Agriculture
☐ 2. conseiller du CIVAM Bio
☐ 3. conseiller viticole privé suite à des analyses de sol
☐ 4. technicien viticole de la zone
☐ 5. vendeur d'engrais et de produits phytosanitaires

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Rang_travail_conseil = "oui"

148. Pratiquez-vous la tonte?
○ 1. oui ○ 2. non

149. Si tonte, combien de fois par an?
○ 1. 1 ○ 2. 2 ○ 3. 3 ○ 4. 4 ○ 5. 5
○ 6. 6

La question n'est pertinente que si Rang_tonte = "oui"

150. Si tonte, quand?
☐ 1. janvier ☐ 2. février ☐ 3. mars
☐ 4. avril ☐ 5. mai ☐ 6. juin
☐ 7. juillet ☐ 8. août ☐ 9. septembre
☐ 10. octobre ☐ 11. novembre ☐ 12. décembre

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Rang_tonte = "oui"

151. Si tonte, comment?
○ 1. débroussailleuse manuelle
○ 2. gyrobroyeur satellites

La question n'est pertinente que si Rang_tonte = "oui"

152. Si tonte, sur quelle superficie, en pourcentage par rapport à l'ensemble de la parcelle?
○ 1. 10 % ○ 2. 20 % ○ 3. 30 %

La question n'est pertinente que si Rang_tonte = "oui"

153. Si tonte, quelqu'un vous conseille-t-il?
○ 1. oui ○ 2. non

La question n'est pertinente que si Rang_tonte = "oui"

154. Si oui, qui?
○ 1. conseiller de la Chambre d'Agriculture
○ 2. conseiller viticole privé suite à des analyses de sol
○ 3. technicien viticole de la zone
○ 4. vendeur d'engrais et de produits phytosanitaires

La question n'est pertinente que si Rang_tonte_conseil = "oui"

D-3-3-2 Sur l'interrang

155. Pratiquez-vous le désherbage chimique?
○ 1. oui ○ 2. non

156. Si désherbage chimique, combien de fois par an?
○ 1. 1 ○ 2. 2 ○ 3. 3 ○ 4. 4 ○ 5. 5

La question n'est pertinente que si Interrang_désherbage = "oui"

157. Si désherbage chimique, quand?
☐ 1. février ☐ 2. mars ☐ 3. avril
☐ 4. mai ☐ 5. juin ☐ 6. juillet
☐ 7. août

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Interrang_désherbage = "oui"

158. Si oui, quel(s) herbicide(s) utilisés?
☐ 1. glyphosate ☐ 2. autre que glyphosate

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Interrang_désherbage = "oui"

159. Si autre que glyphosate, préciser

____

La question n'est pertinente que si désherbage_chimique_interrang_type = "autre que glyphosate"

160. Si désherbage chimique, à quelle dose utilisez-vous ce(ces) herbicide(s)?
Précisons qu'une dose homologuée sera noté 100 %.
○ 1. 100 % ○ 2. 90 % ○ 3. 80 % ○ 4. 70 %
○ 5. 60 ○ 6. 50 %

La question n'est pertinente que si Interrang_désherbage = "oui"

161. Si désherbage chimique, comment?
☐ 1. atomiseur à dos
☐ 2. cuve portée par un quad
☐ 3. cuve portée par un tracteur
☐ 4. gyrojet

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Interrang_désherbage = "oui"

162. Si désherbage chimique, sur quelle superficie, en pourcentage par rapport à l'ensemble de la parcelle?
☐ 1. 90 % ☐ 2. 80 % ☐ 3. 70 % ☐ 4. 60 %
☐ 5. 50 %

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Interrang_désherbage = "oui"

163. Si désherbage chimique, quelqu'un vous conseille-t-il?
○ 1. oui ○ 2. non

La question n'est pertinente que si Interrang_désherbage = "oui"

164. Si oui, qui?
☐ 1. conseiller de la Chambre d'Agriculture
☐ 2. conseiller viticole privé suite à des analyses de sol
☐ 3. technicien viticole de la zone
☐ 4. vendeur d'engrais et de produits phytosanitaires

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Interrang_désherbage_conseil = "oui"

165. Pratiquez-vous le travail du sol?
○ 1. oui ○ 2. non

166. Si travail du sol, combien de fois par an?
○ 1. 1 ○ 2. 2 ○ 3. 3 ○ 4. 4 ○ 5. 5
○ 6. 6 ○ 7. 7 ○ 8. 8

La question n'est pertinente que si Interrang_travail = "oui"

167. Si travail du sol, quand?
☐ 1. janvier ☐ 2. février ☐ 3. mars
☐ 4. avril ☐ 5. mai ☐ 6. juin
☐ 7. juillet ☐ 8. août ☐ 9. septembre
☐ 10. octobre ☐ 11. novembre ☐ 12. décembre

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Interrang_travail = "oui"

168. Si travail du sol, comment?
☐ 1. charrue ☐ 2. chisel ☐ 3. cover-crop
☐ 4. coutre ☐ 5. cultivateur ☐ 6. houe rotative
☐ 7. rotobêche ☐ 8. scarificateur ☐ 9. vibroculteur

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Interrang_travail = "oui"

169. Si travail du sol, sur quelle superficie, en pourcentage par rapport à l'ensemble de la parcelle?

○ 1. 90 % ○ 2. 80 % ○ 3. 75 % ○ 4. 70 %
○ 5. 60 % ○ 6. 50 % ○ 7. 40 %

La question n'est pertinente que si Interrang_travail = "oui"

170. Si travail du sol, sur quelle profondeur en centimètres?

☐ 1. 5 ☐ 2. 10 ☐ 3. 15 ☐ 4. 20 ☐ 5. 25
☐ 6. 30 ☐ 7. 35 ☐ 8. 40

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Interrang_travail = "oui"

171. Si travail du sol, quelqu'un vous conseille-t-il?

○ 1. oui ○ 2. non

La question n'est pertinente que si Interrang_travail = "oui"

172. Si oui, qui?

☐ 1. conseiller de la Chambre d'Agriculture
☐ 2. conseiller du CIVAM Bio
☐ 3. conseiller viticole privé suite à des analyses de sol
☐ 4. technicien viticole de la zone
☐ 5. vendeur d'engrais et de produits phytosanitaires

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Interrang_travail_conseil = "oui"

173. Pratiquez-vous l'enherbement?

○ 1. oui ○ 2. non

174. Si enherbement, sur quel schéma?

○ 1. tous les rangs ○ 2. 1 rang sur 2
○ 3. 1 rang sur 3 ○ 4. 1 rang sur 4

La question n'est pertinente que si Interrang_enherbement = "oui"

175. Si enherbement, est-ce de l'enherbement semé ou de l'enherbement naturel maîtrisé?

○ 1. enherbement semé
○ 2. enherbement naturel maîtrisé

La question n'est pertinente que si Interrang_enherbement = "oui"

176. Si enherbement semé, quelles espèces sont semées?

☐ 1. blé ☐ 2. fétuque élevée
☐ 3. orge ☐ 4. ray grass anglais
☐ 5. seigle

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Interrang_enherbement_semé_ENM = "enherbement semé"

177. Si enherbement semé, à quelle fréquence a lieu le semis?

○ 1. tous les ans ○ 2. 1 an 2 ○ 3. 1 an sur 3
○ 4. 1 an sur 4 ○ 5. 1 an sur 5 ○ 6. 1 an sur 10

La question n'est pertinente que si Interrang_enherbement_semé_ENM = "enherbement semé"

178. Si enherbement, est-il géré par tonte?

○ 1. oui ○ 2. non

La question n'est pertinente que si Interrang_enherbement = "oui"

179. Si tonte, combien de fois par an?

○ 1. 1 ○ 2. 2 ○ 3. 3 ○ 4. 4 ○ 5. 5
○ 6. 6 ○ 7. 7 ○ 8. 8 ○ 9. 9

La question n'est pertinente que si Interrang_enherbement_tonte = "oui"

180. Si tonte, quand?

☐ 1. janvier ☐ 2. février ☐ 3. mars
☐ 4. avril ☐ 5. mai ☐ 6. juin
☐ 7. juillet ☐ 8. août ☐ 9. septembre
☐ 10. octobre ☐ 11. novembre ☐ 12. décembre

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Interrang_enherbement_tonte = "oui"

181. Si tonte, comment?

☐ 1. broyeur à marteaux
☐ 2. débroussailleuse manuelle
☐ 3. gyrobroyeur
☐ 4. pâturage d'ovins

Vous pouvez cocher plusieurs cases (3 au maximum).
La question n'est pertinente que si Interrang_enherbement_tonte = "oui"

182. Si tonte, sur quelle superficie, en pourcentage par rapport à l'ensemble de la parcelle?

○ 1. 90 % ○ 2. 80 % ○ 3. 70 % ○ 4. 60 %
○ 5. 50 %

La question n'est pertinente que si Interrang_enherbement_tonte = "oui"

183. Si tonte, quelqu'un vous conseille-t-il?

○ 1. oui ○ 2. non

La question n'est pertinente que si Interrang_enherbement_tonte = "oui"

184. Si oui, qui?

☐ 1. conseiller de la Chambre d'Agriculture

☐ 2. conseiller viticole privé suite à des analyses de sol

☐ 3. technicien viticole de la zone

☐ 4. vendeur d'engrais et de produits phytosanitaires

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Interrang_enherbement_tonte_conseil = "oui"

185. Si enherbement, est-il détruit au cours de l'année?

○ 1. oui ○ 2. non

La question n'est pertinente que si Interrang_enherbement = "oui"

186. Si oui, quand?

○ 1. février ○ 2. mars ○ 3. avril

○ 4. mai ○ 5. juin ○ 6. juillet

○ 7. novembre

La question n'est pertinente que si Interrang_enherbement_destruction = "oui"

187. Si oui, comment?

☐ 1. désherbage chimique ☐ 2. travail du sol

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Interrang_enherbement_destruction = "oui"

D-3-4 Traitements phytosanitaires

188. Quel type de pulvérisateur utilisez-vous?

☐ 1. pulvérisateur à jet porté

☐ 2. pulvérisateur pneumatique

Vous pouvez cocher plusieurs cases.

189-191. Combien de passages de produits phytosanitaires effectuez-vous par an pour chacune des familles ci-dessous?

Fongicides	________
Insecticides	________
Acaricides	________

192. Pratiquez-vous la confusion sexuelle?

○ 1. oui ○ 2. non

193-195. A quelle dose utilisez-vous les produits phytosanitaires pour chacune des familles ci-dessous? □Précisons qu'une dose homologuée sera noté 100 %.

1 : 100 %, 2 : 90 %, 3 : 80 %, 4 : 75 %, 5 : 65 %, 6 : 60 %, 7 : 50 %, 8 : 30 %, 9 : 25 %

	1	2	3	4	5	6	7	8	9
Fongicides	○	○	○	○	○	○	○	○	○
Insecticides	○	○	○	○	○	○	○	○	○
Acaricides	○	○	○	○	○	○	○	○	○

196-198. Les produits phytosanitaires que vous employez sont-ils naturels ou de synthèse?

1 : naturel, 2 : de synthèse

	1	2
Fongicides	☐	☐
Insecticides	☐	☐
Acaricides	☐	☐

D-3-5 Opérations en vert

199. Pratiquez-vous l'épamprage?

○ 1. oui ○ 2. non

200. Si épamprage, combien de fois par an?

○ 1. 1 ○ 2. 2 ○ 3. 3

La question n'est pertinente que si Epamprage = "oui"

201. Si épamprage, quand?

☐ 1. début avril ☐ 2. mi-avril

☐ 3. fin avril ☐ 4. début mai

☐ 5. mi-mai ☐ 6. fin mai

☐ 7. début juin ☐ 8. mi-juin

☐ 9. fin juin ☐ 10. début juillet

☐ 11. mi-juillet ☐ 12. fin juillet

☐ 13. début août ☐ 14. mi-août

☐ 15. fin août

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Epamprage = "oui"

202. Si épamprage, comment?

☐ 1. chimiquement ☐ 2. manuellement ☐ 3. mécaniquement

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Epamprage = "oui"

---

203. Pratiquez-vous l'ébourgeonnage?

○ 1. oui ○ 2. non

---

204. Si ébourgeonnage, combien de fois par an?

○ 1. 1 ○ 2. 2

La question n'est pertinente que si Ebourgeonnage = "oui"

---

205. Si ébourgeonnage, quand?

☐ 1. mi-avril ☐ 2. fin avril
☐ 3. début mai ☐ 4. mi-mai
☐ 5. fin mai ☐ 6. début juin
☐ 7. mi-juin ☐ 8. fin juin
☐ 9. début juillet ☐ 10. mi-juillet
☐ 11. fin-juillet

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Ebourgeonnage = "oui"

---

206. Si ébourgeonnage, comment?

○ 1. manuellement

La question n'est pertinente que si Ebourgeonnage = "oui"

---

207. Pratiquez-vous le rognage ou écimage?

○ 1. oui ○ 2. non

---

208. Si rognage, combien de fois par an?

○ 1. 1 ○ 2. 2 ○ 3. 3 ○ 4. 4

La question n'est pertinente que si Rognage = "oui"

---

209. Si rognage, quand?

☐ 1. fin mai ☐ 2. début juin
☐ 3. mi-juin ☐ 4. fin juin
☐ 5. début juillet ☐ 6. mi-juillet
☐ 7. fin-juillet ☐ 8. début août
☐ 9. mi-août ☐ 10. fin août
☐ 11. début septembre ☐ 12. mi-septembre

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Rognage = "oui"

---

210. Si rognage, comment?

☐ 1. manuellement ☐ 2. mécaniquement

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Rognage = "oui"

---

211. Pratiquez-vous l'éclaircissage?

○ 1. oui ○ 2. non

---

212. Si éclaircissage, combien de fois par an?

○ 1. 1 ○ 2. 2

La question n'est pertinente que si Eclaircissage = "oui"

---

213. Si éclaircissage, quand?

☐ 1. début juin ☐ 2. mi-juin ☐ 3. fin juin
☐ 4. début juillet ☐ 5. mi-juillet ☐ 6. fin-juillet
☐ 7. début août ☐ 8. mi-août ☐ 9. fin août

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Eclaircissage = "oui"

---

214. Si éclaircissage, comment?

☐ 1. chimiquement ☐ 2. manuellement

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Eclaircissage = "oui"

---

215. Pratiquez-vous l'effeuillage?

○ 1. oui ○ 2. non

---

216. Si effeuillage, combien de fois par an?

○ 1. 1 ○ 2. 2

La question n'est pertinente que si Effeuillage = "oui"

---

217. Si effeuillage, quand?

☐ 1. début mai ☐ 2. mi-mai
☐ 3. fin mai ☐ 4. début juin
☐ 5. mi-juin ☐ 6. fin juin
☐ 7. début juillet ☐ 8. mi-juillet
☐ 9. fin-juillet ☐ 10. début août
☐ 11. mi-août ☐ 12. fin août

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Effeuillage = "oui"

---

218. Si effeuillage, comment?

☐ 1. manuellement ☐ 2. mécaniquement ☐ 3. thermiquement

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Effeuillage = "oui"

D-3-6 Récolte

219. Vendangez-vous manuellement ou mécaniquement?
○ 1. manuellement ○ 2. mécaniquement

D-3-7 Bilan

220-224. Quel est l'indice de fréquence des traitements pour chacune des familles ci-dessous?

Herbicides	________
Fongicides	________
Insecticides	________
Acaricides	________
Total	________

225-238. Pour chacun des postes suivants, combien de passages effectuez-vous avec un engin? □Dans le cas où plusieurs travaux sont réalisés en même temps, nous ne considérerons qu'un seul passage.

Prétaille	________
Traitement des bois de taille	________
Apports d'amendements et/ou d'engrais	________
Mise en place de l'enherbement	________
Désherbage chimique	________
Travail du sol	________
Tonte	________
Traitements phytosanitaires	________
Épamprage	________
Rognage	________
Éclaircissage	________
Effeuillage	________
Récolte	________
TOTAL	________

239-251. Pour chacun des postes suivants réalisés avec un engin, passez-vous tous les rangs, 1 rang sur 2, 1 rang sur 3...?
1 : tous les rangs, 2 : 1 rang sur 2, 3 : 1 rang sur 3, 4 : 1 rang sur 4, 5 : 1 rang sur 5, 6 : 1 rang sur 6

	1	2	3	4	5	6
Prétaille	☐	☐	☐	☐	☐	☐
Traitements des bois de taille	☐	☐	☐	☐	☐	☐
Apports d'amendements et/ou d'engrais	☐	☐	☐	☐	☐	☐
Mise en place de l'enherbement	☐	☐	☐	☐	☐	☐
Désherbage chimique	☐	☐	☐	☐	☐	☐
Travail du sol	☐	☐	☐	☐	☐	☐
Tonte	☐	☐	☐	☐	☐	☐
Traitements phytosanitaires	☐	☐	☐	☐	☐	☐
Épamprage	☐	☐	☐	☐	☐	☐
Rognage	☐	☐	☐	☐	☐	☐
Éclaircissage	☐	☐	☐	☐	☐	☐
Effeuillage	☐	☐	☐	☐	☐	☐
Récolte	☐	☐	☐	☐	☐	☐

252. Conservez-vous le même schéma de passage à chaque traitement?
○ 1. oui ○ 2. non

253. Possédez-vous du matériel qui limite le tassement des sols?
○ 1. oui ○ 2. non

254. Si oui, quel(s) type(s)?
☐ 1. quad
☐ 2. tracteur à chenilles
☐ 3. tracteur avec pneus basse pression

Vous pouvez cocher plusieurs cases.
La question n'est pertinente que si Matériel_limite_tassement = "oui"

AUTRES

255. Que pensez-vous de mon sujet de thèse?
____
____

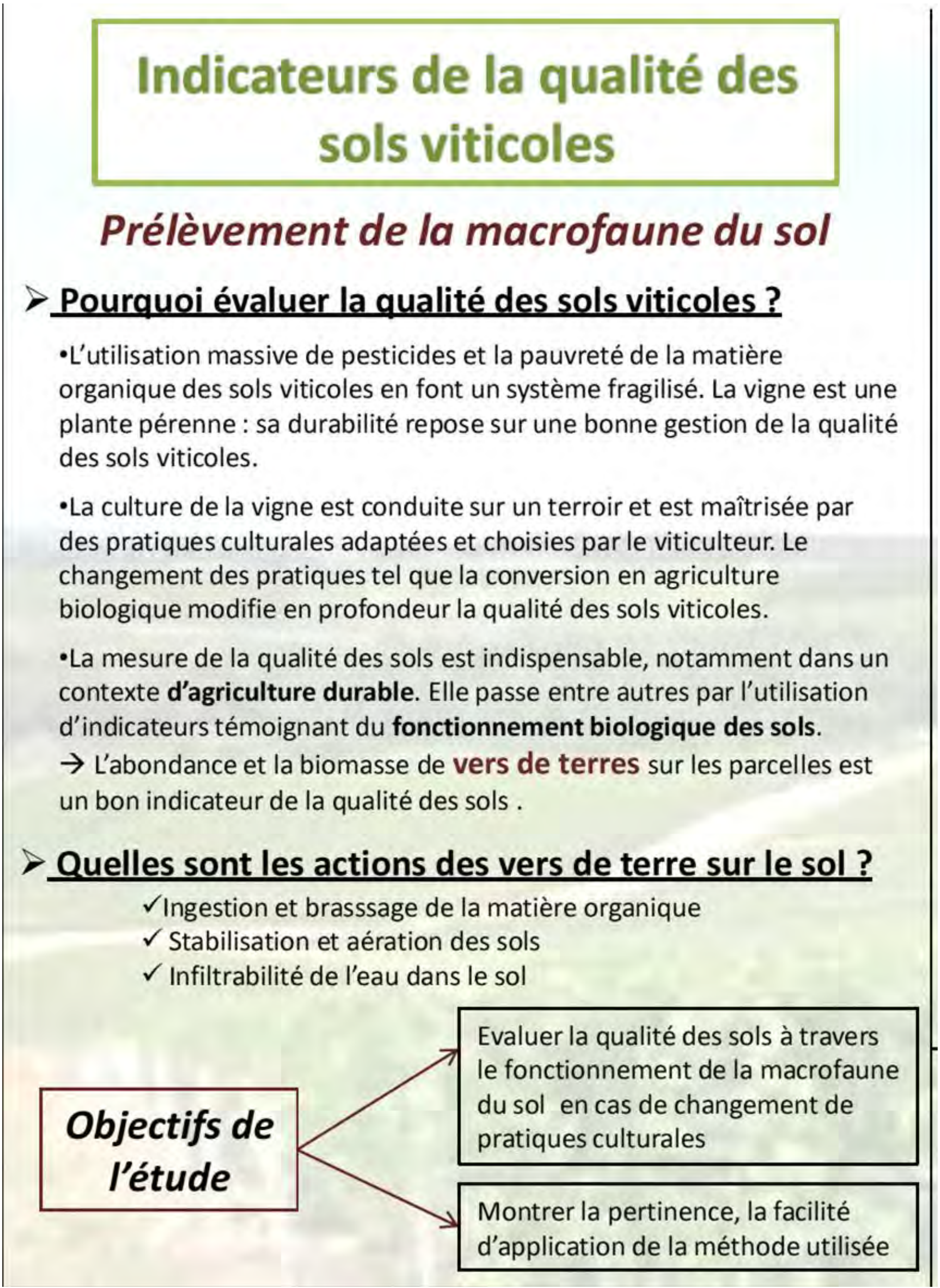
256. CLE
____

257. DATE_SAISIE
___/___/_____

258. IP
____

APPENDIX 2 :

SUPPORT DE COMMUNICATION A DESTINATION DES VITICULTEURS



Indicateurs de la qualité des sols viticoles

Prélèvement de la macrofaune du sol

➢ Pourquoi évaluer la qualité des sols viticoles ?

•L'utilisation massive de pesticides et la pauvreté de la matière organique des sols viticoles en font un système fragilisé. La vigne est une plante pérenne : sa durabilité repose sur une bonne gestion de la qualité des sols viticoles.

•La culture de la vigne est conduite sur un terroir et est maîtrisée par des pratiques culturales adaptées et choisies par le viticulteur. Le changement des pratiques tel que la conversion en agriculture biologique modifie en profondeur la qualité des sols viticoles.

•La mesure de la qualité des sols est indispensable, notamment dans un contexte **d'agriculture durable**. Elle passe entre autres par l'utilisation d'indicateurs témoignant du **fonctionnement biologique des sols**.
→ L'abondance et la biomasse de **vers de terres** sur les parcelles est un bon indicateur de la qualité des sols .

➢ Quelles sont les actions des vers de terre sur le sol ?

✓Ingestion et brasssage de la matière organique
✓ Stabilisation et aération des sols
✓ Infiltrabilité de l'eau dans le sol

Objectifs de l'étude

Evaluer la qualité des sols à travers le fonctionnement de la macrofaune du sol en cas de changement de pratiques culturales

Montrer la pertinence, la facilité d'application de la méthode utilisée

• Matériels et méthodes

Afin de réaliser cette étude, différents prélèvements ont été réalisés sur **13 parcelles différentes**, différant par leur système de culture :

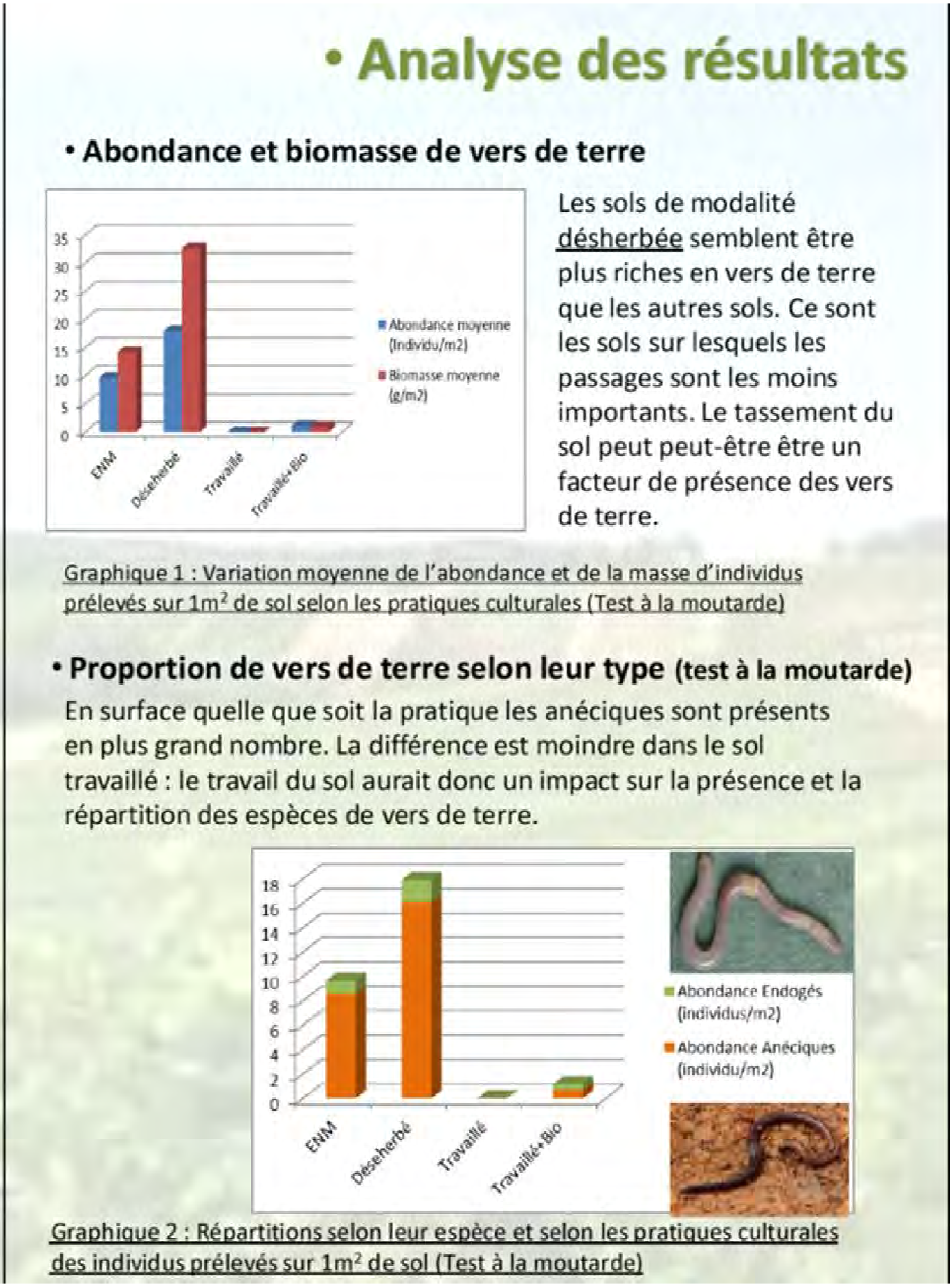
- 4 en agriculture biologique avec travail du sol.
- 9 en agriculture conventionnelle (5 en enherbement maitrisé, 3 en désherbage total et 1 avec un travail du sol).

Méthode pour les prélèvements :

Au sein de chaque parcelle :
-Délimitation de quatre placettes
Sur chaque placette :
-Délimitation d'un carré d'1 m2
- Arrosage par une solution moutardée (150g de moutarde pour 10l d'eau)
- Collecte des vers de terre qui remontent à la surface pendant 10 min
- Trois répétitions pour chaque carré
- Délimitation d'un carré de 25 cm^2 au centre du quadrat initial
- Excavation d'un bloc de 25 cm x 25 cm x 15 cm afin de collecter les vers de terre qui y sont présents.

Analyse des échantillons :

La macrofaune récupérée sur les différentes parcelles a alors été triée afin de séparer les vers de terre en fonction de leur **type** (acéniques ou endogés) et de leur **âge**. Les vers de terre ont été comptés, puis pesés pour évaluer la biomasse de chaque parcelle.



• Analyse des résultats

• Abondance et biomasse de vers de terre

Les sols de modalité désherbée semblent être plus riches en vers de terre que les autres sols. Ce sont les sols sur lesquels les passages sont les moins importants. Le tassement du sol peut peut-être être un facteur de présence des vers de terre.

Graphique 1 : Variation moyenne de l'abondance et de la masse d'individus prélevés sur 1m² de sol selon les pratiques culturales (Test à la moutarde)

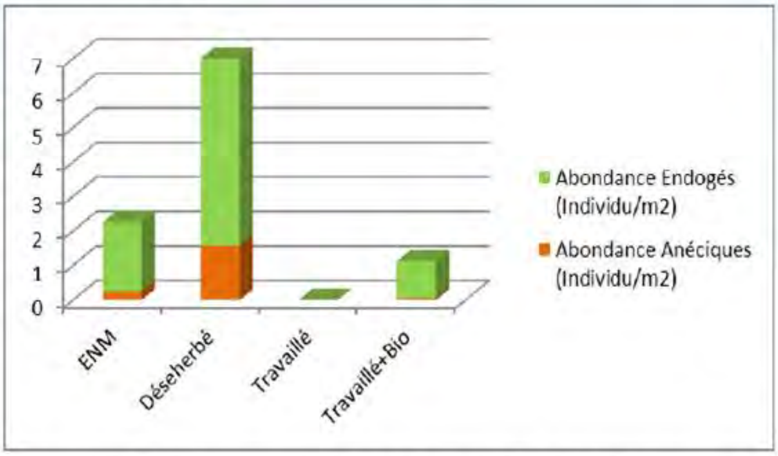
• Proportion de vers de terre selon leur type (test à la moutarde)

En surface quelle que soit la pratique les anéciques sont présents en plus grand nombre. La différence est moindre dans le sol travaillé : le travail du sol aurait donc un impact sur la présence et la répartition des espèces de vers de terre.

Graphique 2 : Répartitions selon leur espèce et selon les pratiques culturales des individus prélevés sur 1m² de sol (Test à la moutarde)

• Analyse des résultats (suite)

• Proportion de vers de terre selon leur type (tri manuel)



Graphique 3 : Répartitions selon leur espèce et selon les pratiques culturales des individus prélevés sur 1m² de sol (Tri manuel)

En profondeur, les endogés sont majoritaires pour les 4 sols triès. Les sols ENM sont ceux pour lesquels cette tendance est la plus importante. Le facteur « travail du sol en surface » peut expliquer cette abondance.

Conclusion

- Les pratiques culturales ont une influence sur l'abondance de la macrofaune dans les sols viticoles .
- La présence de vers terre paraît être un indicateur pertinent de l'activité biologique des sols. Il est facilement reproductible et utilisable.
- Les produits phytosanitaires n'ont pas d'influence négative sur les populations de vers de terre contrairement aux idées reçues.
- Le travail du sol semble perturber la macrofaune viticole par la modification de la structure du sol.

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VINEYARD SOIL QUALITY IN LANGUEDOC-ROUSSILLON
EFFECTS OF AGRICULTURAL PRACTICES

Soils should be considered as a non-renewable yet essential resource for agro-ecosystem functioning. An important component of the Terroir, vineyard soils are nevertheless particularly vulnerable to degradation. The main objective of my PhD was to assess the effect of viticultural practices on soil quality in the Languedoc-Roussillon region. In this aim, I first assessed soil quality on 164 vineyard plots representing a wide range of viticultural practices and located in 9 contrasted soil type zones. I then estimated the speed of change in soil quality, by analyzing 23 plots from one homogeneous zone after their conversion to organic viticulture, undertaken 1 to 17 years ago. Several physical (bulk density, total porosity, structural stability and soil moisture at field capacity) as well as chemical (carbon and nitrogen content, C/N, P, K and Cu availability, cation exchange capacity) and biological (microbial biomass, respiration, nematode and earthworm abundance) indicators were measured in order to provide a holistic appraisal of soil quality. My results show that the variability of vineyard soil quality reflects the perturbations inflicted by different management practices. I have also established that the majority of the studied indicators are sensitive to viticultural practices, independently of soil type. The study of the dynamics of the change in vineyard soil quality revealed stabilization after 7 to 11 years of organic management practices. However, despite a significant increase in biological activity (microbial biomass and free-living nematode abundance), no clear improvement in soil quality was apparent 17 years after conversion to organic viticulture. In conclusion, we have confirmed the vulnerability of Languedoc-Roussillon vineyard soils to current management practices. My work highlights the importance of transferring the acquired knowledge to winegrowers and wine sector professionals in order to improve their perception of soil quality.

Keywords: vineyard, soil quality, bio-indicators, perception, viticultural practices, sustainability

QUALITE DES SOLS VITICOLES EN LANGUEDOC-ROUSSILLON
EFFETS DES PRATIQUES AGRICOLES

Le sol, composante du Terroir doit être considéré comme une ressource non renouvelable essentielle au fonctionnement des agro-écosystèmes. Or, les sols viticoles sont particulièrement vulnérables aux dégradations. L'objectif central de ma thèse est donc d'évaluer comment les pratiques viticoles affectent la qualité des sols dans le Languedoc-Roussillon. Pour ce faire, j'ai d'abord évalué la qualité des sols sur 164 parcelles présentant une grande variabilité de pratiques culturales et réparties sur 9 zones pédologiques très diversifiées. Puis, j'ai évalué la vitesse de changement de la qualité des sols par l'analyse de 23 parcelles d'une zone homogène converties progressivement en viticulture biologique depuis un maximum de 17 ans. Plusieurs indicateurs physiques (densité apparente, porosité totale, stabilité structurale et humidité à la capacité au champ), chimiques (teneur en carbone et azote, C/N, disponibilité des éléments P, K, et Cu, capacité d'échange cationique) et biologiques (biomasse microbienne, respirométrie, nématodes, vers de terre) ont été mesurés afin de fournir une vision holistique de la qualité des sols. Mes résultats montrent une diversité de qualité des sols viticoles au regard des perturbations subies par les différentes pratiques. J'ai également démontré que la majorité des indicateurs étudiés sont sensibles aux pratiques viticoles indépendamment des types de sol étudiés. Concernant la dynamique de changement, la qualité des sols viticoles se stabilise après 7-11 de pratiques biologiques. Toutefois, malgré une augmentation significative des activités biologiques du sol (micro-organismes et nématodes libres), la conversion depuis 17 ans n'a pas mis en évidence une amélioration nette de la qualité du sol. En conclusion, nous avons confirmé la vulnérabilité des sols viticoles languedociens aux pratiques en cours. Mes travaux mettent en lumière l'importance du transfert des connaissances acquises lors de ce travail pour améliorer la perception de la qualité des sols par les viticulteurs et les professionnels de la filière viticole

Mots clés: vigne, qualité des sols, bioindicateurs, perception, pratiques viticoles, durabilité