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Review

Soil health through soil disease suppression: Which strategy from descriptors to indicators?

Céline Janvier[a,b], François Villeneuve[a], Claude Alabouvette[b], Véronique Edel-Hermann[b], Thierry Mateille[c], Christian Steinberg[b,*]

[a]*CTIFL, Centre de Lanxade, BP21, 24130 La Force, France*
[b]*UMR Microbiologie et Géochimie des Sols, INRA/Université de Bourgogne, CMSE, 17 rue Sully, BP 86510, 21065 Dijon cedex, France*
[c]*IRD UMR CBGP, CS 30016, 34988 Montferrier-sur-Lez, France*

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Abstract

Soil is a component of primary importance in crop production, even if it is often neglected, or only regarded as a physical support for the growth of plants. However, with the increasing societal concerns for the sustainability of agriculture, soil must be considered as a living system. Its quality results from the multiple interactions among physicochemical and biological components, notably the microbial communities, primordial for soil function. Crops are threatened by soil-borne diseases. These are often difficult to control, because of the "hidden" status of the pathogens and also because of the absence, noxiousness or lack of efficacy of chemical treatments. In this context, there is a renewed interest for cultural practices such as the use of organic amendments. These practices have a strong influence on soil health, which takes into account plant health, through both changes of physicochemical characteristics and influence on soil microbial communities. Cultural practices are used to improve soil health, and can, in some cases, increase soil disease suppression. The effects of these practices on soil properties have been studied, but the relationship between these properties and soil suppressiveness has not been always very clear. Many different soil descriptors, either abiotic or biotic, have been used to describe the soil health and suppressiveness, but there is a lack of identified, reliable and consistent indicators.

One aim of this review is to show that, despite the age of the soil health concept and all the studies that have been conducted, there are still no guidelines for assessment of soil quality from the plant health point of view. Obviously, the extreme diversity of situations makes any generalisation from a given case-study difficult. However, based on what has already been done in related fields, a methodology to search for indicators of soil health can be proposed.

In this review we will present (i) how a healthy soil can be defined and what are the concepts hidden behind the words "soil health," (ii) which cultural practices have been used to control soil-borne diseases and their limitations, (iii) which soil parameters have been measured when studying soil suppressiveness, and which relationships have been found between these parameters, and finally (iv) how these descriptors could become indicators of soil health, using appropriate analytical and statistical methods.

Keywords: Soil quality; Soil health; Disease suppression; Cultural practices; Indicator; Data analysis; Biotic and abiotic factors; Microbial communities.

1. Introduction

Agriculture is being urged to produce affordable, high-quality food to satisfy the demands of an ever increasing population. Society at large also wants this food to be produced safely and without environmental damage. After having been highly productive for half a century, agriculture now has to be sustainable. This means the integration of three goals: environmental health, economic profitability, and social and economic equity (University of California Sustainable Agriculture Research and Education Program, 1997, website www.sarep.ucdavis.edu/concept.htm). The definition proposed by the Food and

*Corresponding author. Tel.: +33 3 80 69 30 50; fax: +33 3 80 69 32 24.
E-mail address: steinberg@dijon.inra.fr (C. Steinberg).

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Agriculture Organization (FAO, 1989) is "a practice that involves the successful management of resources for agriculture to satisfy human needs, while maintaining or enhancing the quality of the environment and conserving natural resources."

Soil is essential for all but a select few crops. It is not only a support for plant roots, but also a reservoir of essential nutrients necessary for the growth of plants. Due to intensive agriculture, however, soil is threatened by erosion, loss of nutrients, pollution, and so forth. Soil fertility has declined over the last 50 years. Intensive management entailed, in some cases, irreversible damage compromising this non-renewable resource for the future generations. That is why soil is of primary interest when talking about sustainable agriculture.

The concept of soil quality arose in the late 1980s/early 1990s to respond to multiple definitions issuing from the multiple specific concerns of soil science, landscape management, soil mapping, farming, etc. Several factors have been proposed as components of soil quality, and methods are available to measure some of them. Among these numerous factors, it is important to be able to select and validate the most interesting ones as indicators, given the final land use objective. Such an indicator can be defined as "a variable which supplies information on other variables which are difficult to access…and can be used as benchmark to take a decision" (Gras et al., 1989).

Plant health has been neglected in the definition of soil quality. But soil is inhabited by soil-borne plant pathogens, potentially very harmful to crops. Thus, this lack in the definition of soil quality was addressed by the concept of soil health. Nevertheless, the phytopathological component of soils is still often underestimated, if not taken into account at all, in soil health measurements.

Soil-borne diseases are difficult to control, because of the "hidden" status of the causal agents. For a long time, broad spectrum chemicals (e.g. methyl bromide or metam sodium) have been widely used to control soil-borne pathogens. These products are not specific, destroying the whole microflora, pathogenic or not. Moreover, methyl bromide, one of the most used fumigants, has proved to be noxious to people and the environment. Hence its utilisation has been banned since 2005 (Montreal protocol). It is therefore necessary to find alternative methods to chemicals to control soil-borne diseases. There is a renewed interest for "old methods" such as crop rotation and reduced tillage, especially because they can contribute to reduce disease severity. Consequently, it is of primary importance to define soil health indicators to monitor soil health and to predict and measure the impact of cultural practices on soil-borne diseases (van Bruggen and Semenov, 2000). These indicators should be sensitive parameters that are representative of the phytopathological status of soils. These indicators would be very useful, since soil suppressiveness to diseases, which is the main component of soil health, is not easy to measure.

One aim of this review is to show that, despite relative age of the concept of soil health and all the work already done, there are still no guidelines for assessment of soil quality from the plant health point of view. Obviously, the extreme diversity of situations makes any generalization from a given case-study difficult. However, a proposition can be made for a methodology to search indicators of soil health, based on what has already been done on related topics.

In this review, we will present (i) how a healthy soil can be defined and what are the concepts hidden behind the term "soil health," (ii) which cultural practices have been used to control soil-borne diseases and their limitations, (iii) which soil parameters have been measured when studying soil suppressiveness, and which relationships have been found between these parameters, and finally (iv) how these descriptors could become indicators of soil health, using appropriate analytical and statistical methods.

2. Concepts

2.1. Soil quality and soil health

The concept of soil quality emerged in the early 1990s, and the first official definition of this term was proposed by the Soil Science Society of America Ad Hoc Committee on Soil Quality (S-581) in 1997 (Karlen et al., 1997). Soil quality was defined as "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation." For the committee proposing this definition, the term soil quality is not synonymous with soil health, and they should not be used interchangeably. Soil quality is related to soil functions, whereas soil health presents the soil as a finite and dynamic living resource (Doran and Zeiss, 2000). Soil health is defined as "the continued capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, maintain the quality of air and water environments, and promote plant, animal, and human health" (Doran et al., 1996). These two definitions may appear similar, but in this review, we will preferably rely on the soil health concept, since it directly mentions plant health, which is not the case in the definition of soil quality of Karlen et al. (1997). In a simple manner, the Natural Resources Conservation Service of the United States Department of Agriculture proposes on its website (soils.usda.gov/sqi, 2005) the following definition: "soil quality is how well soil does what we want it to do." Because of the numerous possible uses of soil, the meaning of the term soil quality heavily depends on the ecosystem considered. In agricultural soils, plant and animal productivity and health would be of the greatest importance, whereas it would not be the same in urban soils. Even in a given ecosystem, e.g. cultivated soils, their multifunctionality makes it difficult to define a

healthy soil without first defining the targeted goal or aim. Such goals could be plant health, atmospheric balance, avoidance of erosion, etc. We will focus here on plant health as a specific goal. A healthy soil, in this case, is a soil where diseases outbreaks are limited.

2.2. Soil suppressiveness

Suppressive soils have been described by Baker and Cook (1974) as soils in which disease severity or incidence remains low, in spite of the presence of a pathogen, a susceptible host plant, and climatic conditions favourable for disease development. Soils suppressive to diseases caused by the most important soil-borne pathogens have been described. They include fungal and bacterial pathogens and also nematodes (Schneider, 1982; Cook and Baker, 1983; Schippers, 1992; Westphal and Becker, 2001). Different mechanisms can lead to soil suppressiveness (Baker and Cook, 1974): (i) the pathogen does not establish or persist, (ii) it establishes but causes little or no damage, or (iii) it establishes and causes disease for a while but thereafter the disease is less important, although the pathogen may persist in the soil. Disease suppression led to the concept of soil receptivity to diseases (Linderman et al., 1983; Alabouvette, 1990). The receptivity of a soil is its capacity to control more or less the activity of the microbial populations present in the soil. In the case of pathogens, soil receptivity is its capacity to control pathogenic activity. This pathogenic activity depends on three main components: inoculum density, pathogenic capacity of the inoculum (i.e. the genetically based intrinsic aggressivity of the inoculum), and soil factors influencing both the inoculum density and pathogenic capacity, this last component corresponding to soil receptivity (Alabouvette et al., 1982).

Two compatible types of mechanisms have been proposed to characterise soil suppressiveness. General suppression is linked with the biostasis concept. It is directly related to the total amount of microbiological activity at a time critical to the pathogen. In a sense, general suppression of a pathogen in soil is the equivalent of a high degree of soil fungistasis. Not a single microorganism or specific group of microorganisms is responsible by itself for general suppression (Cook and Baker, 1983). Specific suppression operates against a background of general suppression but is more qualitative, owing to more specific effects of individual or selected groups of organisms antagonistic to the pathogen during some stage in its life cycle. As these cases have been extensively studied, their modes of action are better understood.

In this context, soil suppressiveness to diseases is a characteristic of any given soil, ranging along a continuum from highly conducive to suppressive soils. Suppressive soils have thus to be considered as healthy soils. Today, in order to maintain or improve soil health considering crop health as a goal, we have to develop tools enabling one to manage soil biotic and abiotic factors in order to increase soil suppressiveness to diseases.

2.3. Cultural practices used to improve soil health

Cultural practices are known to have a strong influence on soil health and more specifically on soil biological attributes, e.g. microbial communities. In the actual trend to improve soil health and limit the chemical or energetic inputs necessary, cultural techniques are evaluated, notably for their use as alternative methods to chemical control of soil-borne pathogens.

Numerous reports have already been published on the effects of cultural practices on soil quality and disease suppressiveness (Conway, 1996; Abawi and Widmer, 2000; Krupinsky et al., 2002; Bailey and Lazarovits, 2003; Peters et al., 2003). In this review, only representative results will be presented.

2.3.1. Rotations

Crop rotation is a very ancient cultural practise (Howard, 1996). Its benefits include maintenance of soil structure and organic matter, and a reduction in soil erosion that is often associated with continuous row crops. While continuous cropping with the same susceptible host plant will lead to the installation of specific plant pathogenic populations, crop rotation avoids this detrimental effect and is often associated with a reduction in plant diseases caused by soil-borne pathogens. Rotating crops with non-host or less susceptible plants may cause a decline in the specific pathogenic populations due to their natural mortality and the antagonistic activities of other microorganisms (Kurle et al., 2001). This method is best suited for biotrophic pathogens that require the presence of their host to survive or those pathogens with low saprophytic survival capacity (Bailey and Duczek, 1996). It is less successful against pathogens with a wide range of hosts or with efficient survival forms (e.g. sclerotia of *Rhizoctonia solani* or *Sclerotinia sclerotiorum*) (Umaerus et al., 1989).

2.3.2. Tillage

A recent trend aims to reduce excessive cultivation in favour of limited or more strategic tillage practices. Such practices are grouped under the term conservation tillage, as opposed to conventional tillage (Carter, 1994). Conservation tillage is associated with leaving previous crop residues on the soil surface or partially buried in the soil. This organic matter, with a variable level of decomposition, can enhance the microbial biomass and activity (Pankhurst et al., 2002). Concerning plant disease development, contrasting results have been observed (Sturz et al., 1997; Bockus and Shroyer, 1998). Conservation tillage provides a highly competitive environment with possible competition and/or antagonism between microorganisms resulting in disease suppression (Kurle et al., 2001). It also leads to changes in the soil environment, with higher soil

moisture and temperature in the upper layer, which can favour some plant pathogens. In the absence of a host plant, they can survive on plant residues, as saprophytes and/or as long-term survival structures (spores, sclerotia; Rodrigues Almeida et al., 2001). Moreover, the reduced tillage leaves the pathogen in place, whereas conventional deep tillage can displace it into a deeper, less favourable environment (Ntahimpera et al., 1997). The positive or negative effect of limited tillage on plant pathogens greatly depends on specific regional crop–pathogen–environment interactions (Paulitz et al., 2002). Even for the same pathosystem, different effects can be observed. For example, concerning take-all of wheat, Cook and Haglund (1991) found an increase in disease severity with conservation tillage compared with conventional tillage, whereas de Boer et al. (1993) reported that the incidence of take-all on plants was up to twice as high in a conventionally cultivated treatment than in a direct drill treatment.

It is clear that rotation and tillage practices must be taken together, since their effects are interdependent.

2.3.3. Organic amendments

Organic amendments cover a wide range of inputs, from animal manure to solid wastes and various composts. Much research has already been done, most often concluding that organic amendments have a beneficial effect. Sound reviews of their effects can be found in de Ceuster and Hoitink (1999) and Hoitink and Boehm (1999). Organic amendments are often used to improve soil quality, notably by contributing to general suppressiveness through enhanced soil microbial biomass and activity. The main advantage of organic amendments is that they are rich in labile carbon fractions which are a source of energy for microorganisms. Also, organic amendments can contain antagonistic microorganisms. However, differing results have been obtained concerning disease suppression (Termorshuizen et al., 2006). Major key-points for efficiency in controlling plant pathogens are:

- The plant pathosystem: Lumsden et al. (1983) examined the effect of composted municipal wastes on a wide range of diseases. Incorporation of compost controlled Aphanomyces but not Fusarium root rot of pea and also controlled Rhizoctonia but not Thielaviopsis root rot of bean and cotton. Osunlaja (1990) used five different organic materials to control stalk rot of maize, which is caused by two different fungi. All the amendments significantly reduced Fusarium stalk root disease, but only three of them significantly control *Macrophomina phaseolina* root disease, which was even increased with poultry manure amendment.
- The rate of application: in a field experiment to assess two composts for suppression of Fusarium patch (*Microdochium nivale*) and Typhula blight (*Typhula ishikariensis*) snow moulds of turfgrass, compost application at a rate of 97.6 kg/100 m^2 led to significantly lower disease than a rate reduced by half (Boulter et al., 2002). However, there is not always a positive association between the rate of organic amendment and the degree of disease suppression. Testing the effect of incorporation of onion peelings in soil to reduce the viability of sclerotia of *Sclerotium cepivorum*, Coventry et al. (2005) found no significant difference in efficacy between 10% and 50% rates (w/w).
- The nature/type of amendment: Comparing eight different amendments incorporated in soil, Pankhurst et al. (2005) showed that only two of them (poultry manure and chitin) significantly increased the level of suppression of detrimental soil organisms responsible for sugarcane yield decline (e.g. the root rot fungus *Pachymetra chaunorhiza* and the lesion nematode *Pratylenchus zeae*). However, this beneficial aspect took a long time to appear and was only temporary, being detected 7 months after incorporation, but not later. Bulluck and Ristaino (2002) found that cotton-gin trash reduced southern blight (*Sclerotium rolfsii*) of processing tomatoes significantly better than swine manure or rye-vetch. A compost prepared from waste onion peelings was found to be more effective in reducing viability of sclerotia of *Sclerotium cepivorum* than compost prepared from Brassica or carrot wastes (Coventry et al., 2005).
- The degree of maturity of composts/decomposition stage of crop residues: Erhart et al. (1999) found a biowaste compost to be suppressive toward *Pythium ultimum* when it was aged 4 months or more, but not when it was less than 4 months old. Certain batches of composts that were initially not suppressive to Pythium damping-off of creeping bentgrass became suppressive as they aged (Craft and Nelson, 1996).

Until now, a great deal of work has been done on the effect of cultural practices on disease suppression, and on the effect of these practices on soil physicochemical characteristics and properties of the microbial communities. But the link between these studies is rarely made. How do cultural practices influence the soil environment, which soil parameters are sensitive, and how do they render the soil suppressive? Answering these questions and identifying parameters associated with enhanced suppressiveness could provide useful indicators (Mazzola, 2004). They could be used to monitor the effect of cultural practices, and to assess the health of soils before choosing a crop.

3. Soil parameters measured in relation with disease suppression

Both abiotic and biotic parameters have been investigated together with variations in disease suppression (Table 1). Abiotic factors are mainly characterized by quantitative measurements. Concerning biotic factors, they can be divided into several classes, depending on whether they are related to quantitative, structure and diversity, or

Table 1
Types of relationships found between abiotic and biotic microbial soil parameters and disease suppression

Measured parameter	Observed "increase of the parameter = less disease"	Statistical relation "increase of the parameter = less disease"	Observed "decrease of the parameter = less disease"	Statistical relation "decrease of the parameter = less disease"	No relation found
Abiotic parameters					
pH		Höper et al. (1995), Ownley et al. (2003)	Rimé et al. (2003)	Duffy et al. (1997), Lacey and Wilson (2001)	Mallett and Maynard (1998), Oyarzun et al. (1998), Peng et al. (1999), Dominguez et al. (2001), Bulluck and Ristaino (2002), Martinez et al. (2002), Pankhurst et al. (2002), Rasmussen et al. (2002), Manici et al. (2003), Ramette et al. (2003), Hamel et al. (2005a, b), Hiddink et al. (2005), Pérez-Piqueres et al. (2006)
N	Pankhurst et al. (2002), Rasmussen et al. (2002), Rimé et al. (2003), Hamel et al. (2005a, b), Hiddink et al. (2005)	Rotenberg et al. (2005)	Mazzola and Gu (2002)	Oyarzun et al. (1998), Ownley et al. (2003)	Workneh et al. (1993), Höper et al. (1995), Mallett and Maynard (1998), Oyarzun et al. (1998), Peng et al. (1999), van Bruggen and Semenov (1999), Grünwald et al. (2000b), Dominguez et al. (2001), Lacey and Wilson (2001), Bulluck and Ristaino (2002), Martinez et al. (2002), Ramette et al. (2003)
NH_4	van Bruggen and Semenov (1999)	Mallett and Maynard (1998), Ownley et al. (2003)		Grünwald et al. (2000b)	Workneh et al. (1993), Duffy et al. (1997), Oyarzun et al. (1998), Dominguez et al. (2001), Bulluck and Ristaino (2002), Martinez et al. (2002), Pankhurst et al. (2002), Hamel et al. (2005a, b), Hiddink et al. (2005), Rotenberg et al. (2005), Pérez-Piqueres et al. (2006)
NO_3	Hiddink et al. (2005)	Duffy et al. (1997), Martinez et al. (2002)	Workneh et al. (1993)	Workneh et al. (1993), Oyarzun et al. (1998)	Mallett and Maynard (1998), Oyarzun et al. (1998), van Bruggen and Semenov (1999), Grünwald et al. (2000b), Bulluck and Ristaino (2002), Pankhurst et al. (2002), Hamel et al. (2005a, b), Rotenberg et al. (2005), Pérez-Piqueres et al. (2006)
Organic C	Workneh et al. (1993), Pankhurst et al. (2002)			Höper et al. (1995)	Manici et al. (2003), Pérez-Piqueres et al. (2006)
C	van Bruggen and Semenov (1999), Rasmussen et al. (2002)	Oyarzun et al. (1998), Leon et al. (2006)		Oyarzun et al. (1998), Ownley et al. (2003)	Oyarzun et al. (1998), Peng et al. (1999), Grünwald et al. (2000b), Dominguez et al. (2001), Hiddink et al. (2005), Rotenberg et al. (2005)
C/N				Oyarzun et al. (1998)	Höper et al. (1995), Oyarzun et al. (1998), Grünwald et al. (2000b), Rasmussen et al. (2002), Ramette et al. (2003), Rimé et al. (2003), Pérez-Piqueres et al. (2006)
K	Bulluck and Ristaino (2002)	Peng et al. (1999)	Rimé et al. (2003)	Oyarzun et al. (1998)	Duffy et al. (1997), Mallett and Maynard (1998), Oyarzun et al. (1998), Dominguez et al. (2001), Lacey and Wilson (2001), Martinez et al. (2002), Pankhurst et al. (2002), Manici et al. (2003), Ownley et al. (2003), Ramette et al. (2003), Hamel et al. (2005a, b), Pérez-Piqueres et al. (2006)

Table 1 (*continued*)

Measured parameter	Observed "increase of the parameter = less disease"	Statistical relation "increase of the parameter = less disease"	Observed "decrease of the parameter = less disease"	Statistical relation "decrease of the parameter = less disease"	No relation found
Mg	Höper et al. (1995)	Duffy et al. (1997), Oyarzun et al. (1998), Peng et al. (1999)	Rimé et al. (2003)	Oyarzun et al. (1998)	Mallett and Maynard (1998), Oyarzun et al. (1998), Dominguez et al. (2001), Lacey and Wilson (2001), Bulluck and Ristaino (2002), Martinez et al. (2002), Manici et al. (2003), Ramette et al. (2003), Hamel et al. (2005a, b), Pérez-Piqueres et al. (2006)
Na	Höper et al. (1995), Dominguez et al. (2001)	Peng et al. (1999), Ownley et al. (2003)			Duffy et al. (1997), Mallett and Maynard (1998), Oyarzun et al. (1998), Ramette et al. (2003), Rimé et al. (2003), Hamel et al. (2005a, b)
Mn		Hamel et al. (2005a, b)	Höper et al. (1995), Pankhurst et al. (2002), Rimé et al. (2003)	Ownley et al. (2003)	Duffy et al. (1997), Lacey and Wilson (2001), Bulluck and Ristaino (2002), Ramette et al. (2003)
Zn	Pankhurst et al. (2002)	Ownley et al. (2003)			Höper et al. (1995), Duffy et al. (1997), Lacey and Wilson (2001), Bulluck and Ristaino (2002), Ramette et al. (2003), Rimé et al. (2003), Hamel et al. (2005a, b), Pérez-Piqueres et al. (2006)
Electrical conductivity	Dominguez et al. (2001)				Workneh et al. (1993), Lacey and Wilson (2001), Pankhurst et al. (2002), Manici et al. (2003)
CEC	Höper et al. (1995)			Ownley et al. (2003)	Duffy et al. (1997), Mallett and Maynard (1998), Dominguez et al. (2001), Pankhurst et al. (2002), Rasmussen et al. (2002), Ramette et al. (2003), Rimé et al. (2003), Pérez-Piqueres et al. (2006)
P			Rimé et al. (2003)	Duffy et al. (1997), Oyarzun et al. (1998), Pankhurst et al. (2002)	Mallett and Maynard (1998), Oyarzun et al. (1998), Lacey and Wilson (2001), Bulluck and Ristaino (2002), Martinez et al. (2002), Mazzola and Gu (2002), Manici et al. (2003), Ownley et al. (2003), Ramette et al. (2003), Hamel et al. (2005a, b), Pérez-Piqueres et al. (2006)
Cu	Pankhurst et al. (2002)	Duffy et al. (1997)	Pankhurst et al. (2002)		Höper et al. (1995), Lacey and Wilson (2001), Bulluck and Ristaino (2002), Ownley et al. (2003), Ramette et al. (2003), Hamel et al. (2005a, b)
Fe	Pankhurst et al. (2002), Rimé et al. (2003)	Duffy et al. (1997), Martinez et al. (2002)		Höper et al. (1995), Ownley et al. (2003)	Peng et al. (1999), Dominguez et al. (2001), Ramette et al. (2003), Hamel et al. (2005a, b), Pérez-Piqueres et al. (2006)
B		Duffy et al. (1997)			Lacey and Wilson (2001), Bulluck and Ristaino (2002), Manici et al. (2003), Ramette et al. (2003)
Al	Rimé et al. (2003)				Martinez et al. (2002)
Ca		Höper et al. (1995), Peng et al. (1999)	Rimé et al. (2003)	Lacey and Wilson (2001)	Duffy et al. (1997), Mallett and Maynard (1998), Oyarzun et al. (1998), Dominguez et al. (2001), Bulluck and Ristaino (2002), Martinez et al. (2002), Ramette et al. (2003), Hamel et al. (2005a, b), Pérez-Piqueres et al. (2006)

H_2O	Höper et al. (1995)	Rasmussen et al. (2002)		Oyarzun et al. (1998)	Duffy et al. (1997), Oyarzun et al. (1998), Rotenberg et al. (2005)
MO	Rimé et al. (2003)			Oyarzun et al. (1998), Ownley et al. (2003)	Duffy et al. (1997), Oyarzun et al. (1998), Lacey and Wilson (2001), Martinez et al. (2002), Ramette et al. (2003), Hamel et al. (2005a, b), Hiddink et al. (2005), Pérez-Piqueres et al. (2006)
Texture	Höper et al. (1995) (clay)	Duffy et al. (1997) (clay), Ownley et al. (2003) (sand)	Workneh et al. (1993) (clay)	Workneh et al. (1993) (clay), Höper et al. (1995) (sand), Mallett and Maynard (1998) (sand), Ownley et al. (2003) (clay, silt)	Dominguez et al. (2001), Rasmussen et al. (2002), Manici et al. (2003), Ramette et al. (2003), Rimé et al. (2003), Hamel et al. (2005a, b), Pérez-Piqueres et al. (2006)
Quantitative microbial parameters					
Bacterial CFU	Bulluck and Ristaino (2002), Cohen et al. (2005), Wiggins and Kinkel (2005), Larkin and Honeycutt (2006), Pérez-Piqueres et al. (2006)	Höper et al. (1995), Peng et al. (1999), Garbeva et al. (2006)	Benizri et al. (2005)		Oyarzun et al. (1998), Martinez et al. (2002), Mazzola and Gu (2002), Pankhurst et al. (2002), Manici et al. (2003), Rimé et al. (2003)
Fungal CFU	Cohen et al. (2005), Pankhurst et al. (2002), Pérez-Piqueres et al. (2006)	Garbeva et al. (2006), Manici et al. (2003)	Larkin and Honeycutt (2006)	Peng et al. (1999)	Bulluck and Ristaino (2002), Martinez et al. (2002), Mazzola and Gu (2002), Rasmussen et al. (2002), Hamel et al. (2005a, b), Pankhurst et al. (2005)
Pseudomonas spp. CFU	Oyarzun et al. (1998), Larkin and Honeycutt (2006)	Garbeva et al. (2006)		Pankhurst et al. (2002)	Oyarzun et al. (1998)
Fluorescent pseudomonads CFU	Mazzola and Gu (2000)		Höper et al. (1995), Mazzola (1999), Rimé et al. (2003), Cohen et al. (2005)		Oyarzun et al. (1998), Martinez et al. (2002), Mazzola and Gu (2002), Manici et al. (2003), Ramette et al. (2003), Larkin and Honeycutt (2006)
Actinomycetes or Styreptomycetes CFU	Pankhurst et al. (2002)	Peng et al. (1999), Wiggins and Kinkel (2005)			Oyarzun et al. (1998), Martinez et al. (2002), Pankhurst et al. (2002), Garbeva et al. (2006), Larkin and Honeycutt (2006)
Microbial biomass	van Os and van Ginkel (2001), Pankhurst et al. (2002), Kowalchuk et al. (2003), Hamel et al. (2005a, b)	Leon et al. (2006)	Höper et al. (1995)		Pankhurst et al. (2005)
Diversity and structure of microbial communities					
Changes in the profiles					
PLFA profile	Cai et al. (2003), Hamel et al. (2005a, b)				
Biolog	Larkin and Honeycutt (2006)				

Table 1 (*continued*)

Measured parameter	Observed "increase of the parameter = less disease"	Statistical relation "increase of the parameter = less disease"	Observed "decrease of the parameter = less disease"	Statistical relation "decrease of the parameter = less disease"	No relation found
Bacterial PCR DGGE	Yang et al. (2001), Schönfeld et al. (2003), Gorissen et al. (2004), Hiddink et al. (2005), Garbeva et al. (2006)				Kowalchuk et al. (2003)
Fungal PCR DGGE	Garbeva et al. (2006)				Kowalchuk et al. (2003)
Bacterial RISA	Rimé et al. (2003), Benizri et al. (2005)				Yin et al. (2004)
Bacterial T-RFLP	Pérez-Piqueres et al. (2006)				
Fungal T-RFLP	Pérez-Piqueres et al. (2006)				
Microbial activity					
FDA hydrolysis	Workneh et al. (1993), Peng et al. (1999)				Workneh et al. (1993), Grünwald et al. (2000b), Pankhurst et al. (2002), Leon et al. (2006)
Respiration	van Os and van Ginkel (2001), Pankhurst et al. (2002), Kotsou et al. (2004), Pérez-Piqueres et al. (2006)	Höper et al. (1995), Leon et al. (2006)			
Enzymatic activities	van Os and van Ginkel (2001) (dehydrogenase), Hamel et al. (2005a, b) (β-glucosidase, dehydrogenase, phosphatase), Ros et al. (2005) (β-glucosidase)	Rasmussen et al. (2002) (β-glucosidase, cellobiohydrolase), Leon et al. (2006) (arylsulfatase, β-glucosidase)			
Copiotrophic/ oligotrophic ratio	Kotsou et al. (2004)				Garbeva et al. (2006)
N mineralisation, nitrification	Cohen et al. (2005)	Workneh et al. (1993)			Workneh et al. (1993)
2,4 DAPG or HCN-producing *Pseudomonas* spp. CFU					Ramette et al. (2003)

activity measurements. The relations between these soil parameters and suppressiveness of the same soil can be assessed either by simple associations of different results using different variables or by more detailed statistical approaches.

Two different kinds of approach have been used to investigate the relations between soil suppressiveness and other soil parameters. The first one consists in comparing several soils with varying levels of receptivity, and assessing which other parameters differ (Table 2, "without a priori survey" and "natural suppressiveness"). The second approach consists in artificially modifying the level of suppressiveness of a soil, and assessing which other parameters are affected (Table 2). In these studies, more or less detailed data analysis, with or without statistical validation, has been used.

3.1. Abiotic parameters

Höper and Alabouvette (1996) made a comprehensive review of the influence of physicochemical properties on the suppressiveness of soils towards diseases. They concluded that the importance of these factors is far from being clear, partly because of the complexity of the interactions between soil properties. The effect of the physicochemical factors in the soil environment needs to be studied more. Indeed, many authors studying soil suppressiveness include physicochemical analyses in their work, and sometimes try to relate these characteristics with disease incidence. However, these analyses are made by taking each parameter independently, while the overall abiotic soil environment should be taken into account.

The parameters most studied are soil pH and N content (Table 1). Studying the effect of clay addition and liming on soil suppressiveness, Höper et al. (1995) found a positive correlation between pH and soil suppressiveness, soils with higher pH being more suppressive towards Fusarium wilts. On the contrary, comparing a suppressive and a conducive soil to ectoparasitic nematodes, Rimé et al. (2003) found that the most acidic soil was the most suppressive one. Working with 35 soils, Lacey and Wilson (2001) found the same relation between more acidic pH and a lesser incidence of potato scab (*Streptomyces scabies*). Duffy et al. (1997) found that the suppression of take-all of wheat with *Trichoderma koningii* was enhanced at lower pH. However, many other authors measured the pH of their soils and found no relation with disease incidence (Table 1).

Concerning the N content of soil, more associations have been found. A positive association was found between the N content of soil and the suppressiveness towards ectoparasitic nematodes (Rimé et al., 2003), *Pseudomonas syringae* on bean and cucumber (Rotenberg et al., 2005), *Gaeumanomyces graminis* var *tritici* (Ggt) and *R. solani* on wheat (Pankhurst et al., 2002), and *Fusarium* spp. on asparagus (Hamel et al., 2005a). On the contrary, the N content of soil was significantly negatively correlated with increased suppressiveness to *Fusarium solani* f.sp. *pisi* on pea (Oyarzun et al., 1998). The form of N, either NO_3 or NH_4, is also important. Tenuta and Lazarovits (2004) studied the effectiveness of a nitrogenous organic amendment to kill microsclerotia of *Verticillium dahliae* in several soils, and the soil properties associated with this effectiveness. They found that NH_3 is effective in killing *V. dahliae* microsclerotia only in soils where it accumulates above the concentration of 25 mM. Organic C and soil density have been identified by correlation and principal component analyses as potential predictors of the ability of soils to accumulate this NH_3. HNO_2 is also able to kill microsclerotia, but in this case, the soil pH has to be acid.

A higher content of C was associated with less incidence of *Fusarium culmorum* on barley (Rasmussen et al., 2002), Pythium damping-off of tomato (van Bruggen and Semenov, 1999) and *F. solani* f.sp. *pisi* on pea (Oyarzun et al., 1998). Only these latter confirmed this association by a correlation analysis. However, the same authors found that the C content of soil was positively correlated to incidence of *Thielaviopsis basicola*, and was not related to *Aphanomyces euteiche*s on pea.

Concerning only organic C content, it was found to be associated with less incidence of Ggt on wheat (Pankhurst et al., 2002) and less severity of corky root (*Pyrenochaeta lycopersici*) on tomato (Workneh et al., 1993). On the contrary, a significant negative correlation was found between the organic C content of soil and its suppressiveness to Fusarium wilt (Höper et al., 1995).

Other physicochemical characteristics sometimes measured are cations and oligoelements (Table 1). Since all authors did not measure the same set of parameters, it is quite impossible to propose sound conclusions of the possible relations between disease incidence and oligoelements or cations. Mg and K were found associated with disease, higher levels of these elements being associated with lower incidence of fungal disease (Duffy et al., 1997; Peng et al., 1999). On the contrary, a soil suppressive to ectoparasitic nematodes had significantly lower levels of Mg and K than a conducive soil (Rimé et al., 2003). Oyarzun et al. (1998) found contrasting results, depending on the pathogen. When associations have been highlighted between disease and Al, Fe, Na or Zn contents, they were always in the sense of less disease with higher contents of these elements.

Concerning the relation between soil texture and suppressiveness, several results have been obtained. Höper et al. (1995) and Mallett and Maynard (1998) both found a significant negative correlation between the sand content of a soil and its suppressiveness to Fusarium wilts of flax and Armillaria root disease on lodgepole pine, respectively. No relationship was found between soil texture and suppressiveness towards ectoparasitic nematodes (Rimé et al., 2003), Fusarium wilt of banana (Dominguez et al., 2001), Fusarium root rot of asparagus (Hamel et al., 2005a) or replant disease of apple tree (Manici et al., 2003). For clay content, Duffy et al. (1997) found that higher clay content

Table 2
Diversity of agronomic situations and pathosystems used to investigate relationships between soil parameters and disease suppression

Source of disease variability	Pathosystem	Number of samples	Experimental situation	References
Without a priori survey				
	Streptomyces spp./potato	35	Commercial field soils and microcosm	Lacey and Wilson (2001)
	Armillaria root disease/lodgepole pine	36	Stand	Mallett and Maynard (1998)
	Helminthosporium solani/potato	45	Commercial field	Martinez et al. (2002)
	Aphanomyces euteiches/pea	27	Commercial field	Oyarzun et al. (1998)
	Fusarium solani/pea	31	Commercial field	Oyarzun et al. (1998)
	Thielaviopsis basicola/pea	33	Commercial field	Oyarzun et al. (1998)
Natural suppressiveness				
Suppressive/conducive zone in each field	*Fusarium oxysporum* f.sp. *cubense*/banana	7+7	Field	Dominguez et al. (2001)
Suppressive/conducive zone in each field	*Fusarium oxysporum* f.sp. *asparagi*/asparagus	50+50	Commercial field	Hamel et al. (2005a, b)
Suppressive/conducive soil	Ectoparasitic nematodes/sugarcane	2 (× 6 soil samples)	Field	Rimé et al. (2003)
Suppressive/conducive soil	*Fusarium oxysporum* f.sp. *cubense*/banana	2	Field soils and microcosm	Peng et al. (1999)
± suppressive soils	*Thielaviopsis basicola*/tobacco	4	Field soils and microcosm	Ramette et al. (2003)
3 zones in a epidemic area	*Phytophthora cinnamomi*/avocado tree	41	Field	Yin et al. (2004)
Biocontrol/healthy/diseased trees	*Phytophthora cinnamomi*/avocado tree	12 trees × 3 root samples	Field	Yang et al. (2001)
Healthy/sick soils	Replant disease/peach tree	3	Microcosm	Benizri et al. (2005)
Type of farm management				
Organic/conventional	Replant disease/apple tree	6	Field soils and microcosm	Manici et al. (2003)
Organic/conventional	*Fusarium culmorum*/barley	10	Field	Rasmussen et al. (2002)
Organic/transitional/conventional	*Phytophthora parasitica* (and density)/tomato	27	Commercial field	Workneh et al. (1993)
Organic/transitional/conventional	*Pyrenochaeta lycopersici*/tomato	27	Commercial field	Workneh et al. (1993)
Organic/transitional/conventional and biocontrol agent	*Gaeumannomyces graminis* var. *tritici*/barley, triticale, wheat	4+3+4	Experimental field soils and microcosm	Hiddink et al. (2005)
Organic/conventional and incorporated cover crops	*Pythium aphanidermatum*/tomato	2+2 × 3	Experimental field and microcosm	Grünwald et al. (2000a, b)
Organic amendment				
Soil and organic amendment	*Rhizoctonia solani*/pine	8	Microcosm	Pérez-Piqueres et al. (2006)
Organic amendment	*Ralstonia solanacearum*/tomato	3	Microcosm	Cai et al. (2003)
Compost amendment	*Fusarium oxysporum*/melon	5	Microcosm	Ros et al. (2005)

Organic amendment, rate and repetition	*Pseudomonas syringae* pv. *lachrymans*/cucumber	14	Experimental field	Rotenberg et al. (2005)
Organic amendment and rate	*Pseudomonas syringae* pv. *syringae*/snap bean	14	Experimental field	Rotenberg et al. (2005)
organic amendment and rate	*Aphanomyces euteiches*/snap bean	5	Experimental field and microcosm	Leon et al. (2006)
Organic amendment ± N	Yield decline/sugarcane	13	Experimental field soils and microcosm	Pankhurst et al. (2005)
Compost amendment and solarization	*Ralstonia solanacearum* biovar 2/potato	4	Field microplots and microcosm	Schönfeld et al. (2003)
Cover crop incorporation	Pythium damping-off/tomato	3	experimental field and microcosm	van Bruggen and Semenov (1999)
Pig slurry amendment and solarization	*Ralstonia solanacearum* biovar 2/potato	4	Field microplots and microcosm	Gorissen et al. 2004
Soil and meat and bone meal amendment	*Verticillium dahliae* (microsclerotia)	12 × 2	Field soils and microcosm	Tenuta and Lazarovits, 2004
Green manure and rotation	*Streptomyces scabies*/potato	4 × 3	Microcosm	Wiggins and Kinkel (2005)
Liquid organic amendment	*R. solani*/lettuce	3	Microcosm	Kotsou et al. 2004
organic amendment and growth media	*Fusarium oxysporum* f.sp.*lycopersici*/tomato	6	Microcosm	Borrero et al. 2004
Sterilization ± amendement, fumigation, flooding	Pythium root rot/iris	5	Microcosm	Kowalchuk et al. (2003), van Os and van Ginkel (2001)
Tillage and rotation				
Soil and wheat cultivars cultivation	Replant disease/apple tree	52	Field soils and microcosm	Mazzola and Gu, 2000, Gu and Mazzola (2003)
Soil and wheat cultivars cultivation	*R.solani*/apple tree	21	Field soils and microcosm	Mazzola and Gu (2002)
Cropping duration	*R.solani*/apple tree	6	Field	Mazzola (1999)
Grassland/arable land and rotation	*R.solani*/potato	6	Experimental field soils and microcosm	Garbeva et al. (2006)
Tillage	*Heterodera glycines* (density)/soybean	1462	Field	Workneh et al. (1999)
Tillage	*Phytophtora sojae* (density)/soybean	1462	Field	Workneh et al. (1999)
Tillage	*Phialophora gregata*/soybean	1462	Field	Workneh et al. (1999)
Tillage and stubble management	*Gaeumannomyces graminis* var. *tritici* and *Rhizoctonia solani*/wheat	5	Experimental field soils and microcosm	Pankhurst et al. (2002)
Others				
Clay amendments and liming	*Fusarium oxysporum* f.sp. *lini*/flax	9	Microcosm	Höper et al. (1995)
Soil and biocontrol agent	*Gaeumannomyces graminis* var. *tritici*/wheat	16	Field soils and microcosm	Duffy et al. (1997)
Soil and biocontrol agent	*Gaeumannomyces graminis* var. *tritici*/wheat	10	Field soils and microcosm	Ownley et al. (2003)

was associated with less Ggt on wheat after treatment with *T. koningii*, while, on the contrary, Workneh et al. (1993) found that there was more clay in soils of conventional farms, in particular those farms with vertisols, these soils promoting greater severity of the disease caused by *P. lycopersici,* than in soils of organic farms.

Some authors used multivariate analyses, taking into account the whole set of physicochemical parameters together. Studying the effect of compost amendment on soil suppressiveness to *R. solani*, Pérez-Piqueres et al. (2006) found that the most suppressive soil compost mix was clearly separated from the non-amended control after principal component analysis (PCA) of 14 soil parameters. The suppressive mix contained higher rates of CaO, MgO, K_2O and $N–NH_4$ and a higher CEC than the control soil. Ownley et al. (2003) analysed 28 physical and chemical properties of 10 soils. These soils were assessed for take-all disease suppression with seeds treated with phenazine-producing *Pseudomonas fluorescens*. The authors found that 16 soil properties were correlated with disease suppression. Regression analysis enabled them to propose a model including 6 key soil properties ($N–NO_3$, CEC, Fe, %silt, soil pH and zinc) to explain the variance in take-all disease rating of wheat treated with phenazine-producing *P. fluorescens*.

3.2. Quantitative microbial parameters

3.2.1. Colony-forming units (CFU) plate counts

The most ancient method to study the soil microbial communities is the isolation and counting of the CFU, and the identification of the species present in a soil sample. Despite well-known bias, such as the overwhelming number of non-cultivable microorganisms which are not considered by such techniques (Torsvik et al., 1990a, b), CFU counts on more or less specific solid media are still used and informative (Balestra and Misaghi, 1997; Martinez et al., 2002; Cohen et al., 2005). In studies dealing with soil suppressiveness, along with total bacterial and fungal counts, populations which are known or supposed to have antagonistic properties are often surveyed too.

Concerning total bacterial densities, no relation was found with disease incidence of ectoparasitic nematodes (Rimé et al., 2003), *Helminthosporium solani* on potato (Martinez et al., 2002), Ggt and *R. solani* on wheat (Pankhurst et al., 2002), *F. solani* f.sp. *pisi* and *A. euteiches* on pea (Oyarzun et al., 1998) and *R. solani* and replant disease of apple tree (Mazzola, 1999; Manici et al., 2003). Increased bacterial densities were associated with increased suppressiveness of amended soils towards southern blight (*S. rolfsii*) of processing tomatoes (Bulluck and Ristaino, 2002), Phytophthora root rot of alfalfa and potato scab (Wiggins and Kinkel, 2005). In the same way, larger bacterial densities were associated with increased suppressiveness of soils to *Fusarium oxysporum* f.sp. *cubense* (Peng et al., 1999), *R. solani* on apple trees in soils amended with rapeseed meal (Cohen et al., 2005), *R. solani* on pine in a compost-amended soil (Pérez-Piqueres et al., 2006). On the contrary, higher bacterial densities were positively correlated with high receptivity of soils to *T. basicola* on pea (Oyarzun et al., 1998), and sick soils in the replant disease of peach (Benizri et al., 2005).

Fungal population densities were not related to incidence or severity of southern blight of tomatoes (Bulluck and Ristaino, 2002), *H. solani* on potato (Martinez et al., 2002), *Fusarium* spp. on asparagus (Hamel et al., 2005b) and *R. solani* on apple tree (Mazzola, 1999). But higher fungal densities were associated with enhanced suppressiveness to Ggt and *R. solani* on wheat in fields amended with stubble (Pankhurst et al., 2002), *R. solani* on apple tree in fields with rapeseed meal amendment (Cohen et al., 2005), apple tree replant disease in organic soils (Manici et al., 2003) and *R. solani* damping-off of pine in a compost-amended soil (Pérez-Piqueres, 2006). On the contrary, increased suppressiveness was associated with lower fungal densities in soils suppressive to Fusarium wilt of banana (Peng et al., 1999).

Besides total aerobic bacterial and fungal counts, specific populations can also be monitored by dilution plating on selective media. Pseudomonads and fluorescent pseudomonads are among the most studied populations, in soil and in the rhizosphere (Weller et al., 2002). The density of pseudomonads had no influence on the incidence of *F. solani* f.sp. *pisi* and *A. euteiches* on pea (Oyarzun et al., 1998). A greater density of pseudomonads was associated with soil conduciveness to ectoparasitic nematodes (Rimé et al., 2003) and a greater disease incidence of Ggt and *R. solani* on wheat (Pankhurst et al., 2002). On the contrary, the density of pseudomonads was correlated with decreased incidence of *T. basicola* on pea (Oyarzun et al., 1998) and *R. solani* on potato (Garbeva et al., 2006; Larkin and Honeycutt, 2006).

Concerning fluorescent pseudomonads, their density was not related to soil suppressiveness or conduciveness to *H. solani* on potato (Martinez et al., 2002), *F. solani* f.sp. *pisi* or *A. euteiches* on pea (Oyarzun et al., 1998), *R. solani* or replant disease on apple tree (Mazzola, 1999; Manici et al., 2003). Other studies found that more fluorescent pseudomonads were associated with a lesser disease incidence of *S. rolfsii* on tomato (Bulluck and Ristaino, 2002), *T. basicola* on pea (Oyarzun et al., 1998) and replant disease on apple tree (Mazzola, 1999). There were fewer fluorescent pseudomonads in soils amended with rapeseed meal, which were more suppressive to *R. solani* on apple tree (Cohen et al., 2005). A study has also been conducted on the relation between the fluorescent pseudomonads community composition and the apple replant disease in different orchard soils, and how this composition is influenced by the genotype of wheat previously cropped on these soils (Mazzola and Gu, 2000, 2002; Gu and Mazzola, 2003).

Actinomycetes, and among them many *Streptomyces* spp., are known for their antagonistic properties (Jones and Samac, 1996; Samac and Kinkel, 2001), i.e. by

producing antifungal compounds (Chamberlain and Crawford, 1999). Actinomycete densities were not consistently associated with disease incidence of *H. solani, R. solani* or other soil-borne diseases on potato (Martinez et al., 2002; Garbeva et al., 2006; Larkin and Honeycutt, 2006) or *F. solan*i f.sp. *pisi*, *T. basicola* and *A. euteiches* on pea (Oyarzun et al., 1998). However, there were greater densities of actinomycetes in soils resistant to Fusarium wilt of banana (Peng et al., 1999) and soils under conservation tillage showing higher suppressiveness to Ggt and *R. solani* on wheat (Pankhurst et al., 2002). Concerning more particularly *Streptomyces* spp., Wiggins and Kinkel (2005) found a significant negative correlation between *Streptomyces* spp. densities and the disease incidence of alfalfa root rot and potato scab after green manure amendment. The density of antagonistic *Streptomyces* spp. was also significantly negatively correlated to alfalfa root rot.

In conclusion, the variations in microbial densities may depend on the pathosystem and the soil in which the disease occurs. Generally there is a positive association between microbial densities and soil suppressiveness. However, in experiments conducted for several years, different results may appear (Garbeva et al., 2006).

3.2.2. Microbial biomass

Soil microbial biomass can be assessed by several methods, among which are the chloroform fumigation–extraction method (Vance et al., 1987) and the substrate-induced respiration method (Anderson and Domsch, 1978). It is generally admitted that disease suppressiveness is related to a global increase in soil microbial biomass. A large biomass would create a competitive environment deleterious for the pathogens. Enhancement of the microbial biomass is also one of the aims of some cultural practices, mainly organic amendments. Increased microbial biomass was associated with decreased disease incidence of Pythium root-rot on iris (van Os and van Ginkel, 2001), Ggt and *R. solani* on wheat (Pankhurst et al., 2002) and *F. oxysporum* on asparagus (Hamel et al., 2005b), but no statistical correlations were made. Leon et al. (2006) found a significant negative correlation between microbial biomass and disease severity of *A. euteiches* on snap bean. Concerning the yield decline of sugarcane, the results were not so clear (Pankhurst et al., 2005). Seven months after incorporation of different organic amendments in soil, microbial biomass was not significantly different between most amended soils and the non-amended control. However, all of the amended soils showed an increased suppressiveness towards yield decline. In the only two cases where microbial biomass was significantly increased, disease suppression was not. This example shows that the relationship between microbial biomass and disease incidence is not consistent. Studying the effect of cover-crop incorporation in both organic and conventional farming system on soil suppressiveness to *Pythium aphanidermatum*, Grünwald et al. (2000a, b) found no relation between the soil microbial biomass and disease incidence.

3.3. Diversity and structure of microbial communities

A greater biodiversity (number of species present in the ecosystem) has long been synonymous with better soil quality, diversity being considered as a key component of soil stability and function (Agenda 21, United Nations Conference on Environment and Development, Rio de Janeiro, 1992: "The current decline in biodiversity is largely the result of human activity and represents a serious threat to human development"; Naeem et al., 1994). However, functional redundancy has been shown, and it is now admitted that the functional characteristics of individual species are at least as important as the total diversity (Andrén and Balandreau, 1999; Griffiths et al., 2000, 2001). Indeed, the diversity and the structure of soil microbial communities are of primary interest when studying soil suppressiveness.

Isolation of microorganisms from soil has long been the only method to assess the diversity and structure of microbial populations. However, this method only allows access to cultivable microorganisms, which represent a very little proportion of the whole microbial community of soil (Torsvik et al., 1990a, b). Nowadays, direct extraction methods are available, without prior cultivation of the microorganisms. These methods allow the study of a much greater part of the soil microflora.

Phospholipid fatty acid (PLFA) analysis is one solution to overcome the problem of finding unculturable microorganisms when assessing soil microbial diversity. Many fatty acids have been isolated from, and are representative of, specific microbial groups, making PLFA analysis a useful tool to describe microbial diversity and structure (Bossio et al., 1998; Ibekwe and Kennedy, 1998; Zelles, 1999). Discriminant analysis conducted on the whole microbial PLFA profiles revealed the existence of significantly distinct microbial community structures in soils depending on the classes of Fusarium crown and root rot of asparagus in fields (Hamel et al., 2005b). However, this distinction was cultivar specific, highlighted only when comparing fields with the same cultivar. Studying the effect of biological organic fertilizers, Cai et al. (2003) found that fatty acid methyl ester (FAME) microbial markers would be a useful indicator of soil health and that the soil odd-number fatty acid proportion changed due to organic amendment, which also reduced the incidence of bacterial wilt of tomato (*R. solanacearum*).

The community level physiological patterns established using the Biolog systems are used to detect differences in the ability of microbial communities to degrade different carbon substrates (Garland and Mills, 1991). These methods are biased. Biolog substrates favour bacteria, and so the microbial community studied is in fact part of the bacterial community. And among the bacteria, the faster growing ones are overrepresented (Hill et al., 2000).

Pérez-Piqueres et al. (2006) compared the Biolog profiles of different soil and compost mixes. Analysis of the metabolic diversity by PCA clearly separated the mixes most suppressive to *R. solani* from the non-amended highly conducive control soil. Similarly, Benizri et al. (2005) compared the Biolog profiles of the bacteria inhabiting two healthy and one sick soil, mimicking peach tree replant disease. The second principal component of the PCA analysis separated the soil bacteria isolated from healthy soils from those isolated from sick soils. However, this separation was not statistically significant.

The development of DNA-based methods provided new insights into the composition and structure of microbial communities. It enabled the access to a greater part of the soil microflora without the bias of cultivation (Tiedje et al., 1999; Ranjard et al., 2000b). Methods such as ribosomal intergenic spacer analysis (RISA, Borneman and Triplett, 1997; Ranjard et al., 2000a), (terminal)-restriction fragment length polymorphism ((T)-RFLP, Liu et al., 1997; Marsh, 1999) or denaturing gradient gel electrophoresis (DGGE, Muyzer et al., 1993) give complex molecular fingerprints of the microbial communities after direct extraction of the soil DNA and polymerase chain reaction (PCR) amplification of DNA markers of the community of interest, mainly ribosomal DNA (rDNA). These techniques allow the analysis of both culturable and non-culturable microorganisms and provide a rapid method for observing changes in community structure in response to different environmental factors. Besides total bacterial and fungal communities, the structure of specific subgroups can also be assessed (Garbeva et al., 2006).

In a soil having received pig slurry or compost and showing an increased suppressiveness to *R. solanacearum* biovar 2 on potato, PCR-DGGE revealed differences in the bacterial community structure (Schönfeld et al., 2003; Gorissen et al., 2004). These amendments resulted in the appearance of several novel bands and different relative intensities of bands common to the treated and non-treated soils. In the case of compost amendment, several discriminant DGGE bands and PCR products were cloned and/or sequenced in order to identify the corresponding microorganisms; but their involvement in disease suppressiveness remains to be tested. Nevertheless, even if the micro-organisms are not directly responsible, these DNA markers might serve as indicators of these treatments and thus as indicator of the *R. solanacearum*-suppressive status of soil. Comparing bacterial DGGE patterns of soils receiving different treatments, Kowalchuk et al. (2003) found that, except for a sterilised and then amended soil, all DGGE patterns from the treated and control soils were highly similar. The same samples were also examined by fungal PCR-DGGE. The profiles obtained were much simpler than those obtained for bacteria. Once again the sterilised and amended soil was very different from the others. Yang et al. (2001) compared DGGE fingerprinting of rhizospheric bacterial communities associated with healthy or *Phytophthora cinnamomi* infected avocado roots. A PCA clearly revealed that bacterial communities from healthy roots, both of control trees or trees treated with biocontrol bacteria, were highly similar, but different from the communities on infected roots. A Monte-Carlo permutation test showed that root infection had a statistically significant effect on bacterial community structure. However, with the same pathosystem in a field with different levels of *P. cinnamomi* infestation, Yin et al. (2004) found no significant differences in the RISA profiles of soil bacterial communities.

The bacterial community structure in rhizospheric soil of peach grown in healthy or replant disease sick soils (Benizri et al., 2005), or sugarcane from suppressive or conducive soil to ectoparasitic nematodes (Rimé et al., 2003), were compared by RISA analysis. In the case of peach rhizosphere communities, PCA on the profile data clearly separated the three samples from healthy soils from the ones from sick soils. This separation was statistically significant. In the second study, the separation between nematodes conducive and suppressive soil samples was less clear, because of the variability between plots, given the highest number of samples (6 plots and 2 replications in each of the two fields). However, PCA partially distinguished the plots from the suppressive field from those from the conducive.

Pérez-Piqueres et al. (2006) used the T-RFLP method to characterise microbial communities. Correspondence analyses clearly separated both fungal and bacterial community structures of the most suppressive amended soil from the other treatments.

All these results demonstrate that the microbial communities' structure and diversity are often sensitive to the phytopathological status of soils, but until now, no microbial component was identified as potential indicator of disease suppression from such studies. Indeed, after the whole community fingerprinting, it is necessary to select the discriminating markers and to identify the microorganisms "hidden" behind. Such a study has already been conducted to identify microorganisms associated with *Heterodera schachtii* cysts present in suppressive soils (Yin et al., 2003a, b).

3.4. Microbial activity

A soil of good quality should be suitable for all the processes which are presumed to occur in it: geochemical cycles, plant growth, buffering for pollutants, etc. Microorganisms are the major actors for the completion of these functions, and several microbial functions can be assessed when trying to characterize soil properties.

By measuring global or specific microbial biomass/densities, one also has an indication of a potential activity. However, it is the real, expressed, activity which is important to measure.

Soil microbial activity is the quantified reflection of the soil functioning. Soil functions include C and N geochemical cycles, organic matter degradation, etc. Activities

resulting from the whole microbial community can be measured globally through different methods. Fluorescein diacetate (FDA) hydrolysis (Schnürer and Rosswall, 1982; Adam and Duncan, 2001) is a good estimate of total microbial activity because multiple enzymes present in both bacteria and fungi are responsible for this hydrolysis. Soil respiration can also be used as a method to assess the microbial activity (Hersman and Temple, 1979). Enzymes are an integral part of nutrient cycling in the soil and are usually associated with viable proliferating cells, so specific enzyme activities, such as dehydrogenase, phosphatase, β-glucosidase and many others can also be measured as an estimate of soil microbial activity (Trasar-Cepeda et al., 1998; Bandick and Dick, 1999). These global activities might be related with the general suppressiveness potential of soils, as an active microbial community is thought to be more efficient to control soil pathogens.

Increased FDA hydrolysis was associated with lower disease incidence of *F. oxysporum* f.sp. *cubense* on banana in suppressive soils (Peng et al., 1999) and of *P. lycopersici* on tomato in organic farms (Workneh et al., 1993). However, Workneh et al. (1993) found no relation between FDA hydrolysis and the presence of *Phytophthora parasitica* in soil of tomato farms neither did Grünwald et al. (2000a, b) with *P. aphanidermatum* damping-off of tomato. Pankhurst et al. (2005), as for microbial biomass, found no consistent association between FDA hydrolysis in amended soils and their suppressiveness towards sugarcane yield decline.

In all the studies where soil respiration was assessed, higher respiration rates were associated with lower disease incidence or severity (van Os and van Ginkel, 2001; Pankhurst et al., 2002; Kotsou et al., 2004; Leon et al., 2006; Pérez-Piqueres et al., 2006).

Concerning specific enzyme activities, Rasmussen et al. (2002) found significant positive correlations between soil suppressiveness to seedling blight of barley (*F. culmorum*) and the activities of β-glucosidase and cellobiohydrolase, two cellulolytic enzymes. Higher phosphatase and β-glucosidase activities were also associated with soil–compost mixes more suppressive than control soil to *F. oxysporum* on melon plants (Ros et al., 2005) and with soils suppressive to Fusarium crown and root rot of asparagus (Hamel et al., 2005b). Leon et al. (2006) found that arylsulfatase activity, a possible biomarker for fungal biomass, was well correlated with suppression of common root rot of snap bean.

Metabolic profiles obtained with a Biolog system give a qualitative picture of microbial community, but can also provide a quantitative measurement of its activity. In this way, Pérez-Piqueres et al. (2006) compared the Biolog profiles of different soil and compost mixes. The analysis of the quantitative data (average well colour development) showed no differences between the suppressive and conducive mixes.

The ratio of oligotrophs to copiotrophs, or r to K-strategists, has also been proposed as an interesting indicator of potential disease suppression (van Bruggen and Semenov, 1999; Kotsou et al., 2004). Borrero et al. (2004) used these ratios to predict the suppressiveness of plant growth media towards Fusarium wilt of tomato.

Soil microbial activities might also be more specific, with only a part of the microbial community able to perform specific functions. For example, concerning the N cycle, nitrification and denitrification (potential) activities might be measured (Kandeler et al., 1999; Staley et al., 1990). Another specific activity is the production of antibiotics or other toxic compounds. In this case, this specific activity might be related to the phenomenon of specific disease suppressiveness, due to antagonistic microorganisms (Fravel, 1988). These specific activities can be quantified by classical methods, but as more and more "responsible" genes are being identified and sequenced, they can also now be detected by molecular DNA-based methods. In this last case, we think it is better to talk about function than activity, because only a potential ability is measured, not a real activity. An example of this type of measurement is the detection by PCR of the 2,4-diacetylphloroglucinol (2,4-DAPG) and phenazine-1-carboxilic acid (PCA) biosynthesis genes (phlD and phz) in pseudomonads in soils (Raaijmakers et al., 1997).

Nitrogen mineralization or nitrification, assessed by different methods is associated with a reduction in disease severity of *R. solani* on apple trees in soils amended with rapeseed meal (Cohen et al., 2005). Workneh et al. (1993) also found that the N mineralization potential of soil was positively correlated with disease suppressiveness to *P. lycopersici* in organic farms, but it had no association with the recovery of *P. parasitica* in soil.

Production of hydrogen cyanide could be an interesting parameter to measure for predicting the status of soils concerning the replant problem of peaches, since it is thought to be, at least partially, responsible for this problem. In the sick soils, 61.1% of the rhizospheric bacteria isolated produced cyanide, whereas this proportion was only of 16.4% in the healthy soil (Benizri et al., 2005). However, in the rhizosphere and roots of tobacco growing in soils naturally suppressive or conducive to tobacco black root rot (*T. basicola*), no relationship was found between the number of HCN or 2,4-DAPG-producing fluorescent pseudomonads and the disease-suppressive status of the soil (Ramette et al., 2003). Nevertheless, expressed as a percentage of the total fluorescent pseudomonads population, the proportion of 2,4 DAPG producing pseudomonads was higher in the rhizosphere and roots of tobacco grown in the suppressive soil. A deeper study, looking at the phlD gene polymorphism, also found no clear relationship between phlD alleles and disease suppressiveness. From the fluorescent pseudomonads isolated from non-cultivated (suppressive to *R. solani*) and 3rd-year (conducive) orchard soils, 35% and 6.7%, respectively, possessed the Phl biosynthetic loci (Mazzola, 1999). The role of 2,4-DAPG produced by pseudomonads in take-all decline was also demonstrated

several times (Weller et al., 2002), but it is not the only mechanism, as demonstrated in organic soils by Hiddink et al. (2005).

Authors studying soil disease suppressiveness have also assessed other soil characteristics. However, emerging from all these studies is that no consistent and validated association between disease suppression and one or several soil parameters have been evidenced.

4. Strategy for identification of soil health indicators

Healthy soils are suppressive soils, thus disease suppressiveness can be considered as an indicator of soil health. However suppressiveness is a complex process, depending on several factors. And its measure, through pathogen-specific bioassays, if possible, is time and labour intensive. That is why it would be very interesting, and useful, to find other soil characteristics highly related to soil suppressiveness, but easier to measure.

This need for indicators of soil health is an actual concern, from the field scale to the global level. Therefore, it is necessary to define an accurate strategy, from sampling to validation, which would permit to propose indicators.

4.1. Data analyses

Only a few authors have studied the relationships between disease incidence or soil suppressiveness and others soil parameters. Even though, it is commonly accepted that all the soil characteristics interact. More precisely, the biological components and functions of soils depend on, and emerge from, the physicochemical component (Girvan et al., 2003). Among the articles reviewed here, several have analysed and discussed the results obtained for each variable separately. Generally, several treatments were compared, and the results were analysed with analysis of variance (ANOVA). Conclusions have been presented on the eventual relationship between disease incidence and the other measured variables, but merely through comparisons with existing literature and without any statistical confirmation. This is in part due to the fact that the authors are often interested in finding a mechanistic explanation of the relation between these parameters and soil suppressiveness. However, that is not of primary importance when searching for indicators. Oyarzun et al. (1998) used single correlations, which enable them to attribute a statistical significance to the relation found between disease severity and each soil parameter. That is interesting, but given that interactions between biological, physical and chemical characteristics are of primary importance, it has to be considered as insufficient.

Multiple regression and discriminant analyses have been used to establish relationships between disease and the other variables. Multiple regression analysis was applied when disease incidence or severity was considered as a variable which value would be a combination of the values of other variables (Oyarzun et al., 1998; Lacey and Wilson, 2001; Rotenberg et al., 2005). Discriminant analysis was used to determine which variables discriminated best between two or more naturally occurring groups, e.g. classes of disease severity or incidence (Workneh et al., 1993; Grünwald et al., 2000a, b). This approach enables one to choose which variables, among all the variables measured, are the best predictors of disease incidence. This statistical approach, taking into account all the parameters, is appropriate for the search of indicators.

Community structure analyses, and for example molecular DNA fingerprints, generate large datasets. These data need multivariate analysis methods to be fully exploited. PCA and correspondence analysis are among the techniques used. They enable the reduction of the number of explanatory variables, and the detection of an eventual structure among the samples, given the variables measured, or a structure in the relationships between variables. Using these methods, rhizosphere bacterial communities from healthy/sick or conducive/suppressive soils were separated (Yang et al., 2001; Rimé et al., 2003; Benizri et al., 2005; Pérez-Piqueres et al., 2006). However multivariate analysis alone does not give a statistical measure of the differences between samples. Monte-Carlo permutation tests or analysis of variance (or other statistical analysis) with the factor loadings of samples (values of the projection of the sample on the principal components) can give a statistical meaning to the findings. Multivariate analysis is interesting in that it also provides the ordination of the variables. In this way, correlation between variables and the importance of each individual variable in the discrimination between samples were highlighted (van Os and van Ginkel, 2001; Rimé et al., 2003; Hamel et al., 2005a, b; Rotenberg et al., 2005). This is an important feature, when trying to identify potential indicators or markers. On the contrary, when data are simply analysed by tree and cluster analysis, it is much more difficult to attribute the differences between samples to identifiable variables.

The analytical tool to be used in an experiment should be defined before the experiment is conducted. Otherwise, the results will probably be spurious and/or misleading.

4.2. Strategy for identification of indicators

According to Gras et al. (1989), "an indicator is a variable which supplies information on other variables which are difficult to access … and can be used as benchmark to take a decision." Mitchell et al. (1995) stated that "alternative measures … enable us to gain an understanding of a complex system … so that effective management decisions can be taken that lead towards initial objectives."

Thus, an indicator has both an informative function (about the system) and a decision-making function (to achieve the initial objectives). Indicators may results from a set of measurements, from calculated indices, or they may be based on expert systems (Girardin et al., 1999). In our case, for soil health indicators from the plant disease point

of view, authors have only worked with sets of measurements.

Given the complexity of soil function, it is improbable, and even impossible, that one unique indicator can assess for soil health. Larson and Pierce (1991) proposed the idea of a minimum dataset (MDS), that is a limited number of indicators, required to describe the soil quality, and which could be common to all soil quality assessments. Doran et al. (1996) proposed such a MDS. According to the same authors, indicators should:

- encompass ecosystem processes and relate to process-oriented modelling,
- integrate soil physical, chemical, and biological properties and processes,
- be accessible to many users and applicable to field conditions,
- be sensitive to variations in management and climate at an appropriate time-scale,
- when possible, be components of existing soil databases.

Andrews and Carroll (2001) present in their paper the "guideline" they used to obtain such a MDS. First of all, one has to decide which goals are of primary interest in the studied ecosystem. It could be, for example, to maximize the crop yield and to minimize pest problems. End-point measures representative of these goals are identified (e.g. crop yield in t/ha, disease incidence of a fungal pathogen, number of insect pests, etc.) and serve as dependant variables to validate the MDS. The study should be conducted in different sites, to compare the results and assess if generalization is possible. The contrasting situations (e.g. different amendments, different cultural practices) which are to be evaluated by the quality indicators have to be tested on the same site. The analysis should be done for each site separately. In order to select the most pertinent variables, as many variables as possible are measured at first. These numerous data are then reduced to a MDS through a series of uni- and multivariate analyses.

A possible procedure is as follows. Univariate statistics allow the determination of parameters with significant treatment differences. These parameters are chosen for the next step. A PCA is performed on the significant variables. The parameters retained at this step are the ones which are highly weighted on the principal components chosen (e.g. only the ones explaining at least 5% of the variation in the data). The set of variables is indeed reduced. Then, multivariate correlation coefficients should be calculated to determine the strength of the relationships among variables. Well-correlated variables are considered redundant, and should be eliminated. Only one variable is kept from groups of highly correlated variables. The final step, to check whether it is still possible to further reduce the number of variables in the MDS, is to perform a forward stepwise regression of the chosen variables against the goal variable. If any of these variables remained non-selective after stepwise regression, it is eliminated from the MDS. The obtained MDS is validated by running multiple regressions using the MDS components as the independent variables and each goal attribute as a dependant variable. The MDS indicators could then be combined in a soil quality index, to be used by practitioners.

This strategy, more or less finalised, has been successfully used by several authors working on soil quality and even farm sustainability (Bockstaller et al., 1997; Hussain et al., 1999; Rigby et al., 2001; Andrews et al., 2002; Suzuki et al., 2005; Yemefack et al., 2006). However, the goals were yield, water or nutrient availability, erosion resistance, but not plant health. To our knowledge, such a comprehensive proposition of testing and validating a minimum dataset, and even more a soil health index, directed towards the crop health end-point has never been achieved.

Kang et al. (2005) used 18 parameters, mostly from the MDS proposed by Larson and Pierce (1991). These 18 parameters were allocated between three indexes representing the nutrient status, the microbial activity and the productivity of soil. A sustainability index was measured from these three values, through a "geometrical" approach. The calculation of the value of this index in different treatments allows a comparison between them. This approach is interesting, but the choice of the variables was not statistically based, and the diseases were not taken into account, unless indirectly through the crop yield measurement.

Apart from the measurement of a set of indicators compiled in an integrative index, another possible approach is the use of models. Epidemiological models of several diseases have been proposed, using the disease progress curves as the response variable (Gilligan, 1990; Jeger, 2004). The effect of many parameters has been studied: source and density of inoculum, climatic factors, crop characteristics, eventual chemical control, etc. Examples of models are available, but they are restricted to foliar diseases and they only take into account as predictive variables weather- or plant-related variables (Madden et al., 2000; Schoeny et al., 2001). When soil-borne diseases are concerned, soil parameters are not taken into account (Bailey and Gilligan, 1999).

Artificial neural networks are another tool to develop models (Paul and Munkvold, 2005). Their advantage is that even if the system being modelled is poorly understood, they are capable of extracting subtle patterns and depicting complex relationships among variables, due to a "learning" process. In plant pathology, artificial neural networks have been shown to perform at least as well as the traditional approaches at classifying incidence and detecting infection periods of tan spot on wheat (de Wolf and Francl, 1997, 2000).

The development of an epidemiological model for soil-borne diseases requires taking into account a large range of variables. The dispersion and extension of the disease is often reduced to the field scale. Besides environmental and plant parameters, soil characteristics must be considered,

which represent a great amount of potential explanatory factors. This work has been done (Otten et al., 2001), but rarely with the aim of studying the impact of soil management on soil quality (Otten et al., 2004; Stacey et al., 2004). Indeed, little work has been done concerning the incorporation of soil parameters in a predictive model for soil-borne diseases.

4.3. Sampling strategy

Of major importance in proposing soil health indicators is the validation of the relevance of the chosen descriptors in several agronomic situations. Given the complexity of the interactions between environmental, abiotic and biotic factors, it is not evident that one set of parameters used in a given situation would still be explicative in another context. For one to be allowed to generalise the use of certain descriptors, it is of primary importance to take into account different environmental contexts. However, even at the field scale, caution must be applied to the sampling strategy; because, first of all, of spatial variability. It is well known that microbial parameters can vary at a very fine scale (Nunan et al., 2002). That is why it might be important to pool different samples from the same treatment to minimize this heterogeneity, even in mesocosmes. Another approach is to keep each sample separate, and to integrate the spatial variability in the data analysis. Besides spatial variability, microbial characteristics are also very sensitive to climatic conditions, and exhibit temporal/seasonal variability (Schutter et al., 2001), that may be several-fold higher than spatial variability (Parkin, 1993). This temporal variability can confound comparisons among treatments, thus it is interesting, if possible, to sample soils at several dates and assess the consistency of the descriptors chosen.

As already mentioned, the studies on soil suppressiveness and its relation with other soil characteristics can be conducted with two distinct approaches. One can work with artificially created contrasting situations, most often in experimental microplots or in micro/mesocosmes (Table 2). In this first case, it is difficult to form conclusions of a general nature. Another approach is to assess the relationships between disease suppressiveness and soil characteristics in natural situations. The soils of these fields have different levels of disease receptivity, either because of intrinsic disease suppression, or because of cultural practices in place (Table 2). This second approach seems more appropriate to the search of reliable indicators, as long as a sufficient number of situations are taken into account.

Concerning surveys in natural soils, (i) Dominguez et al. (2001) compared conducive and suppressive areas in seven banana plots in two islands from the Canary Islands, (ii) Martinez et al. (2002) sampled 45 soils throughout the entire province of Quebec, (iii) Lacey and Wilson (2001) analysed 35 potato fields across the Tasmanian potato-cropping region, (iv) Oyarzun et al. (1998) surveyed a total of 51 soils from commercial fields and six experimental plots, (v) Hamel et al. (2005a, b) sampled 50 commercial asparagus fields in four regions of southern Quebec and (vi) Mallett and Maynard (1998) measured the incidence of Armillaria root disease in 36 stands of young lodgepole pine. The most extensive survey has been done with 1462 fields assessed for the relations between soybean diseases, soil texture and tillage (Workneh et al., 1999). In all these cases, the soils were not placed under specific cultural practices. It is noteworthy that, except for Martinez et al. (2002), who evaluated microbial populations by plate counts, these large studies only characterized the pedological and physicochemical statuses of soils. This is certainly insufficient of the search of integrative indicators. The other field surveys often dealt with comparison of organic and conventional farming systems or comparison of different amendments and tillage practices (Table 2).

4.4. Validation of indicators

These searches of MDS indicators would normally result in the proposal of soil health indexes, generally valid for one disease or one type of disease/crop association. However, what is theoretically sought-after is a global index, valid for as many situations as possible. The risk, if one absolutely wants to generalize, is to come back to "ancient" notions that are that a soil is healthy when microbial community is diverse and active. In our opinion, soil health, contrary to more "neutral" notions such as soil physical quality, should be studied at the regional level, in close association with local agricultural extension personnel. Indeed, the validation of the proposed indicators and indexes is a key-point of major importance, which should not be omitted. The "output validation" (Bockstaller and Girardin, 2003) focuses on the informative function of indicators: does this indicator give reliable, realistic information?

Concerning indicators as decision-making tools for soil management, Bockstaller and Girardin (2003) recommend an "end-use" validation. This has been done by Andrews et al. (2003), who constructed soil quality indices and examined farmers' reactions to, and uses of, these indices. They also compared on-farm indices outcomes with the farmers own perceptions. In our opinion, this might be the only way to propose sound indicators, useful for both risk prediction and technical advice. First, these indicators would be measured before any planting of crops. Then, according to the results, one would decide which kind of crop could be grown. The understanding of the mechanisms behind cultural practices, and their relation with the indicators, would allow the proposal of practices useful to maintain the soil health.

5. Conclusion

Plant diseases caused by soil-borne pathogens result from multiple and complex interactions they have with

plants and both biotic and abiotic soil compartments. The determining functions leading to disease are not yet fully understood, neither are all the mechanisms involved in soil suppressiveness. In the actual concern for sustainable environmental protection, the possibility of controlling soil-borne diseases by adapting agricultural practices is assessed. Such practices are likely to modify a wide range of soil characteristics. In fact, researchers are more interested in investigating the effect of such practices on microbial communities, or in assessing their potential to control soil-borne pathogens than in finding soil health indicators. However, a combined approached is needed. Many results have been published, but integrated analysis and modelling are lacking. Nevertheless, soil health indicators would be very useful for risk prevision and technical advice. Given the number of biotic and abiotic parameters potentially related to soil suppressiveness, and thus potential indicators, it seems obvious that a holistic approach, involving several areas of soil science (physics, chemistry, microbiology, pathology, parasitology, etc.) has to be followed. This approach should first be limited to the local scale. This work needs a rigorous experimental approach supported by numerous field trials and taking into account many different soil types and crop systems. The analysis of such a huge mass of data should not be neglected to lead to indicator proposal. A key-point is also the perception and the use of such indicators by growers. General guidelines for obtaining indicators and for their use to monitor the improvement of soil health should arise from the application of this approach in many places. This ambitious task is not unrealistic if we consider indicators and decision-making tools that have already been developed in related fields such as assessment of farm sustainability or soil conservation.

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