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Biological indicators of soil quality in organic farming systems

E.A. Stockdale[1,*] and C.A. Watson[2]

[1]School of Agriculture, Food and Rural Development, Agriculture Building, Newcastle University, Newcastle-upon-Tyne NE1 7RU, UK.
[2]SAC, Craibstone Estate, Aberdeen AB21 9YA, UK.
*Corresponding author: e.a.stockdale@newcastle.ac.uk

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Abstract

The health of the soil, recognized by its active role in the linked processes of decomposition and nutrient supply, is considered as the foundation of agriculture by the organic farming movement. Nutrient management in organically managed soils is fundamentally different from that of conventional agricultural systems. Crop rotations are designed with regard to maintenance of fertility with a focus on nutrient recycling. Where nutrients are added to the system, inputs are in organic and/or non-synthetic fertilizer sources that are mostly slow release in nature. Hence a greater reliance is placed on soil chemical and biological processes to release nutrients in plant-available forms. In this respect, nutrient availability in organically farmed soils is more dependent upon soil processes than is the case in conventional agriculture. The development and use of biological indicators of soil quality may therefore be more important in organic (and other low input) farming systems. The aim of this paper is to evaluate current evidence for the impact of organic farming systems on soil biological quality and consider the identification of appropriate biological indicators for use by organic farmers and their advisors. Organic farming systems are generally associated with increased biological activity and increased below-ground biodiversity. The main impacts on biological fertility do not result from the systems *per se* but are related to the amount and quality of the soil organic matter pool and disruptions of soil habitat via tillage. Even within the constraints of organic farming practices it is possible for farmers to make changes to management practices which will tend to improve soil biological quality. It is, however, by no means clear that distinct indicators of soil biological quality are needed for organic farming systems. It is important not only to identify the most appropriate indicators but also to ensure that farmers and land managers can understand and relate to them to support on-farm management decisions.

Key words: microbial biomass, organic matter inputs, soil ecosystem, tillage

Introduction

Concerns about environmental degradation and protection, together with increasing consumer awareness of food safety issues, have contributed to the development of a number of 'sustainable' or 'eco' farming approaches in recent decades. Organic farming, first developed in the 1940s, has found a booming market for its products and it is now considered to provide viable livelihoods in many circumstances and a realistic alternative to other more high input–high output approaches to agriculture[1]. Across the world organic farming and processing has well-developed certification systems and, in many countries, the definition and practices of organic agriculture are defined in law (e.g. Regulation 834/2007 of the European Union). There is no single homogeneous and easily recognizable organic farming system. Organic farming systems are underpinned by a set of agreed global principles (Table 1), thereafter crops, livestock and their management on organic farms are regionally diverse and locally adapted.

The health of the soil, recognized by its active role in the linked processes of decomposition and nutrient supply, was proposed as the foundation of agriculture by the pioneers of the organic movement[2,3]. The organic farming movement has developed its principles and recommendations for farm management from an underpinning recognition of the biological, ecological conception of nature and the importance of the relationships and interactions between organisms—plant, animals and within the soil. In contrast, intensification of agricultural production is often marked by increased use of mechanical and manufactured inputs and increased specialization of production; these changes mean

Table 1. Principles of Organic Agriculture—International Federation of Organic Agriculture Movements, 2005 (http://www.ifoam.org/about_ifoam/principles/index.html).[1]

Principle of health
Organic agriculture should sustain and enhance the health of soil, plant, animal, human and planet as one and indivisible.
Principle of ecology
Organic agriculture should be based on living ecological systems and cycles, work with them, emulate them and help sustain them.
Principle of fairness
Organic agriculture should build on relationships that ensure fairness with regard to the common environment and life opportunities.
Principle of care
Organic agriculture should be managed in a precautionary and responsible manner to protect the health and well-being of current and future generations and the environment.

[1] In the full text, each principle is articulated through a statement followed by an explanation, which is not given here. They are given as ethical principles to inspire action and consequently should be taken as a whole. The principles of organic agriculture serve to inspire the organic movement in its full diversity and guide IFOAM's development of positions, programmes and standards.

that regulation of the agro-ecosystem through biological processes is displaced[4]. Hence in organic farming systems, use of manufactured fertilizers is prohibited (or at least significantly restricted), crops must be grown in rotation or as mixtures. Rotations/mixtures are designed with a strong awareness of their impact on soil structure. The cropping plan is also designed with regard to the fertility building and depleting role of the crops, with a focus on nutrient recycling to reduce the need for external input[5]. Nutrients are dominantly added to the soil as organic (e.g. manures, compost, crop residues and legumes) or slow-release sources (e.g. rock phosphate). Consequently in organic farming systems a greater reliance is placed on chemical and biological processes within the soil to release nutrients in forms available for plant uptake. In this respect, while the processes controlling nutrient availability are the same in soils whether under organic or conventional management, nutrient availability in organically farmed soils is more dependent on soil processes than is the case in conventional agriculture[6]. It is also clear that the role of the soil in weed, disease and pest management may be significant for organic farming systems[7,8]. Soils also play an important role in the regulation of broader environmental quality; for example, taking key roles in the regulation of water flow in watersheds, global emissions of greenhouse gases and degradation of wastes.

There is strong evidence that organic agriculture, particularly in temperate arable systems, is able to deliver positive impacts on biodiversity[9–11], which offset the declines in farmland biodiversity that have been seen in these regions as a result of the intensification of farming systems and consequent homogenization of the landscape[12,13]. A full range of evidence in all climates and farming systems has yet to be collected. The absence of synthetic fertilizers and pesticides, increased diversity of crop types in space and time, together with requirements in organic certification schemes for beneficial management for wildlife in non-cropped areas, are likely to contribute to the increases in biodiversity seen in organic systems[11].

In considering soil biological quality, it is important to take a broad view of 'which organisms count?' and in the first instance consider the whole food web and its interactions. For example it has been shown that the activity of soil fauna is responsible for 30–40% of the N released into plant-available forms in the soil[14]; mineralization is not purely a microbially driven process. Often agricultural systems are associated with simplified soil food webs compared to semi-natural systems; dominantly pastoral systems also have been shown to have qualitatively different ecological interactions below ground than dominantly arable systems[15]. However, agricultural intensification need not necessarily have adverse consequences on below-ground biodiversity[4,16]. In contrast, in a range of grassland systems, it has been shown that increased intensity of management tended to reduce the diversity of soil organisms within most functional groups[17]. This paper will therefore further investigate the evidence for the impact of organic farming systems on soil biological quality and consider the identification of appropriate biological indicators for use by organic farmers and their advisors.

In the following review, where differences between treatments are cited from previously published work, these refer only to significant differences reported in the original work. However, in many cases the published studies reviewed contain evidence of significant increases, significant decreases and no significant differences as a result of farming systems or treatments; the authors of this review have therefore, on many occasions, applied their expert judgment to assess the overall implications of a number of contrasting studies. In these cases, no formal meta-analysis has been carried out and hence no statistical significance is discussed.

Impact of Organic Farming on Soil Biological Quality

Pastoral systems

A large body of work carried out on soil biodiversity at an unimproved grassland site in the uplands of southern Scotland (320 m above sea level) showed that even soils with relatively low above-ground vegetation diversity had

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extremely high below-ground biodiversity and were able to process carbon inputs rapidly[18], this resulted in a soil ecosystem that was highly resistant to perturbations, including the application of lime, nitrogen fertilizer and biocides. Almost no work has been done to study the impact of differences between farming systems on soil biological quality in hill pastures. Given that differences between organic and conventional management in hill pasture systems are relatively small, large differences in soil biological quality are not expected. No significant differences were seen in bacterial diversity between improved and unimproved grassland despite differences in grazing intensity, fertilizer use and plant species[19]; there was, however, some indication of an underlying difference in specific population components. Organic management, which is likely to reduce stocking density on unimproved grazing land, may have a negative impact on below-ground ecology in these areas due to reduced nutrient inputs[20,21]. Soil biota was studied along a fertility gradient in permanent pastures in the hills of New Zealand[22] with a range of plant species, stocking rates (6–16 ewe equivalents) and fertilizer applications (to a maximum of 90 kg N and 33 kg P ha^{-1}). Bacteria and nematode populations showed an increase with increasing fertility; the same trends were found in both organic and conventional pastures and the farming systems were not distinguishable[22].

In lowland dairy systems, there are much larger differences between organic and conventional practices. Stocking density is often lower in organic systems. Conventional systems are generally associated with more intensive grassland management. Temperate organic dairy systems are dependent on grass–legume leys, rather than intensively fertilized predominantly rye-grass swards. There is some evidence of reduced numbers and activity of dung beetles where veterinary drugs are used regularly in lowland grassland systems[23]; anecdotal evidence suggests that dung decomposes more slowly where wormers have been used. Impacts on earthworms are less clear; studies have shown both no significant differences in earthworm numbers and species diversity[24,25] and also reduced earthworm numbers[26] when comparing grassland management systems. In a comparison of grassland under conventional (*c*. 5-year grass–clover swards receiving NPK fertilizers) and organic management (>10-year grass–clover swards with a significant proportion of other grass species, slurry applied at one site) on three contrasting soil types (silt, loam and sand), strong interactions were shown between soil and farming system on soil biological quality. Bacterial and mite populations tended to increase under organic management, while fungal and total nematode populations were significantly increased under organic management at all sites[26]. Detailed analysis of nematode populations under conventional and organic management showed that fungal feeders were increased at all sites under organic management, whereas bacterial feeders, predatory and plant feeding species showed strong interactions with site and no clear effect of management[26]. Results from a gradient of grassland sites in The Netherlands[17] showed higher diversity of bacterial and fungal feeding nematodes under organic than intensive grassland management systems—a gradient of practice related to management intensity including increasing livestock density, increasing use of mineral fertilizers and biocides and reducing use of farmyard manure was studied. A study of nematodes across a management intensity gradient in Germany and Switzerland also showed similar trends[27]. The highest nematode diversity was recorded on an organic farm[17]. There was a strong relationship between higher bacterial populations and bacterial feeding nematodes, both increasing with intensity of management. Hyphal feeding nematodes show much lower resilience than bacterial feeders to increasing intensity of farming practices in all grassland systems with lower number of taxa and fewer individuals in general[17]. Arbuscular mycorrhizal fungi have shown greater spore density and infectivity under organic management (grass-clover swards) than at paired conventional sites (with higher rates of fertilizer use and lower proportions of clover[28]). Arbuscular mycorrhizal fungi are likely to be increased as a result of increased plant diversity and decreasing P availability in organic systems[29]; conventional dairy pastures often have very high P availability[30]. Taken together the data collected in grassland systems suggest that decomposition pathways in low-intensity and/or organically managed grassland are likely to be more complex/diverse than under high-intensity conventional grassland, with consequent impacts on the higher trophic levels of the food web. However, there are few studies of the impact of organic management on predatory meso- and macrofauna in lowland grassland systems.

Rainfed arable cropping systems

Most studies comparing the effects of organic, integrated and conventional systems have been carried out in temperate rainfed arable systems. In these systems, there are large differences between organic and conventional management. All systems are permitted to use lime to maintain an optimum pH. However, there are marked differences in the use of mineral fertilizer, herbicides and pesticides. Organic livestock-based ley–arable systems use grass-clover leys and manures to maintain soil fertility; stockless organic farms use N fixing green manure crops at the heart of their rotations[5]. Tillage intensity varies in both conventional and organic systems, though due to the prohibition of herbicides, zero-till systems are less common in organic systems.

Paired farm studies in New Zealand have shown greater microbial biomass in organic than conventional systems[31,32]. However, where organic management was compared with conventional systems using reduced tillage, no differences were found in the size of the microbial biomass[33]. Soil type (sand compared with clay) was shown to have a larger effect on the size of the microbial biomass than farming system in a comparison of 13 paired sites[34].

Under field conditions in a long-term trial comparing a conventional system, an organic system based around animal production using manures, and a stockless organic system using N fixing cover crops[35], there were only very small differences between the size of the microbial biomass but significant differences between activity of the populations[36]. Larger microbial biomass populations and higher respiration rates have been measured in the grass–clover ley phase of organic rotations[37]. Increased microbial biomass in forage compared with arable rotations has also been found in conventional and integrated systems[38]. There was no equivalent distinction between organic arable and forage rotation in the same trial; it was proposed that the higher returns of organic matter, as a result of the inclusion of ley and green manure crops in the organic arable rotation, offset the impact of increased tillage[38]. In a long-term comparison of farming systems under the same crop rotation in Switzerland, soil microbial biomass size and activity were shown to be more sensitive than the total soil organic carbon pool to differences in the quantity and quality of applied animal manure[39]. Detailed observations of microbial population size, composition and dynamics and populations of other below-ground fauna made in a long-term multidisciplinary study under irrigation in a Mediterranean climate[40–42] confirm the findings from temperate climates that the main factors leading to the increase in microbial populations and activity that are observed under organic management are the quantity and quality of the carbon inputs.

There is some indication that organically managed soils have a larger population of viable but non-culturable microorganisms[43]. There is also some indication of increased diversity of bacterial populations under organic management[44]; however, a large number of factors varied between the sites studied. Soil properties that regulate microbial activity may also regulate microbial community composition[45]; management practices that modify soil pH and cycling of dissolved organic matter are most important in modifying microbial community structure and activity. Higher functional diversity coupled with higher microbial carbon efficiency have been measured under organic management[46]. At the same site genotyping approaches have been used to show that the structural diversity of bacterial communities was influenced more by the application of animal manures than by conventional or organic management *per se*[47]. This work was extended using lipid profiling to study microbial phenotypes to confirm that application of farmyard manure had the strongest influence on microbial community structure[48]; in addition an influence of conventional versus organic management could be distinguished, whereas no direct impact of the immediately previous crop could be identified. Interaction between tillage and organic matter inputs within the constraints set by climate and soil texture rather than management system *per se* dominantly control the size and activity of the soil microbial biomass in arable systems.

Ergosterol (as an indicator of fungal biomass) was compared in soils from an organic, a conventional arable and conventional livestock farm[49]. The conventional livestock farm had greater ergosterol contents than the conventional arable farm. The biodynamic system that had a mixed cropping rotation, and intermediate inputs of organic matter had intermediate ergosterol contents. Spatial heterogeneity in ergosterol also increased with increasing pool size. However, in other cases few (and no consistent) differences in fungal biomass appear between organic and conventional systems[43]; indeed, the variation in fungal abundance within farming systems has been shown to be as great (and often greater) than differences between farming systems[50]. Higher arbuscular mycorrhizal colonization has been shown in organic than conventional paired cropping systems[51–53]. Using a paired farm approach it was shown that arbuscular mycorrhizal fungi in organic farms had a higher infectivity to roots than conventional systems (compared at the same inoculum levels)[54], infectivity also increased with time since conversion to organic management; the largest difference was seen on an inherently low P status soil. At the Rodale Research Institute in Pennsylvania, three farming systems (conventional, organic based around animal production using manures and stockless organic system using N fixing cover crops) showed similar levels of arbuscular mycorrhizal fungi[55]; all plots also had very high levels of available P. A higher diversity of arbuscular mycorrhizal fungal spores under organic management regimes has also been shown[51,56]. Summarized evidence from 13 available studies showed greater root colonization, larger numbers of spores and greater diversity of arbuscular mycorrhizal fungi in organically managed soils[28]. However, poor performance of arbuscular mycorrhizal fungi was also identified in some organic systems[28]; the causes could not be identified because of differences in the details of management practices used in organic systems and contrasting land management at the sites before conversion.

Protozoans and nematodes are primary consumers of the soil microbial biomass and may be more sensitive indicators of the microbial dynamics than the measurements of the microbial biomass itself[57,58]. No differences were shown in protozoan populations between organic and conventional farming systems in Austria[23]. The nematode community structure has been shown to vary with fertilizer and crop protection systems[59]; different components of nematode biomass responded differently to different management practices. Overall nematode abundance has been shown to be higher under organic management than in comparable conventional systems[23,60]. However, a larger effect of soil type (sand compared with clay) compared to farming system was found in The Netherlands on the size of the total nematode population in a comparison of 13 paired sites[34]. It has been observed that organically managed arable land in a crop rotation maintained nematode species diversity and species type at a level more similar to low intensity grass than comparable conventional arable systems[26].

Long-term system studies have found fundamental differences in soil food web structure between conventional and less intensive farming systems (The Netherlands[61], USA[62] and Sweden[63]). Microbes, protozoa and nematodes have been shown to contribute more to the total amount of N mineralized in a lower-input system, while in the conventional system mites and enchytraeids made a larger contribution to mineralization[64]. Contribution to mineralization is a function of both species abundance and turnover[64]. It has been suggested that, as for grassland systems discussed above, under conventional arable cultivation, the bacterial community dominates the microbial component while, in less intensive systems, the fungal community is the dominant microbial component. Such differences influence nutrient cycling and have implications for the efficient use of nutrient inputs and leaching potential[65,66]. Long-term system studies in The Netherlands, USA and Sweden[61–63] have also found that most soil faunal groups were more diverse or unchanged in less intensive farming systems (organic and integrated) than in conventional systems. In addition, no difference in collembolan population size or species abundance was evident between conventional systems using reduced tillage and organic farming systems[33]. Many collembolan taxa have been shown to be ubiquitous in arable farming systems[67], where the most important source of variation was local differences between management practices. However, in general, taxa responded differently to farming systems; it has been suggested that collembolan species showing an increase in organic farming systems are those that prefer increased humidity and hence higher weed populations[67]. Significantly higher carabid populations have also been reported in organic management regimes[68]. A meta-analysis of all the data collected on comparisons of carabids in organic and conventional systems in southern Germany and Switzerland showed that on average there were 34% more species found in organically managed winter wheat[69]; carabid species also responded to management systems differently, with some species showing increases and some decreases in organic systems. Identification of key species traits and requirements is needed if optimum management practices for any particular species are to be developed, e.g., *Carabus auratus* often shows increased populations in organic farming systems. However, this effect is not found on very sandy soils, and shows a strongly negative response to mechanical weeding in spring due to its long larval stage[69]. Earthworms are generally higher in organic than conventional systems[31,68]. Within organic rotations earthworm numbers were found to be highest in the second year of grass–clover ley, the population declined through the tillage phase of the rotation with increased time after the ley phase[70]. Increases in earthworm population have been strongly linked to farming systems with reduced cultivation[71].

Beneficial effects of organic farming on the abundance and species richness of arable weeds are often reported, e.g., Roschewitz et al.[72]. This clearly has benefits for plant species diversity and can therefore impact on above ground insect diversity[73]. The presence of weeds can act as an important bridge for arbuscular mycorrhizal fungi in non-mycorrhizal crops[74]. It is likely that the presence of increased weed populations may have broader impacts on the soil ecosystems. Selected biological indicators of soil quality have also been associated with potential weed-suppressive activity in soil. In reduced tillage systems, the proportion of water-stable soil aggregates was the greatest in soils with the highest organic matter and was found to be related to higher enzyme and weed-suppressive activity[75]. Interactions between crops, weed and soil biological quality are complex and not much studied.

Lowland rice (paddy) systems

Little work has been carried out in paddy systems to compare biological soil quality between organic and conventionally managed systems. However, differences have been found in the ground arthropod community structure and insect pest regulatory mechanisms[76]. No consistent structural differences were found in the abundance of plant eating and predatory arthropods in comparisons of organic and conventional rice paddies[77]. The same study also demonstrated that soils under organic management had lower bulk densities. Improved soil physical quality (including ease of cultivation) has been shown in organic rice systems and this has been linked to the larger returns of organic matter through rice straw and animal manure typically associated with organic management practices[78]. Given the very different soil processes operating under the reducing environment in rice paddies, more work is needed to establish whether these changes in soil physical quality and organic matter management have any measurable impact on soil biological quality.

Overall impacts on soil biological quality

Given our limited ability to apply robust taxonomic classification systems to below-ground groups, it is probably not surprising that a range of positive and negative effects on below-ground ecology are observed as a result of the application of contrasting management systems. The evidence collected until 1992 on the impacts of organic management on soil biodiversity showed uncertain results: ‘It is increasingly evident that generalisations like—conventional farming destroys life in the soil or Eco-farming stimulates soil life—are only partially supported by the data’[23]. More recent reviews have largely shown positive impacts of organic farming systems on soil biological quality. A larger number of studies showing positive impacts of organic farming systems on below-ground species than studies showing no difference or negative impacts were reported in a 2005 review[10]. As part of a meta-analysis considering all aspects of biodiversity in organic farming systems in 2005, it was shown that despite the considerable heterogeneity amongst studies, soil organisms were generally more abundant in organic farming systems[8]. Effects on bacterial biomass and activity were unclear, whereas positive impacts on earthworms, collembolan, mites and fungal populations were confirmed. For groups that can be resolved to the species level, e.g., collembola and carabids, differential effects of systems are found for different species.

Interactions between tillage and management of the carbon cycle (both the amount and quality of inputs) dominantly control soil biological quality within the constraints set by the particular climate/soil conditions at any site. Tillage intensity seems to have the most significant effect in reducing soil biological quality. Impacts of cropping management (particularly the amount and quality of organic matter returned to the soil) can moderate the impact of even quite severe tillage operations and seem to increase the resilience of below-ground ecosystems. Increased use of ley–arable rotations and green manures in organic farming systems tends to increase the amounts and diversity of organic matter inputs compared to conventional arable rotations. Consequently, both organic and reduced tillage systems have positive effects on soil biological quality, though significant variations are found within any defined farm management system. Much smaller differences in soil biological quality are seen in grassland systems, where differences in management between organic and conventional management are also often smaller. For grassland systems, balancing grazing intensity in space and time, together with the considered use of drainage, aeration, fertilizers, lime and organic inputs, all affect the impact of agricultural management on soil biological quality.

Using indicators of soil biological quality in organic farming systems

Consideration of the current evidence on the impact of organic farming systems on soil biological quality indicates that while organic farming practices generally have a positive impact on soil biological quality, differences between practices within farming systems have as great (or often greater) impact on soil biological activity than the farming system *per se*. Consequently, even within the constraints of organic farming practices, it is possible for farmers to make changes that will improve soil biological quality. It is, however, by no means clear that distinct indicators of soil biological quality will be needed for organic farming. Most of the measurements of soil biological quality and soil ecology discussed above have used the same methods for both organic and conventional systems. Although a greater reliance is placed on chemical and biological processes within the soil in organic farming systems to release nutrients in forms available for plant uptake, the processes controlling nutrient availability are the same in soils whether under organic or conventional management[5]. There is much that can and should be learned from the literature on soil quality indicators for conventional farming systems[79,80] in the search for appropriate indicators of biological quality for application within organic farming systems.

There is currently no reliable method to predict the impact of management on the soil microbial biomass and its whole range of activity due to the complex interaction of site and management factors (both directly and indirectly) and the ability of the soil microbial biomass itself to alter the soil habitat in response to management changes[81]. Changes in biological methods, including (but not exclusively) those based on molecular methods, now offer new ways of examining the size, diversity and activities of the groups within the soil population. This is an area of intense research activity and scientific excitement and provides major opportunities for developing new indicators of changes in soil relevant to specific activities and functions. However, in the context of monitoring soils and detecting trends or problems, caution is required in interpreting the large amount of data that can now be collected[82–84]. Factors and management practices that increase resilience are also likely to vary for different below-ground organisms and may include management in both cropped and no-cropped habitats—for insect species the maintenance of a source of organisms able to re-invade may be critical (i.e., size, proximity and connectivity with an unaffected community). In some circumstances, management practices can also provide a reservoir population, e.g., using intercrops or tree saplings inoculated with appropriate mycorrhizal fungi. Where inoculation with mycorrhizal fungi and pseudomonads had been used to improve crop yield under organic management then a modification of the soil microbial structural diversity can be detected using denaturing gradient gel electrophoresis[85]. Such analytical approaches have not yet been developed to allow definition of target states or ideal ranges so that their measurement could guide management, e.g., distinction between sites that would benefit from inoculation from those with appropriate existing microbial diversity. Even where the use of biological inoculation is so far advanced, such as for rhizobia, the understanding of the soil and environmental factors necessary to characterize the specific requirements or limitations in the soil for establishing *Rhizobium* populations to ensure optimal nitrogen fixation following inoculation of legumes remains incomplete[86]. In this case a simple chemical measurement, pH, was found to be the best indicator of an aspect of soil biological quality, i.e., the survival and effectiveness of rhizobial strains[87]. A quest for indicators of soil biological quality should not immediately reject chemical and physical measurements.

In a search for appropriate indicators of soil biological quality it is appropriate to note the cautionary comment made by the late Ted Elliott[88]:

> The ideal bioindicator of soil health would be simply measured, work equally well in all environments and reliably reveal what problems existed where. For the reasons outlined . . ., we are more likely to develop bioindicators for which information is laboriously obtained, that are specific to a given ecosystem or environmental problem and only tell us that there is a problem

and not show us what the problem is. Even with this gloomy forecast, it is unquestionable that we will continue to seek ways by which we can determine the health of ecosystems, or their components, such as soil.

In the literature on soil quality, almost entirely written by soil scientists rather than soil users, there is a strong tendency to develop lists of measurements that can be made on soils and then interpret them as indicators of soil quality, e.g., Karlen et al.[89]. In part, this tendency to make measurements reflects the training and mode of working of reductionist scientists. Consequently, a common approach, contained in much of the literature summarized in the consideration of the impact of organic farming systems on soil quality above, is to measure as many things as possible in contrasting systems and then use statistical approaches to identify those showing significant differences, so that these can be proposed as indicators, e.g., Xua et al.[90] This can lead to the identification of a good set of descriptor measurements which can be used to distinguish between systems and/or high and yield variants in a system[91]. Some groups favor the development of an index that normalizes measured soil quality indicator data and generates a numeric value that can be used to compare various management practices or to assess management-induced changes over time[92]. However, there has been much less work showing the added value of using these approaches predictively and/or to guide management. In practice, these approaches will often lead to a sensible analysis of an issue or problem, given that soil scientists should have a good understanding of the relationships between soil properties and functions. However, we suggest that the stakeholders or land managers most concerned in a given situation should be engaged at an early stage of the process to define the outcomes or functions they require. The soil scientists should then, and only then, work alongside them to develop a set of measurements or observations that will provide information on these functions. In practice, the two approaches may often lead to the same set of measurements—but not always.

Where we are seeking to develop indicators that will guide changes in farming practice, then farmers must also be able to manipulate the indicator beneficially and such manipulation must be cost effective. Consequently, it is important not just to identify the most appropriate indices but also to ensure that these can be quantified with the necessary precision and that farmers and land managers can understand and relate to them[93]. This requires an awareness of the constraints of a farming system, whether legislative, as for many organic farming systems, or physical, economic, etc. For example, the constraints of the organic principles to on-farm practice may mean that some indicators developed for conventional farming systems therefore have little/limited use in organic farming system since the actions which they are designed to trigger are not permitted in organic farming management. For example, while development of a rapid and reliable detection method for evaluating soil inoculum levels in naturally infested soils might trigger the selection of resistant or partly resistant cultivars (e.g., for *Plasmodiophora brassicae*[94]) and hence be a useful screening method in organic as well as conventional systems, a screening method developed for use within the growing season to trigger a fungicide application would be of limited use to organic farmers.

Often authors of reviews on soil biological fertility argue that maintenance and enhancement of soil biological fertility is generally of benefit within agricultural systems, e.g., Doran and Smith[95], Beauchamp and Hume[96] and Clapperton et al.[97]. However their guidance as to monitoring and management of soil biological fertility at a farming system level is given only in very general way. For example: 'Ideally agroecosystems should be managed to maintain the structural integrity of the [soil] habitat, increase SOM and optimise the C : N ratios in soil organic matter using cover crops and/or crop sequence to synchronise nutrient release and plant uptake'.[97] But a farmer might well ask how many cover crops and which ones, where the right balance (economic as well as ecological) is between minimizing tillage and optimizing weed control ... and many more pertinent questions. Interactions between practices, rather than the impact of any single practice, are often the focus of farm management decisions. In the development of indicators of soil quality, closer links to management practices are needed, so that indicators can support improved quality of soil management.

Conclusions

The legislative requirements placed on organic farming systems mean that many of the practices which are likely to maintain or enhance soil biological fertility are at the heart of this approach to farming. It is a requirement of organic farming systems that they recycle nutrients within the farming system, so that total returns of organic materials to the soil are often higher under organic management. In addition, organic farming systems develop diverse cropping patterns in space and time, hence increasing the diversity of residue quality input to the soil. Consequently, many organic farming systems have increased biological activity and increased below-ground biodiversity compared with conventional farming in the same region. However, within organic farming systems, weed management is largely achieved through tillage and perhaps the key remaining question for organic arable farming systems with regard to the enhancement of soil biological fertility is to what extent can minimum tillage approaches can be adopted?

There is no evidence that new distinct indicators are needed to measure biological soil quality in organic farming systems. For all farming systems, the key is to identify indicators that are suitably responsive to changes in practice and can be readily interpreted by the farmer. More work is needed, however, to test existing indicator frameworks (e.g., Idowu et al.[79]) to guide management within organic farming systems, rather than simply to compare organic and conventional management.

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References

1 Stockdale, E.A., Lampkin, N.H., Hovi, M., Keatinge, R., Lennartsson, E.K.M., Macdonald, D.W., Padel, S., Tattersall, F.H., Wolfe, M.S., and Watson, C.A. 2001. Agronomic and environmental implications of organic farming systems. Advances in Agronomy 70:261–327.

2 Howard, A. 1943. An Agricultural Testament. Oxford University Press, London.

3 Balfour, E. 1943. The Living Soil and the Haughley Experiment. Faber and Faber, London.

4 Giller, K.E., Beare, M.H., Lavelle, P., Izac, A.M.N., and Swift, M.J. 1997. Agricultural intensification, soil biodiversity and agroecosystem function. Applied Soil Ecology 6:3–16.

5 Watson, C.A., Atkinson, D., Gosling, P., Jackson, L.R., and Rayns, F.W. 2002. Managing soil fertility in organic farming systems. Soil Use and Management 18:239–247.

6 Stockdale, E.A., Shepherd, M.A., Fortune, S., and Cuttle, S.P. 2002. Soil fertility in organic farming systems—fundamentally different? Soil Use and Management 18:301–308.

7 Van Bruggen, A.H.C. 1995. Plant disease severity in high input compared to low input and organic farming systems. Plant Disease 79:976–984.

8 Jackson, L.E. (ed.). 1997. Ecology in Agriculture. Academic Press, San Diego, CA.

9 Bengtsson, J., Ahnstrom, J., and Weibull, A.C. 2005. The effects of organic agriculture on biodiversity and abundance: a meta-analysis. Journal of Applied Ecology 42:261–269.

10 Fuller, R.J., Norton, L.R., Feber, R.E., Johnson, P.J., Chamberlain, D.E., Joys, A.C., Matthews, F., Stuart, R.C., Townsend, M.C., Manley, W.J., Wolfe, M.S., Macdonald, D.W., and Firbank, L.G. 2005. Benefits of organic farming to biodiversity vary among taxa. Biology Letters 1:431–434.

11 Hole, D.G., Perkins, A.J., Wilson, J.D., Alexander, I.H., Grice, F., and Evans, A.D. 2005. Does organic farming benefit biodiversity? Biological Conservation 122:113–130.

12 Benton, T.G., Vickery, J.A., and Wilson, J.D. 2003. Farmland biodiversity. Trends in Ecology and Evolution 18:182–188.

13 Krebs, J.R., Wilson, J.D., Bradbury, R.B., and Siriwardena, G.M. 1999. The second silent spring? Nature 400:611–612.

14 Brussaard, L., Behan-Pelletier, V.M., Bignell, D.E., Brown, V.K., Didden, W.A.M., Folgarait, P.I., Fragoso, C., Freckman, D.W., Gupta, V.V.S.R., Hattori, T., Hawksworth, D., Klopatek, C., Lavelle, P., Malloch, D., Rusek, J., Söderström, B., Tiedje, J.M., and Virginia, R.A. 1997. Biodiversity and ecosystem functioning in soil. Ambio 26:563–570.

15 Van der Putten, W.H., De Ruiter, P.C., Bezemer, T.M., Harvey, J.A., Wassen, M., and Wolters, V. 2004. Trophic interactions in a changing world. Basic and Applied Ecology 5:487–494.

16 Wardle, D.A., Nicholoson, K.S., Bonner, K.I., and Yeates, G.W. 1999. Effects of agricultural intensification on soil-associated arthropod population dynamics, community structure, diversity and temporal variability over a seven-year period. Soil Biology and Biochemistry 31:1691–1706.

17 Mulder, C., De Zwart, D., Van Wijnen, H.J., Schouten, A.J., and Breure, A.M. 2003. Observational and simulated evidence of ecological shifts within the soil nematode community of agroecosystems under conventional and organic farming. Functional Ecology 17:516–525.

18 Fitter, A.H., Gilligan, C.A., Hollingworth, K., Kleczkowski, A., Twyman, R.M., Pitchford, J.W., and the members of the NERC Soil Biodiversity Programme 2005. Biodiversity and ecosystem function in soil. Functional Ecology 19:369–377.

19 McCaig, A.E., Glover, L.A., and Prosser, J.I. 1999. Molecular analysis of bacterial community structure and diversity in unimproved and improved upland grass pastures. Applied and Environmental Microbiology 65:1721–1730.

20 Bardgett, R.D., Whittaker, J.B., and Frankland, J.C. 1993. The diet and food preferences of *Onychiurus procampatus* (collembola) from upland grassland soils. Biology and Fertility of Soils 16:296–298.

21 Bardgett, R.D., Leemans, D.K., Cook, R., and Hobb, P.J. 1997. Seasonality of the soil biota of grazed and ungrazed hill grasslands. Soil Biology and Biochemistry 29:1285–1294.

22 Parfitt, R.L., Yeates, G.W., Ross, D.J., Mackay, A.D., and Budding, P.J. 2005. Relationships between soil biota, nitrogen and phosphorus availability, and pasture growth under organic and conventional management. Applied Soil Ecology 28:1–13.

23 Hutton, S.A. and Giller, P.S. 2003. The effects of the intensification of agriculture on northern temperate dung beetle communities. Journal of Applied Ecology 40:994–1007.

24 Foissner, W. 1992. Comparative studies on the soil life in ecofarmed and conventionally farmed fields and grasslands of Austria. Agriculture Ecosystems and Environment 40:207–218.

25 Younie, D. and Armstrong, G. 1995. Botanical and invertebrate diversity in organic and intensively fertilised grassland. In J. Isart and J.J. Llerena (eds). Proceedings of the First ENOF Workshop—Biodiversity and Land Use. Multitext, Barcelona. p. 34–44.

26 Yeates, G.W., Bardgett, R.D., Cook, R., Hobbs, P.J., Bowling, P.J., and Potter, J.F. 1997. Faunal and microbial diversity in three Welsh grassland soils under conventional and organic management regimes. Journal of Applied Ecology 34:453–470.

27 Oehl, F., Sieverding, E., Ineichen, K., Mäder, P., Boller, T., and Wiemken, A. 2003. Impact of land use intensity on the species diversity of arbuscular mycorrhizal fungi in agroecosystems of Central Europe. Applied and Environmental Microbiology 69:2816–2824.

28 Eason, W.R., Scullion, J., and Scott, E.P. 1999. Soil parameters and plant responses associated with arbuscular mycorrhizas from contrasting grassland management regimes. Agriculture Ecosystems and Environment 73:245–255.

29 Gosling, P., Hodge, A., Goodlass, G., and Bending, G.D. 2006. Arbuscular mycorrhizal fungi and organic farming. Agriculture, Ecosystems and Environment 113:17–35.

30 Haygarth, P.M., Chapman, P.J., Jarvis, S.C., and Smith, R.V. 1998. Phosphorus budgets for two contrasting grassland farming systems in the UK. Soil Use and Management 14:160–167.

31 Reganold, J.P., Palmer, A.S., Lockhart, J.C., and Macgregor, A.N. 1993. Soil quality and financial performance of biodynamic and conventional farms in New Zealand. Science 260:344–349.
32 Murata, T. and Goh, K.M. 1997. Effects of cropping systems on soil organic matter in a pair of conventional and biodynamic mixed cropping farms in Canterbury, New Zealand. Biology and Fertility of Soils 25:372–381.
33 Filser, J., Mebes, K.H., Winter, K., Lang, A., and Kampichler, C. 2002. Long-term dynamics and interrelationships of soil Collembola and microorganisms in an arable landscape following land use change. Geoderma 105:201–221.
34 Van Diepeningen, A.D., De Vos, O.J., Korthals, G.W., and Van Bruggen, A.H.C. 2006. Effects of organic versus conventional management on chemical and biological parameters in agricultural soils. Applied Soil Ecology 31:120–135.
35 Drinkwater, L.E., Waggoner, P., and Sarrantonio, M. 1998. Legume based cropping systems have reduced carbon and nitrogen losses. Nature 396:262–265.
36 Wander, M.M., Hedrick, D.S., Kaufman, D., Traina, S.J., Stinner, B.R., Kehrmeyer, S.R., and White, D.C. 1995. The functional-significance of the microbial biomass in organic and conventionally managed soils. Plant and Soil 170:87–97.
37 Watson, C.A., Ritz, K., Younie, D., and Franklin, M. 1996. Nitrogen and soil biomass dynamics in ley/arable crop rotations. Aspects of Applied Biology 47:43–50.
38 Breland, T.A. and Eltun, R. 1999. Soil microbial biomass and mineralization of carbon and nitrogen in ecological, integrated and conventional forage and arable cropping systems. Biology and Fertility of Soils 30:193–201.
39 Flieβbach, A., Oberholzer, H.-R., Gunst, L., and Mäder, P. 2007. Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming. Agriculture, Ecosystems and Environment 118:273–284.
40 Bossio, D.A., Scow, K.M., Gunapala, N., and Graham, K.J. 1998. Determinants of soil microbial communities: effects of agricultural management, season, and soil type on phospholipid fatty acid profiles. Microbial Ecology 36:1–12.
41 Gunapala, N. and Scow, K.M. 1998. Dynamics of soil microbial biomass and activity in conventional and organic farming systems. Soil Biology and Biochemistry 30:805–816.
42 Berkelmans, R., Ferris, H., Tenuta, M., and Van Bruggen, A.H.C. 2003. Effects of long-term crop management on nematode trophic levels other than plant feeders disappear after 1 year of disruptive soil management. Applied Soil Ecology 23:223–235.
43 Shannon, D., Sen, A.M., and Johnson, D.B. 2002. A comparative study of the microbiology of soils managed under organic and conventional regimes. Soil Use and Management 18:274–283.
44 Girvan, M.S., Bullimore, J., Pretty, J.N., Osborn, A.M., and Ball, A.S. 2003. Soil type is the primary determinant of the composition of the total and active bacterial communities in arable soils. Applied and Environmental Microbiology 69:1800–1809.
45 Cookson, W.R., Osman, M., Marschner, P., Abaye, D.A., Clark, I., Murphy, D.V., Stockdale, E.A., and Watson, C.A. 2007. Controls on soil nitrogen cycling and microbial community composition across land use and incubation temperature. Soil Biology and Biochemistry 39:744–756.
46 Flieβbach, A. and Mäder, P. 1997. Carbon source utilization by microbial communities in soils under organic and conventional farming practice. In H. Insan and A. Rangger (eds). Microbial Communities. Functional versus Structural Approaches. Springer Verlag, Berlin. p. 109–120.
47 Hartmann, M., Flieβbach, A., Oberholzer, H.-R., and Widmer, W. 2006. Ranking the magnitude of crop and farming system effects on soil microbial biomass and genetic structure of bacterial communities. FEMS Microbiology Ecology 57:378–388.
48 Esperschütz, J., Gattinger, A., Mäder, P., Schloter, M., and Flieβbach, A. 2007. Response of soil microbial biomass and community structures to conventional and organic farming systems under identical crop rotations. FEMS Microbiology Ecology 61:26–37.
49 Jensen, U.B., Elmholt, S., and Labouriau, R. 2000. Distribution of ergosterol in organically and conventionally cultivated agricultural soils. Biological Agriculture and Horticulture 18:113–125.
50 Elmholt, S. and Labouriau, R. 2005. Fungi in Danish soils under organic and conventional farming. Agriculture Ecosystems and Environment 107:65–73.
51 Sattelmacher, B., Reinhard, S., and Pomikalko, A. 1991. Differences in mycorrhizal colonization of rye (*Secale cereale* L.) grown in conventional or organic (biological-dynamic) farming system. Journal of Agronomy and Crop Science-Zeitschrift fur Acker und Pflanzenbau 167:350–355.
52 Ryan, M.H., Chilvers, G.A., and Dumaresq, D.C. 1994. Colonization of wheat by VA-mycorrhizal fungi was found to be higher on a farm managed in an organic manner than on a conventional neighbor. Plant and Soil 160:33–40.
53 Bending, G.D., Turner, M.K., Rayns, F., Marx, M.C., and Wood, M. 2004. Microbial and biochemical soil quality indicators and their potential for differentiating areas under contrasting agricultural management regimes. Soil Biology and Biochemistry 36:1785–1792.
54 Scullion, J., Eason, W.R., and Scott, E.P. 1998. The effectivity of arbuscular mycorrhizal fungi from high input conventional and organic grassland and grass-arable rotations. Plant and Soil 204:243–254.
55 Franke-Snyder, M., Douds, D.D., Galvez, L., Phillips, J.G., Wagoner, P., Drinkwater, L., and Morton, J.B. 2001. Diversity of communities of arbuscular mycorrhizal (AM) fungi present in conventional versus low-input agricultural sites in eastern Pennsylvania, USA. Applied Soil Ecology 16:35–48.
56 Oehl, F., Sieverding, E., Mäder, P., Dubois, D., Ineichen, K., Boller, T., and Wiemkein, A. 2004. Impact of long-term conventional and organic farming on the diversity of arbuscular mycorrhizal fungi. Oecologia 138:574–583.
57 Foissner, W. 1997. Protozoa as bioindicators in agroecosystems, with emphasis on farming practices, biocides, and biodiversity. Agriculture Ecosystems and Environment 62:93–103.
58 Bongers, T. and Ferris, H. 1999. Nematode community structure as a bioindicator in environmental monitoring. Trends in Ecology and Evolution 14:224–228.
59 Neher, D.A. and Olson, R.K. 1999. Nematode communities in soils of four farm cropping management systems. Pedobiologia 43:430–438.
60 Neher, D.A. 1999. Nematode communities in organically and conventionally managed agricultural soils. Journal of Nematology 31:142–154.
61 Brussaard, L. 1994. Soil ecology of conventional and integrated farming systems. Agricultural Ecosystems and Environment 51:ix.

62 Crossley, D.A. Jr, Coleman, D.C., and Hendrix, P.F. 1989. The importance of the fauna in agricultural soils: research approaches and perspectives. Agriculture Ecosystems and Environment 27:47–55.
63 Andren, O., Lindberg, T., Paustian, K., and Rosswall, T. 1990. Ecology of arable land—organism, carbon and nitrogen cycling. Ecological Bulletins 40:1–222.
64 De Ruiter, P.C., Moore, J.C., Zwart, K.B., Bouwan, L.A., Hassink, J., Bloem, J., Devos, J.A., Marinissen, J.C.Y., Didden, W.A.M., Lebbink, G., and Brussaard, L. 1993. Simulation of nitrogen mineralization in the belowground food webs of 2 winter-wheat fields. Journal of Applied Ecology 30:95–106.
65 De Ruiter, P.C., Neutel, A.N., and Moore, J.C. 1994. Modelling food webs and nutrient cycling in agroecosystems. Trends in Ecology and Evolution 9:378–383.
66 Pankhurst, C.E., Doube, B.M., Gupta, V.V.S.R., and Grace, P.R. 1994. Soil Biota—Management in Sustainable Farming Systems. CSIRO, Melbourne.
67 Alvarez, T., Frampton, G.K., and Goulson, D. 2001. Epigeic collembola in winter wheat under organic, integrated and conventional farm management regimes. Agriculture Ecosystems and Environment 83:95–110.
68 Mäder, P., Flieβbach, A., Dubois, D., Gunst, L., Fried, P., and Niggli, U. 2002. Soil fertility and biodiversity in organic farming. Science 296:1694–1697.
69 Doring, T.F. and Kromp, B. 2003. Which carabid species benefit from organic agriculture? A review of comparative studies in winter cereals from Germany and Switzerland. Agriculture Ecosystems and Environment 98:153–161.
70 Watson, C.A., Younie, D., and Armstrong, G. 1999. Designing crop rotations for organic farming: importance of the ley-arable balance. In J.E. Olesen, R. Eltun, M.J. Gooding, E.S. Jensen, and U. Kopke (eds). Designing and Testing Crop Rotations for Organic Farming. DARCOF Report Number 1, Darcof; Foulum, p. 91–98.
71 Higginbotham, S., Leake, A.R., Jordan, V.W., and Ogilvy, S.E. 2000. Environmental and ecological aspects of integrated, organic and conventional farming systems. Aspects of Applied Biology 62:15–20.
72 Roschewitz, I., Gabriel, D., Tscharntke, T., and Carsten, T. 2005. The effects of landscape complexity on arable weed species diversity in organic and conventional farming. Journal of Applied Ecology 42:873–882.
73 Clough, Y., Holzschuh, A., Gabriel, D., Purtauf, T., Kleijn, D., Kruess, A., Steffan-Dewenter, I., and Tscharntke, T. 2007. Alpha and beta diversity of arthropods and plants in organically and conventionally managed wheat fields. Journal of Applied Ecology 44:804–812.
74 Kabir, Z. and Koide, R.T. 2000. The effect of dandelion or a cover crop on mycorrhiza inoculum potential, soil aggregation and yield of maize. Agriculture Ecosystems and Environment 78:167–174.
75 Kremer, R.J. and Li, J.M. 2003. Developing weed-suppressive soils through improved soil quality management. Soil and Tillage Research 72:193–202.
76 Hidaka, K. 1997. Community structure and regulatory mechanism of pest populations in rice paddies cultivated under intensive, traditionally organic and lower input farming in Japan. Biological Agriculture and Horticulture 15:35–49.
77 Hossain, M.Z., Choudhury, M.H.K., Hossain, M.F., and Alam, Q.K. 2002. Effects of ecological agriculture on soil properties and arthropod diversity in rice-based cropping systems in floodplain areas in Bangladesh. Biological Agriculture and Horticulture 20:215–227.
78 Mendoza, T.C. 2004. Evaluating the benefits of organic farming in rice agroecosystems in the Philippines. Journal of Sustainable Agriculture 24:93–115.
79 Idowu, O.J., Van Es, H.M., Abawi, G.S., Wolfe, D.W., Ball, J.I., Gugino, B.K., Moebius, B.N., Schindelbeck, R.R., and Bilgili, A.V. 2008. Farmer-oriented assessment of soil quality using field, laboratory and VNIR spectroscopy methods. Plant and Soil 307:243–253.
80 Winding, A., Hund-Rinke, K., and Rutgers, M. 2005. The use of microorganisms in ecological soil classification and assessment concepts. Ecotoxicology and Environmental Safety 62:230–248.
81 Stockdale, E.A. and Brookes, P.C. 2006. Detection and quantification of the soil microbial biomass—impacts on the management of agricultural soils. Journal of Agricultural Science 144:285–302.
82 Alabouvette, C., Backhouse, D., Steinberg, C., Donovan, N.J., Edel-hermann, V., and Burgess, L.W. 2004. Microbial diversity in soil—effects on crop health. In P. Schjønning, S. Elmholt, and B.T. Christensen (eds). Managing Soil Quality: Challenges in Modern Agriculture. CABI Publishing, Wallingford. p. 121–138.
83 Brussaard, L., Kuyper, T.W., Didden, W.A.M., de Goede, R.G.M., and Bloem, J. 2004. Biological soil quality from biomass to biodiversity—importance and resilience to management stress and disturbance. In P. Schjønning, S. Elmholt, and B.T. Christensen (eds). Managing Soil Quality: Challenges in Modern Agriculture. CABI Publishing, Wallingford. p. 139–161.
84 Johnson, M.J., Lee, K.Y., and Scow, K.M. 2003. DNA fingerprinting reveals links among agricultural crops, soil properties, and the composition of soil microbial communities. Geoderma 114:279–303.
85 Srivastava, R., Roseti, D., and Sharma, A.K. 2007. The evaluation of microbial diversity in a vegetable based cropping system under organic farming practice. Applied Soil Ecology 36:116–123.
86 Slattery, J.F., Coventry, D.R., and Slattery, W.J. 2001. Rhizobial ecology as affected by the soil environment. Australian Journal of Experimental Agriculture 41: 289–298.
87 Evans, J. 2005. An evaluation of potential Rhizobium inoculant strains used for pulse production in acidic soils of south-east Australia. Australian Journal of Experimental Agriculture 45:257–268.
88 Elliott, E.T. 1997. Rationale for developing bioindicators of soil health. In P. Schjønning, S. Elmholt, and B.T. Christensen (eds). Managing Soil Quality: Challenges in Modern Agriculture. CABI Publishing, Wallingford. p. 49–78.
89 Karlen, D.L., Andrews, S.S., and Doran, J.W. 2001. Soil quality: current concepts and applications. Advances in Agronomy 74:1–40.
90 Xua, M.X., Zhao, Y.G., Liu, G.B., and Argent, R.M. 2006. Soil quality indices and their application in the hilly loess plateau region of China. Australian Journal of Soil Research 44:245–254.
91 Rezaei, S.A., Gilkes, R.J., and Andrews, S.S. 2006. A minimum data set for assessing soil quality in rangelands. Geoderma 136:229–234.

92 Andrews, S.S., Karlen, D.L., and Cambardella, C.A. 2004. The soil management assessment framework: a quantitative soil quality evaluation method. Soil Science Society of America Journal 68:1945–1962.
93 Lal, R. 2001. Managing world soils for food security and environmental quality. Advances in Agronomy 74:155–192.
94 Wallenhamar, A.-C. and Arvidsson, O. 2001. Detection of *Plasmodiophora brassicae* by PCR in naturally infested soils. European Journal of Plant Pathology 107:313–321.
95 Doran, J.W. and Smith, M.S. 1987. Organic matter management and utilization of soil and fertilizer nutrients. In Soil Science Society of America Special Publication 19. Soil Fertility and Organic Matter as Critical Components of Production Systems. Soil Science Society of America and American Society of Agronomy, Madison, Wisconsin. p. 53–72.
96 Beauchamp, E.G. and Hume, D.J. 1997. Agricultural soil manipulation: the use of bacteria, manuring and plowing. In J.D. Van Elsas, J.T. Trevors, and E.M.H. Wellington (eds). Modern Soil Microbiology. Marcel Dekker, New York. p. 643–664.
97 Clapperton, M.J., Chan, K.Y., and Larney, F.J. 2003. Managing the soil habitat for enhanced biological fertility. In L.K. Abbott and D.V. Murphy (eds). Soil Biological Fertility—A Key to Sustainable Land Use in Agriculture. Kluwer Academic, Dordrecht, The Netherlands. p. 203–224.