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Soil and soil health: an overview

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1 Introduction

Soil security is critical to human security (Minami, 2009) and underpins food and water security (McBratney et al., 2014). Humans have observed variations in soil properties and especially its fertility since the advent of settled agricultural societies. Until the emergence of modern science in the seventeenth century, this assessment was subjective and experiential, and this remains an important approach for many farmers (Romig et al., 1995). However, science has revealed insights into the working of the soil system and its role in supporting agriculture and the wider land system, leading to more objective and quantitative assessments of soil quality and health. Interest and studies in this area have been intense over recent decades, but a final understanding of how best to assess soil status remains elusive. This chapter outlines some theories of the soil system and applies this to clarify the meaning of 'quality' and 'health' as they apply to soil. It explores how to assess soil health and provides a commentary on which indicators of soil health may be useful in practical agriculture. It underlines the importance of soil governance and how this may be optimized.

http://dx.doi.org/10.19103/AS.2017.0033.01

Chapter taken from: Reicosky, D. (ed.), *Managing soil health for sustainable agriculture Volume 1: Fundamentals,* Burleigh Dodds Science Publishing, Cambridge, UK, 2018, (ISBN: 978 1 78676 188 0; www.bdspublishing.com)

2 Constructs of soil quality and health: utilitarian and holistic

The consequence of variation in soil-forming factors over space and time is that soil properties vary widely between and across landscapes and give rise to distinct soil types. Soil taxonomic systems are used as legends for maps and spatial inventories of soils. The practical reason for collecting this soil information has been mainly to inform land capability assessment for agriculture. Different soil types have different potentials for agricultural production, for example depending on their depth, texture, wetness and acidity. Thus soils can be assigned to different categories of 'quality' for agriculture. From the early nineteenth century to the late twentieth century, land capability assessment was widely applied as part of the introduction of modern farming techniques to existing agricultural land and its widespread extension to natural and semi-natural lands. Therefore, the focus was on the inherent properties and potential of soils to support modern agriculture. Subsequently, a new concern arose about the loss of soil condition from degradation caused by inappropriate agricultural exploitation, often described as a loss of soil quality. Thus, alongside its older meaning, the concept of soil quality developed as a descriptor of soil condition in terms of its fitness for agricultural production relative to its potential.

The utilitarian concept of soil quality as a measure of fitness for agricultural production developed when the dominant construct of soil was as a medium for plant growth in which the driving processes were physical and chemical. However, a different and richer concept of the soil system has emerged. This views soil as an ecosystem in which soil biology, moderated by physical and chemical properties, is central to its functionality. Moreover, especially following the Millennium Ecosystem Assessment (2005) and the introduction of the concept of natural capital, new emphasis is being given to the full range of ecosystem services that are supported by soil, including but not confined to food and fibre production. At its heart, this perspective is informed by a cosmology that is holistic and that at some level encompasses the idea that humans have a stewardship role for life on Earth, rather than that nature exists solely for humans to exploit. In this context, a holistic construct of soil health has emerged, as an integrative measure of the condition of a multifunctional living system (Doran and Zeiss, 2000). At the same time, causing some confusion, the utilitarian meaning of soil quality has been extended to include its fitness to support the full range of ecosystem services. A critical message in this chapter is that soil quality and health are distinct concepts and should not be confused (Lal, 2016): soil quality refers to the inherent potential capacity of a particular soil to support specified services (Karlen et al., 1997) while soil health describes its actual condition as a system for supporting those services (McBratney et al., 2014). Therefore, at least from a utilitarian perspective, soil health indicates how close the condition of a soil is to its optimal one for supporting specified services, that is, those that define its inherent quality. It focuses assessment towards the quantity and quality of specified services that the soil is able to support; for example, if the specified service is to support agricultural production then the assessment of soil health will be directed towards measurement of agricultural yields and the soil properties that control these outputs. By contrast, the holistic approach to soil health (Doran and Zeiss, 2000; Van Bruggen and Semenov, 2000) considers overall multifunctional capacity and focuses on the status of the soil system to deliver all its functions. These two constructs of soil health are equally valid but present different challenges when considering options for assessing soil health. The utilitarian approach focuses particularly on factors that impact on the level of specified services that a soil is currently capable of supporting, relative to those that can be supported by a completely healthy soil of the same quality. The holistic approach focuses more on the current status of the biotic community in response to land use and management and its impact on soil processes and in turn their level of support for multifunctionality. The utilitarian approach is the one mainly adopted in this chapter, since here the focus is towards soil as a resource for agriculture.

3 The soil system and its performance

3.1 The soil system

The soil system is a sub-system of the overall land system. Its main functions are organic matter decomposition, nutrient cycling, soil structure maintenance and community moderation, and associated pest and disease control (Van Bruggen and Semenov, 2000; Kibblewhite et al., 2008). These functions support ecosystem services (see Fig. 1) within the wider land system, some of which deliver final goods and services to the human economy, including agricultural products.

The soil system has both abiotic and biotic components and processes. Distinctive habitats characterised by their physical and chemical properties evolve within different soils depending on soil-forming factors (Jenny, 1941) including time, parent materials, climate, natural vegetation and human land use and land management. Although soil systems operate across a wide range of scales, from micrometres to kilometres, arguably, the scale that is most relevant to soil health extends from a few microns to millimetres, as this is the one at which the soil architecture moderates biotic activity (Young and Crawford, 2004). Of particular importance in determining this architecture is firstly the soil pore structure, as characterised by overall pore volume, dimensions, continuity and tortuosity, and secondly, the chemistry of clay and other surfaces within the soil and their interaction with solution chemistry. The resulting soil habitats define the living space of the ecological community that is a phenotypic expression of the genetic information within the many different species present in soil. A key function of soil is the decomposition of plant and animal residues and the release of nutrients for uptake by plants. Importantly, this decomposition harvests energy for the living soil system and so underpins the delivery of

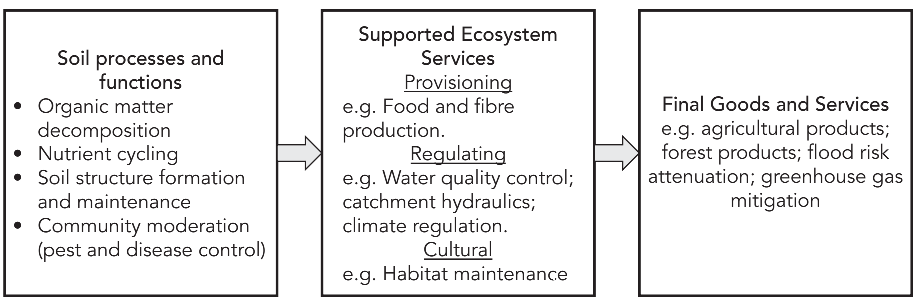

Figure 1 Cascading of functions, services and final goods from the soil system.

all of its functions. The uptake of carbon from plant residues and its progressive oxidation, as it moves through a complex food web and is respired, drives the different processes required for the maintenance of soil structure, nutrient cycling and community moderation, as well as organic matter decomposition. Thus the levels and forms of soil organic carbon are critical to the functioning of soil and, by implication, to its health.

3.2 System performance

The performance of systems can be viewed as a measure of the efficiency of conversion of inputs to outputs. In general, a performance curve (Fig. 2) can be described with a 'working range' extending to a point at which there is no further increase in output for an increment in inputs (and beyond which further inputs likely lead to a deterioration of performance). Applying this approach, inherent quality is represented by the working range of a fully functional system, that is a completely healthy system, while an indicator of system health is provided by the current working range, expressed as a percentage of the optimal one. The working range of a system can also be related to its resilience, or how well the performance recovers from a disturbance (short-term pressure) or stress (long-term or chronic pressure) after this is removed (Fig. 3). A completely resilient system is one whose performance returns to that immediately before the introduction of the disturbance or stress (Szabolcs, 1994). If the system state remains within its working range, resilience is expected. However, if the working range is exceeded this may damage system components, altering its state and leading to a new and degraded performance curve and a loss of health. Thus resilience to loading is reduced if the working range is exceeded and degree of resilience is related to system health.

3.3 Applying the general systems approach to soil

If the general systems approach described above is applied to soil, the health of a soil depends on its current working range relative to its potential one, as defined by its quality.

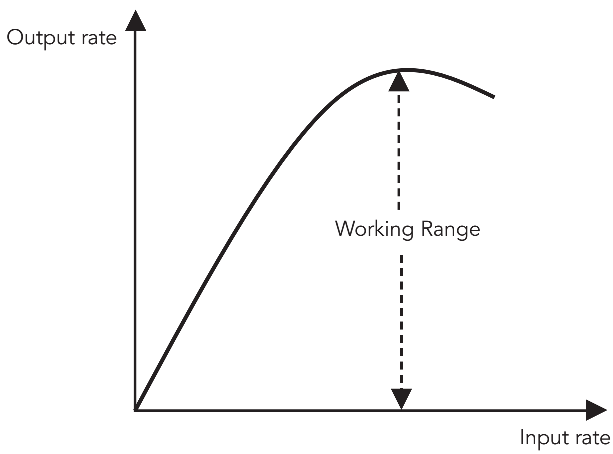

Figure 2 System performance curve and working range.

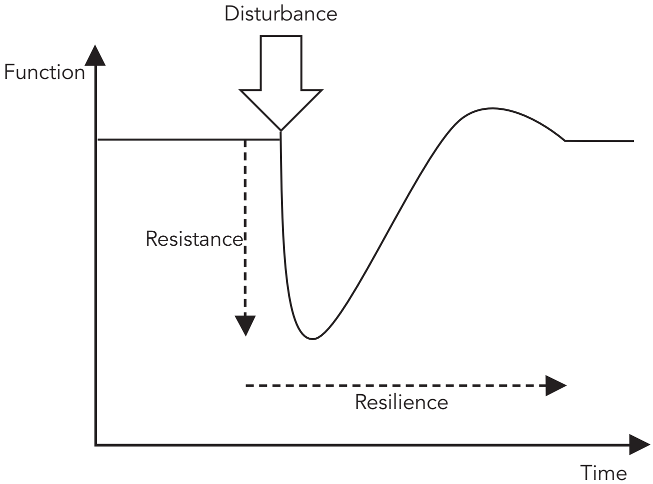

Figure 3 System response and resilience (after Griffiths and Philippot, 2012).

And the healthier the soil, the more likely it is that its performance will be resilient to management challenges such as tillage, topsoil compaction, or a wetting and drying cycle under irrigation. However, a loss of performance may be reversible or not, depending on its cause and form. Where the working range is not recoverable, a permanent reduction in the potential of the soil to deliver its functions means there will be a loss of quality rather than health. For example, soil quality is reduced when a soil system is stressed by inappropriate land use and there is a permanent loss of functionality from soil erosion and reduced soil depth, or from salinisation.

4 Soil health and its assessment

4.1 Approaches

Considering soil health as an integrative property, its assessment could be approached directly, in principle, by estimation of the working ranges for delivery of the different functions. One method would be to estimate the limiting functional output (e.g. respiration and nutrient release) when the supply of carbon substrate is not limited; another could be estimation of the range over which functionality is resilient. Alternatively, soil health may be inferred from information about the system that supports it, by assessment of the condition of the abiotic habitat (e.g. aggregate stability, bulk density and acidity) and/or observation of critical biotic components and processes. Considering the latter, overall microbial biomass provides information about the biotic state of the soil system, but more specific information is accessible from observation of the 'soil genome' and its phenotypic expression, as represented by, for example, gene diversity, community structure, the populations of individual species and/or enzyme activities. Further, the quantities of different forms of soil organic carbon are likely indicative of soil health because these provide 'buffer stocks of energy' in the food chain that connect the system's components and their levels will affect resilience. However, no single approach is adequate by itself. A very large number of indicators have been proposed for assessing soil health and the complexity of the soil system means that several are needed to properly describe its condition. A selection of indicators is needed to provide information about different critical features. This selection is itself complicated and requires a systematic framework (Ritz et al., 2009). Only a brief overview of some indicators is provided here with an emphasis on those that might be applied more routinely in practical agriculture. More comprehensive reviews (Van Bruggen and Semenov, 2000; Bastida et al., 2008; Ritz et al., 2009) cover indicators and measurements relevant to researching the soil system and its environmental responses. To be of practical use, indicators should provide meaningful information to support soil management decisions. This requires indicator thresholds corresponding to different levels of soil health. In this regard, generic guidance on what levels of indicators indicate good and poor soil health is often of limited value because the variety and variability of soils and their properties and qualities means there is also variation in threshold values representing acceptable and unacceptable health. Ideally, thresholds need to be established for different soils depending on their land use and land management, but these data are not generally available, especially for biological indicators (Pulleman et al., 2012). However, even where meaningful thresholds are not available, trends in indicator values are an indication of the trajectory of soil health.

4.2 Physical and chemical properties

Some physical and chemical properties, including texture, are essentially fixed and strongly influence the potential functionality of soil (i.e. its quality), and while they are important for soil management they are not strictly relevant as indicators of soil health. Other physical and chemical properties vary with soil health and provide useful information about changes in the condition of the habitat within which the biotic soil system operates. These include bulk density and water-holding capacity (which both reflect soil pore characteristics), aggregate stability, pH, electrical conductivity (as a measure of the salt content of the soil solution) and estimates of the available inorganic pool of nutrients (e.g. available phosphate and potassium).

4.3 Functional performance

The respiration rates of isotopically labelled organic materials added to incubated soil samples can provide information about the key function of soil to decompose organic residues (Jenkinson, 1971). However, this is somewhat complicated and costly for general application. Simple measurement of soil respiration is valuable but includes respiration of carbon in soil organic matter as well as plant residues and therefore is only a partial measure of the rate of plant residue decomposition. The quantity of nitrogen mineralised on incubation of soil (Keeney, 1982) provides information on the nutrient cycling function and this is relatively straightforward to do and gives valuable information about a soil's ability to provide nitrogen to crops. Direct assessment of rates of soil structure formation and maintenance is problematic, but the current aggregate stability of the soil and its resistance and resilience to pressures may provide an indirect estimation of this functionality.

4.4 Soil organic carbon

Total soil organic carbon provides a measure of the chemical energy derived from photosynthesis that is stored in the soil system. Its level reflects the relative rates of inputs of organic carbon to respired carbon. Increasing total soil organic carbon indicates that the supply of carbon substrate exceeds demand, while a decreasing trend indicates the reverse and that the energy requirements of the system are not being met fully by external inputs. A rising trajectory of total soil organic carbon is indicative of less stress on the soil system than a falling one, meaning that an upward trend is likely associated with improving soil health and downward one with reducing soil health. Therefore, the trend in total soil organic carbon and its rate of change are useful indicators of whether soil health is improving or deteriorating. Thus there is a rationale for the measurement and monitoring of trends in soil organic carbon in agricultural soils as a basic indicator of soil health.

Knowledge remains incomplete about the forms of soil organic carbon in terms of molecular structures, their association with soil surfaces and inorganic components and the effects of pore structure on their physical accessibility to microbes. The half-life of organic compounds in soil depends only partially on their molecular structure, but also on their combination with inorganic materials and their potential occlusion from microbes within the soil matrix (Dungait et al., 2012; Lal, 2016). A possible order of energy accessibility and yield for different soil organic matter fractions is highest for sugars and other low-molecular-weight compounds in the soil solution, less for polysaccharides including polyuronic acids that are weakly bound to soil surfaces and not occluded in soil pores, and even less for polyphenolic and other complex polymers that are strongly bound to soil surfaces or occluded in the soil matrix. However, simple sugars that are strongly bound to soil surfaces or occluded within the soil matrix may be inaccessible and not available as substrate. The distribution of organic carbon in terms of its molecular structure and its locus within the physical soil architecture may be indicative of soil health since as a soil system is stressed, by lowered inputs of organic carbon or high functional demands, forms of existing soil organic carbon that are more accessible and that have higher energy yields will be progressively drawn down with greater use being made of less-favourable energy sources. Therefore, the proportion of total organic carbon within accessible and higher energy-yielding forms may be an indicator of soil health. The rate of respiration when soil is incubated provides a basic indicator of this carbon. Another more valuable indicator of accessible carbon is the proportion of microbial biomass carbon to total soil organic carbon (Bastida et al., 2008), which allows an estimation of the carbon being utilised per unit of microbial biomass carbon, either from within the active microbial food chain or from 'accessible' soil organic carbon.

Selective extraction of soil organic carbon has been proposed as an indicator of soil health. Cold water extraction (Chantigny, 2003) removes organic matter in the soil solution, which is readily accessible to microbes; hot water extraction removes more organic matter, including polysaccharides which are an energetically preferred source of substrate relative to more recalcitrant compounds. Other extractions proposed for estimating 'labile' soil organic carbon rely on partial oxidation (e.g. with $KMnO_4$) or target particular organo-mineral combinations (e.g. by reducing Fe oxides). These methods continue a long tradition of using solvents and chemical solutions to extract apparently meaningful fractions of soil organic matter. While some of these methods for estimating labile carbon may be shown to be useful empirically, the mechanistic rationale for them is less certain because the fraction of soil organic matter they extract is likely heterogeneous and includes materials within a wide range of microbial accessibility.

4.5 Biological status

The level of active soil biomass provides only a crude indirect indicator of the gross capacity of the soil system to deliver its functions. Recognition that the soil system is an ecosystem with a community operating over several trophic levels with large and varied populations of species, suggests that characterising the ecological community in terms of its diversity may be a useful tool for assessing soil health. Some methods for characterisation of community composition are mature (e.g. phospholipid fatty acids (PLFA) profiling or DNA-based techniques such as terminal restriction fragment length polymorphism) while other emergent techniques (metagenomics and metaproteomics) offer potential (Ritz et al., 2009). The results from application of these techniques demonstrate that community composition is dynamic and that observable trajectories can be related to changes in land use and land management (e.g. Jangid et al., 2011). However, an answer to the question: 'What is a healthy community composition?' is not easily provided. One consideration is the extent to which diversity confers functional resilience relative to other factors (Orwin and Wardle, 2004) such as the evenness of the microbial community composition (Griffiths and Philippot, 2012). This unmet need to provide interpretative guidelines for community composition limits the practical application of its measurement in agriculture. Enzymatic activity (e.g. dehydrogenase and phenol oxidase) has been correlated with indicators of soil condition (Veum et al., 2014). Estimation of populations of particular species (Römbkea et al., 2006) as sentinels for soil health is an alternative approach. Species in higher trophic levels, for example, worms, mites and nematodes are likely useful indicators as their populations depend in good part on the health of lower trophic levels. Worm populations are quite easily estimated in the field and therefore may provide a useful indicator of trends in soil health that can be applied in practical agriculture.

5 Practical assessment and governance of soil health

5.1 Practical assessment of soil health in agricultural operations

In any scheme for assessing soil health, a fundamental indicator is soil organic carbon level. Unfortunately, the spatial and temporal variability of its rate of change means that changes are usually only confidently observable over several years. To partly overcome this lack of temporal sensitivity, its measurement can be supplemented by estimation of an active or accessible carbon pool, for which microbial biomass carbon and its ratio to total soil organic carbon appear of most value.

Effective soil management requires observation focused on indicators of soil health and their trends. The indicators chosen for field use by farmers and other land managers should be meaningful for field management of agricultural soils, straightforward to apply in the field or available from routine testing laboratories at reasonable cost. Table 1 lists an example of a set of indicators recommended as an aid to assessing soil health (Friedman et al., 2001), some of which are applicable in the field, although most require laboratory-based testing. The current state-of-the-art, which reflects previous indicator selections but is based on a systematic trial of indicators as applied to long-term field

Table 1 Example of a minimum data set of indicators for soil health (Friedman et al., 2001)

Indicator	Relationship to soil health
Soil organic matter (SOM)	Soil fertility, structure, stability, nutrient retention, soil erosion and available water capacity
Physical	
Soil structure	Retention and transport of water and nutrients, habitat for microbes and soil erosion
Depth of soil and rooting	Estimate of crop productivity potential, compaction and plough pan
Infiltration and bulk density	Water movement, porosity and workability
Water-holding capacity	Water storage and availability
Chemical	
pH	Biological and nutrient availability
Electrical conductivity	Plant growth, microbial activity and salt tolerance
Extractable nitrogen (N), phosphorus (P) and potassium (K)	Plant-available nutrients and potential for nitrogen (N) and phosphorus (P) loss
Biological	
Microbial biomass carbon (C) and N	Microbial catalytic potential and repository for C and N
Potentially mineralisable N	Soil productivity and N-supplying potential
Soil respiration	Microbial activity measure

experiments, is the Cornell Soil Health Assessment (Omololu et al., 2008; Moebius-Clune et al., 2016) which focuses on the soil processes relevant to the crop production function of soil. A set of soil tests (see Table 2) were selected from 39 candidates and a scoring algorithm developed for each to provide a set of scores related to soil properties together with the total score. The same set of tests were used to develop an Ontario Soil Health Assessment (Congreves et al., 2015) but with weighting of different test scores to reflect the sensitivity of these to soils in Ontario. In addition to laboratory testing of soil, there is advantage from encouraging integration of farmers' experiential observation and knowledge of their soils with scientific understanding by identifying field tests that are applicable without specialist training and that have a supporting scientific rationale. Candidate tests for this include in-field soil structure assessment (Ball et al., 2007) and earthworm counts. However, the use of proximate field sensors such as near-infrared reflectance spectroscopy (Stenberg, 2010) is already generating real-time information about soil conditions and this technology, combined with advanced data analysis and fusion methods, promises to provide farmers with a rich and sophisticated source of interpreted information on the health of their soils.

5.2 Governance of soil health

Soil is multifunctional and supports the interests of many different actors in society. While individual farmers and land managers should take practical action to optimise the health of their soils, institutions at all levels from local to regional to national to transnational have

Table 2 Soil quality indicators included in the Cornell soil health test (Omolulu et al., 2008)

Soil indicator	Related soil process
Physical	
Soil texture and stone content	All
Aggregate stability	Aeration, infiltration, shallow rooting and crusting
Available water capacity	Plant-available water retention
Soil strength (penetrometer)	Rooting
Biological	
Organic matter content	Energy/carbon storage, water and nutrient retention
Active carbon content	Organic materials to support biological functions
Potentially mineralisable nitrogen	Ability to supply nitrogen
Root health rating	Soil-borne pest pressure
Chemical	
pH	Toxicity, nutrient availability
Extractable phosphorus	Phosphorus availability, environmental loss potential
Extractable potassium	Potassium availability
Minor element contents	Micronutrient availability

a critical role in developing and implementing agricultural and environmental policies that support soil health. Some relevant policy measures are fiscal incentives, regulation, training, monitoring and research. As well as the public interest, private commercial actors in upstream agricultural supply and downstream food industry chains have a direct interest in ensuring that primary agricultural production has continuing access to healthy soil resources, so that the agriculture sector is sustainable and continues to support their activities. Additionally, commercial operators have a wider social responsibility to support sustainability including via appropriate management of soil resources, which is emphasised by evidence that by far the majority of the costs of soil degradation are incurred off-farm and borne by the wider community (Graves et al., 2015). Therefore, effective governance of soil health requires the connected and congruent participation of many different public and private actors to achieve the common good as realisable within prevailing social norms and political contexts. Specifically, effective legal frameworks for optimising soil health require integration of bottom-up with top-down measures (Kibblewhite et al., 2013).

Some encouraging progress has been made towards achieving the common good of healthy soils. The Global Soil Partnership (Montanarella, 2014) and its constituent regional soil partnerships offer technical support for global soil governance. Continental-scale initiatives include those of the European Union (European Commission, 2006) and the US Department of Agriculture (Natural Resources Conservation Service, 2017). An increasing number of regions, as represented by national or state authorities and agencies, have soil security programmes that support soil health. There are already many local initiatives on soil health often led by farmer organisations and their number is increasing. Some key lessons can be drawn from the experience gained to date, as follows.

Well-found soil monitoring is necessary to provide evidence both to justify public investment in interventions that encourage good soil management practices and to demonstrate their effectiveness. Unfortunately, the rate of change of soil properties at policy-relevant landscape scales is slow and this means that results are not always timely in relation to policy review cycles of typically only a few years. However, effective soil monitoring schemes are essential to provide data to direct efficient investment in soil health.

The variety and variation in soil types, conditions, use and management is immense and policy measures that are top-down and adopt a 'one-size-fits-all' approach prove inefficient. They also have the potential to discourage action and innovation by farmers and land managers because of obvious mismatches between compliance requirements and local knowledge and understanding. Therefore, a more successful approach is to set broad objectives and provide facilitating resources for a 'bottom-up' approach, informed by farmers and land managers' experiential understanding.

6 Conclusions

1. Soil health is a measure of the current performance of a soil relative to its inherent capability, which defines its quality.
2. Soil health is an integrative property of a living system that comprises biotic and abiotic components; it describes how well the soil system can deliver functions (organic residue decomposition, nutrient cycling, soil structure maintenance and ecological community moderation) to support outputs from the wider land system.
3. Experimental assessment of soil health is complicated by the great complexity and multifunctionality of the soil system. At present, understanding of this system is not sufficiently complete to confirm which components and processes are most critical to its functions and inform an unequivocal choice of biological parameters that are indicative of soil health status. However, knowledge of the system is increasing quickly and with it the prospect of such biological indicators.
4. Soil organic carbon levels and trajectories are indicative of soil health. A rising level of total soil organic carbon indicates that the soil system is adequately supplied with substrate carbon whereas a falling one is indicative of stress due to an insufficient supply of energy substrate. Trends in the ratio of active microbial carbon to total soil organic carbon also provide useful indications.
5. Monitoring to support management of soil health in the field should make use of the experiential knowledge of farmers and land managers. This can be supported by in-field soil structural assessment and observation of sentinel organisms, for example, earthworms and routine laboratory-based testing.
6. Soil health is critical to soil security, which is a shared responsibility from local to global levels and for public institutions and private actors. Effective governance of soil health requires investment in monitoring and needs to be participatory with an emphasis on bottom-up as well as top-down policy initiatives.

7 Where to look for further information

The website of the Natural Resources Conservation Service of the US Department of Agriculture (see Natural Resources Conservation Service, 2017) includes many informative pages devoted to soil health. These provide commentaries on different aspects of soil health and include a set of literature reviews.

8 Acknowledgements

This chapter has benefited greatly from many discussions with colleagues, especially at Cranfield University, over the past decade. Its development was helped considerably by the discussions at a workshop on soil health held at Landcare Research in Lincoln, New Zealand, in January 2017 and the author thanks all the participants in that workshop and especially its organiser, Professor David Whitehead.

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