Chapter 2
Soil Health Indicators Under Climate Change: A Review of Current Knowledge

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2.1 Soil Health Indicators, Soil Health and Climate Change: Background

Soil health indicators are a composite set of measurable physical, chemical and biological attributes which relate to functional soil processes and can be used to evaluate soil health status, as affected by management and climate change drivers. Defining soil health in relation to climate change should consider the impacts of a range of predicted global change drivers such as rising atmospheric carbon dioxide (CO_2) levels, elevated temperature, altered precipitation (rainfall) and atmospheric nitrogen (N) deposition, on soil chemical, physical and biological functions (French et al. 2009). Many studies have progressed our understanding of relationships between particular soil properties and climate change drivers, e.g. responses to temperature, CO_2 or rainfall; however, Wixon and Balser (2009) note that “a comprehensive explanation of the factors at the heart of the issue is currently lacking”. Determination of how predicted changes in climate relate to soil health will thus depend on our capacity to clearly define soil health properties and their relationship with specific soil functions, including complexity associated with interactive effects of climate change.

Note that both the terms “soil health” and “soil quality” are used synonymously in this chapter, although it is realised that the former term gives greater emphasis on soil biodiversity and ecological functions that make soil a dynamic living resource with capacity for self-organisation.

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Indicators, calculated values or estimated statistics *relative* to a threshold level are being increasingly used across biological, environmental, economical, social, institutional and political disciplines to assess current condition or trend of soil health (Dalal et al. 2003a, b; Riley 2001c). Indicators may be used as an indirect measure of soil function, serving to assess soil quality or health and its direction of change with time, by linking functional relationships among measurable attributes and monitoring for sustainable land management, including environmental impacts (Dalal et al. 2003a, b; Doran 2002; Doran and Zeiss 2000).

Kinyangi (2007) proposes that soil health assessment involves an evaluation process consisting of a series of actions: (1) selection of soil health indicators, (2) determination of a minimum data set, (3) development of an interpretation scheme of indices, and (4) on-farm assessment and validation. While the use of integrative soil health tests is increasing (e.g. Idowu et al. 2009), limited information exists to evaluate the applicability of soil health indicators for monitoring soil functions within the context of climate change.

A range of frameworks identifying soil health indicators to measure change and implement strategies to adapt to climate change exist (Dalal et al. 1999; Dalal and Moloney 2000; Doran 2002; Kibblewhite et al. 2008; Lal 1999; Nuttall 2007; Schjønning et al. 2004; Stenberg 1999). Potential linkages between soil health indicators, land management and climate change from these reviews are summarised in Fig. 2.1. Elevated CO_2 concentration, increasing temperature, atmospheric N deposition and changes in total and seasonal distribution of rainfall and extreme events such as droughts and floods will impact on soil biological processes, C and N cycling, and consequently on soil structure and erosion events, nutrient availability and plant diseases, and hence on ecosystem functionality and agricultural productivity.

Major soil physical, chemical and biological properties which may indicate the status of soil health in relation to climate change impacts are listed in Table 2.1 and outlined below.

2.2 Soil Physical Properties, Soil Health and Climate Change

Soil physical properties provide information related to water and air movement through soil, as well as conditions affecting germination, root growth and erosion processes. Many soil physical properties thus form the foundation of other chemical and biological processes, which may be further governed by climate, landscape position and land use. A range of soil physical properties are highlighted as potential soil health indicators, and key soil physical indicators in relation to climate change include soil structure, water infiltration, bulk density, rooting depth, and soil surface cover, which are discussed below.

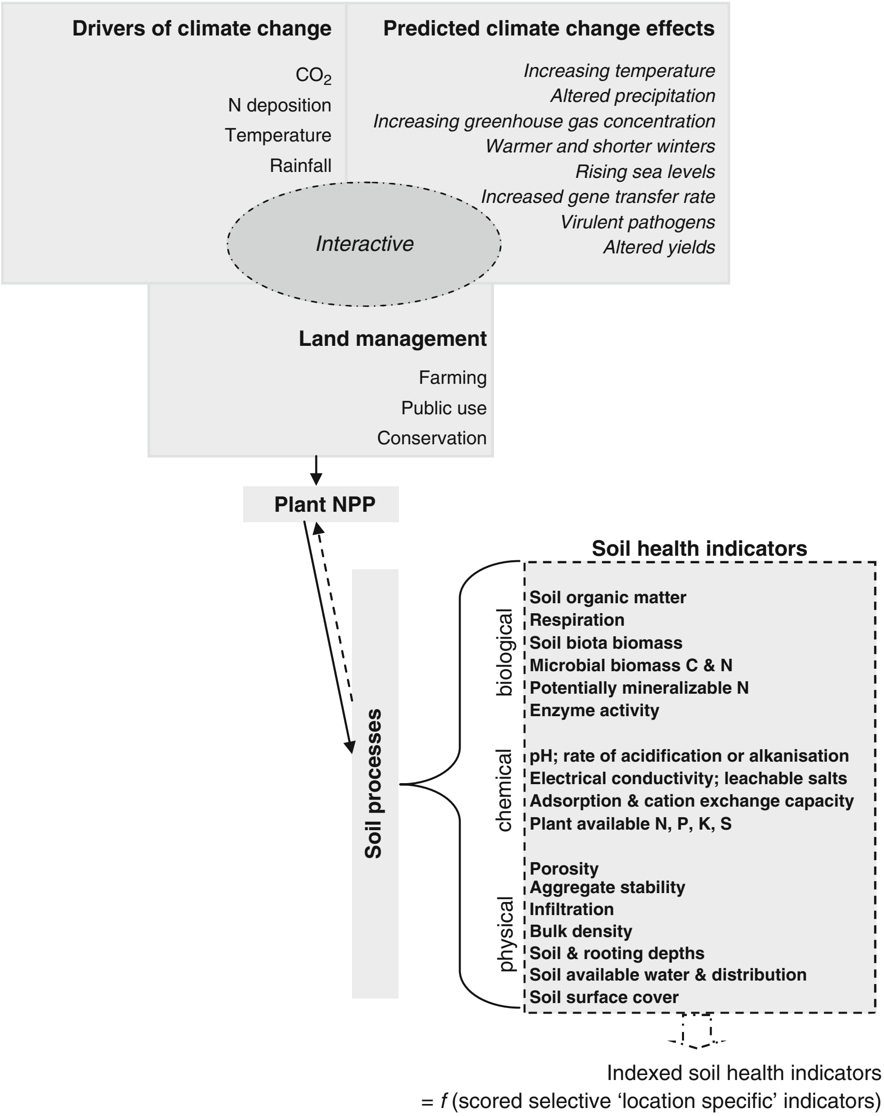

Fig. 2.1 Schematic representation of the potential links between climate change, land use and management change, and soil health indicators (modified from Dalal and Moloney 2000; French et al. 2009; Karlen et al. 2003; Nuttall 2007), including indexing of location-specific indicators to assess soil health

2.2.1 Soil Structure (Aggregate Stability, Porosity)

Aggregate stability, the resistance of soil aggregates to external energy such as high intensity rainfall and cultivation, is determined by soil structure, as well as a range

Table 2.1 Soil health indicators and relations to processes and functions under projected climate change scenarios[a]

Soil health indicators		Soil processes affected	Landscape scale (direct determination or estimated from pedotransfer functions)	Relevance to assess climate change impacts	Inclusion in a minimum data set
Physical	Soil structure	Aggregate stability, organic matter turnover	Aggregation, surface seal, indication of water and chemical retention and transportation	Medium	Frequent
	Porosity	Air capacity, plant available water capacity, relative field capacity	Soil crusting, reduced seed germination, aeration, water entry	High	Occasional/ frequent
	Infiltration	Soil water availability and movement	Potential for leaching, productivity, erosion	High	Occasional
	Bulk density	Soil structural condition; compaction	Volumetric basis for soil reporting	Low	Frequent
	Soil depth and rooting	Plant available water capacity, subsoil salinity	Productivity potential; uncertain whether trends can be discerned over long time periods	Medium	Occasional
	Soil/plant available water and distribution	Field capacity, permanent wilting point, macropore flow, texture	Water and chemical retention and transportation; yield	High	Frequent
	Soil protective cover	Soil water and nutrient movement, soil stabilisation, C and N fixation	Soil physical movement, organic matter input and movement	Medium	Frequent
Chemical	pH	Biological and chemical activity thresholds	Soil acidification, salinisation, electrical conductivity, soil structural stability	Medium	Frequent
	EC	Plant and microbial activity thresholds	Soil structural decline; leachable salts	Medium	Frequent
	Plant available N, P, K	Plant available nutrients and potential for loss	Capacity for crop growth and yield; environmental hazard (e.g. algal blooms)	Medium	Frequent

Biological	Soil organic matter				
	Light fraction or Macro-organic matter	Plant residue decomposition, organic matter storage and quality, macroaggregate formation	Loss of organic matter, soil aggregate formation	High	Frequent
	Mineralisable C and N	Metabolic activity of soil organisms, net inorganic N flux from mineralisation and immobilisation	Total organic C, soil respiration rate, nutrient supply Microbial activity, nutrient supply	High	Occasional
	Soil total C and N	C and N mass and balance	Soil structure, nutrient supply	High	Occasional/ frequent
	Soil respiration	Microbial activity	Microbial activity	High	Occasional
	Microbial biomass C and N	Microbial activity	Soil structure, nutrient supply, pesticide degradation	High	Frequent/ Occasional
	Microbial quotients	Substrate use efficiency	Substrate quality	High	Occasional
	Microbial diversity	Nutrient cycling and availability		High	Occasional
	Other microbiological indicators, enzyme activity	Soil structure, labile carbon, K_m, V_{max}, K_i, Q_{10}	Biochemical activity, nutrient supply	High	Occasional

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[a] Adapted from Dalal and Moloney 2000; Gregorich et al. 1994; Haynes 2008; Idowu et al. 2009; Kinyangi 2007; Reynolds et al. 2009; Stenberg 1999

of chemical and biological properties and management practices (Dalal and Moloney 2000; Moebius et al. 2007). It is considered a useful soil health indicator since it is involved in maintaining important ecosystem functions in soil including organic carbon (C) accumulation, infiltration capacity, movement and storage of water, and root and microbial community activity; it can also be used to measure soil resistance to erosion and management changes (Arias et al. 2005; Blanco-Canqui and Lal 2004; Lal 1999; Moebius et al. 2007; Rimal and Lal 2009; Weil and Magdoff 2004; see Chap. 3). Because of its association with the storage of soil organic carbon (SOC) and water, its measurement can be useful to guide climate adaptation strategies, especially in areas that are likely to experience high and intense rainfall and consequently increased erosion events. Since aggregate stability is measured in many different ways, standardised procedures are required within a soil health monitoring framework under climate change scenarios (Dalal and Moloney 2000; Salvador Sanchis et al. 2008).

Porosity, a measure of the void spaces in a material as a fraction (volume of voids to that of the total volume), and pore size distribution provide a direct, quantitative estimate of the ability of a soil to store root-zone water and air necessary for plant growth (Reynolds et al. 2002). Pore characteristics are strongly linked to soil physical quality; bulk density and macroporosity are functions of pore volume, while soil porosity and water release characteristics directly influence a range of soil physical indices including soil aeration capacity, plant available water capacity and relative field capacity (Reynolds et al. 2009). Recent studies to model soil water balance and ecosystem conditions under present-day and projected climatic scenarios use porosity as a model parameter (Porporato et al. 2005). Since root development and soil enzyme activities are closely related to soil porosity and pore size distribution (Piglai and De Nobili 1993) and because future climate change scenarios (e.g. elevated CO_2 and temperature, and variable and extreme rainfall events) may alter root development and soil biological activities (see Chaps. 7 and 8), soil porosity and pore size distribution and consequently soil functions are likely to be affected in unexpected directions; this aspect needs attention in future studies on the relationship of soil health and climate change. Moreover, pore size distribution and aeration status, besides other factors, are the key factors in governing methane (CH_4) fluxes, both CH_4 emission and uptake (Dalal et al. 2008), and nitrous oxide (N_2O) emissions from soil (Dalal et al. 2003a, b). However, data on relationships of greenhouse gas emissions and soil porosity and pore size distribution in response to climate change are limited and hence urgently required to guide development of climate adaptive strategies.

2.2.2 *Infiltration, Soil Available Water and Distribution*

Soil water infiltration, the rate at which water enters the soil surface and moves through soil depth, is gaining increasing interest within soil water modelling, as field-based measurements continue to improve (Dalal and Moloney 2000;

Joel and Messing 2001). Since infiltration rate may change significantly with soil use, management and time, it has been included as an indicator of soil health for assessments of land use change impacts (Arias et al. 2005; O'Farrell et al. 2010).

The availability of water for plant growth and important soil processes is governed by a range of soil properties including porosity, field capacity, lower limit of plant available water (thus excluding osmotic potential) and hence plant available water capacity, macropore flow and texture (Jarvis 2007; Reynolds et al. 2002). Plant available water capacity has been used as part of integrative soil health tests to assess management impacts, although variation in methodology may complicate the interpretation of results (Idowu et al. 2009). Furthermore, the soil available water and distribution may respond rapidly to climate change, especially to variable and high intensity rainfall or drought events, and thus management strategies, such as the planting of cover crops, conservation tillage and incorporation of organic matter, that maintain or even enhance water infiltration and available water in soil may help in mitigating the impacts of severe rainfall and drought events or severe erosion events (Lal 1995; Salvador Sanchis et al. 2008).

2.2.3 Bulk Density

Bulk density is routinely assessed in agricultural systems to characterise the state of soil compactness in response to land use and management (Håkansson and Lipiec 2000). It is considered as a useful indicator for the assessment of soil health with respect to soil functions such as aeration and infiltration (e.g. Dalal and Moloney 2000; Pattison et al. 2008; Reynolds et al. 2009). Since bulk density is in general negatively correlated with soil organic matter (SOM) or SOC content (Weil and Magdoff 2004), loss of organic C from increased decomposition due to elevated temperatures (Davidson and Janssens 2006) may lead to increase in bulk density and hence making soil more prone to compaction via land management activities and climate change stresses, for example, from variable and high intensity rainfall and drought events (Birkás et al. 2009).

2.2.4 Rooting Depth

Rooting depth is considered an important indicator of soil health, since changes in this property is likely to affect plant available water capacity, subsoil salinity, SOC content or other properties to indicate physicochemical constraints in the soil profile (Arias et al. 2005; Birkás et al. 2009; Dalal and Moloney 2000). Under prolonged drought, the impact of subsoil constraints such as salinity and high chloride concentrations (Dang et al. 2008; Rengasamy 2010) is likely to be greater on plant available water and hence plant productivity. Also, Birkás et al. (2008)

included rooting depth as a soil health parameter for monitoring of soil condition and plant growth under extreme drought and variable rainfall events to indicate the potential for adaptability and mitigation of climate stresses through alteration of rooting depth.

2.2.5 Soil Surface Cover

Soil surface cover (e.g. a layer of crop residues or biological soil crust) provides a range of important ecological functions including protection of soil surface by dissipating raindrop impact energy, soil stabilisation, reduction in erodible surface area, water and nutrient retention, C fixation and, in some instances, N fixation and support of native seed germination (Box and Bruce 1996; see Chap. 11). Dalal and Moloney (2000) note that soil surface cover provides an integrated indicator of soil physical management, organic matter input and effects associated with erosion and runoff, although correct timing of monitoring of soil surface cover change is required to evaluate impacts of management and climate change on soil health.

Soil structural conditions such as soil crust and soil seal formation, primarily related to sodicity, are also indicators that may be used to characterise soil health under climate change. The formation of soil crusts and seals can affect a range of soil processes, including water infiltration, oxygen diffusion, runoff, surface water evaporation and wind erosion. A range of methods exist to measure their thickness and strength, although research effort is needed to relate these properties with soil processes (Assouline 2004) affecting ecosystem functions and plant productivity, as well as to evaluate their role in mitigating adverse climate change impacts, thereby assisting in climate change adaptation.

2.3 Soil Chemical Properties, Soil Health and Climate Change

2.3.1 pH

Soil pH, a function of parent material, time of weathering, vegetation and climate, is considered as one of the dominant chemical indicators of soil health, identifying trends in change for a range of soil biological and chemical functions including acidification, salinisation, crop performance, nutrient availability and cycling and biological activity (Dalal and Moloney 2000; see Chap. 4). Soil pH has thus been included in integrative soil health tests to assess impacts of land use change and agricultural practices (Gil et al. 2009; Idowu et al. 2009; Pattison et al. 2008; Schindelbeck et al. 2008). While Brinkman and Sombroek (1999) suggested that most soils would not be subjected to rapid pH changes resulting from drivers of climate change such as elevated temperatures, CO_2 fertilisation, variable precipitation and atmospheric N deposition (DeVries and Breeuwsma 1987; McCarthy et al. 2001), it is likely, however, that these drivers of climate change will affect organic matter status, C and nutrient cycling, plant available water and hence plant productivity, which in turn will affect soil pH (Reth et al. 2005, see Chap. 4).

2.3.2 Electrical Conductivity

Soil electrical conductivity (EC), a measure of salt concentration, is considered an easily measured, reliable indicator of soil quality/health (Arnold et al. 2005). It can inform trends in salinity, crop performance, nutrient cycling (particularly nitrate) and biological activity and, along with pH, can act as a surrogate measure of soil structural decline especially in sodic soils (Arnold et al. 2005; Dalal and Moloney 2000). Electrical conductivity has been used as a chemical indicator to inform soil biological quality in response to crop management practices (Gil et al. 2009). Using elevation gradient as a surrogate for increasing temperatures and decreasing precipitation under climate change scenarios, Smith et al. (2002) found that EC decreased and pH increased in a semi-arid environment. Pariente (2001) examined the dynamics of soluble salts concentration in soils from four climatic regions (Mediterranean, semi-arid, mildly arid and arid) and found a non-linear relationship between the soluble salts content and rainfall, with sites that received <200 mm rainfall contained significantly high soluble contents and vice versa. Clearly, there is a need for comprehensive assessment of the influence of drivers of climate change on soil EC as an important soil health indicator in different ecosystems.

2.3.3 Sorption Capacity and Cation Exchange Capacity

Sorption capacity and cation exchange capacity (CEC) are considered important determinants of soil chemical quality, particularly the retention of major nutrient cations Ca, Mg and K, and immobilisation of potentially toxic cations Al and Mn; these properties can thus be useful indicators of soil health, informing of a soil's capacity to absorb nutrients, as well as pesticides and chemicals (Dalal and Moloney 2000; Ross et al. 2008). This may qualify CEC as a useful soil health indicator that is also required to be monitored in response to climate change. Since CEC of coarse-textured soils and low-activity clay soils is attributed to that of SOM (Weil and Magdoff 2004), the increasing decomposition and loss of SOM due to elevated temperatures (Davidson and Janssens 2006) may lead to the loss of CEC of these soils. Low CEC of soil may result in increased leaching of base cations in response to high and intense rainfall events, thus transporting alkalinity from soil to waterways (see Chap. 4).

2.3.4 Plant Available Nutrients

In their identification of basic soil properties to meet requirements of indicators for screening soil quality/health, Doran et al. (1999) list extractable nutrients N, phosphorus, potassium, since "they provide information on plant available nutrients and potential loss from soil…providing indication of productivity and environment quality". Measurement of extractable nutrients may provide indication of a soil's capacity to support plant growth; conversely, it may identify critical or threshold values for environmental hazard assessment (Dalal and Moloney 2000). Nutrient cycling, especially N, is intimately linked with soil organic C cycling (Weil and Magdoff 2004), and hence drivers of climate change such as elevated temperatures, variable precipitation and atmospheric N deposition are likely to impact on N cycling (see Chap. 6) and possibly the cycling of other plant available nutrients such as phosphorus and sulphur, although direction and exact magnitude of change in plant available nutrients need to be investigated in detail.

2.4 Soil Biological Properties, Soil Health and Climate Change

"While the chemistry (and physics) of the soil system provides the context… it is the soil biota which is adaptive to changes in environmental circumstances" (Kibblewhite et al. 2008). Under conditions of climate change, biological indicators form an integral component in soil health assessment, since, by virtue, they involve complex *adaptive* systems (i.e. the biota) by integrating key soil processes in ways that other indicators do not (Ritz et al. 2009; see Chap. 8 for a detailed overview).

Ritz et al. (2009) note that published information on potential biological indicators has shown an almost exponential increase since the 1970s; however, many of these publications cover a range of processes, for example, microbial, invertebrate or ecological processes. Consequently, a comprehensive explanation of the factors including formal criteria identifying a collective set of biological indicators is limited. Key biological indicators selected for the scope of this study include SOM and its constituents, soil C, respiration and soil microbial biomass. Other microbiological indicators will also be briefly discussed.

2.4.1 Soil Organic Matter

SOM comprises an extensive range of living and non-living components; it has been widely acknowledged that SOM is one of the most complex and heterogeneous components of soils, which vary in their properties, functions and turnover rates (Weil and Magdoff 2004). It is considered an important attribute of soil quality (or soil health) due to the many functions it provide and/or support, including the contribution to the charge characteristics of soils, a sink for and source of C and N, and to a variable extent regulates phosphorus and sulphur cycling, possesses an ability to complex with multivalent ions and organic compounds, provides microbial and faunal habitat and substrates, as well as affecting aggregate stability, trafficability, water retention and hydraulic properties (Haynes 2008; Weil and Magdoff 2004). Main indicators for evaluating SOM status include: SOC, since it comprises about 50% of SOM; organic N, since it is closely associated with organic C and is the most important nutrient for plant productivity; and readily mineralisable C and N (Gregorich et al. 1994; Haynes 2008; see Chaps. 5 and 6).

As SOM drives the majority of soil functions, decreases in SOM can lead to a decrease in fertility and biodiversity, as well as a loss of soil structure, resulting in reduced water holding capacity, increased risk of erosion and increased bulk density and hence soil compaction (Weil and Magdoff 2004). Land use and management practices that lead to build up of SOM will help in absorbing CO_2 from the atmosphere, thus mitigating global warming. By increasing water storage, SOM can play an important role in the mitigation of flooding impacts following extreme rainfall events, while storing water in the event of droughts thus increasing soil resilience.

SOM indicators have been used in long-term soil experiments for the assessment of climate change (Richter et al. 2007; Rinnan et al. 2007), although the response of SOM to elevated temperature remains scientifically controversial and without consensus (Ågren and Wetterstedt 2007; see Chap. 5). In general, increases in temperature have been reported to enhance decomposition of SOM, but rising temperature and precipitation, CO_2 fertilisation and atmospheric N deposition may support high plant productivity and organic matter input to soil and consequently increase SOM. According to Davidson and Janssens (2006) and Kuzyakov and Gavrichkova (2010), it is the accessibility and availability of SOM to microorganisms that govern SOM losses rather than the rate-modifying climate factor (i.e. temperature).

2.4.2 *Soil Carbon*

Soil C can be used as an indicator of change for a number of reasons: it is familiar, direct, linked to ecosystem performance and it has “memory”, that is, changes across time; however, it may not be reliable as a solitary indicator of soil quality/health, as it may not encompass all ecosystem traits (Janzen 2005). While soil contains C in diverse forms and residence times, considerable research attention has focused on the SOC form, since it (1) has been largely modified through human activities, and (2) is predicted to decline with increase in mean global temperatures, which would have adverse effects on important soil functions and processes and soil quality/health (Lal et al. 2007). However, in his review on the role of soil C in the changing global C cycle, Janzen (2005) proposed that “if soil C is to be used as an indicator of ecosystem performance, we may need to rethink how it is measured and interpreted... since, although we have been measuring soil C for a long time, our methods were not developed to measure changing C stocks". Since then substantial progress has been made, especially in geospatial and geostatistical methodologies to measure soil C across the landscape and over time (Allen et al. 2010; Worsham et al. 2010).

2.4.3 Light Fraction and Macro-Organic Matter (Labile Organic Matter)

Light (or low-density) fraction and macro-organic components of SOM consist mainly of mineral-free particulate plant and animal residues, which serve as readily decomposable substrate for soil micro-organisms, as well as a labile nutrient reservoir (Gregorich et al. 1994; Post and Kwon 2000; Wagai et al. 2009). Since light fraction and macro-organic matter are responsive to management practices, they may act as early indicators to measure the effectiveness of changing management practice in adaptive response to climate change (Gregorich et al. 1994). For example, the labile soil organic C is rapidly depleted as the temperature rises (Davidson and Janssens 2006; Knorr et al. 2005). In addition, elevated CO_2 in the future may reduce sequestration of root-derived soil C, a major source of labile, light fraction C (Heath et al. 2005).

2.4.4 Potentially Mineralisable C and N

The amount of mineralisable organic matter in soil is an indicator of organic matter quality, acting as the interface between autotrophic and heterotrophic organisms during the nutrient cycling process (Gregorich et al. 1994). While potentially mineralisable C and N may be measured in both the field and laboratory, it is generally treated as a relative rather than an absolute value due to inconsistencies in methods (Haynes 2008). However, mineralisable organic matter may be a useful indicator to assess soil health under climate change, since it affects nutrient dynamics within single growing seasons, and may be used to compare management regimes and C sequestration over extended periods of time (Gregorich et al. 1994).

2.4.5 Soil Respiration

Soil respiration is often used as a biological indicator for soil health (see Chap. 7), since it is positively correlated with SOM content (and often with microbial biomass and activity) and can be determined as either CO_2 production or O_2 consumption, e.g. "soil" or "basal" respiration, using a range of in situ or laboratory methods (Dalal and Moloney 2000; Arias et al. 2005; Haynes 2008). Soil respiration, particularly its temperature response (often expressed as the Q_{10} function), is widely acknowledged to be a critical link between climate change and the global C cycle (Wixon and Balser 2009), although the nature of this relationship is under current scientific debate (Ågren and Wetterstedt 2007; Balser et al. 2006; Kuzyakov and Gavrichkova 2010; also see Chap. 7). Recent studies have also shown that soil respiration is relatively responsive to changes in the seasonal timing of rainfall (see Chap. 7), which is predicted to change according to global and regional climate models (Chou et al. 2008).

2.4.6 Soil Microbial Biomass

Microbial biomass, the living component of SOM, is considered the most labile C pool in soils and a sensitive indicator of changes in soil processes, with links to soil nutrient and energy dynamics, including mediating the transfer between SOC fractions (Haynes 2008; Post and Kwon 2000; Saha and Mandal 2009; Weil and Magdoff 2004). While it has been compared to related soil properties to determine change in SOM quality (Gregorich et al. 1994), its use as an indicator of soil quality or soil health is currently limited due to unavailability of benchmark values, difficulty in interpretation and cost-effectiveness of measurement procedures (Dalal 1998). However, soil microbial biomass, similar to labile C, has been shown to be responsive to short-term environmental changes (Haynes 2008), with recent studies revealing significant decline in the soil microbial biomass during long-term simulated climatic warming experiments (Rinnan et al. 2007). When combined with ^{13}C isotope labelling technique, the shift in microbial biomass ^{13}C may provide a more sensitive measure of changes in soil C processes in response to climate and land use changes than the total microbial biomass C (Paterson et al. 2009).

2.4.7 The Use of Microbial and Metabolic "Quotients"

In addition to individual biological indicators, ecophysiological indices or "quotients" have also been used to assess environmental change. Indices of physiological performance (e.g. respiration, growth/death, C uptake) against the total organic C or total microbial biomass C per unit time are expressed as microbial quotient (microbial C/organic C), and respiratory or metabolic quotient (CO_2-C respired/hr/microbial C), respectively, and have been used to assess management impacts on organic C dynamics (Moscatelli et al. 2005).

While the effectiveness of these quotients to assess ecosystem disturbance and development has been questioned (Moscatelli et al. 2005), there are cases where these quotients have provided useful information on substrate quality and ecosystem response to stresses across different soil types and environments (Haynes 2008; Sparling 1997; Weil and Magdoff 2004). Their potential for use as soil health indicators to assess climate change impacts is also promising, with research under controlled Free Air CO_2 Enrichment and N fertilisation trials, reporting that both microbial and metabolic quotients were sensitive to changes due to elevated CO_2 and N fertilisation (Moscatelli et al. 2005).

2.4.8 Enzyme Activity

Soil enzyme activities may serve to indicate change within the plant-soil system, since these (1) are closely linked to the cycling of nutrients and soil biology, (2) are easily measured, (3) integrate information on both the microbial status and the physicochemical soil conditions, and (4) show rapid response to changes in soil management (Aon et al. 2001; García-Ruiz et al. 2009). Studies of individual enzyme activities report strong temporal and spatial variability, thus often leading to conflicting results (Aon et al. 2001; García-Ruiz et al. 2009). Furthermore, Dorodnikov et al. (2009) showed that by altering the quantity and quality of belowground C input by plants, elevated CO_2 may stimulate microbial enzyme activities, abundance of microbial enzymes and C turnover possibly affecting microbial community functioning in soil, and furthermore, the extent of stimulation of microbial enzyme activities may depend on soil aggregate size. In addition, atmospheric N deposition may affect extracellular enzymes, which are involved in SOC decomposition and nutrient cycling processes (Frey et al. 2004). It is still to be known how soil microbial enzyme activities involved in organic C turnover, nutrient cycling and greenhouse gas emissions will respond to the interactive effects of multiple global change drivers (such as climate change, land use change), thereby supporting the generalised view of their use as indicators of changes in soil health.

2.4.9 Other Microbiological Indicators as Integrative Indicators of Soil Health

Many other soil microbial properties may be considered with respect to soil health indicators; their inclusion within research literature is gaining popularity as more holistic definitions of soil health include soil and plant attributes and functionality, and as advances in microbiological techniques offer promising developments in the detection of soil health status (see Chap. 8). Other microbial indicators noted in the literature, although not included in the scope of this chapter, include microbial autotrophic nitrification, arbuscular mycorrhiza, community studies of soil macroand microfauna, and soil disease suppressiveness and plant disease incidence (for extended reviews, see Arias et al. 2005; Doran and Zeiss 2000; French et al. 2009; Kibblewhite et al. 2008; Pankhurst et al. 1997; Ritz et al. 2009).

2.5 Genetic and Functional Biodiversity of Soils, Soil Health and Climate Change

Soil community structure and function is a current theme for debate among soil scientists, particularly whether ecosystem functioning is influenced by biodiversity, and how the loss of microbial functional groups influences ecosystem functioning (Hunt and Wall 2002; Kibblewhite et al. 2008). Hunt and Wall (2002) note that much of the focus has been on aboveground systems to assess potential effects of climate change on plant biodiversity and biochemistry, although recent studies suggest that climatic stresses, such as warming, will have a profound effect on the rhizosphere, soil heterotrophic community structure and soil processes, including soil respiration, N mineralisation and ecosystem C functioning (Bardgett et al. 2008; Briones et al. 2009; see Chaps. 7 and 8). Changing climatic factors is also of concern due to possible evolutionary changes, which allow the spread of virulence factors and genes that aid in environmental survival (French et al. 2009). As molecular technique advancements continue to expand our understanding of microbial diversity and the conditions driving changes in microbial diversity and community structure (Arias et al. 2005; Prosser 2002), it is likely that the adoption of genetic and functional biodiversity indicators of soil health will increase, particularly within food web and nutrient cycling models, to improve predictions of climate change impacts on soil health (see Chap. 8).

2.6 Selection of Soil Health Key Indicators: Requirements and Conceptual Framework for In Situ Soil Health Assessment Under Climate Change

Many soil health indicators discussed above need prioritisation with regard to assessment of soil health under sustainable management practices and predicted climate change scenarios. Recent reviews have focused upon measurement of individual indicators or a suite of indicators to assess changes in soil health within a soil physical, chemical and/or biological context (Moebius et al. 2007; Zagal et al. 2009), although Stockdale and Watson (2009) note that work is needed to test existing indicator frameworks to guide management decisions, rather than simply to compare with the status quo.

The indicators of soil health are interlinked (Fig. 2.1) and so are the drivers of global change (land use change, elevated temperatures, elevated atmospheric

CO_2 concentration, increasing atmospheric N deposition, variability in the amount, intensity and distribution of rainfall, extreme climatic events, and their interactions). Conceptualisation of interactions between climate change, land management and soil health indicators, as presented in Fig. 2.1, further highlights the complexity and interdependence of many of these drivers to influence soil health, primarily through their influence on plant primary productivity, microbial and faunal biomass diversity and activity, including their products (intracellular and extracellular enzymes), as well as the overall C and N cycles (Bardgett et al. 2008; Kibblewhite et al. 2008; Wixon and Balser 2009; see Chaps. 6 and 8).

Table 2.1 presents a summary of major soil health indicators, their processes and functions under projected climate change scenarios, their relevance to climate change impacts and their frequency of inclusion within a minimum data set for soil health assessment. Most studies agree that a minimum data set for the assessment of soil health should include key indicators that: (1) are sensitive to changes due to management and climate variations, (2) integrate soil physical, chemical and biological properties, (3) are relatable to important soil functions, (4) are applicable to field conditions and (5) are accessible to many users (Idowu et al. 2009; Karlen et al. 2003; Lagomarsino et al. 2009; Pattison et al. 2008; Rao and Siddaramappa 2008; Schindelbeck et al. 2008). The selection of key indicators of soil health under climate change scenarios, as discussed in this chapter, should be able to reflect the mitigation and adaptive capability of soil and its resilience to climate change over short to long term.

2.7 Summary and Future Directions

Understanding soil health impacts in relation to climate change is possible through the use of indicators (measurable attributes or values) which relate soil physical, chemical and biological properties to ecological functions and which can be monitored in the context of sustainable land management and climate change. Key soil health indicators affected by climate change include aggregate stability, SOM, carbon and nitrogen cycling, microbial biomass and activity, and microbial fauna and flora diversity. Selection of indicators within a minimum data set depends on their sensitivity to management and climate changes, capacity to integrate and relate to other soil functions, ease of use, repeatability and cost of measurement. Soil health "tests" recommending a minimum data set of soil health indicators are being promoted within research and government organisations for agricultural management (e.g. Nelson et al. 2009; Pattison et al. 2008) and to assist monitoring efforts and policy development (Ritz et al. 2009; Schindelbeck et al. 2008). This minimum dataset could be used to assess the effect of climate change on soil health. Although tentative steps are underway, greater efforts are required to explore individual and interactive effects of drivers of global change (e.g. land use change, increasing temperatures, elevated CO_2 concentration, variability in the amount, intensity and distribution of rainfall, and increasing atmospheric N deposition) using controlled environment and long-term research experiments to assess soil health indicators that can be responsive to such treatment variations over wider spatiotemporal scales, and consequently, their monitoring and inclusion in a minimum data set can assist us in devising greenhouse gas mitigation and climate adaptive strategies.

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