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Soil Quality and Soil Health: A Review

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ABSTRACT

Soil health and soil quality are defined as the capacity of soil to function as a vital living system within land use boundaries. This function which sustains biological productivity of soil also maintains the quality of surrounding environment and human health. Thus the two terms are used interchangeably although it is important to distinguish that, soil quality is related to soil function, whereas soil health presents the soil as a finite non-renewable and dynamic living resource. In this review, we deal with soil health concept which includes interactions between plant inputs and soil in creating a healthy environment. Adverse effects on soil health and soil quality arise from nutrient imbalance in soil, excessive fertilization, soil pollution and soil loss processes that are increasingly becoming common in developing countries. This review will examine the development of soil health approaches as well as the content of soil health and soil quality information and its application to reduce negative impacts on agricultural productivity and long term sustainability.

Key Words: Soil Functions, Soil Indicators, Soil Quality Indices, Soil Organic Carbon, Carbon Management Index

INTRODUCTION

Soil, like air and water, is a fundamental natural resource supporting a variety of ecosystem goods and services to the benefit of the mankind. While production function of soil was recognized long back, importance of conservation and enhancement of ecosystem services rendered by soil (e.g., carbon sequestration, water purification, recharge of ground water, control of populations of pathogens, biological nitrogen fixation and biodiversity conservation) has been realized only in the recent past. A concern for maintaing/improving soil quality arose long after that for water and soil. Soil processes are such that soil has been considered as an ecosystem by itself rather than a component of ecosystem. While criteria, indicators and standards of water and air quality are unambiguous and universally accepted, the concept of soil quality, further elaborated as soil health is still evolving, with soil quality legislations framed so far only in a few countries (Filip 2002, Nortcliff 2002)

MEANING OF SOIL QUALITY AND SOIL HEALTH

Soil quality can be defined as the fitness of a specific kind of soil, to function within its capacity and within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation (Karlen et al. 1997, Arshad and Martin 2002). Consideration of soil as a finite and living resource, led to the concept of soil health defined as the continued capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, maintain or enhance the quality of air and water, and promote plant, animal and human health (Doran et al. 1996, 1998, Doran and Zeiss 2000). Though the use of soil health has emerged in recent years, variation in ability of soils to suppress plant diseases is known since many decades (Janvier et al. 2007). Baker and Cook (1974) described the suppressive soils in which disease severity or incidence remains low, in spite of the presence of a pathogen, a susceptible host plant and climatic conditions favourable for disease development. Another concept linked to soil suppressiveness is the concept of soil receptivity to diseases addressing the role of soil factors in determining the expression of inoculum density and pathogenic capacity of the inoculum or intrinsic aggressivity of the inoculum in terms of appearance or severity of the disease (Linderman et al. 1983). Arbuscular mycorrhizal fungi not only improve crop nutrition but also protect crops from pathogens and toxic substances (Jeffries et al. 2003). Further, a soil rich in organic carbon and nutrients (considered commonly as high quality soils) may not be considered to be a healthy soil if it causes injury to crops or supports large parasite populations (Abawi and Widmer 2000). van Bruggen and Semenov (2000) viewed soil health as a dimension of ecosystem health and explained soil health as the resistance and resilience of soil in response to various stresses and disturbances. Thus, there is a considerable degree of overlap in the meaning of soil quality and soil health (Doran 2002), though soil health perceptions tend to focus more on biotic components of soil (Anderson 2003). Soil degradation or deterioration in soil health or quality implies loss of the vital functions of soil: (i) providing physical support, water and essential nutrients required for growth of terrestrial plants; (ii) regulation of the flow of water in the environment and (iii) elimi-nation of the harmful effects of contaminants by means of physical, chemical and biological processes, i.e., environmental buffer or filter (Constanza et al. 1992a,b, Bastida et al. 2006). The quality and health of soil determine agricultural sustainability and environmental quality, which jointly determine plant, animal and human health (Haberern 1992, Doran 2002). Minor variations in articulation and expression of soil functions are evident in the available literature (Tables 1 and 2).

MULTIPLE FUNCTIONS OF SOILS: **Looking Beyond Soil Fertility and Productivity**

Soil performs multiple functions: (i) providing physical support to terrestrial plants, (ii) supplying fundamental resources viz., water, nutrients and oxygen required for

Table 1. A profile of soil functions

Karlen et al. (1997)	Constanza et al. (1992b), Bastida et al. (2006)	Harris et al. (1996)	Kelting et al. (1999)	Andrews et al. (2004)	Nortcliff (2002)
Accommodate water entry	Meeting the requirements of plant growth (physical support, water and nutrients)	Provide plant nutrients	Store, supply and cycle nutrients	Nutrient cycling	Provide physical, chemical and biological setting for living organisms
Retain and supply water to plants	Regulation of flow of water in the environment		Accept, hold and supply water	Water relations	Regulate and partition water flow, storage and recycling of nutrients and other elements
Resist degradation	Environmental buffer or filter	Resist erosion		Physical stability and support	Filter, buffer, degrade, immobilise and detoxify organic and inorganic substances
Support plant growth		Provide a favourable root environment	Promote root growth	Filtering and buffering	Support biological activity and diversity for plant growth and animal productivity, and provide mechanical support for living organisms and their structures
			Promote gas exchange	Resistance and resilience	
			Promote biological activity	Biodiversity and habitat	

Table 2. Ecological functions of soil (FAO 1995) and their indicators

Ecological Functions of Soil	Indicators of Proper Functioning
Production function	High levels of crop yields and incomes
Biotic environmental function/living space function	High levels of species richness and functional dominance of beneficial organisms – High levels of crop yields and incomes and high quality food and habitation
Climate-regulative function/storage function	High levels of carbon stocks and slow rates of greenhouse gas emissions
Hydrologic function	Adequate availability of water/reduced risks floods
Waste and pollution control function	High levels of crop yields and incomes and high quality food and habitation
Archive or heritage function	
Connective space function	

terrestrial primary production, (iii) providing habitat to a variety of soil organisms, with taxonomic identity and functions of several organisms still unknown/lesser known to the scientific and wider community, (iii) regulating hydrological and mineral/nutrient cycling, with significant impacts on global climate, (iv) detoxification of organic and inorganic substances, leading to purification of water resource and (v) resisting erosion. A given soil function is achieved through several mechanisms/processes and a given mechanism/process may contribute to several functions. Thus, litter decomposition and mineralization contribute to detoxification as well as nutrient supply/agricultural production functions of soil. The overall assessment about whether a soil is good or bad depends on the objective of assessment and the net outcome of different soil processes and functions in given conditions. Thus, a soil may supply huge quantities of nutrients supporting high primary production but may not provide suitable habitats to many soil organisms, e.g., cropping soon after deforestation using agrochemicals. One may get high crop productivity but with contamination of water and infected food products, a situation of high production but low detoxification function. In situations where low agricultural productivity is the one and the only problem faced by the mankind, one may ignore functions of soil other than production function (i.e., capacity of soil to supply water, nutrients and oxygen and to reduce crop yield losses due to pests and diseases). However, in the present widespread scenario of multiple problems (including increased levels of greenhouse gases in the atmosphere, soil erosion and land degradation, production of infected crop products, depletion and pollution of water resources, and depletion of biodiversity), there is a need of addressing multiple functions of soil in an objective manner. The concept of soil quality/health is essentially an elaboration of the concept of soil productivity/fertility to deal with the multiple and complex problems faced by the world today. This perspective of optimizing multiple functions makes soil health an integral dimension of agroecosystem health and sustainable development.

The soil functions can be weighted according to the relative importance of each function in fulfilling the management goals based on expert opinions (Masto et al. 2007). Regulation of each function is determined by a large number of soil attributes and a single attribute or a statistical/mathematical derivative of several attributes (in the form of an index) can be viewed as an indicator of one or more soil functions if a systematic relationship exists between the attribute(s) or its derivative with the soil functions. As a single measurable soil attribute is unlikely to be correlated with soil function(s) and measurement of 'all' soil attributes is not practical, one needs to draw a minimum number of indicators (minimum data set). Many soil indicators in the minimum data set interact with each other, and thus, values of one is affected by one or more of these selected parameters (Tables 3 and 4).

Scientific relevance of an indicator of soil quality/health depends on (i) its sensitivity to variations in soil management, (ii) good correlation with the beneficial soil functions and other variables which are difficult to access or measure, (iii) helpfulness in revealing ecosystem processes (iv) comprehensibility and utility for land managers, i.e., utility of the indicator as a benchmark in land use decision making (v) cheap and easy to measure (Parisi et al. 2005). Karlen et al. (1997) listed the desired features of indices or indicators as (i) easy to measure parameters, (ii) rapid/less time consuming

Table 3. Key soil indicators for soil quality assessment (after Arshad and Coen 1992, Doran and Parkin 1994, Gregorich et al. 1994, Larson and Pierce 1991, Carter et al. 1997, Karlen et al. 1997, Martin et al. 1998)

Selected indicator	Rationale for selection
Organic matter	Defines soil fertility and soil structure, pesticide and water retention, and use in process models
Topsoil-depth	Estimate rooting volume for crop production and erosion
Aggregation	Soil structure, erosion resistance, crop emergence an early indicator of soil management effect
Texture	Retention and transport of water and chemicals, modeling use
Bulk density	Plant root penetration, porosity, adjust analysis to volumetric basis
Infiltration	Runoff, leaching and erosion potential
pH	Nutrient availability, pesticide absorption and mobility, process models
Electrical conductivity	Defines crop growth, soil structure, water infiltration; presently lacking in most process models
Suspected pollutants	Plant quality, and human and animal health
Soil respiration	Biological activity, process modeling; estimate of biomass activity, early warning of management effect on organic matter
Forms of N	Availability of crops, leaching potential, mineralization/ immobilization rates, process modeling
Extractable N, P and K	Capacity to support plant growth, environmental quality indicator

Table 4. Interrelationship of soil indicators (based on Arshad and Martin 2002)

Selected indicator	Other soil quality indicators in the MIDS affecting the selected indicator
Aggregation	Organic matter, microbial (especially, fungal) activity, texture
Infiltration	Organic matter, aggregation, electrical conductivity, ex-changeable sodium percentage (ESP)
Bulk density	Organic matter, aggregation, topsoil-depth, ESP, biological activity
Microbial biomass	Organic matter, aggregation, bulk density, pH, texture, ESP and/or respiration
Available nutrients	Organic matter, pH, topsoil-depth, texture, microbial parameters (mineralization and immobilization rates)

methods, and (iii) high sensitivity of parameters to detect differences on a temporal and spatial scales. Soil quality indicators would be useful to farmers and planners only if we know their critical limits, i.e., the desirable range of values of a given indicator that must be maintained for normal functioning of the soil. The critical limits would vary depending on the goal of management within an ecoregion. Most crops grow over a pH range of 6.5 to 7.0. Reduction in yields of alfalfa and blueberries occur when pH drops below 6.5 in case of the former and 4.0 in case of the latter crop (Doll 1964). Generalization about critical limits are difficult as critical limit of a soil indicator can be ameliorated or exacerbated by limits of other soil properties and the interactions among soil quality indicators (Arshad and Martin 2002). Based on farm level studies in Phillipines, Gomez et al. (1996) considered an indicator to be at a sustainable level if it exceeds a designated trigger or threshold level; thresholds are tentatively set based on the average local conditions.

SOIL QUALITY INDICES

Soil quality indices are decision tools that effectively combine a variety of information for multi-objective decision making (Karlen and Stott 1994). A number of soil quality and fertility indices have been proposed (Stefanic et al. 1984, Beck 1984, Karlen et al. 1998, Trasar-Cepeda et al. 1998, Andrews et al. 2002), none identifies state of soil degradation that affects its functionality. Bastida et al. (2006), building on the approach of Andrews et al. (2002), suggested microbiological degradation index. While many workers appreciated and recommended the use of soil quality indices, reservations about their utility also expressed. Many a times the concepts associated with soil quality are used in close association with the concepts of sustainability, leading to a degree of confusion and inappropriate use of the term soil quality (Sojka and Upchurch 1999). Even though the importance of evaluation of soil quality is being increasingly realized, there is yet no global consensus on how this should be defined. While the notion of soil quality includes soil fertility, soil productivity, resource sustainability and environmental quality in the USA, soil contamination is the focus in Canada and much of western Europe (Singer and Ewing 1998). Sojka and Upchurch (1999) suggest that the search for a single, affordable, workable soil quality index is unattainable

Selection of soil quality indicators or synthetic indices is guided by the goal of ecosystem management. If achieving sustainability is the goal of agroecosystem management, a soil quality index will constitute one component within a nested agroecosystem sustainability hierarchy (Figure 1). Management goals may also differ by the interests and visions of different sections of people concerned with agriculture (Table 5).

Once the management goals are identified, soil quality indexing involves three steps: (i) selection of soil properties/indicators constituting the minimum data set (ii) transformation of indicator scores enabling quantification of all indicators to a common measurement scale and (iii) combining the indicator scores into the index (Figures 2 and 3). Selection of soil properties/indicators of soil quality and their statistical/mathematical treatment to derive a composite index vary a lot (Tables 6 and 7).

Velasquez et al. (2007) stressed the importance of identifying sub indicators (e.g., macrofauna, organic matter, physical quality, chemical quality and soil morphology) reflecting different aspects of soil quality. Statistical tools such as principal component analysis, multiple correlation, factor analysis, cluster analysis and star plots may be used to select the variables for inclusion in index, avoiding the possibilities of disciplinary biases in expert opinion based approaches (Bachmann and Kinzel 1992, Doran and Parkin 1996). A careful consideration of sampling intensity and inherent variability of different soil attributes is required while combining several soil attributes as one synthetic index. Warrick and Nielsen (1980) report that 2,110 and 1,300 samples were required to achieve the same level of precision in estimation of bulk density, percent clay and hydraulic conductivity. A huge degree of spatio-temporal variation within a given land use/ecosystem is observed in soil microbial properties and micronutrients by many workers (Parkin 1993, Khan and Nortcliff 1982).

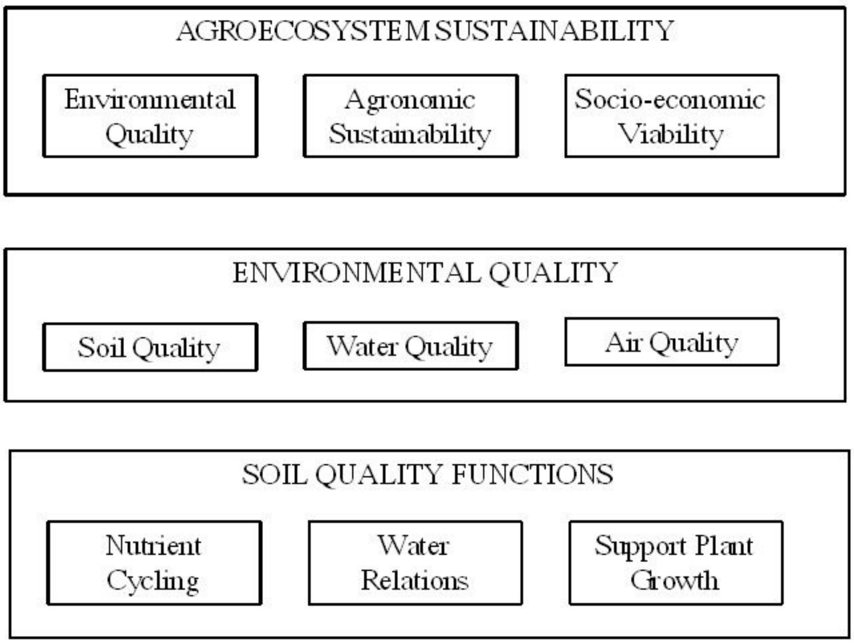

Figure 1. Nested hierarchy of agroecosystem sustainability showing the relationship of soil quality to the larger agroecosystem.

Table 5. Goals of agroecosystem management in Uttarakhand Himalaya

Interest group	Goals
Forestry experts	Reduction in dependence of farmers on forests for their fodder, manure (forest leaf litter) and fuelwood needs
	Farmers' participation in checking fires in forests
	Farmers' participation in avoiding killing the wildlife, even in cases of crop and livestock depredation by wildlife
	Conservation of traditional agrobiodiversity
	Reducing the rates of conversion of forest to agricultural land use
	Promotion of income generating activities contributing to and not competing with the goal of forest conservation
Farmers	Income from farm produce after securing local food needs
	Production of healthy food, particularly in terms of absence of any disease/pest symptoms on edible parts
	Control of white grub population
Agricultural policy planners	Promotion of organic farming – use of vermicomposting
	(Organic farming programme of Uttarakhand government)
	Conversion of rainfed to irrigated farming
	Introduction of new crops – tea, kiwis, apple etc
	Promotion of chemical fertilizers and pesticides (IFFCO adopted villages)
Economic policy planners	Promotion of off-farm means of livelihood – income from secondary and tertiary sectors
	Promotion of market based food security

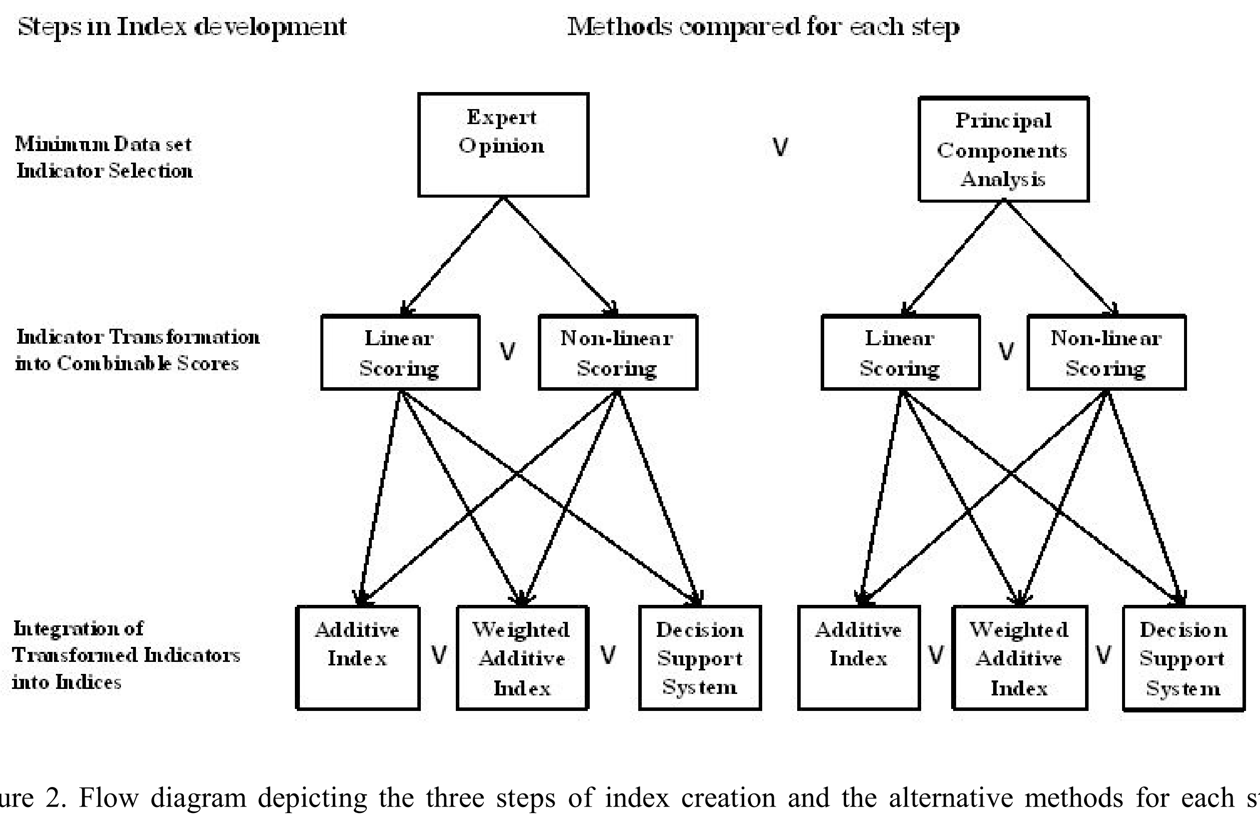

Figure 2. Flow diagram depicting the three steps of index creation and the alternative methods for each step compared in this study

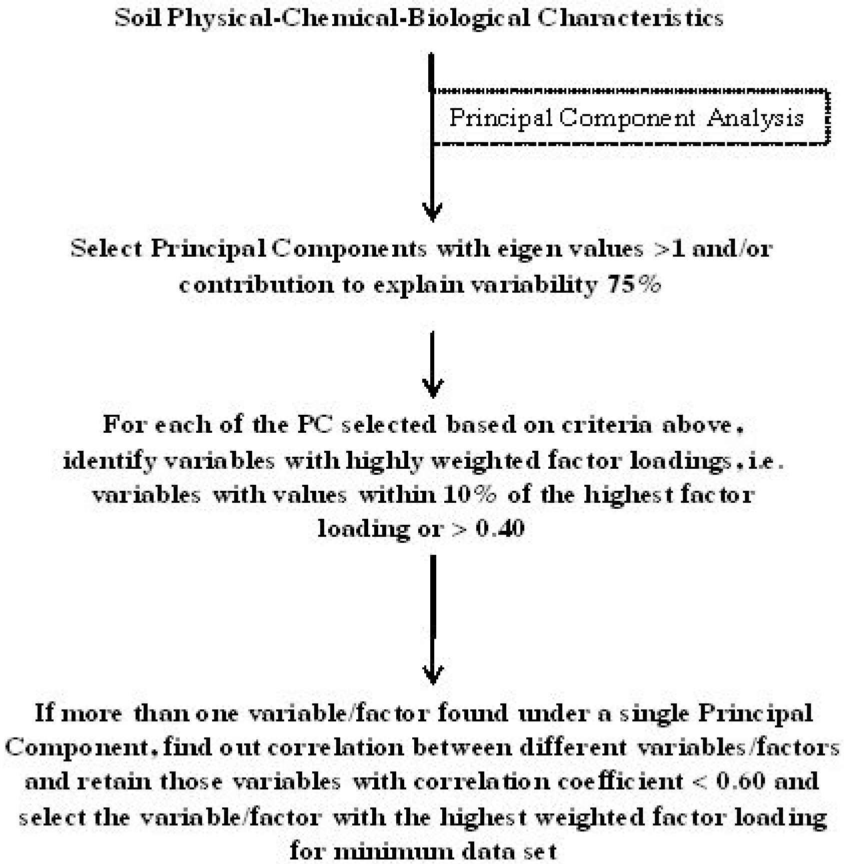

Figure 3. Approach to selection of variables/factors for minimum data set (from Andrews et al. 2002)

Data Compression

Principal Component Analysis (PCA) is a data compression technique designed for data that are in the form of continuous measurements, though it has been also been applied to other kind of data such as presence/ absence of an element or measurements in the form of discrete variables. Ordination, a collective term for multivariate techniques that arrange sites along axes on the basis of soil properties can help to show whether important environmental variables have been overlooked. Ordination is like a linear regression model, but with the major difference that the explanatory variables here are theoretical variable and not known environmental variables (Jongman et al. 1995). Principal Components (PCs) for a data set are defined as linear combinations of the variables that account for maximum variance within the set by describing vectors of closest fit to the n observations in p-dimensional feature space, subject to being orthogonal to one another. The PCA output gives as many PCs as the input variables but it is assumed that PCs receiving high eigenvalues (setting a threshold, e.g., eigenvalues > 1) or those explaining variation in the data exceeding a limit (e.g., > 5% of the variability) are 'important' and not the others (Kaiser 1960, Wander and Bollero 1999). Contribution of a variable to a particular PC is represented by a weight or factor loading. Only the highly weighted variables are retained from each PC and highly weighted factor loadings identified based on thresholds such as those variables with absolute values within 10% of the highest factor loading or > 0.4. When more than one factor is retained under a single PC, multivariate correlation coefficients are employed to determine if variables could be considered redundant and if the variables are correlated, that with the highest value is chosen for multi dimensional scaling (MDS) (Andrews and Carroll 2001, Andrews et al. 2002).

Table 6. Selection of soil properties in a cross section of studies

Reference	Soil Properties
Andrews et al. (2002)	Comparison of conventional, low input and organic agroecosystems EC*, ExCa, ExK, ExMg, Moisture, NH_4-N, NO_3-N, pH, PLFA, Pot min N, SAR, Soluble P, SOM, TN, TOC, TS, Zn
Masto et al. (2007)	Long term fertilizer experiments Porosity, Bulk density, WHC, CEC, pH, EC, SOC, TN, NH_4-N, NO_3-N, AvP, ExK, AvS, AvZn, AvCu, AvMn, AvFe, MBC, P fixing capacity, K fixing capacity, Dehydrogenase, Phosphatase
Valasquez et al. (2007)	17 groups of macro fauna, ExP, Total P, ExK, ExCa, ExMg, ExNa, pH, Bulk density, Real density, Moisture, Shear strength, Penetration resistance, Aggregation (small, medium and large aggregates), TC, TN, NH_4-N, NO_3-N, Mineralization, Density factions of SOC
Bastida et al. (2006)	Microbiological degradation index EC, pH, TN, AvP, ExK, TOC, Water soluble C, Water soluble carbohydrates, MBC, Respiration, ATP, Dehydrogenase, Urease, Protease, Phosphatase, Glocosidase
Sparling et al. (2004)	Soil quality indicators Total C, Total N, PH, ExCa, ExMg, ExK, ExNa, Base saturation, Soil respiration, Microbial biomass C, Mineralizable N, Bulk density, Particle density, Saturated and non-saturated hydraulic conductivity, Readily available water, Macro porosity, Total porosity, Olsen P, Aggregate stability
Sparling and Schipper (2002)	Key soil properties Total C, Total N, Mineralizable N, pH, Olsen P, Bulk density, Macroporosity
Sangha et al. (2005)	Soil health attributes in pastures C, pH, Nitrate, Microbial biomass C, Microbial biomass N

* EC - Electrical conductivity; PLFA - Phospholipid fatty acids; SOM - Soil organic matter; TN - Total nitrogen; TOC - Total organic carbon; WHC - Water holding capacity; CEC - Cation exchange capacity; MBC - Microbial biomass carbon; SAR - Sodium absorption ratio; SOC - Soil organic carbon; TS - Total solids. Prefix Ex - Exchangeable and Av - Available.

Data Transformation

The selected indicators can be transformed following a linear or a non-linear scoring rule. For 'more is better' indicators, each observation is divided by the highest observed value such that the highest observed value received a score of 1. For 'less is better' indicators, the lowest observed value (in the numerator) is divided by each observation (in the denominator) such that the lowest observed value receives a score of 1. For some indicators, observations are scored as 'higher is better' up to a threshold value and as 'lower is better' above the threshold (Leibig et al. 2001). The values of different variables can be transformed to a common range, between 0.1 to 1.0 with homothetic transformation (Velasquez et al. 2007):

$$y = 0.1 + (x-b)/(a-b) * 0.9$$

where, y = value of the variable after transformation, x = the variable to transform, a = the maximum value of the variable, and b = the minimum value of the variable

Non-linear scoring functions are constructed based on literature review and consensus of the collaborating researchers. Masto et al. (2007) used the following equation for deriving non-linear scores:

$$\text{Non-linear score } (y) = 1/1+e^{-b\,(x-a)}$$

where, x = soil property value, a = the baseline or value of the soil property (the scoring function equals 0.5 and equals the midpoint between the upper threshold value and the lower threshold value), and b = slope.
The upper threshold value is the soil property value for which the score equals 1 and which corresponds to the most favourable level. The lower threshold value is the soil property value where the score equals 0 and which corresponds to an unacceptable level. Baselines are generally regarded as the minimum target values.

Table 7. Selected studies dealing with soil quality indices

Author	Index used/proposed
Andrews et al. (2002)	Indices based on parameters related to entrance of water and plant growth
Bastida et al. (2006)	Microbiological index of soil degradation – dehydrogenase, water soluble carbohydrates, urease, water soluble carbon and respiration
Beck (1984)	EAN – more enzyme activities (dehydrogenase, phosphatase, protease and amylase)
Dilly and Blume (1998)	As many as ten parameters
Doran and Parkin (1994)	Index based on sustainable production, environmental quality and human and animal health
Doran and Parkin (1994)	Soil quality index = function of (food and fibre production, erosivity, groundwater quality, surface water quality, air quality and food quality)
Kandeler and Eder (1993), Gil-Stores et al. (2005)	Simple indices – quotients between enzymatic activity and microbial biomass
Kang et al. (2005)	Microbial index of soil (CHECK) based on microbial biomass C and N, potentially mineralisable N, soil respiration, bacterial population, mycorrhizal infection, and dehydrogenase and phosphatase activities
Karlen et al. (1994)	Soil quality index based on four soil functions: ability of soil to accommodate water entry, retain and supply water to plants, resist degradation and support plant growth
Klein and Paschke (2000)	Total/active fungal and bacteria ratio – the ratio of total to active fungal plus bacterial biovolume is divided by the ratio of the active fungal to bacterial biovolume
Parr et al. (1992)	Soil quality index based on different functions: soil properties, potential productivity, environmental factors, human and animal health, erodibility, biological diversity, food quality and safety and management inputs
Parr et al. (1992)	Soil quality index = function of (soil properties, potential productivity, environmental factors, human/ animal health, erodibility, biological diversity, food quality/safety and management input
Puglisi et al. (2005)	Soil alteration index
Stefanic et al. (1984)	Biological index of soil fertility based on activity of two enzymes – dehydrogenase and catalase
Trasar-cepeda et al. (1998), de la Paz-Jimenez et al. (2002)	Indices/equations based on parameters that reflect the total content of N or organic C
Harris et al. (1996)	Soil quality index based on three soil functions: ability to resist soil erosion, provide plant nutrients and provide a favourable root environment
Velasquez et al. (2007)	General indicator of soil quality based on abundance of 17 groups of macrofauna, eight soil chemical properties (extractable P, total P, exchangeable K, Mg, Ca, Na and pH, six physical properties (bulk density, real density, porosity, moisture content, shear strength, penetration resistance, soil morphological features and organic C fractions

Data Integration

There are basically two ways of integrating indicators to derive one soil quality index – by summing the scores from MDS indicators and by summing MDS variables after weighting them by considering the % variation explained by a PC, standardized to unity, as the weight for variable(s) chosen under a given PC.

Soil Organic Carbon and Carbon Management Index

Soil organic matter serves as a primary indicator of soil quality and health for both scientists and farmers (Romig et al. 1995, Komatsuzaki and Ohta 2007). Gadja et al. (2001) have demonstrated the utility of particulate and total soil organic matter as indicator of soil quality and in assessing the sustainability of conventional and alternative management systems in the US Central Great Plains. As carbon sink capacity of the world's agricultural and degraded lands is 50-66% of the historic carbon loss of 42-72 Pg, soil management offers a significant scope of sequestration of atmospheric carbon (Lal 2004). Kapkiyai et al. (1999) explained the utility of labile fraction of soil organic carbon as an indicator of soil quality and fertility. Each metabolic activity of organisms is dependent on available carbon sources and soil microbial carbon : total organic carbon ratio could be developed to a site-specific baseline value for different soil systems (Anderson 2003). Several researchers have observed a decline in soil organic matter with increasing agricultural land use intensity and duration (Dalal and Mayer 1986, Golchin et al. 1995, Spaccini et al. 2001, Lemenih et al. 2005) due to changes in soil structure caused by tillage, removal of biomass and increased mineralization and decomposition of exposed soils (Oldeman et al. 1990). Mann (1986) found soil C in cultivated soil on average 20% less than uncultivated soils and the greatest rate of change during the first 20 years after land use change based on analysis of soil data from 50 different sources. The magnitude of decline in soil carbon depends on the soil depth used for carbon estimations and time scale of land use change. Davidson and Ackerman (1993) found mean carbon loss of 30% if both A and B horizons were considered as compared to 40% if only A horizon was considered. However, such a decline is more prominent in labile carbon fractions, which are highly correlated with soil microbial biomass and the availability of labile nutrients such as nitrogen, phosphorus and sulfur, than in total soil organic matter. Impacts of altered land management may be reflected in terms of loss of the labile fractions or soil microbial biomass but not in terms of that of the total SOC (Powlson et al. 1987, Blair et al. 1995, Sangha et al. 2005, Collard and Zammit 2006). Based on a 6-year trial of soil quality monitoring in New Zealand, Sparling et al. (2004) did not find utility of microbial biomass and soil respiration as measures of soil quality because of difficulty in ephemeral nature of such biological measurements and the difficulty in justifying their target ranges. However, microbial biomass has been shown to be correlated with anaerobically mineralized C and thus the latter may be a surrogate for the former (Hart et al. 1986, Stockdale and Rees 1994). While soil organic C and N have been measured in virtually all soil quality measurement methods, there is little evidence to show that organic matter contributes to yield on irrigated and fertilized croplands (Sojka and Upchurch 1999).

The loss of SOC following conversion of natural ecosystems to agroecosystems occurs at rates much faster than the rates of recovery following abandonment of agricultural land use. Knops and Tilman (2000) estimated a period of about 250 years for total recovery of carbon to pre-agricultural levels after abandonment in a continental climate. Though some estimates on critical levels of SOC are available (e.g., Greenland et al. (1975) considered 2% of SOC as the minimum requirement for maintenance of satisfactory soil aggregate stability and above which no further increases in productivity are achieved (Janzen et al. 1992), the quantitative basis for such thresholds is limited (Loveland and Webb 2003). Janssen and de Willigen (2006) considered 6 g kg^{-1} of soil organic carbon as the minimum limit to prevent collapse of soil structure of sandy loams and showed that this level cannot be maintained by roots and stubble alone if maize yield is below 7-8 Mg ha^{-1}. Prasad et al. (2003), with particular reference to the Indian agriculture, considered soils with organic carbon (%) values < 0.5 as low fertility soils, 0.5 to 0.75 as medium fertility soils and > 0.75 as high fertility soils. Magdoff (1998) reported potential crop yield increases by 12% for every 1% of soil organic matter based on his studies in USA. There has been no consensus on what the critical level of soil organic matter should be in an agricultural soil and how this level will vary between soils of different textural classes under different environmental conditions (Nortcliff 2002). While increase in organic matter is desirable from the point of view of its contribution in terms of improvement in soil aggregation, it may be undesirable if such an increase coupled with an increase in application requirement of soil incorporated pesticides and in more rapid flow through soils with consequent rapid transport of applied nutrients and other soil amendments (Stevenson 1972, Ross and Lembi 1985, Sojka and Upchurch 1999). Further, as high levels of soil organic matter and manure may enhance P solubility in the water and result in nutrient loss if soil is easily eroded (Robinson and Sharpley 1995, Sharpley and Smith 1995).

Chemically labile carbon fractions include a variety of organic substances, e.g., water soluble carbon (carbon extracted in distilled water, 1:5 solid : liquid, shaken for 2 hrs), water soluble carbohydrates (carbohydrates in above solution) (Brink et al. 1960, Bastida et al. 2006). Labile fractions, microbial biomass, dehydrogenase activity and ATP levels may be highly correlated (Nannipieri et al. 1990, Garcia et al. 1994). In general, bacteria contribute more in terms of decomposition of labile/soluble components of residues and fungi of the resistant (lignocellulose) component. Microbial biomass consists of both dormant and metabolically active organisms and has been considered as an integrative indicator of microbial significance of soils (Powlson 1994). However, variation in soil microbial biomass may not be necessarily correlated to soil quality (Martens 1995, Dilly and Munch 1998).

Soil organic matter, the primary source and temporary sink for plant nutrients and soil organic carbon in agroecosystems has been considered as the best surrogate for soil health (Dumanski and Pieri 2000). The impacts of land management practices are marked in terms of variation in labile fraction of organic carbon or microbial quotients than in total soil organic carbon (Breland and Eltun 1999). Thus, an index derived from both labile and non-labile carbon fractions is likely to be a more sensitive indicator of land use intensification or land management practices compared with a single measure of soil carbon content.

As a change in land use is coupled with change in bulk density, the method of calculation of soil carbon is also likely to influence the conclusion on land use change-carbon stock relationship. The most common method is to sample soil from similar depths in different land uses and express soil carbon stocks in terms of Mg C ha^{-1} using bulk density values. An alternative method is to measure bulk density first and then to calculate the sampling depths to obtain the same mass (dry soil) of soil in different land uses (Ellert and Gregorisch 1996). Similarly three distinct types of approaches could be adopted to quantify the change: (i) repeated measurements on a single site (ii) paired sites and (iii) chronosequences where neighbouring sites experienced land use change at different times in the past, each having its own limitations and advantages (Murty et al. 2002). As labile fractions respond to seasonal variations more than total soil organic carbon (Bastida et al. 2006), sampling season need to be carefully considered while using labile organic carbon as an indicator of soil quality.

Adoption of United Nations Framework for Convention on Climate Change was followed by development of procedures to quantify the flux of greenhouse gas inventories (IPCC 1997). The procedure suggested for calculating soil carbon amounts following a land use change was:

$$Cm = Cn * B * T * I$$

where,
Cm = the amount of soil carbon some time after land use change;
Cn = the amount of soil carbon under the original native vegetation;
B = base factor, with values varying from 0.5 to 1.1 depending on environmental factors and the type of agricultural activities following the transition and the lowest values referring to long-term cultivated aquic soils or degraded land in the tropics and the highest values to improved pasture and rice paddies;
T = tillage factor which takes on higher values (1.1) for no tillage and lower values for full tillage (0.9-1.0);
I = input factor accounting for different levels of input from different residue management systems varying between 0.8 for shortened fallow under shifting cultivation to 1.2 for high input systems, such as those receiving regular fertilizer additions.

Assumptions are made in inventorying national greenhouse gas emissions. Australian National Greenhouse Gas Inventory assumes that 30% of soil C is lost in conversion to unimproved pasture and 10% is gained in conversion to improved pasture (Kirschbaum et al. 2000).

Blair et al. (1995) proposed Carbon Management Index (CMI), a multiplicative function of Carbon Pool Index (CPI) and Lability Index (LI) as an indicator of the rate of change of soil organic matter in response to land management changes, relative to a more stable reference soil:

Carbon Pool Index (CPI) =
Total C of a given land use/
Total C of the reference land use

Lability Index (LI) =
[Labile carbon content of a given land use/Non-labile carbon content of a given land use] * [Labile carbon content of the reference land use/Non-labile carbon content of the reference land use]

Carbon Management Index (CMI) = CPI * LI * 100

Collard and Zammit (2006) extended this concept and initially applied at ecosystem/land use type scale to landscape scale. They calculated 'landscape CMI' as sum of the products of multiplication of the CMI values of different land uses differentiated in a landscape by the relative areas (%) of different land uses.

Enzymes As Indicators of Organic Matter Quality and Microbial Activity

Soil enzyme assays generally provide a measure of the potential activity, i.e., that encoded in the genotype, but this will rarely be ever expressed. Further, there are at least 500 enzymes and one has to decide as to which enzymes would be the best indicators of soil quality (Schloter et al. 2003). Three enzymes viz., phosphomonoesterase, chitinase and phenol oxidase, as a group reflect relative importance of bacteria and fungi, as well as the nature of organic matter complex (Giai and Boerner 2007). Phosphomonoesterase (acid phosphatase) activity is often correlated with microbial biomass (Clarholm 1993, Kandeler and Eder 1993), fungal hyphal length (Haussling and Marschner 1989) and nitrogen mineralization (Decker et al. 1999). Chitinase is a bacterial enzyme which converts chitin, a substance intermediate in its resistance to microbial metabolism produced by fungi and arthropods, into carbohydrates and inorganic nitrogen (Hanzlikova and Jandera 1993). Phenol oxidase is produced primarily by white rot fungi, and is specific for highly recalcitrant organic matter, such as lignin (Carlisle and Watkinson 1994).

Soil Microbiological Degradation Index (MDI)

Computation of this index involves : (i) selection of appropriate parameters, e.g., total organic carbon, water soluble carbon, water soluble carbohydrates, microbial biomass carbon, respiration, ATP, dehydrogenase, urease, protease, phosphatase and beta-glucosidase acitivity estimated by methods given in Brink et al. (1960), Vance et al. (1987), Garcia et al. (1997), Kandeler and Gerber (1988), Nannipieri et al. (1980) and Tabatabai and Bremmer (1969) as detailed in Bastida et al. (2006), (ii) transformation and weighting of values and (iii) combining the scores into an index. Factor analysis can be used to identify the most important parameters. As absolute values of some parameters are bigger than those of others, the values of the selected parameters are normalized (Glover et al. 2000). The MDI is the sum of the normalized and weighted values of the most important parameters.

General Indicator of Soil Quality (GISQ)

Soil organisms and biotic parameters (e.g., abundance, diversity, food web structure, or community stability) meet most of the desired criteria of soil quality indicators (Doran and Zeiss 2000). According to Schloter et al. (2003), the use of faunal groups as indicators for soil quality needs a choice of organisms, that (a) form a dominant group and occur in all soil types, (b) have high abundance and high biodiversity and (c) play an important role in soil functioning, e.g., food webs. Velasquez et al. (2007) developed a general indicator of soil quality (GISQ) based on estimation of around 50 soil properties related to macrofauna, chemical fertility, physical state, organic matter fractions and soil morphology. The computational procedure involved four steps: (i) PCA analysis of the variables allowing testing of the significance of their variation among land use types; (ii) identification of the variables that best differentiate the sites according to the soil quality; (iii) creation of sub-indicators of soil physical quality, chemical fertility, organic matter, morphology and soil macrofauna, with values ranging from 0.1 to 1.0; (iv) combination of all five subindicators into a general one. This indicator allows the evaluation of soil quality and facilitates identification of problem areas through the individual values of each subindicator (Velasquez et al. 2007).

A faunal group, such as nematodes, is likely to be effective indicator of soil quality if it is dominant and occurs in all soil types, has high abundance and high biodiversity and plays an important role in soil functioning, e.g., in food webs. Some indicators provide limited interpretations of soil quality, e.g., soil enzyme assays generally provide a measure of the potential activity which is rarely expressed. Based on a 6-year trial of soil quality monitoring in New Zealand, Sparling et al. (2004) did not find utility of earthworms as a measure of soil quality because of difficulty in ephemeral nature of such biological measurements and the difficulty in justifying their target ranges.

QBS (Qualita Biologica del Suolo) Index

The methods of characterizing soil quality based on microfauna fall in two groups: those based on general evaluations of microarthropods (Parisi 2001) and those based on the evaluation of a single taxon (Bernini et al. 1995, Paoletti and Hassal 1999, Parisi 2001). Difficulties in classification of organisms at species level has a major constraint delimiting use of indicators based on soil organisms, more so the microfauna. A collembola expert is expected to analyse 5 samples a day and a nematode expert two samples a day (Ekscmitt et al. 2003). As a means of overcoming this constraint, Parisi et al. (2005) proposed the QBS (Qualita Biologica del Suolo, meaning biological quality of soil) index values based on evaluation of microarthropods' level of adaptation to the soil environment life rather than the species richness/diversity. Reduction or loss of pigmentation and visual apparatus, streamlined body form, with reduced and more compact appendages, reduction or loss of flying, jumping or running adaptations and reduced water retention capacity (e.g., by having thinner cuticle and lack of hydrophobic compounds) are some of the adaptations of microarthropods to soil environment (Parisi 1974). Thus, instead of identifying organisms by species, distinguishes the morphotypes varying in terms of their degree of adaptation to soil quantified as eco-morphological score. As a general rule, eu-edaphic (i.e., deep soil-living) forms get a score of 20, epi-edaphic forms (surface living forms) of 1. Groups like Protura and Diplura have a single value of 20, because all species belonging to these groups show a similar level of adaptation to soil (Parisi et al. 2005).

Vegetation Attributes as a Surrogate to the Soil Quality

Another alternative to reduce the cost and time involved in sampling and classifying soil organisms is to find out (i) environmental parameters which are expected to regulate soil fauna composition, e.g., climate, soil and vegetation characteristics and (ii) measures inherent to soil fauna community itself, such as higher taxon richness, indicator taxa and maximum dominance. Ekschmitt et al. (2003) found that environmental variables could explain only 34-60% of the variance in soil animal richness, while the remaining variation remained unexplained. Coefficient of variation of soil animal richness between replicate samples was as high as 60% in many cases indicating a high degree of independence of richness from environmental condi-tions. The poor correlation between soil animal community and environmental factors could be explained as due to significant influence of autogeneous dynamics of the population under consideration, interaction of this population with predators, parasites and competitors and by presently indiscernible past conditions (Salt and Hollick 1946). Ekschmitt et al. (2003) concluded that a rough guess of soil faunal diversity can be cost-effectively derived from environ-mental data while an estimate of moderate quality can be obtained with reduced taxonomic efforts. Gillison et al. (2003) found highly significant positive correlations between species richness of all termites and mean canopy height, woody plant basal area, ratio of plant richness to plant functional types, while there was no significant correlation between individual plant and termite species.

Soil Fertility, Land Quality and Farm Level Environmental Indicators

Land quality indicators represent generic directives for the functional role of land, indicating condition and capacity of land, including its soil, weather and biological properties, for purposes of production, conservation and environmental management (Parisi et al. 2005). Land quality indices integrate factors and processes that determine land quality (Bindraban et al. 2000). A soil test is a chemical method for estimating the nutrient-supplying capacity of a soil and has an edge for biological methods of evaluating soil fertility in that it can be done rapidly and before the crop is planted (Tisdale et al. 1985). Soil quality thus could be viewed as a component of land quality and the most useful soil or land quality index is the one that is able to provide early warning of adverse trends and to identify problem areas. Dumanski and Pieri (2000) have listed four key characteristics of land quality indicators: (i) measurable in space, i.e., over the landscape and in all countries (ii) reflect change over recognizable time periods (5-10 years) (iii) showing relationships with independent variables (iv) quantifiable and usually dimensionless. Further, practical utility of an indicator derives from cost effectiveness and precision of its measurement and availability of an interpretative framework to translate it in terms of identifying sustainable management practices (Carter et al. 1999, Sparling and Schipper 2002, Sparling et al. 2004). Bindraban et al. (2000) elaborated two kinds of land quality indicators: (i) the yield gap indicator which is a measure of the difference between yields under optimum management conditions, i.e., potential yields determined by absorbed photosynthetic radiation under adequate supply of water and nutrients and crop protection, and actual yields of the 'most suitable crop' (Monteith 1990) (ii) soil nutrient balance indicator which measures the rate with which soil fertility changes which are estimated as net differences between nutrient inputs (mineral fertilizer, organic fertilizer, wet and dry deposition, nitrogen fixation and sedimentation) and outputs (crop products, crop residues, leaching, gaseous losses and soil erosion integrated over a certain area and time (Stoorvogel and Smaling 1990).

Classical soil fertility rating is a function of the crop response to added nutrients and fertilizers recommendations are primarily based on expected financial returns from the crop from applied nutrients rather than an integrated consideration of the costs and benefits of the outcomes of fertilizer addition, e.g., of environmental cost associated with leaching and volatilization of added fertilizers (Smaling et al. 1999, Oenema et al. 2003). Janssen (1999) gave the concepts of target soil fertility (also referred as ideal soil fertility by Janssen and de Willigen (2006) and target soil fertility (Table 8).

Table 8. Concepts related to soil fertility of agricultural systems

Target soil fertility (also referred as ideal soil fertility)	Fertility at which the soil is characterized by neutral nutrient balances
Saturated soil fertility	Fertility at which the soil by itself does exactly satisfy the nutrient demand of a crop producing the target yield, provided no nutrients get lost.
Equilibrium fertilization or replacement input	Nutrients in the harvested component of the crop producing target yield, which is the maximum possible yield or potential yield, as determined by the genetic properties of the crop cultivar, irradiance and temperature (van Ittersum and Rabbinge 1997).
Uptake efficiency of added nutrients/ Recovery Fraction	(Nutrient in stover + grains derived from the input) / (Input)
Physiological efficeincy	Yield of grains/uptake in grain and stover
Agronomic efficiency	Recovery Fraction x Physiological Efficiency, i.e., the yield increment per unit of added nutrients

Janssen and de Willigen (2006) presented Ideal Soil Fertility-Saturated Soil Fertility framework integrating the concepts of plant physiology, agronomy and soil chemistry, that explicitly takes sustainable soil fertility, environmental protection and balanced plant nutrition as starting points unlike most existing fertilizer recommen-dations based on the economics of fertilizer use. While we have accumulated significant knowledge about soil fertility targets required for obtaining high crop yields (Roberts and Morton 1999, Clarke et al. 1986), there is scant knowledge on target ranges required for avoiding off-site environmental impacts such as eutrophication of water bodies. Soil macroporosity below 10% (v/v) is reported to decrease pasture production but if this threshold is true for other land uses is not known in New Zealand (Sparling et al. 2004).

Green accounts or input-output accounts are based on a set of indicators to express the degree of environmental impact from a farm based on the use external inputs in relation to the production and/or use of specific management practices (Goodlass et al. 2001). Increasing interest in such accounts as farm level environmental indicators seem to derive from a hypothesis that such voluntary systems for environmental improvement of farms may supplement mandatory regulation and those farmers by benchmarking against each other using the indicators will increase their awareness of possible environmental improvements. Halberg (1998) distinguished control indicators (those based on farmers' management practices) and state indicators (those based on recordings of consequences for the farming system). van der Werf and Petit (2002) distinguished means-based versus effect-based farm level environmental indicators and argued that means-based indicators were not likely to be effective in promoting positive changes in farming practices like organic farming or integrated farming that have been defined a priori as sustainable.

CONCLUSIONS

Although many indicators and indices of soil quality and soil health have been proposed (Table 9), a globally acceptable and applicable definition and methodology of assessment of soil quality or soil health are still not in place. Further, the existing knowledge provides a better understanding of the current capacity of a soil to function than of making predictions about capacity of the soil to continue to function under a range of stresses and disturbances. Another limitation of most of the available studies is that efforts have been made to measure soil characteristics in surface soil and not in the whole profile (Sparling et al. 2004). While simultaneous analysis of physical, chemical and biological characteristics of soil is required to evaluate sustainability/ unsustainability of different management practices, most studies in developing countries have looked at physical and chemical characteristics only.

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