Soil quality and health: a review

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1. Introduction

Soil, as air and water, is a fundamental resource required for meeting the diverse needs of humans. The concerns about deterioration of soil quality have been raised long after those related to deterioration of water and air quality. Thus the changed perception of the importance of soil in terms of its ability to perform environmental funcitons in addition to the more widely recognised production function has arisen against a background where there has long been an understanding of the importance water and air (Nortcliff, 2002) . The International Standardisation Organization (ISO) established a Technical Committee in 1985 to consider the development of methodologies for monitoring the quality of soil (Hortensius and Nortcliff, 1991; Hortensius and Welling, 1996). While desired water and air quality indicators are explicitly defined in legislations in the country and elsewhere, those defining soil quality are not yet in place except in a few countries, e.g., Federal Soil Protection Act put in force in 1999 in Germany (Filip, 2002).

2. 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 (Arshad and Martin, 2002). Soil health has been broadly defined as the capacity of a living soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health (Doran et al., 1996, 1998). Soil quality is related to soil functions and soil health concepts views soil as a finite and dynamic living resource (Doran and Zeiss, 2000). Plant health is clearly a component of soil health but necessarily not of soil quality (Karlen et al., 1997). 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 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, as suppressive soils. Soil biota like arbuscular mycorrhizal fungi play a significant role in improving plant nutrition but also act as bioprotectants against pathogens and toxic substances (Jeffries et al., 2003). Further, a soil rich is 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) elimination of the harmful effects of contaminants by means of physical, chemical and biological processes, i.e., environmental buffer or filter (Constanza et al., 1992; 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 and ther are evident in the available literature (Table 1, 2).

3. Multiple functions of soils

The soil functions can be weighted according to the relative importance of each function in fulfilling the management goals based on expert opinions. For example, in long term fertility experiments where sustaining crop productivity is the major goal, sustaining crop productivity was given the highest weighting factor of 0.3 followed by plant nutrient supply and resistance to biochemical degradation (0.2 to each of the two functions), facilitation of movement and storage of water (0.15), resistance to surface degradation and accommodation to water entry (0.05) (sum of all weighting factors = 1) (Masto et al., 2007). Regulation of each function is determined by a large number of soil attributes and a single attribute or a statistical/mathematic derivative of several attributes (in the form 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 (Table 3, 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, (iii) helpfulness in revealing ecosystem processes (iv) comprehensibility and utility for land managers (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 methods (iii) high sensitivity of parameters to detect differences on a temporal and spatial point scale. 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.

4. 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 have appreciated and recommended the use of soil quality indices, reservations about their utility have also been 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 realised, 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 visons 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 (Figure 2, 3). Selection of soil properties/indicators of soil quality and their statistical/mathematicl treatment to derive a composite index vary a lot (Table 6, Table 7).

Velasquez et al. (2007) stressed the importance of identifying subindicators (e.g., macrofauna, organic matter, physical quality, chemical quality and soil morphology) reflecting different aspects of soil 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 sampling intensity and inherent variability of different soil attributes is required while combining several soil attributes as one synthetic index. Warrick and Nielsen (1990) report that 2, 110 and 1300 samples were required to achieve the same level of precison 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).

4.1. 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 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 > 0.40. 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 MDS (Andrews et al., 2001, 2002).

4.2. Data transformation

The selected indicators can be transformed following a linear or a non-linearing 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 (Lebig 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
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:

Non-linear score (y) = 1/1+e-b(x-a)

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

4.3. 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.

5. 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 ration 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 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 mirobial 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 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 anerobically 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 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 levls 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 achieve (Janzen et al., 1992), the quantitative basis for such thresholds is limited (Loveland and webb, 2003). Janssen and Willigen (2006) considered 6 g/kg 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 t/ha. 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 of 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 undersirable if such an increase in couple with an increase in application requirement of soil incorporated pesticides and in more rapid flow of through soils with consequent rapid transport fo 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; Garcial 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 for 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 t carbon/ha using bulk density values. An alternative method is to measure bulk density first and then to calculate the sampling depths in different land uses 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 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 faloow under shifting cultivation to 1.2 for high input systems, such as those receiving regular fertilizer additions.

Assmptions are made in inventorying national greenhouse gase 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 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.

5.1. 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 decide as to which enzymes would be the best indicators fo soil quality (Schloter et al., 2003). Three enzymes viz., phosphomonoesterase, chitinase and phenol oxidase, as a group reflect relative importance of bacterial 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).

6. 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.

7. 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 critera of soil quality indicators (Doran and Zeiss, 2000). According to Schloter et al. (2002), the use of fanual 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, the conditions fulfilled by nematodes. 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 rom 0.1 to 1.0; (iv) combinataion 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).

Desired features of indices or indicators (i) easy to measure parameters (ii) rapid/less time consuming methods (iii) high sensitivity of parameters to detect differences on a temporal and spatial point scale (Karlen et al., 1997). A faunal group, such as nematodes, is likely to be effective indicator of soil quality if it forms a dominant group 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. Further, there are at least 500 enzymes participating in the C and N cycles and it is difficult to know as to which enzymes are most relevant for soil quality characterization (Schloter et al., 2003). 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.

8. QBS 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. (2000) proposed the QBX (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).

9. 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). 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 conditions. 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 environmental data whicle 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.

10. 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 (Pieri et al., 2000). 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 timbe 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 precion of its measurement and availability of an interpretative framework to translate it in terms of identifying sustainable management practices (Carter et al., 1999; Schipper and Sparling, 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 Willigen, 2006) and target soil fertility (Table 8).

Janssen and 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 recommendations based on the economics of fertilizer use. While we have accumulated significant knowledge about soil fertility targets required for obtaining high crop yields (During, 1984; 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 Newzealand (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 that 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.

11. Conclusions: Limitations

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 analysis of physical, chemical and biological characteristics of soil simultaneously is required to evaluate sustainability/ unsustainability of different management practices, most studies in developing countries have looked at physical and chemical characteristics only.

12. References

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Table 1. A profile of soil functions listed by different authors

Karlen et al. (1994)	Constanza et al., 1992; Bastida et al., 2006	Harris et al. (1996)	Ketling 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 susbstances
Support plant growth		Provide a farourable 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 organims 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	

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, 1994; 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 and/or respiration	Organic matter, aggregation, bulk density, pH, texture, ESP
Available nutrients	Organic matter, pH, topsoil-depth, texture, microbial parameters (mineralization and immobilization rates)

Table 5. Goals of agroecosystem management in Uttarakhand Himalaya (Maikhuri et al., unpublished)

Interest group	Goals
Forestry experts	Reduction in dependence of farmers on forests to meet 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 development 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 development policy planners	Promotion of off-farm means of livelihood – income from secondary and tertiary sectors
	Promotion of market based food security

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

Andrews et al. (2002)	Masto et al. (2007)	Velasquez et al. (2007)	Bastida et al. (2006)	Sparling et al. (2004)	Sparling and Schipper (2002)	Sangha et al. (2005)
Comparison of conventional, low input and organic agroecosystems	Long term fertilizer experiments		Microbiological degradation index	Soil quality indicators	Key soil properties	Soil health attributes in pastures
EC	porosity	17 groups of macro fauna	EC	total C	total C	Total organic C
Ex Ca	bulk density	Ex P	pH	Total N	total N	pH
Ex K	WHC	Total P	TN	pH	mineralizable N	Nitrate
Ex Mg	CEC	Ex K	Avail P	exch Ca	pH	Microbial biomass C
Moisture	pH	Ex Ca	Ex K	exch Mg	Olsen P	Microbial biomass N
NH4-N	EC	Ex Mg	TOC	exch K	bulk density	
NO3-N	SOC	Ex Na	Water soluble C	exch Na	macroporosity	
pH	TN	pH	Water soluble carbohydrates	base saturation		
PLFA	NH4-N	Bulk density	MBC	*soil respiration		
Pot min N	NO3-N	Real density	Respiration	*micobial biomass C		
SAR	Av P	Moisture	ATP	mineralizable N		
Soluble P	Ex K	Shear strength	Dehydrogenase	bulk density		
SOM	Av S	Penetration resistance	Urease	particle density		
TN	Av Zn	Aggregation (small, medium and large aggregates)	Protease	*saturated and non saturated hydraulic conductivity		
TOC	Av Cu	TC	Phosphatase	readily available water		
TS	Av Mn	TN	Glocosidase	total available water		
Zn	Av Fe	NH4-N		macro poprosity		
	MBC	NO3-N		total porosity		
	P fixing capacity	Mineralization		Olsen P		
	K fixing capacity	Density fractions of SOC		Aggregate stability		
	Deydrogenase				*not suitable because of high variability, high cost and/or lack of an interpretative framework	
	Phosphatase					

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) and 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 sour 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 funagal and bacteria ratio – the ratio of total total to active fungal plus bacterial biovolumes 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 prameters 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

Table 8. Concepts related to soil fertility of agricultural systems

Target soil fertility (also referred as ideal soil fertility)	Fertilityat 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 efficiencey	Recovery Fraction x Physiological Efficiency, i.e., the yield increment per unit of added nutrients

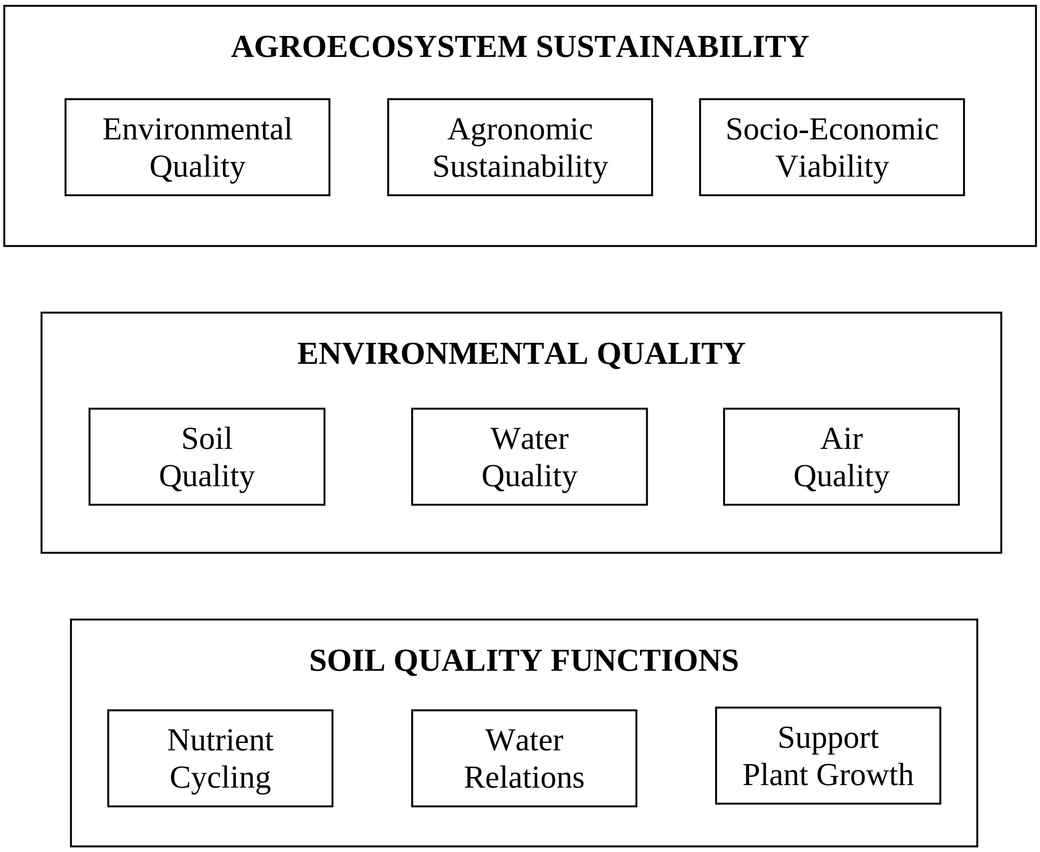

Fig. 1 Nested hierarchy of agroecosystem sustainability showing the relationship of soil quality to the larger agroecosystem.

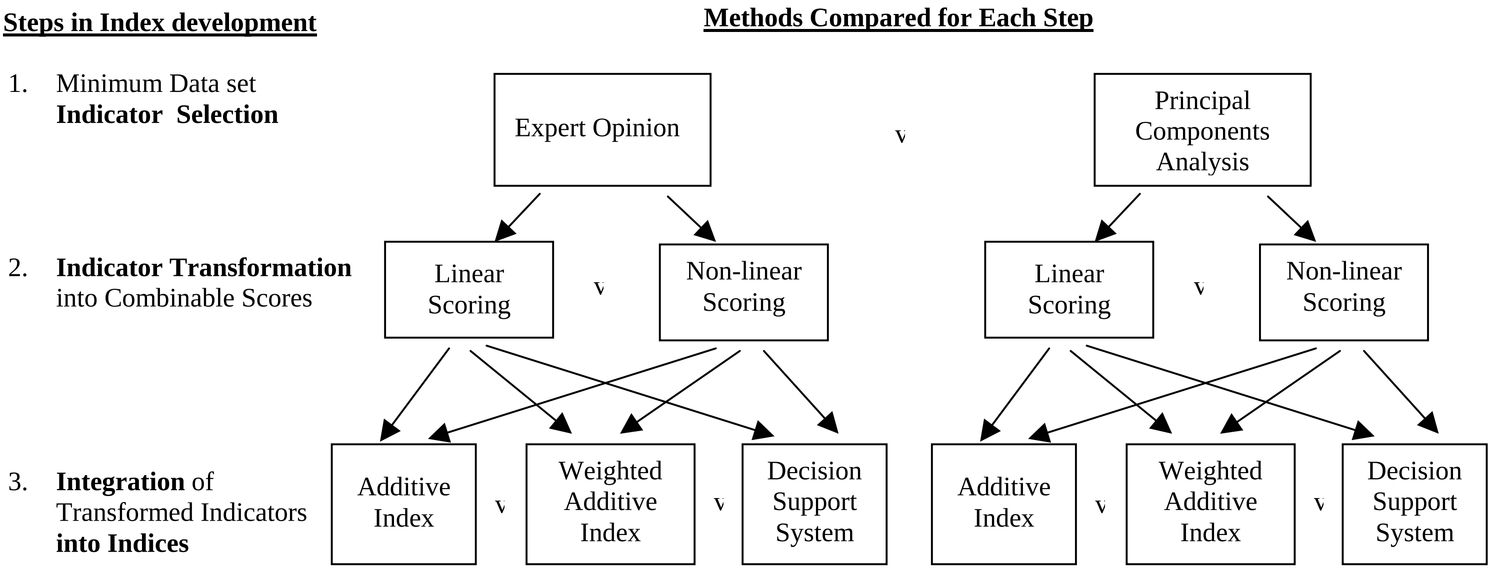

Fig. 2. Flow diagram depicting the tree steps of index creation and the alternative methods for each step compared in this study.

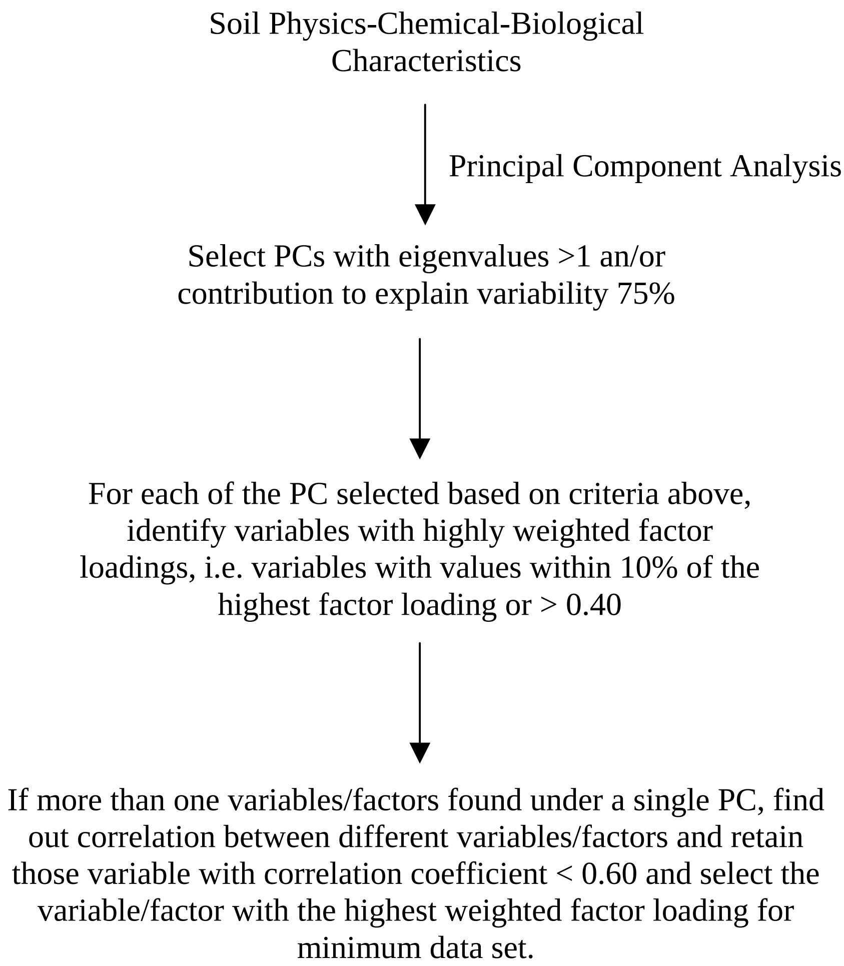

Fig. 3. Approach to selection of variables/factors for minimum data set (Andrews et al., 2002)