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SOIL HEALTH AND SOIL QUALITY: A REVIEW

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BACKGROUND

Soil health is defined as the continued capacity of soil to function as a vital living system, by recognizing that it contains biological elements that are key to ecosystem function within land-use boundaries (Doran and Zeiss, 2000; Karlen et al., 2001). These functions are able to sustain biological productivity of soil, maintain the quality of surrounding air and water environments, as well as promote plant, animal, and human health (Doran et al., 1996).

The concept of soil quality emerged in the literature in the early 1990s (Doran and Safely, 1997; Wienhold et al., 2004), and the first official application of the term was approved by the Soil Science Society of America Ad Hoc Committee on Soil Quality (S-581) and discussed by Karlen et al., (1997). Soil quality was been defined as ''the capacity of a reference soil to function, 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.'' Subsequently the two terms are used interchangeably (Karlen et al., 2001) although it is important to distinguish that, soil quality is related to soil function (Karlen et al., 2003; Letey et al, 2003), whereas soil health presents the soil as a finite non-renewable and dynamic living resource (Doran and Zeiss, 2000).

For the purpose of this review, we will preferably rely on the soil health concept, since it directly includes interactions between plant inputs and soil in creating a healthy environment. Because of the numerous alternative uses of soil as a living resource, the meaning of the terms soil health and soil quality depend on the defined purpose such as for agricultural use (Andrews and Carroll, 2001; Doran and Parkin, 1994). In agriculture, we mainly pay attention to plant and animal productivity as these would be of greatest importance in cultivated soils (Doran et al., 1996a) as opposed to urban soils (Idowu et al., 2007). More comments on the meaning of these terminologies and the context in which they are applied can be found by examining the contributions of Doran and Zeiss, (2000)

Protection of soil quality under intensive land use and fast economic development is a major challenge for sustainable resource use in the developing world (Doran et al., 1996b). The basic assessment of soil health and soil quality is necessary to evaluate the degradation status and changing trends following different land use and smallholder management interventions (Lal and Stewart, 1995). In Asia, adverse effects on soil health and soil quality arise from nutrient imbalance in soil, excessive fertilization, soil pollution and soil loss processes (Zhang et al., 1996; Hedlund et al., 2003). In Africa, three-quarters of farm land is severely degraded (Eswaran et al., 1997; Stocking 2003). As a result, Africa cannot produce enough food to keep pace with its needs, and per capita

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food production is declining (Lal et al., 1997; Lal, 1998) largely due to loss of soil health and soil quality. For the purpose of this review, we will focus on examining the development of soil health approaches as well as the content of soil health and soil quality information and its application to smallholder farmers across the tropics, with emphasis on Africa and Asia since these are the regions where loss in soil quality is expected to continue to negatively impact agricultural productivity and longterm sustainability.

THE SOIL HEALTH FRAMEWOK

The concept of soil health and soil quality has consistently evolved with an increase in the understanding of soils and soil quality attributes (Karlen and Stott, 1994). Soil quality cannot be measured directly, but soil properties that are sensitive to changes in management can be used as indicators (Andrews and Cambardella, 2004). Soil health indicators are needed that help smallholder farmers understand the chain of cause and effect that links farm decisions to ultimate productivity and health of plants and animals (cite). The soil health approach is better applied when specific goals are defined for a desired outcome from a set of decisions. Therefore we can think of the soil health soil quality as an evaluation process which consists of a series of actions:-

- Selection of soil health indicators
- Determination of a minimum data set (MDS)
- Development of an interpretation scheme of indices
- On-farm assessment and validation

Soil Health Indicators

The quality of soil is rather dynamic and can affect the sustainability and productivity of land use (cite). It is the end product of soil degradative or conserving processes and is controlled by chemical, physical, and biological components of a soil and their interactions (Papendick and Parr, 1992). Indicators, however, will vary according to the location, and the level of sophistication at which measurements are likely to be made (Riley, 2001). Therefore, it is not possible to develop a single short list which is suitable for all purposes (Table 1). Syers et al. (1995) also emphasized the range of likely indicators rather than the use of a single indicator.

1. Biological

Identification of biological indicators of soil quality is reported as critically important by several authors (Doran and Parkin, 1994; Abawi and Widmer, 2000) because soil quality is strongly influenced by microbiological mediated processes (nutrient cycling, nutrient capacity, aggregate stability). Of particular importance is to identify those components that rapidly respond to changes in soil quality (Romig et al., 1995). Biological indicators of soil quality that are commonly measured include soil organic matter, respiration, microbial biomass (total bacteria and fungi,) and mineralizable nitrogen. Soil organic matter plays a key role in soil function, determining soil quality, water holding capacity and susceptibility of soil to degradation (Giller and Cadisch, 1997; Feller et al., 2001). In addition, soil organic matter may serve as a source or sink to atmospheric CO_2 (Lal, 1997) and an increase in the soil C content is indicated by a higher microbial biomass and elevated respiration (Sparling et al., 2003). It is also the principal reserve of nutrients such as N in the soil and some tropical soils may contain large quantities of mineral N in the top 2m depth (Havlin et al., 2005).

2. **Chemical**

In order to achieve high crop yields smallholder farmers have to provide soil nutrients in large quantities (Sanchez and Swaminathan, 2005). Therefore it is possible to alter the pool of available nutrients by adding inorganic fertilizers, incorporating cover crops, and using other organic materials in form of manures and composts (Stocking, 2003). Results of chemical tests are soil quality indicators which provide information on the capacity of soil to supply mineral nutrients, which is dependent on the soil pH. Soil pH is an estimate of the activity of hydrogen ions in the soil solution. It is also an indicator of plant available nutrients. High activity is not desirable and the soil may require liming with base cations Ca or Mg in order to bring the solution back to neutral.

3. **Physical**

Soil physical properties are estimated from the soil's texture, bulk density (a measure of compaction), porosity, water-holding capacity (Hillel, 1982). The presence or absence of hard pans usually presents barriers to rooting depth. These properties are all improved through additions of organic matter to soils. Therefore, the suitability of soil for **s**ustaining plant growth and biological activity is a function of its physical properties (porosity, water holding capacity, structure, and tilth).

There are several criteria to consider when selecting soil health and soil quality indicators. In general, appropriate indicators should be:

- • easy to asses.
- • able to measure changes in soil function both at plot and landscape scales.
- • assessed in time to make management decisions.
- • accessible to many farmers.
- • sensitive to variations in agro-ecological zone.
- • representative of physical, biological or chemical properties of soil.
- • assessed by both qualitative and/or quantitative approaches.

Table 1 Summary of soil health indicators used to asses soil function

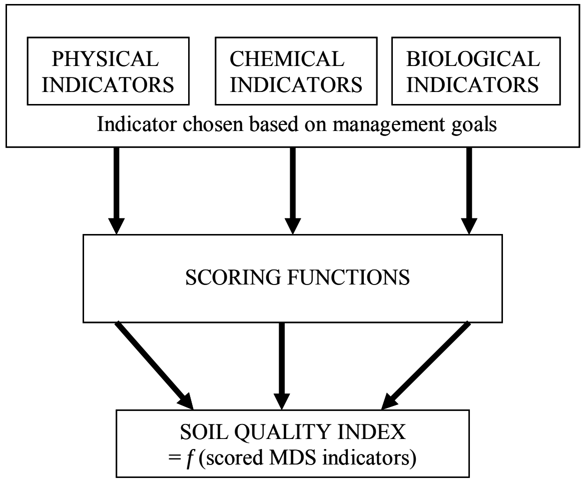
Indicator	Soil function
Soil organic matter (SOM)	Soil structure, stability, nutrient retention; soil erosion (Carter, 2002)
Physical: soil aggregate stability, infiltration and bulk density	Retention and mobility of water and nutrients; habitat for macro and micro fauna (Bengtsson, 1998; Swift et al., 2004)
Chemical: pH, extractable soil nutrients, N-P-K and base cations Ca Mg & K	Soil biological and chemical activity thresholds; plant available nutrients and potential for N and P as well as loss of Ca, g & K (Doran and Jones, 1996a; Drinkwater et al., 1996)
Biological: microbial biomass C and N; potentially mineralizable N	Microbial catalytic potential and repository for C and N; soil productivity and N supplying potential (Cadisch and Giller, 1997; Doran and Jones, 1996b)

In much of the literature, it is postulated that basic soil quality indicators should reflect criteria which are relevant to existing soil data bases (Doran and Parkin, 1994). Based on these propositions a list of basic soil properties that should be indicative of soil quality was established (Table 2). This list has been included in the MDS by Larson and Pierce (1994), and expanded with a few biological aspects of soil quality, namely microbial biomass C and N, and soil respiration by Doran and Parkin (1994).

Minimum Data Set: Concept and Application

A minimum data set (MDS) was proposed to measure soil quality and its changes due to management practices through selection of key indicators such as soil texture, organic matter, pH, nutrient status, bulk density, electrical conductivity and rooting depth (Larson and Pierce, 1994). Collecting a minimum data set helps to identify locally relevant soil indicators and to evaluate the link between selected indicators and significant soil and plant properties (Arshad and Martin, 2002). It is a minimum set of indicators required to obtain a comprehensive understanding of the soil attributes evaluated (Figure 1). More importantly they serve as a useful tool for screening the condition, quality, and health of soil (Doran et al., 1996; Larson and Pierce, 1994; and Doran and Parkin, 1994). For smallholder farmers these tools need to be simple measures of soil health and soil quality such as consistency, color and workability (Murage et al. 2000; Mairura et al., 2007). For extension and policy personnel, they provide basic information needed to arrive at management decisions (Barrios et al., 2006). For researchers, there is need to conduct sufficiently detailed tests while controlling for variation in order to develop meaningful assessments of soil status, often expressed as an index of soil quality (Kang et al., 2005).

Figure 1.



Adapted from Karlen et al, 2003

Due to these complexities, there is need to develop diagnostic measures and indicators of soil health and soil quality changes in order to derive classifications from the minimum data set (Table 2) that can better assist farmers and inform research and extension to target solutions at farm level (Murage et al., 2000).

Table 2. Proposed minimum data set (MDS) of physical, chemical, and biological indicators for assessing soil quality

Indicator	Rationale for assessment
Biological	
Microbial biomass C and N	Describes microbial catalytic potential and repository for carbon and nitrogen. Provides an early warning of management effects on organic matter.
Potentially mineralizable N	Describes soil productivity and nitrogen supplying potential. Provides an estimate of biomass.
Soil respiration	Defines a level of microbial activity. Provides an estimate of biomass activity.
Chemical	
Soil organic matter (OM)	As a proxy for soil fertility and nutrient availability.
pH	biological and chemical activity thresholds.
Electrical conductivity	plant and microbial activity thresholds.
Extractable N, P, and K	Describes plant-available nutrients and potential for N loss. Indicates productivity and environmental quality.
Physical	
Soil texture	Indicates how well water and chemicals are retained and transported. Provides an estimate of soil erosion and variability.
Soil depth and rooting	Indicates productivity potential. Evens out landscape and geographic variability.

Infiltration and soil bulk density (ρb)	Describes the potential for leaching, productivity, and erosion. ρb is used to correct soil analyses to volumetric basis.
Water holding capacity	Describes water retention, transport, and erosion. Available water is used to calculate soil bulk density and organic matter.

Source: Doran et al., 1996; Larson and Pierce, 1994; and Doran and Parkin, 1994

On-farm soil health assessment

On-farm assessment of soil quality and health is recommended to assist farmers evaluate the effects of their management decisions on soil productivity (Andrews and Carroll, 2001; cite). Also, this approach permits interaction between researchers, extension and policy personnel when providing interpretation to link on-farm knowledge to soil health information. The main challenge is to develop soil quality and soil health standards to assess changes which are practical and useful to farmers (Barrios and Trejo, 2003). For instance, linking soil health measurements with farmer perceptions of soil quality can bridge the gap in interpretation of complex data sets (Table 3). In Africa several studies (Murage et al., 2000; Barrios et al., 2006) show that by using local knowledge, smallholder farmers are able to accurately predict soil quality differences of productive and non-productive fields.

Table 3. Example of an interpretation framework for soil health indicators under agricultural land uses

Indicator		**Ranking**	
	Low	**Medium**	**High**
Total organic matter content (organic C % × 1.7)	poor pore structure, hard workability (<1.7%)	friable, but poor workability (1.7-2.6%)	extremely friable and easy workability (> 2.6%)
Light fraction organic matter	noticeable fine root fragments and weed seeds	mixtures of root and leaf litter fragments	dominated by large leaf litter fragments.
Organomineral fraction organic matter	deep red red with discolored brown flakes of clay particles	deep red with consistent brown colored clay particles	near pitch-dark organic with mixtures of consistent red mineral flakes
Soil pH	high acid < 5.5	medium acid to neutral 5.5 to 7.0	neutral to basic 7.0 to 8.0
Soil cation exchange capacity	< 10 $mmol_c\ kg^{-1}$	10 to 20 $mmol_c\ kg^{-1}$	> 20 $mmol_c\ kg^{-1}$
Soil aggregate stability	water stable aggregation of 50-60% indicates weak structure highly erodible	water stable aggregation of 60-80% indicates stable structure but still susceptible to erosion	water stable aggregation of >80% indicates highly stable structure and little susceptibility to erosion

1. **Scorecards:** The use of scorecards for on-farm soil quality assessment is emphasized where qualitative observations of soil health are scored to obtain an overall measure of soil quality soil health (Romig et al, 1995). These cards may be

developed to evaluate soil health through farmer observations of soil physical, chemical and biological properties (Romig et al, 1996). These soil characteristics are classified in terms of descriptive indicators which are interpreted on a graded scale. Examples such as observations on earthworm numbers can yield a general index of biological activity in the soil.

2. **Soil quality test kits:** Assessment tools such as soil quality test kits (Liebig et al., 1996) focus on farmer-based evaluations and education regarding various soil and smallholder management practices. Further, they aim to produce an educational tool to increase public awareness of the importance of soil quality. Such kits, which are commercially available, provide for measurements of soil respiration, infiltration, bulk density, water content, electric conductivity (EC), pH, soil nitrates, aggregate stability, slake test and earthworm numbers (USDA, 1999). Some recent validation of the kit is provided by Seybold et al. (2002).

3. **Soil quality indices:** Finally, various soil quality indexing approaches (Andrews and Carroll, 2001; Granatstein and Bezdicek, 1992) are available and can be applied to derive a range of critical test values within which soil quality and soil health assessments can be defined (Arshad and martin, 2002).

EMERGING ISSUES

Sensing soil health

Assessments of soil chemical properties normally rely on laboratory data with large numbers of samples required to adequately characterize spatial variability at farm scales (Sanchez et al., 2003). Shepherd and Walsh (2002) have developed a promising approach that directly estimates several soil properties simultaneously from diffuse reflectance spectra in rapid nondestructive ways. The soil reflectance spectral data successfully predicted crop yields of an 18-year field experiment in Kenya testing different levels of fertilizer, manure and crop residue management (Shepherd and Walsh, 2002). Since spectral techniques allow large numbers of samples to be rapidly analyzed, resources can be directed towards thorough characterization of the soil and its spatial variability within a target region.

Soil and human health

Hunger in Africa has been linked to unhealthy people and unhealthy soils (Sanchez and Swaminathan, 2005). Currently, the concept of soil quality is in the process of evolution and progressively moving from a concept focused on yield potential and nutrient levels to one of environmental quality, food safety and human health (Karlen et al., 1997).

Soil and climate change

Global climate change is dramatically increasing the variability of weather conditions worldwide and soil is a critical buffer medium for hydrologic and biogeochemical processes and therefore can mitigate the effects of extreme weather conditions and uncertainty in the availability of water resources (Larson and Pierce

1994). The present threats of global climate change and ozone depletion, through elevated levels of certain atmospheric gases and altered hydrological cycles, necessitate a better understanding of the influence of land management on soil quality (Doran and Safley 1997). Management systems need to be further fine tuned in order to balance the need and priorities for food production with those for a safe and clean environment.

SOIL HEALTH RESOURCES

Educational materials are being developed because most smallholder farmers still lack the basis on which to evaluate the complexity of soil health and soil quality changes. Again, most smallholders may not be aware of how soil literally provides the foundation for sustainability through processes such as nutrient and hydrological cycles(Arshad and Martin 2002), filtering and buffering of soil pollutants (Shi et al., 2006), decomposition of crop residues and organic matter inputs (Carter 2002). The availability of internet based soil health resources continues to significantly bridge the gap between these sources and users. Presently, there exists a wealth of soil health and soil quality related information from educational institutions, private corporations, foundations and networks, agricultural commodity companies as well as national, regional and international research and development bodies.

The soil health portal (http://mulch.mannlib.cornell.edu/TSSearch) serves as a key entry point to access soil health information on-line. It offers an extensive, searchable database of annotated English and Spanish language soil health information resources. The portal gives users access to a subject-specific browsing library, an online resource of FAO technical information on soils. By using a TropSCORE search engine, it is possible to navigate through a reference service, and classified resource listings for products, services, organizations, databases, and literature related to soil health.

For Asia and Africa, we list below examples of current active sites:-

- Soil fertility newsletter by the south East Asia regional network on soil fertility and improved fallow management (http://www.worldagroforestry.org/sea/networks/ifm/contents.htm).
- Articles on management of salt affected soils by FAO-global network on integrated soil management (http://www.fao.org/landandwater/agll/spush/topic4.htm)
- Soil health publications by the Rice-Wheat consortium for the Indo-Gangetic Plains (http://www.rwc-prism.cgiar.org/rwc/).
- Publications on legume research in Asia by the International Crop Research Institute for the Semi-Arid Tropics (http://www.icrisat.org/text/research/nrmp/cdlegumes/e-book/Legumes.pdf)
- Article on no-till and conservation agriculture in south Asia (http://www.css.cornell.edu/faculty/hobbs/)
- Information on weed management in smallholder rice production highlighting fallow systems and chemical control (http://ipmworld.umn.edu/chapters/johnson.htm)
- Highlights on discussions of green manure, cover crops and mulch (http://ppathw3.cals.cornell.edu/mba_project/moist/mulchmail.html).

- Documents on news, events, products and services covering soil health and soil quality in tropical agriculture ecosystems by TSBF-CIAT (http://www.ciat.cgiar.org/tsbf_institute/index_tsbf.htm)
- Information on soil biodiversity and functions of soil organisms (http://www.fao.org/ag/AGL/agll/soilbiod/index_en.stm)
- Soil health: conservation, cover crops and nutrient management (http://www.sustainableag.net/soil_health.htm)
- Soil health extension material from Legume Research Network, ILRI, DFID and ICIPE, Kenya (http://ppathw3.cals.cornell.edu/mba_project/CIEPCA/exmats/)
- Links to FAO soil classification schemes (http://www.gsf.de/UFIS/ufis/thesaur/soil.html)

Whereas most of these sources are free of charge, other low-cost resources of soil health related information are available from the following sources:-

1. The Essential Electronic Agricultural Library (TEEAL): http://www.teeal.org
   TEEAL service contains annual updated full-text and bibliographic library content from over 100 of the most current scientific journals in the agricultural sciences. TEEAL content is delivered well below cost to over 100 low-income countries.

2. Access to Glob. Online Research in Ag. (AGORA): http://www.aginternetwork.org/en
   The AGORA program is provided through FAO, bringing together major publishers and enabling developing country scientists to gain access to a digital library collection of food, agriculture, environmental and related social sciences. It is designed to enhance the scholarship of students, faculty and researchers in agriculture and life sciences in the developing world.

3. The Land and Water Publications: http://www.fao.org/ag/agl/public.stm
   A collection of technical information on soils containing entire books in PDF version and can be downloaded for printing. HTML formats are available for reading on-line.

4. Corporate Document Repository: http://www.fao.org/documents
   When PDF versions of specific FAO technical books and reports are too large to access without fast internet connection, the CDR is an ideal site for their HTML versions.

5. World Agricultural. Information Centre (WAICENT): http://www.fao.org/waicent
   Is a directory that provides links to main sites and subject entry points for accessing FAO technical information

6. The Agricultural Library: http://www.soilandhealth.org/
   The Agricultural Library contains the full text HTML and PDF versions of organic farming. Other journal related soil health information as well as soil

health related discussion topics from electronic mailing lists serve a wide scope of the on-line research community.

SMALLHOLDER OVERVIEW

In African smallholder farms, soil health and soil quality can vary dramatically from one end of field to the other (Nandwa and Bekunda, 1998). On many of these farms, soils also respond poorly to fertilizer alone (Palm et al., 2001). This low efficiency can be raised through complementary management of organic matter inputs. In order to reduce the variability, most framers need to manage these soils for improved soil structure, including water holding capacity. The high variability of soil health and soil quality, cropping systems, and market opportunities mean that it is necessary to adapt the principles of soil health to local situations.

In tropical agriculture, soil health improvement includes consideration of the complexity of soils, farmer decision-making and long-term access to knowledge as well as improved inputs and market opportunities. Smallholder farmers' decisions to adopt the labor and knowledge-intensive practices required to improve their soil health depend on the impact of those practices on their food security and incomes. Therefore, they need incentives to both invest in soil health for long-term sustainable agricultural growth and have the short-term ability to purchase and effectively use organic and inorganic fertilizers and improved crop varieties (Barrios et al., 2006):

Studies conducted in Africa indicate that biological indicators like native plant species and soil fauna are among the most often reported local indicators of soil quality (Barrios et al., 2001). These reports are consistent with a review by Pankhurst et al. (1997) on biological indicators of soil health as biological indicators have the potential to integrate changes in soil quality at the same time reflecting changes in the physical, chemical and biological characteristics of the soil.

FUTURE DIRECTIONS

Rapidly increasing population in countries that can least afford it have made them food-insecure. With inadequate inputs in agriculture, developing countries are degrading their lands rapidly and destroying ecosystems. Currently, soil resource assessment and monitoring is entering a new era, in terms of quality of information produced by new information technologies through the innovative use of Geographic Information Systems and remote sensing and will significantly improving the acceptance and use of soil health information.

The use of electronic technology will significantly increase the demand for and ability to process more data. Further innovations will result in model approaches in soil genetic studies that will demonstrate the integral role of soils in ecosystems. Particularly the use of ICT including on-line delivery content through wikis, blogs and social book marking is set to push sharing of soil health information to a new level. At the more fundamental level, basic research will be needed in order to select and develop proper indicators, applicable at different farmer scales. Innovations will be required in setting up effective study programs, which would guarantee the accumulation of the necessary baseline soil data in order to develop appropriate minimum datasets.

SUGGESTED READING

Barrios E., Delve R.J., Bekunda M., Mowo J., Agunda J., Ramisch J., Trejo M.T., Thomas R.J. Indicators of soil quality: A South-South development of a methodological guide for linking local and technical knowledge. 2006 Geoderma, 135, pp. 248-259.

Doran, J.W., 2002. Soil health and global sustainability: translating science into practice. Agriculture, Ecosystem & Environment 88, 119–127.

Karlen, D. L., Mausbach, M. J., Doran, J. W., Cline, R. G., Harris, R. F. and Schuman, G. E. 1997. Soil quality: a concept, definition, and framework for evaluation. Soil Science Society of America Journal. 61: 4-10.

REFERENCES

Abawi, G.S., Widmer, T.L., 2000. Impact of soil health management practices on soil borne pathogens, nematodes and root diseases of vegetables crops. Applied Soil Ecology 15, 37–47.

Andrews S S Karlen D L and Cambardella C A 2004 The soil management assessment framework: A quantitative soil quality evaluation method. Soil Sci.Soc. Am. J. 68, 1945-1962.

Andrews, S.S., Carroll, C.R., 2001. Designing a soil quality assessment tool for sustainable agroecosystem management. Ecological Applications 11, 1573–1585.

Arshad, M.A. and Martin, S. 2002. Identifying critical limits for soil quality indicators in agro-ecosystems. Agriculture, Ecosystems and Environment 88: 153–160.

Barrios, E., Trejo, M.T., 2003. Implications of local soil knowledge for integrated soil fertility management in Latin America. Geoderma 111, 217–231.

Barrios E., Delve R.J., Bekunda M., Mowo J., Agunda J., Ramisch J., Trejo M.T., Thomas R.J. Indicators of soil quality: A South-South development of a methodological guide for linking local and technical knowledge. 2006 Geoderma, 135, pp. 248-259.

Bengtsson, J., 1998. Which species? What kind of diversity? Which ecosystem function? Some problems in studies of relations between biodiversity and ecosystem function. Appl. Soil. Ecol. 10, 191–199.

Carter, Martin R. 2002. Soil quality for sustainable land management: Organic matter and aggregation interactions that maintain soil functions. Agron J 94: 38-47

Cadisch, G. & Giller, K.E. (1997) Driven by Nature, Plant Litter Quality and Decomposition. CAB International, Wallingford

Doran, J. W., and Parkin, T. B. 1994. Defining and assessing soil quality. Pages 3-21 in J. W. Doran et al., (eds.) Defining soil quality for a sustainable environment. Soil Science Society of America Special Publication no. 35, Madison, WI.

Doran, J.W., Jones, A.J. (Eds.), 1996a. Methods for Assessing Soil Quality. Soil Science Society of America Special Publication, vol. 49. Soil Science Society of America, Madison, Wisconsin. Doran, J.W., Parkin, T.B., 1994. Defining and assessing soil quality. In: Doran, J.W., Coleman, D.C., Bezdicek, D.F., Stewart, B.A. (Eds.), Defining Soil Quality for a Sustainable Environment. Soil Science Society of America Special Publication, vol. 35. Soil Science Society of America, Madison, Wisconsin, pp. 3–21.

Doran, J.W., Sarrantonio, M., Liebig, M., 1996b. Soil health and sustainability. In: Sparks, D.L. (Ed.), Advances in Agronomy, Vol. 56. Academic Press, San Diego, pp. 1–54.

Doran, J.W. and Safley, M. 1997. Defining and assessing soil health and sustainable productivity. In: Pankhurst, C. et al. (eds.). Biological indicators of soil health. Wallingford, UK: CAB International. p. 1–28.

Doran, J.W., Zeiss, M.R., 2000. Soil health and sustainability: managing the biotic component of soil quality. Applied Soil Ecology 15, 3–11.

Doran, J.W., 2002. Soil health and global sustainability: translating science into practice. Agriculture, Ecosystem & Environment 88, 119–127.

Drinkwater, L.E., Cambardella, C.A., Reeder, J.D., Rice, C.W., 1996. Potentially mineralizable nitrogen as an indicator of biologically active soil nitrogen. In: Doran, J.W., Jones, A.J. (Eds.), Methods for Assessing Soil Quality. Soil Science Society of America, Special Publication 49, Madison, WI, pp. 217–229

Eswaran, H., Almaraz, R., van den Berg, E., Reich, P., 1997. An assessment of the soil resources of Africa in relation to productivity. Geoderma 77, 1–18.

Feller C., Balesdent J, Nicolardot B & Cerri C. 2001. Approaching functional soil organic matter pools through particle-size fractionation Examples for tropical soils. In Lal R, Kimble KM & Follet RF(eds) Assessment methods for soil carbon. Advances in Soil Science, pp 53-67 CRC

Giller K. E and Cadisch G. 1997. Driven by nature: a sense of arrival or departure. In: Cadisch G. and Giller K. E (eds), Driven by nature: Plant Litter Quality and Decomposition. CAB International, Wallingford, UK pp 393-399

Granatstein, D., Bezdicek, D.F., 1992. The need for a soil quality index: local and regional perspectives. Am. J. Altern. Agric. 7, 12–16.

Havlin, J.L., J.D. Beaton, S.L. Tisdale, and W.L. Nelson. 2005. Soil fertility and nutrient management: An introduction to nutrient management. 7th Edition. 515 p. Pearson/Prentice Hall. Upper Saddle River, NJ

Hedlund, A., Witter, E., An, B.X., 2003. Assessment of N, P and K management by nutrient balances and flows on peri-urban smallholder farms in southern Vietnam. Eur. J. Agron. 20, 71–87.

Hillel, D. 1982. Introduction to soil physics. Academic Press, San Diego, CA.

http://soilhealth.cals.cornell.edu/

http://soils.usda.gov/. USDA, Natural Resources Conservation Service.

Idowu O J van Es H Schindelbeck R Abawi G Wolfe D Thies J Gugino B Moebius B and Clune D 2007 The new Cornell Soil Health Test: Protocols and interpretation. What's Cropping Up? 17, (1) 6-7 (http://www.css.cornell.edu/extension/)

Kang, G.S., Beri, V., Sidhu, B.S., Rupela, O.P., 2005. A new index to assess soil quality and sustainability of wheat-based cropping systems. Biology and Fertility of Soils 41, 389–398.

Karlen, D. L., Mausbach, M. J., Doran, J. W., Cline, R. G., Harris, R. F. and Schuman, G. E. 1997. Soil quality: a concept, definition, and framework for evaluation. Soil Science Society of America Journal. 61: 4-10.

Karlen, D. L. and Stott, D. E. 1994. Framework for evaluating physical and chemical indicators of soil quality. Pages 53-72 in J. W. Doran, D. C. Leman, D. F. Bezdicek and B. A. Stewart, eds. Defining soil quality for a sustainable environment; Proceedings of a symposium, Minneapolis, MN, USA, 4-5 November 1992. Soil Science Society of America, Inc., Madison, WI.

Karlen, D. L., Andrews, S. S. and Doran, J. W. 2001. Soil quality: Current concepts and applications. Advances in Agronomy 74: 1-40.

Karlen, D. L., Doran, J. W., Weinhold, B. J. and Andrews, S. S. 2003. Soil quality: Humankind's foundation for survival. Journal of Soil and Water Conservation 58.

Lal, R., 1998. Basic concepts and global issues: soil quality and agricultural sustainability. In: Lal, R (Ed.), Soil Quality and Agricultural Sustainability. Ann Arbor Science, Chelsea, MI, USA, pp. 3–12.

Lal et al., (Eds) 1997. Methods for assessment of soil degradation

Lal, R. and Stewart, B.A., 1995. Soil Management: Experimental Basis for Sustainability and Environmental Quality. Advances in Soil ScienceCRC Press, Boca Raton, Florida.

Larson, W. E. and Pierce, F. J. 1994. The dynamics of soil quality as a measure of sustainable mangement. Pages 37 - 51 in J. W. Doran, D. C. Coleman, D. F. Bezdicek and B. A. Stewart, eds. Defining soil quality for a sustainable environment. SSSA- Special Publication 35. Soil Science Society of America, Madison , WI, USA.

Letey, J., Sojka, R. E., Upchurch, D. R., Cassel, D. K., Olson, K. R., Payne, W. A., Petrie, S. E., Price, G. H., Reginato, R. J., Scott, H. D., Smethurst, P. J. and Triplett, G. B. 2003. Deficiencies in the soil quality concept and its application. Journal of Soil and Water Conservation 58: 180 - 187.

Liebig, M.A., Doran, J.W., Gardner, J.C., 1996. Evaluation of a field test kit for measuring selected soil quality indicators. Agronomy Journal 88, 683–686.

Nandwa, S.M., Bekunda, M.A., 1998. Research on nutrient flows and balances in East and South Africa: state of the art. Agriculture, Ecosystems and Environment 71, 1–4.

Nortcliff, S. 2002. Standardization of soil quality attributes. Agriculture, Ecosystems and Environment 88: 161–168

Murage E.W., Karanja N.K., Smithson P.C. and Woomer P.L. 2000. Diagnostic indicators of soil quality in productive and non-productive smallholders fields of Kenya's Central highlands. Agriculture, Ecosystems and Environment. 79: 1–8

Palm C. A., Gachengo C.N., Delve R. J., Cadisch G and Giller K. 2001 Organic Inputs for Soil fertility management in tropical agro-ecosystems; Application of organic resource database Agriculture,Ecosystems, and Environment 83:27-42

Pankhurst, C., Doube, B.M., Gupta, V.V.S.R. (Eds.), 1997. Biological Indicators of Soil Health. CAB International, Wallingford.

Papendick, R.I., Parr, J., 1992. Soil quality — the key to a sustainable agriculture. Am. J. Altern. Agric. 7, 2–3.

Romig, D.E., Garlynd, M.J., Harris, R.F., McSweeney, K., 1995. How farmers assess soil health and quality. Journal of Soil and Water Conservation 50, 229–236.

Romig, D.E., Garlynd, M.J., Harris, R.F., 1996. Farmer-based assessment of soil quality: A soil health scorecard. In: Doran, J.W., Jones, A.J. (Eds.), Methods for Assessing Soil Quality. Soil Science Society of America, Special Publication 49, Madison, WI, pp. 39–60.

Sanchez PA, Palm CA, Buol SW. 2003. Fertility capability soil classification: a tool to help assess soil quality in the tropics. Geoderma 114: 157-185

Sanchez, P. A., Swaminathan M. S., 2005. Hunger in Africa: the link between unhealthy people and unhealthy soils. The Lancet 365: 442-444

Seybold, C.A., Hubbs, M.D. & Tyler, D.D. 2002. On-farm tests indicate effects of long-term tillage systems on soil quality. Journal of Sustainable Agriculture 19: 61–73.

Shepherd, K.D., Walsh, M.G., 2002. Development of reflectance spectral libraries for characterization of soil properties. Soil Science Society of America Journal 66, 988–998.

Shi, L. L., Shan, Z. J., Kong, D. Y. and Cai, D. J. 2006 'The Health and Ecological Impacts of Organochlorine Pesticide Pollution in China: Bioaccumulation of Organochlorine Pesticides in Human and Fish Fats', Human and Ecological Risk Assessment, 12:2, 402 – 407

Riley, J. 2001. The indicator explosion: local needs and international challenges. Agriculture, Ecosystems, and Environment 87: 119-120.

Sparling, G., Parfitt, R. L., Hewitt, A. E., Schipper, L. A. 2003. Three approaches to define desired soil organic matter contents. J Environ Qual 32: 760-766

Stocking, M. A, 2003. Tropical soils and food security: The next 50 years. Science 302, 1356-1359

Swift, M.J., A. Izac, and M. Van Noordwijk. 2004. Biodiversity and ecosystem services in agricultural landscapes—are we asking the right questions? Agriculture, Ecosystems and Environment 104(1): 113-134.

USDA 1999. Soil quality test kit guide. United States Department of Agriculture, Agricultural Research Service and Natural Resources Conservation Centre. Available at: http://soils.usda.gov/sqi/kit2.html.

Wienhold B J Andrews S S and Karlen D L 2004 Soil quality: A review of the science and experiences in the USA. Environ. Geochem. Hlth. 26, 89-95.

Woomer, P.L., Bekunda, M.A., Karanja, N.K., Moorehouse, T., Okalebo, J.R., 1998. Agricultural resource management by smallhold farmers in East Africa. Nature and Resources 34 (4), 22–34.

Zhang WL,Tian ZX, Zhang N, Li XQ. 1996. Nitrate pollution of groundwater in northern China. Agricult, Ecosyst Environ 59, 223–231.