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Identifying critical limits for soil quality indicators in agro-ecosystems

M.A. Arshad[a,*], S. Martin[b]

[a] *Agriculture and Agri-Food Canada, P.O. Box 29, Beaverlodge, AB, Canada T0H 0C0*
[b] *Ministère de l'Aménagement du Territoire et de l'Environnement, DIREN Ile-de-France, 18 Avenue Carnot, 94234 Cachan Cedex, France*

Abstract

The maintenance of soil quality is critical to environmental sustainability. Although, several papers have been published on this subject, progress in soil quality monitoring has been slow. Knowledge and assessment of changes (positive or negative) in its status with time is needed to evaluate the impact of different management practices. Selection of key indicators and their critical limits (threshold values), which must be maintained for normal functioning of the soil, are required to monitor changes and determine trends in improvement or deterioration in soil quality for various agro-ecological zones for use at district, national and global levels. Many soil indicators interact with each other, and thus, the value of one is affected by one or more of the selected parameters. Interdependence of pH and nutrient availability, electrical conductivity and infiltration, etc. has been well documented by many researchers. Some researchers have proposed procedures for evaluating soil quality functions by combining and integrating specific elements into soil quality indices. These procedures allow for weighting of various functions, depending upon the user goals and socio-economic concerns.

Although, selection of soil indicators will vary with societal goals, the followings seem to be suitable indicators for crop production in most cases: organic matter, topsoil-depth, infiltration, aggregation, pH, electrical conductivity, suspected pollutants and soil respiration. Crop yield can be used as an integrator of the foregoing soil indicators. A minimum set of data on soil indicators must be identified to develop meaningful soil quality assessment. Also, monitoring soil indicators needs to set up sampling strategies allowing assessment of changes in soil quality which might be hidden by soil heterogeneity, by seasonal fluctuations or by analytical uncertainties. This paper describes the guidelines that can be followed to identify critical limits for the key indicators and the procedure for monitoring changes in soil quality trend. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Indicators of soil quality; Monitoring of soil quality; Threshold values; Soil functions; Environmental sustainability

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1. Introduction

A significant decline in soil quality has occurred worldwide through adverse changes in its physical, chemical and biological properties and contamination by inorganic and organic chemicals. In the past half a century, about 2 billion of the 8.7 billion ha of agricultural land, permanent pastures, and forests and woodlands have been degraded. The rate of growth of global grain production dropped from 3% in the 1970s to 1.3% in the 1983–1993 period, and one of the key reasons of this decline is inadequate soil and water management (Steer, 1998).

Concerned by the decline in soil quality, and in an attempt to reverse this trend, Dennis Keeney, director of the Leopold Center for Sustainable Agriculture (IO, USA), calls for an enactment of a national soil quality act, similar to the water and air quality

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[*] Corresponding author. Tel.: +1-780-354-5110; fax: +1-780-354-8171.
E-mail address: arshadc@em.agr.ca (M.A. Arshad).

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legislation with an emphasis on a strong, co-ordinated research-demonstration-incentives approach. When soils are degraded to the level that they can no longer perform their ecosystem functions, restoration is slow, expensive, and uncertain. “How many waste sites have been truly reclaimed?” “How many salt slicks made productive?” Asks Keeney. Any nation or state that supports an ecosystem that degrades soil is not sustainable (Keeney, 1999).

In 1996, a review by the Consultative Group of International Agricultural Research (CGIAR) of 14 international research centers found good progress in reorienting their research towards soil and water management, but it also found inadequate attention paid to off-site interactions at the river basin and regional levels (Steer, 1998). This was of particular concern since, off-site costs of unsustainable management practices are often greater than their impacts on on-site productivity.

The soil, like air and water, is an integral component of our environment, and together with water constitutes the most important natural resource. The wise use of this vital resource is essential for sustainable development and feeding the growing world population. In the past decade, several studies have dealt with the selection of suitable criteria for assessment of soil quality. However, monitoring of changes in soil quality, resulting from various management systems, have been slow. Selection of key indicators and their threshold values, which must be maintained for normal functioning of the soil, are required to monitor changes (direction, rate, magnitude, extent, etc.), and determine trends in improvement or deterioration in soil quality for various ecosystems.

The objectives of this paper are: (1) to review work done in the last decade on indicators for soil quality assessment; (2) to propose guidelines that can be followed to identify critical limits for the key indicators, and (3) describe a procedure for monitoring changes in soil quality trends.

2. Defining soil quality

Many definitions of soil quality have been proposed in the last 10 years (Arshad and Coen, 1992; Doran and Parkin, 1994; Karlen et al., 1997) with similar elements. The most recent, proposed by Karlen and a committee for the Soil Science Society of America is as follows: “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”.

The various functions of soil, as for land, described by Sombroek and Sims (FAO, 1995) in their background paper, are:

- production function;
- biotic environmental function;
- climate-regulative function;
- hydrologic function;
- storage function;
- waste and pollution control function;
- living space function;
- archive or heritage function;
- connective space function.

In this context, land refers not just to soil, but to the combined resources of soil, water, vegetation and terrain that provide the basis for land use. Land quality is the condition or health of land relative to its capacity for sustainable land use and environmental management (Dumanski, J. and Pieri, C. in FAO, 1997).

3. Soil quality indices

Three basic components of a soil quality index were proposed at the International Conference on the Assessment and Monitoring of Soil Quality held at the Rodale Institute (Rodale Institute, 1991). The components were: (1) the ability of soil to enhance crop production (productivity component); (2) the ability of soil to function in attenuation of environmental contaminants, pathogens, and offsite damage (environment component); and (3) the linkage between soil quality and plant, animal and human health (health component). At this conference, Parr et al. (1992), proposed a soil quality index (SQ) as follows:

$$\mathrm{SQ} = f(\mathrm{SP}, P, E, H, \mathrm{ER}, \mathrm{BD}, \mathrm{FQ}, \mathrm{MI}) \qquad (1)$$

where SP are the soil properties, P the potential productivity, E the environmental factors, H the health (human/animal), ER the erodibility, BD the biological diversity, FQ the food quality/safety and MI are management inputs.

Table 1
Interrelationship of soil indicators

Selected indicator	Other soil quality indicators in the MDS affecting the selected indicator
Aggregation	Organic matter, microbial (especially fungal) activity, texture
Infiltration	Organic matter, aggregation, electrical conductivity, exchangeable 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)

Subsequent to the Rodale Conference, many soil scientists have proposed more detailed procedures for evaluating soil quality functions by combining and integrating specific soil quality elements into soil quality indices (Doran and Parkin, 1994; Karlen and Stott, 1994). These procedures allow for weighting of various functions, depending upon the user goals and socio-economic concerns.

Doran and Parkin (1994) described a performance based index of soil quality that could be used to provide an evaluation of soil function with regard to the major issues of (i) sustainable production, (ii) environmental quality, and (iii) human and animal health. They proposed a soil quality index consisting of six elements:

$$SQ = f(\mathrm{SQE1}, \mathrm{SQE2}, \mathrm{SQE3}, \mathrm{SQE4}, \mathrm{SQE5}, \mathrm{SQE6}) \quad (2)$$

where SQE1 is the food and fibre production, SQE2 the erosivity, SQE3 the ground water quality, SQE4 the surface water quality, SQE5 the air quality, and SQE6 is the food quality.

According to these scientists, advantage of this approach is that soil functions can be assessed based on specific performance criteria established for each element, for a given ecosystem (for details, see Doran et al., 1997).

4. Soil quality indicators

Soil quality indicators refer to measurable soil attributes that influence the capacity of soil to perform crop production or environmental functions. Attributes that are most sensitive to management are most desirable as indicators. In a given agro-climatic region, the measurable soil attributes that are primarily influenced are: soil-depth, organic matter, respiration, aggregation, texture, bulk density, infiltration, nutrient availability and retention capacity. A minimum number of indicators (minimum data set (MSD)) need to be measured to evaluate changes in soil quality resulting from various management systems.

4.1. Inter-dependence of soil indicators

Many soil indicators in the MDS interact with each other, and thus, values of one is affected by one or more of these selected parameters. Some examples are listed in Table 1. Chappell et al. (1999) studied variations in aggregate stability in a tropical Ultisol (Borneo, Indonesia) disturbed by various forestry operations (a range of denudational processes including piping, rilling and landslide-triggered erosion). Differences in aggregate stability were correlated with organic C, clay content and exchangeable sodium percentage (ESP) at sites undergoing erosion. Organic C was the most important governing factor, accounting for 56% of the variance in aggregate stability. Similar results were reported earlier by Franzluebbers and Arshad (1996). Interdependence of pH and nutrient availability, electrical conductivity and infiltration, etc. has been well documented by many researchers.

5. Assessment of soil quality

Changes in soil quality can be assessed by measuring appropriate indicators and comparing them with desired values (critical limits or threshold level), at different time intervals, for a specific use in a selected agro-ecosystem. Such a monitoring system will provide information on the effectiveness of the selected farming system, land use practices, technologies and policies. A farming system or policies that contribute negatively to any of the selected indicators could be considered potentially unsustainable and thus, discouraged or modified. Systems that improve performance of the indicators can be promoted and advanced to assure sustainability.

5.1. Identifying critical limits

While many papers and reports have been published in the last 5–10 years relating to the MDS (Arshad and Coen, 1992; Doran and Parkin, 1994; Gregorich et al., 1994; Larson and Pierce, 1994; Karlen et al., 1997; Martin et al., 1998, Table 2), limited effort has been made to determine threshold values or critical limits for the proposed soil indicators.

What is a critical limit? It is the desirable range of values for a selected soil indicator that must be maintained for normal functioning of the soil ecosystem health. Within this critical range, the soil performs its specific functions in natural ecosystems. For example, to grow most crops the pH may be 6.5–7.0 or soil-depth may be 50 cm or more.

Selection of critical limits for soil quality indicators poses several difficult problems. The ability to supply moisture, nutrients and physical rooting support in the absence of toxic substances can be affected by many physical, chemical and biological parameters. A detrimental change in any of these can reduce the quality of the soil, but the quantitative values beyond which a further reduction in these properties is limiting depend strongly on the crop. For example, a pH below about 6.5 reduces the yield of alfalfa, but pH must drop below about 4.0 before critical yield reduction occur in blueberries (Doll, 1964). A critical limit of a soil indicator can be ameliorated or exacerbated by limits of other soil properties and the interactions among soil quality indicators (Table 1). Given the complexities of yield response to critical soil parameter values, perhaps, the best we can do is to develop a set of guidelines that can help set limits for defined crop/environment situations. In watershed analysis, the potential optimum functioning of watersheds can be obtained from studying the best of the undisturbed ecosystems (Warkentin, 1996). A similar procedure is used when soils that have been under a certain land management for a number of years are compared with soils that have not been disturbed. The influence of climate, especially temperature and distribution of precipitation, and geomorphology and weathering rate could be eliminated by comparing soils only within an ecological region or soil type.

Table 2
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 and early indicator of soil management effect
Texture	Retention and transport of water and chemicals, modeling use
Bulk density	Plant root penetration, porosity, adjust analyses 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 to crops, leaching potential, mineralization/immobilization rates, process modeling
Extractable N, P and K	Capacity to support plant growth, environmental quality indicator

Table 3
Threshold levels for sustainability indicators (after Gomez et al., 1996)

Indicator	Threshold level
Yield	The 20% more than average yield in the community
Profit	The 20% better than average in the community, whichever is lower
Frequency of crop failure	The 20% or average frequency for the community, which ever is lower
Soil-depth	The 50 cm or average of similar soil types in the community
Organic matter	The 1% or average of the community, whichever is higher
Permanent ground cover	The 15% or average of the community, whichever is higher

Gomez et al. (1996) proposed a framework for evaluating sustainability at the farm level in the Philippines based on field indicators that take into account both the farmer's satisfaction and resource conservation. High yield, low labor requirement, low input cost, high profit, and stability are some of the features that are likely to enhance farmer satisfaction. Natural resource conservation is usually associated with soil-depth, water holding capacity, nutrient balance, organic matter content, ground cover, and biological diversity. According to these workers, an indicator is said 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 (Table 3).

In Europe, measurable quantities of trace metals have been added to the environment for over 2000 years. Lately, waste and sewage sludges have become major potential sources of metal pollution of soils. At present, there is one set of critical levels for concentrations of heavy metals in soils (Cd, Cu, Ni, Pb, Zn, Hg and Cr) which apply to all countries of the EU, defined in annex 1A of the Council Directive 86/278/EEC; these values should not be exceeded when sewage sludge is applied in agriculture. This directive has been implemented in the form of national laws, with, in many cases, much lower nationally defined critical levels. In addition, in many cases, critical values were extended to soils in general and not limited to the application of sewage sludge. Alongside these precautionary levels, separate critical values are established for the cleaning up of contaminated sites, based on functional criteria and health aspects. One of the basic characters of European environment policy is the precautionary principle. Therefore, preference should not necessarily be given to the scientific approach leading to higher permissible metal concentrations in soil, but also to other factors which could endanger soil quality in the longer term. The precautionary approach is aimed at keeping soil trace metal concentrations to average natural concentrations (Reiniger, 1997).

6. Models to assess soil quality

The development of relationships between soil attributes and soil functions may be a monumental task. However, algorithms in existing simulation models (e.g. NLEAP, EPIC, CREAMS, WEPP) may serve a useful starting point (Doran and Parkin, 1994). The models provide a predictive tool about the process such that given what we know, if we change one of the parameters that affect the process, we can predict the change in outcome caused by the change in the parameter. We can often measure the things that dominantly affect the process more easily than we can measure the net effect (Coen, 1996). Models are normally constructed using results of detailed long-term data. Because climatic conditions vary from year to year, reliable long-term data is mandatory if we wish to reflect the historical reality and predict future events with some degree of confidence. Models can assist us in organizing what we know about soil processes and identifying what we should emphasize in research. By using soil process models, we can predict the rates and direction of soil quality change. They can allow us to simulate various management practices in order to predict their consequences.

7. Requirements for monitoring soil indicators

The following details in measuring changes in each selected indicator within a defined ecological zone required are as follows.

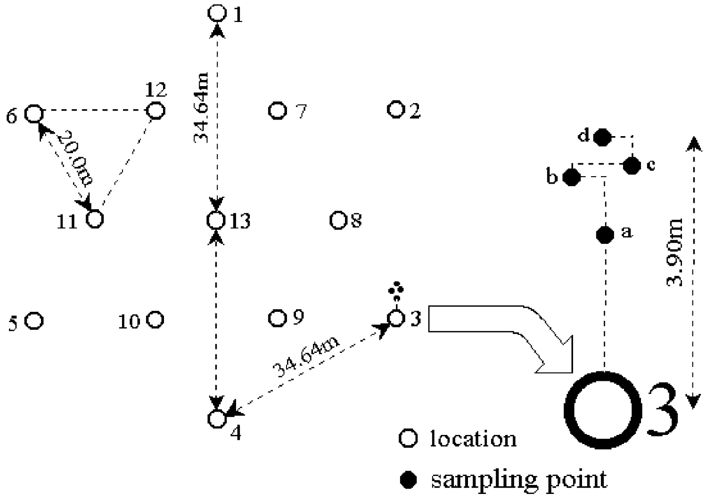

Fig. 1. An example of sampling pattern (13 locations; 13 × 4 = 52 sampling points): the "Observatoire de la Qualité des Sols" in France (after Leprêtre and Martin, 1994).

- Direction of change — positive or negative, increase or decrease, etc.
- Magnitude of change — percent change over the baseline values.
- Rate of change — duration: months, years.
- Extent of change — percentage of the area being monitored i.e. what percentage of the farm or district has changed with respect to the selected indicator during a specified period.

Monitoring soil indicators needs to set up sampling strategies allowing assessment of changes in soil quality that might be hidden by soil heterogeneity, by seasonal fluctuations or by analytical uncertainties (Leprêtre and Martin, 1994; Arshad et al., 1996). A sampling strategy is a set of processes that yields a data set corresponding to the objectives of the study and to the characteristics of the terrain. It includes a sampling pattern (as in Fig. 1), analytical procedures, sample storage, and data management in view of statistical analysis (Leprêtre and Martin, 1994).

Similar qualitative data/observations on soil conditions, land use, cropping systems, inputs/outputs including information provided by the farmer, must be collected over the monitoring period. A genuine discussion between scientists and local people is very important; the scientist can take what is useful from the local expertise and use the information in the design of the program. It is important to understand human behavior and then choose policies and technologies accordingly (Steer, 1998). Understanding of the factors involved for the observed changes, both socio-economic as well as agro-ecological (e.g. cost of land, availability of labor, capital, etc. skill of farm managers, and factors beyond their control such as weather, market conditions, policies and legislation, technical support, infrastructure, etc.), are also important (Benites et al., in FAO, 1997). Take a multidisciplinary approach; same situation or condition is viewed differently by individuals in different disciplines. Thus, it is better to involve them at the commencement of the project; this will help in gaining support from the community, governments and other agencies throughout the life of the project.

8. Guidelines for monitoring soil quality

The following guidelines and steps are suggested to monitor soil quality.

1. Divide the region or the country into different ecological zones.
2. Select the ecological zone, farms or watershed with similar soil types.

3. Define the goal or requirements for sustainability; the goal could be production of a crop or a group of crops, environmental protection or any other use.
4. Select a set of indicators for the ecological zone, farms or watershed. Although, selection of soil indicators will vary with the societal goals, the followings seem to be suitable indicators for crop production in most cases: organic matter, topsoil-depth, infiltration, aggregation, pH, electrical conductivity, suspected soil pollutants and soil respiration. Crop yield can be used as an integrator of the foregoing soil indicators.
5. Select a reference point (baseline value) for each indicator. This could be the average value of crop yield/soil indicator used for the ecological zone or soil type at the commencement of the monitoring period. Information from the existing databases may be useful to determine the baseline values for different regions.
6. Specify the critical limits for selected indicators. Critical limits will vary with each indicator. For some indicators, a 10% increase or decrease may be significant while others may not be affected by a 20% decline. For organic matter, a 15% increase or decrease over the average or baseline value seems reasonable to use as a critical limit. For example, if the baseline value of organic carbon is 2%, the organic matter must increase by 15% or to 2.3% carbon in order for us to conclude that a significant positive change has occurred in this indicator. This value must decrease to 1.7% carbon (negative change) to signal that a corrective action must be taken to reverse the trend.
7. Transform the indicators into a soil quality/sustainability index.
8. Test the procedure using the actual data from different soil and land management practices being used in the ecological zones, farms or watersheds.

9. Concluding remarks

In order to quantify and evaluate changes in soil quality, various combinations of management practices and their interactions with different soil indicators must be understood. Case studies in different agro-ecological zones should be conducted, with emphasis on the quality of the data.

A minimum set of data on soil indicators and relevant sampling strategies must be identified to develop meaningful soil quality assessment and monitoring program.

Long-term experiments (10–30 years) should be conducted to establish the positive and negative effects of different land uses on soil indicators for developing models so that appropriate action could be taken accordingly.

Research should be undertaken to develop simple techniques for use by the farmers and extension-workers.

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