BIOLOGICAL INDICATORS OF SOIL HEALTH

Biological Indicators of Soil Health

Edited by

C. Pankhurst, B.M. Doube
CSIRO Land and Water
Glen Osmond
Australia

and

V.V.S.R. Gupta
Cooperative Research Centre for Soil and Land Management
Glen Osmond
Australia

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CABI *Publishing* is a division of CAB *International*

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Oxon OX10 8DE
UK

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Email: cabi@cabi.org
Web site: www.cabi-publishing.org

CABI Publishing
10 E 40th Street
Suite 3203
New York, NY 10016
USA

Tel: +1 212 481 7018
Fax: +1 212 686 7993
Email: cabi-nao@cabi.org

A catalogue record for this book is available from the British Library, London, UK
A catalogue record for this book is available from the Library of Congress, Washington DC, USA

ISBN 0 85199 158 0

First published 1997
Transferred to print on demand 2002

Printed and bound in the UK by Antony Rowe Limited, Eastbourne.

Contents

Contributors

G.L. Bateman *IACR – Rothamsted, Harpenden, Hertfordshire AL5 2JQ, UK.*

C.D. Campbell *Macaulay Land Use Research Institute, Craigiebuckler, Aberdeen AB9 2QJ, UK.*

M.S. Cresser *Department of Plant and Soil Science, Cruickshank Building, University of Aberdeen, Aberdeen AB9 2UE, UK.*

R.P. Dick *Department of Crop and Soil Science, Oregon State University, Corvallis, Oregon 97331, USA.*

J.W. Doran *Soil/Water Conservation Research Unit, United States Department of Agriculture, Agricultural Research Service, University of Nebraska, Lincoln, Nebraska 68583, USA.*

B.M. Doube, *CSIRO Land and Water, Private Bag No. 2, Glen Osmond, South Australia 5064, Australia.*

E.T. Elliott *Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, Colorado 80524, USA.*

L.F. Elliott *National Forage Seed Production Research Centre, United States Department of Agriculture, Agricultural Research Service, Oregon State University, Corvallis, Oregon 97331, USA.*

R. Gabbrielli *Dipartimento di Biologia Vegetale, Università di Frienze, Via Micheli 1, I-50121 Firenze, Italy.*

L.A. Glover *Department of Molecular and Cell Biology, Marischal College, University of Aberdeen, Aberdeen AB9 1AS, UK.*

P. Gremigni *Dipartimento di Biologia Vegetale, Università di Frienze, Via Micheli 1, I-50121 Firenze, Italy.*

V.V.S.R. Gupta *Cooperative Research Centre for Soil and Land Management, Private Bag No. 2, Glen Osmond, South Australia 5064, Australia.*

D. Hornby *IACR – Rothamsted, Harpenden, Hertfordshire AL5 2JQ, UK.*

K. Killham *Department of Plant and Soil Science, Cruickshank Building, University of Aberdeen, Aberdeen AB9 2UE, UK.*

J.M. Lynch *School of Biological Sciences, University of Surrey, Guildford, Surrey GU2 5XH, UK.*

S.J. Macnaughton *Microbial Insights, Inc., 201 Center Park Drive, Knoxville, Tennessee 37922-2105, USA.*

J.H. McCullum *Department of Land Resource Science, University of Guelph, Guelph, Ontario N1G 2W1, Canada.*

J.C.L. Meeussen *Macaulay Land Use Research Institute, Craigiebuckler, Aberdeen AB9 2QJ, UK.*

G.N. Mhatre *304 A, Kohinoor Tower, Bal Govindas Marg, Dadar, Bombay 400 028, India.*

M.H. Miller *Department of Land Resource Science, University of Guelph, Guelph, Ontario N1G 2W1, Canada*

K.M. Ophel-Keller *Cooperative Research Centre for Soil and Land Management, Private Bag No. 2, Glen Osmond, South Australia 5064, Australia.*

T. Pandolfini *Dipartimento di Biologia Vegetale, Università di Firenze, Via Micheli 1, I-50121 Firenze, Italy.*

C.E. Pankhurst, *CSIRO Land and Water, Private Bag No. 2, Glen Osmond, South Australia 5064, Australia.*

G.I. Paton *Department of Plant and Soil Science, Cruickshank Building, University of Aberdeen, Aberdeen AB9 2UE, UK.*

D.J. Rapport *Eco-Research Chair in Ecosystem Health, Faculty of Environmental Sciences, University of Guelph, Guelph, Ontario NIG 2W1, Canada.*

E.A.S. Rattray *Department of Plant and Soil Science, Cruickshank Building, University of Aberdeen, Aberdeen AB9 2UE, UK.*

M.M. Roper *Division of Plant Industry, CSIRO, Private Bag, Wembley, PO, Western Australia 6014, Australia.*

M. Safley *Biological Conservation Sciences Division, United States Department of Agriculture, Natural Resources Conservation Service, Post Box 2890, Washington DC 20013, USA.*

O. Schmidt *Department of Environmental Resource Management, Faculty of Agriculture, University College Dublin, Belfield, Dublin 4, Ireland.*

G.P. Sparling *Manaaki Whenua – Landcare Research, Private Bag 3127, Hamilton, New Zealand.*

N.M. van Straalen, *Vrije Universiteit, Department of Ecology and Ecotoxicology, De Boelelaan 1087, 1081 HV Amsterdam, The Netherlands.*

D.C. White *Center for Environmental Biotechnology, University of Tennessee, 10515 Research Drive, Knoxville, Tennessee 37932-2575, USA.*

G.W. Yeates *Manaaki Whenua – Landcare Research, Private Bag 11052, Palmerston North, New Zealand.*

Preface

Our ability to assess the health of soils and to identify key soil properties which can serve as indicators of soil health has become a major issue for land managers and for food and fibre producers throughout the world. The driving force behind this is the need to produce 'more' from our soils and to maintain increasing levels of production in the face of diminishing land resources resulting from expanding urbanization and land degradation. More than ever before, we now appreciate the wisdom of 'sustainable production' and realize that soils must be 'looked after' if they are to continue to produce an abundance of healthy foods. Hence the arrival of the concept of soil health and the desire to be able to assess and monitor it in some way.

Soil health, defined as 'the continued capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, promote the quality of air and water environments, and maintain plant, animal, and human health' is a term that is used synonymously with soil quality, although many, including authors in this book, would argue for a distinction. The definition does, however, remind us that soils are living systems which contain vast assemblages of soil organisms which perform many of the functions that are critical to terrestrial life. These functions include the decomposition and recycling of nutrients from dead plant and animal tissues, the fixation of nitrogen, the maintenance of soil structure and the detoxification of pollutants. Often these functions are ignored and soil is regarded as an inanimate entity composed of minerals and chemicals. The key roles played by its living components are not recognized. Commonly, we are only reminded of the presence of or lack of specific soil biota only when a soilborne root disease wreaks havoc on a crop or when plants fail to grow through lack of an appropriate soil symbiont. The linkage between soil biota, soil health and the health of plants, animals and human beings is rarely considered.

The principles of soil conservation have been known for centuries and in many countries recognition of the dangers of soil degradation has prompted national soil conservation programmes. However, recent regional and global assessments of human-induced soil degradation (erosion, salinization, acidification, heavy metal pollution, organic matter decline) indicate that the productive capacity of millions of hectares of land continues to decline each year and warn us of ecological collapse of the world's productive soils. At a local level, we need to be able to assess how farming practices are affecting the capacity of the land to remain productive and how such practices are reducing or improving the health of the soil. The search for indicators which can be used as quantitative tools to assess the health of the soil has thus become a major challenge for both scientists and land managers. Indicators need to be robust and meaningful, and easy to measure and interpret. To date, emphasis has been given to physical and chemical soil properties as indicators of soil health, rather than to biological properties which are generally regarded as more difficult to measure, predict, or quantify. However, biological processes are intimately linked with the maintenance of soil structure and fertility and are potentially more sensitive to changes in the soil than indicators based on physical and chemical soil properties. Biological indicators therefore may provide an 'early warning' of system collapse and allow us to react before irreversible damage occurs. Although many problems surround the use of soil biological properties as indicators of soil health (e.g. the inherent temporal and spatial heterogeneity of soil organism populations and the unpredictable interaction of soil organisms with the climatic factors), modern technology is providing many new methodologies and approaches which may ultimately overcome some of these problems.

In 1994, a workshop entitled 'Soil Biota: Management in Sustainable Farming Systems' was held in Adelaide, Australia. The workshop was sponsored by the OECD Cooperative Research Project on Biological Resource Management, the CSIRO Division of Soils, The Cooperative Research Centre for Soil and Land Management (based in Adelaide) and by three Australian Research Corporations. This workshop was unique in that it focused attention on the soil biota and how it can be better managed to make agriculture more sustainable and less dependent on the use of non-renewable resources. The workshop also focused on opportunities for using the soil biota and soil biotic processes as biological indicators in farming systems. An outcome of the workshop was identification of the need for a detailed synthesis of current research of the soil biota and how it might be used as a component of an indicator package for the assessment and monitoring of soil health. This book is a response to that need for a synthesis. It contains 17 chapters, each prepared by authors who are internationally recognized for their knowledge and expertise in a particular area of soil/plant biology. There are four introductory chapters which address the concept of soil health, its relationship to ecosystem health and what is needed from biological indicators of soil health. These are followed by chapters which evaluate the potential of using different components of the soil biota and its activity as biological indicators. These cover soil microorganisms (including plant root pathogens), soil micro-, meso- and macrofauna, soil biodiversity, soil biotic processes and soil enzymes. In addition, two chapters address the development of new technologies which probe the composition and functioning of soil microbial communities, and two chapters review the use of plants as indicators of soil pollution. The final chapter is a synthesis that brings together the views and major points made by the authors of the volume and offers an analysis of the current status of the different biological indicators.

Throughout this volume the term 'bioindicator' is used whereas the term 'biological indicator' is used in the title. We do not differentiate between the two terms. The term 'bioindicator' is in common usage whereas the term 'biological indicator' is more technically correct.

C.E. Pankhurst
B.M. Doube
V.V.S.R. Gupta

1

Defining and Assessing Soil Health and Sustainable Productivity

J.W. Doran[1] and M. Safley[2]

[1] *Soil/Water Conservation Research Unit, United States Department of Agriculture, Agricultural Research Service, University of Nebraska, Lincoln, Nebraska 68583, USA;*
[2]*Biological Conservation Sciences Division, United States Department of Agriculture, Natural Resources Conservation Service, Post Box 2890, Washington DC 20013, USA*

Introduction

Increasing human populations, decreasing resources, social instability, and environmental degradation pose serious threats to the natural processes that sustain the global ecosphere and life on earth (Costanza *et al.*, 1992; Pearce and Warford, 1993). Agriculture, and society in general, is challenged to develop strategies for sustainability that conserve non-renewable natural resources such as soil, enhance use of renewable resources and are aligned with the natural processes that sustain life on earth. The problems of sustainability which we currently face are considered by some to result from an abandonment of ecological principles to produce human food and the acceptance of a cultural premise that places humankind as the ruler of the world, and therefore not subject to the laws of nature (Quinn, 1993). We often suffer from the delusion that we as humans can control nature when, in reality, the only thing we can control and manage is ourselves (Cline and Ruark, 1995). The challenge ahead in sustaining life on earth will require new vision, holistic approaches for ecosystem management and a renewed partnership between science and society. We must muster our cultural resources and 'put science to work' for both humanity and the natural ecosystems of which it is part and on which it depends.

We present the thesis that 'soil' is a dynamic, living resource whose condition is vital to both the production of food and fibre and to global balance and ecosystem function (Doran *et al.*, 1996). The quality and health of soils deter-

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CAB INTERNATIONAL 1997. *Biological Indicators of Soil Health*
(eds C.E. Pankhurst, B.M. Doube and V.V.S.R. Gupta)

mine agricultural sustainability (Acton and Gregorich, 1995), environmental quality (Pierzynski *et al.*, 1994) and, as a consequence of both – plant, animal and human health (Haberern, 1992). In its broadest sense, soil health can be defined as the ability of soil to perform or function according to its potential, and changes over time due to human use and management or to natural events. In this sense, soil health is enhanced by management and land-use decisions that weigh the multiple functions of soil and is impaired by decisions which focus only on single functions, such as crop productivity. In this chapter we present approaches to assessing the quality and health of soils and present the value of soil health to strategies for sustainable management of our natural resources.

Soil – a Vital and Finite Resource

Global function and sustainability

We enter the twenty-first century with greater awareness of our technological capability to influence the global environment and of the impending challenge for sustaining life on earth (Gore, 1993; Postel, 1994). Global climate change, depletion of the protective ozone layer, serious declines in species biodiversity, and degradation and loss of productive agricultural land are among the most pressing concerns associated with our technological search for a higher standard of living for an ever growing human population. Increasing worldwide concern for sustainable global development and preservation of our soil resources is reflected by numerous recent international conferences such as the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro, Brazil in 1992; the Soil Resilience and Sustainable Land Use Symposium in Budapest, Hungary in 1992; the Sustainable Land Management Conference in Lethbridge, Canada in 1993; and the International Congress of Soil Science in Acapulco, Mexico in 1994. Central to discussions at these conferences were the threats to sustainability posed by soil and environmental degradation associated with increasing intensity of land use and the search among increasing populations of the world for a higher standard of living. Sustainability of the energy and chemically intensive industrial agricultural model, which has enabled a two- to three-fold growth in agricultural output of many countries since World War II, is increasingly questioned by ecologists, earth scientists, and clergy (Jackson and Piper, 1989; Bhagat, 1990; Hillel, 1991 and Sagan, 1992).

Interest in evaluating the quality and health of our soil resources has been stimulated by increasing awareness that 'soil' is a critically important component of the earth's biosphere, functioning not only in the production of food and fibre but also in the maintenance of local, regional, and global environmental quality (Glanz, 1995). The thin layer of soil covering the surface of the earth represents the difference between survival and extinction for most land-based life. Like water, soil is a vital natural resource essential to civilization but, unlike water, soil is non-renewable on a human time scale (Jenny, 1980, 1984). Modern conservationists are quick to point out that, 'mismanagement and neglect can ruin the fragile resource and become a threat to human survival' (Lal and Pierce, 1991). This fact is supported by archaeological evidence showing that soil degradation was responsible for extinction or collapse of the Harappan civilization in western India, Mesopotamia in Asia Minor, and the Mayan culture in Central America (Olson, 1981).

Present-day agriculture evolved as we sought to control nature to meet the food and fibre needs of an increasingly urbanized society. With the development of modern chemistry during and after World War II, agriculturists often assumed a position of dominance in their struggle against a seemingly hostile natural environment, often failing to recognize the consequences of management approaches upon long-term productivity and environmental quality. Increased monocultural production of cash grain crops, extensive soil cultivation and greater reliance on chemical fertilizers and pesticides to maintain crop growth have resulted in two to three fold increases in grain yields and on-farm labour efficiency (Brown *et al.*, 1994; Northwest Area Foundation, 1994; Avery, 1995; Power and Papendick, 1985). However, these management practices have also increased soil organic matter loss, soil erosion, and surface and ground water contamination in the USA and elsewhere (Gliessman 1984; Hallberg, 1987; Reganold *et al.,* 1987). Motivations for shifting from input-intensive management to reduced external input farming include concern for protecting soil, human, and animal health from the potential hazards of pesticides; concern for protection of the environment and soil resources; and a need to lower production costs in the face of stagnant farm-gate receipts (Soule and Piper, 1992; US Department of Agriculture, 1980).

Past management of agriculture and other ecosystems to meet the needs of increasing populations has taxed the resiliency of soil and natural processes to maintain global balances of energy and matter. The quality of many soils in North America has declined significantly since grasslands and forests were converted to arable agriculture and cultivation was initiated (Campbell *et al.,* 1976). Mechanical cultivation and the production of continuous row crops has resulted in physical soil loss and displacement through erosion, large decreases in soil organic matter content, and a concomitant release of that organic C as carbon dioxide to the atmosphere (Houghton *et al.*, 1983). Within the last decade, inventories of the soil's productive capacity indicate severe degradation on well over 10% of the earth's arable land as a result of soil erosion, atmospheric pollution, cultivation, over-grazing, land clearing, salinization, and desertification (Sanders, 1992; World Resources Institute, 1992). Findings from a project of the United Nations Environment Program on 'Global Assessment of Soil Degradation' indicate that almost 40% of agricultural land has been adversely affected by human-induced soil degradation, and that more than 6% is degraded to such a degree that restoration of its original productive capacity is only possible through major capital investments (Oldeman, 1994). The quality of surface and sub-surface water has been jeopardized in many parts of the world by intensive land management practices and the consequent imbalance of C, N and water cycles in soil. At present, agriculture is considered the most widespread contributor to nonpoint source water pollution in the USA (CAST, 1992b; National Research Council, 1989). The major water contaminant in North America and Europe is nitrate-N; the principal sources of which are conversion of native to arable land use, animal manures and fertilizers. Soil management practices such as tillage, cropping patterns, and pesticide and fertilizer use are known to influence water quality. However, these management practices can also influence atmospheric quality through changes in the soil's capacity to produce or consume important atmospheric gases such as carbon dioxide, nitrous oxide and methane (CAST, 1992a; Rolston *et al.,* 1993). The present threat of global climate change and ozone depletion, through elevated levels of atmospheric gases and altered hydrological cycles, necessitates a better understanding of the influence of land management on soil processes.

Development of sustainable agricultural management systems has been complicated by the need to consider their utility to humans, their efficiency of resource use, and their ability to maintain a balance with the environment that is favourable both to humans and most other species (Harwood, 1990). We are challenged to develop management systems which balance the needs and priorities for production of food and fibre with those for a safe and clean environment. In the USA, the importance of soil quality in maintaining balance between environmental and production concerns was reflected by a major conclusion of a recent National Academy of Science report that, 'Protecting soil quality, like protecting air and water quality, should be a fundamental goal of national environmental policy' (National Research Council, 1993).

A recent call for development of a 'soil health index' was stimulated by the perception that human health and welfare is associated with the quality and health of soils (Haberern, 1992). However, defining and assessing soil quality or health is complicated by the fact that soils perform multiple functions in maintaining productivity and environmental well-being. Identifying and integrating the physical, chemical and biological soil attributes which define soil functions is the challenge (Rodale Institute, 1991; Papendick and Parr, 1992). Forums were held in Washington, DC, in the winter of 1995 to ensure that emphasis on maintaining the quality of our soil resources was included in the 1995 Farm Bill. Many agriculturists, scientists, politicians, and citizens recognize that maintaining the health and quality of soil should be a major goal of a sustainable society. An important question, however, is 'What defines a healthy or high quality soil and how might soil quality and health be maintained or improved through agricultural and land-use management?'

Defining soil quality and soil health

Soil is a dynamic, living, natural body that is vital to the function of terrestrial ecosystems and represents a unique balance between physical, chemical and biological factors. Soils form slowly, averaging 100 to 400 years per centimetre of topsoil, through the interaction of climate, topography, vegetation, and mineral parent material over time (Jenny, 1980; Lal, 1994). The major components of soil include inorganic minerals and sand, silt, and clay particles; reactive and stable forms of organic matter derived from decomposed soil biota; living organisms such as earthworms, insects, bacteria, fungi, algae, nematodes, etc. – in such a multitude that the numbers in a teaspoon (10 g) of soil can exceed the human population of the earth; water; and gases including O_2, CO_2, N_2, NO_x, and CH_4. Continual interchanges of molecules/ions between the solid, liquid and gaseous phases are mediated by physical, chemical, and biological processes in soil. The inorganic components of soil play a major role in retaining cations through ion exchange and non-polar organic compounds and anions through sorption reactions. Essential parts of the global C, N, P and S and water cycles occur in soil and soil organic matter is a major terrestrial pool for C, N, P and S; the cycling rate and availability of these elements is continually being altered by soil organisms in their constant search for food and energy sources.

The sun is the basis for most life on earth and provides radiant energy for heating the biosphere and for the photosynthetic conversion of carbon dioxide (CO_2) and water into food sources and oxygen for consumption by animals and other aerobic organisms. Most living organisms utilize oxygen to metabolize these food sources, capture their energy and recycle heat, CO_2, and water to the environment to begin this cycle again.

A simplified version of this 'Equation of Life' can be depicted as follows:

$$\begin{array}{ccc} & \text{Photosynthesis} & \\ & \text{(radiant)}\longrightarrow\text{(food)} & \\ 6CO_2 + 6H_2O + \text{ENERGY} & & C_6H_{12}O_6 + 6O_2 \\ & \text{(heat)}\longleftarrow\text{(fuel)} & \\ & \text{Decomposition and combustion} & \end{array}$$

The amount of CO_2 in the atmosphere is rather small and represents less than 0.04% of all gases present. If all combustion and respiration processes on earth were halted the plant life of the earth would consume all available CO_2 within a year or two (Lehninger, 1973). Thus, there is a fine balance between CO_2 production and utilization in the biosphere. Decomposition processes in soil play a predominant role in maintaining this balance. These processes are brought about by a complex web of organisms in soil, each group playing unique roles in the physical and chemical breakdown of organic plant and animal residues and reacting differently to a soil environment which is continually changing. Soils breathe and play a major role in transforming sunlight and stored energy and recycling matter through plants and animals. As such, living soils are vital to providing human food and fibre needs and in maintaining the ecosystems on which all life ultimately depends.

The concept of soil quality – soil function

Blum and Santelises (1994) describe a concept of sustainability and soil resilience based on six main soil functions – three ecological functions and three which are linked to human activity. Ecological functions include: (i) biomass production (food, fibre, and energy); (ii) the soil as a reactor which filters, buffers, and transforms matter to protect the environment, groundwater, and the food chain from pollution; and (iii) soil as a biological habitat and genetic reserve for many plants, animals, and organisms which should be protected from extinction. Functions linked to human activity include: (i) the soil as a physical medium, serving as a spatial base for technical and industrial structures and socio-economic activities such as housing, industrial development, transportation systems, recreation and refuse disposal; (ii) soil as a source of raw materials supplying water, clay, sand, gravel, minerals, etc.; and (iii) soil as part of our cultural heritage, containing palaeontological and archaeological treasures important to preserving the history of earth and humankind.

Our concepts of soil quality change as we become aware of the many essential functions soil performs in the biosphere, in addition to serving as a medium for plant growth, and as societal priorities change. In the late seventies, Warkentin and Fletcher (1977) discussed the evolution of soil quality concepts in intensive agriculture. The oldest and most frequently used concept was one of 'suitability for chosen uses', with emphasis on capability to support crop growth or engineering structures. This evolved to a 'range of possible uses' concept which is ecologically based and recognizes the importance of soil to biosphere function and its multiple roles in enhancing biological productivity, abating pollution, and even serving to enhance human health and aesthetic and recreational use of landscapes. Another stage in this evolution was development of the 'intrinsic value' concept of soil as a unique and irreplaceable resource, of value apart from its importance to crop growth or ecosystem function. As noted by Warkentin (1995), this view of soils is not widely explored by soil scientists but is held in various forms by naturalists and people who see a special relationship with the earth (Leopold, 1949). Historically soil has been used as a waste disposal system; it was conceived to be a biological incinerator destroying all the organic wastes deposited on or in it over time. However, in the 1960s and 1970s it became increasingly apparent that soils were receiving wastes of a type, and at a rate, that overwhelmed their assimilative capacity. This trend threatened soil function and called for a major responsibility by agriculturists in defining soil quality criteria (Alexander, 1971).

Quality of soil, as distinct from health, is largely defined by the ability of soil to perform various intrinsic and extrinsic functions. Quality is represented by a suite of physical, chemical, and biological properties that together: (i) provide a medium for plant growth and biological activity; (ii) regulate and partition water flow and storage in the environment; and (iii) serve as an environmental buffer in the formation and destruction of environmentally hazardous compounds (Larson and Pierce, 1991, 1994).

Soil serves as a medium for plant growth by providing physical support, water, essential nutrients and oxygen for roots. Suitability of soil for sustaining plant growth and biological activity is a function of physical properties (porosity, water holding capacity, structure and tilth) and chemical properties (nutrient supplying ability, pH, salt content, etc.), many of which are a function of soil organic matter content.

Soil plays a key role in completing the cycling of major elements required by biological systems (C, N, P, S, etc.), decomposing organic wastes and detoxifying certain hazardous compounds. The key role played by soils in recycling organic materials into CO_2 and water and degrading synthetic compounds foreign to the soil is brought about by microbial decomposition and chemical reactions. Ability of a soil to store and transmit water is a major factor controlling water availability to plants and transport of environmental pollutants to surface and ground water.

Much like air or water, the quality of soil has a profound effect on the health and productivity of any given biome and the environments and ecosystems related to it. However, unlike air or water for which we have quality standards, the definition and quantification of soil quality is complicated by the fact that it is not directly ingested or respired by humans and animals as are air and water. Soil quality is often thought of as an abstract characteristic of soils which can't be defined because it depends on external factors such as land use and soil management practices, ecosystem and environmental interactions, socioeconomic and political priorities, and so on. Historically, perceptions of what constitutes a good soil vary depending on individual priorities for soil function and intended land use. However, to manage and maintain our soils in an acceptable state for future generations, soil quality must be defined, and the definition must be broad enough to encompass the many functions of soil. In other words, as a natural body soil has importance and value in itself not necessarily as defined by its managed applications. These considerations led to the following definition: 'Soil quality is the capacity of soil to function, within ecosystem and land-use boundaries, to sustain biological productivity, maintain environmental quality and promote plant, animal and human health' (after Doran and Parkin, 1994).

Defining soil health

The terms soil quality and soil health are often used interchangeably in the scientific literature and popular press with scientists, in general, preferring soil quality and producers preferring soil health (Harris and Bezdicek, 1994). Some prefer the term soil health because it portrays soil as a living, dynamic organism that functions holistically rather than as an inanimate mixture of sand, silt and clay. Others prefer the term soil quality and descriptors of its innate quantifiable physical, chemical and biological characteristics. Much discussion at a recent soil health conference in the midwest USA centred on the importance of defining soil health (Soil Health: The Basis of Current and Future Production, Decatur, Illinois, December 7, 1994). In those discussions it was observed that efforts to define the concept of soil health have produced a polarization of attitudes concerning the term. On the one hand are those, typically speaking from outside agriculture, who view maintenance of soil health as an absolute moral imperative – critical to our very survival as a species. On the other hand is the attitude, perhaps ironically expressed most adamantly by academics, that the term is a misnomer – a viewpoint seated, in part, in fear that the concept requires value judgments which go beyond scientific or technical fact. The producers, and therefore society's management of the soil, are caught in the middle of these opposing views and the communication failures that result.

'Health' is defined as, 'the condition of an organism or one of its parts in which it performs its vital functions normally or properly' (Webster's Third New International Dictionary, 1986). The word is derived from the Old English word 'haelth' that was itself derived from the concept of 'whole'. Dr David White, a natural resource economist and speaker at the aforementioned soil health conference, proposed that any definition of soil health should: (i) reflect the soil as a living system; (ii) address all essential functions of soil in the landscape; (iii) compare the condition of a given soil against its own unique potential within climatic, landscape, and vegetation patterns; and (iv) somehow enable meaningful assessment of trends. It is interesting to note that with some modification, the definition of soil quality presented earlier could serve as a definition of soil health.

With consideration of the aforementioned factors, soil health can be defined as: 'the continued capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, promote the quality of air and water environments, and maintain plant, animal and human health'. The challenge we face, however, is in quantitatively defining the state of soil health and its assessment using measurable properties or parameters. Unlike human health, the magnitude of critical indicators of soil health ranges considerably over dimensions of time and space.

For the remainder of this chapter the terms soil quality and soil health will be used synonymously. However, the term soil health is preferred in that it more clearly portrays the idea of soil as a living dynamic organism that functions in a holistic way depending on its condition or state rather than as an inanimate object whose value depends on its innate characteristics and intended use.

Assessment of Soil Quality and Health

Establishing an ongoing assessment of the condition and health of our soil resources is vital to maintaining the sustainability of agriculture and civilization. As discussed earlier, the failure of several earlier civilizations was sealed by their disregard for the health of finite soil resources. In today's energy- and technology-intensive world, the need for maintaining the health of our soil resources is imperative to sustaining productivity for increasing populations and in maintaining global function and balance. Assessment of soil quality and health is invaluable in determining the sustainability of soil and land management systems and in evaluating their long-term effectiveness. However, we need a framework for evaluation and standards of soil quality and health to identify problems in production areas, to make realistic estimates of sustainable food production, to monitor changes in environmental quality as related to agricultural management, and to assist government agencies in formulating and evaluating sustainable agricultural and other land-use policies (Granatstein and Bezdicek, 1992; Acton, 1993). Identification of appropriate indicators for soil health assessment is complicated by the fact that they must account both for multiple dimensions of soil function, such as productivity and environmental well-being, and the multiplicity of physical, chemical and biological factors which control biogeochemical processes; and their variation in intensity over time and space.

Use of indicators

Assessing soil health can be likened to a medical examination of humans in which certain measurements are taken of the quality of certain parameters as basic indicators of system function (Larson and Pierce, 1991). In a medical examination, the physician takes measurements of body system functions such as temperature, blood pressure, pulse rate, and perhaps certain blood or urine chemistries. The physician will also take note of visible, outward signs of health status. If these basic indicators are outside specific ranges, more diagnostic tests can be conducted to help identify the cause of the problem and find a solution. For example, excessively high blood pressure may indicate a potential for system failure (death) through stroke or cardiac arrest. Because one of the causes of high blood pressure may be improper diet, lack of exercise, or high stress level, the physician may request a secondary blood chemistry test for cholesterol, electrolytes, etc. Assessment of stress level as a causative factor for high blood pressure is less straightforward and generally involves implementing some change in lifestyle followed by periodic monitoring of blood pressure to assess change. This is a good example of using a basic indicator both to identify a problem and to monitor the effects of management on the health of a system.

Applying this human health analogy to soil health is fairly straightforward. Larson and Pierce (1991) proposed that a minimum data set (MDS) of soil parameters be adopted for assessing the health of world soils, and that standardized methodologies and procedures be established to assess changes in the quality of those factors. A set of basic indicators of soil quality and, therefore, health has not previously been defined, largely due to difficulty in defining soil quality and health, the wide range over which soil indicators vary in magnitude and importance, and disagreement among scientists and soil and land managers over which basic indicators should be measured.

Acton and Padbury (1993) defined soil quality attributes as measurable soil properties that influence the capacity of soil to perform crop production or environmental functions. Soil attributes are useful in defining soil quality criteria and serve as indicators of change in quality. Attributes that are most sensitive to management are most desirable as indicators and some such as soil depth, soil organic matter and electrical conductivity are often affected by soil degradation processes (Arshad and Coen, 1992).

To be practical for use by practitioners, extension workers, conservationists, scientists, and policy makers the set of basic soil quality/health indicators should be useful over a range of ecological and socioeconomic situations.
Indicators should:

1. Correlate well with ecosystem processes (this also increases their utility in process oriented modelling).
2. Integrate soil physical, chemical, and biological properties and processes and serve as basic inputs needed for estimation of soil properties or functions which are more difficult to measure directly.
3. Be relatively easy to use under field conditions and be assessable by both specialists and producers.
4. Be sensitive to variations in management and climate. The indicators should be sensitive enough to reflect the influence of management and climate on long-term changes in soil quality but not be so sensitive as to be influenced by short-term weather patterns.
5. Be components of existing soil data bases where possible.

The need for basic soil quality and health indicators is reflected in the question commonly posed by producers, researchers, and conservationists: 'What measurements should I make or what can I observe that will help me evaluate the effects of management on soil function now and in the future?'. Too often scientists confine their interests and efforts to the discipline with which they are most familiar. Microbiologists often limit their studies to soil microbial populations, having little or no regard for soil physical or chemical characteristics which define the limits of activity for microorganisms, plants, and other life forms. The proper approach in defining soil quality and health indicators must be holistic, not reductionistic. The indicators chosen must also be measurable by as many people as possible, especially managers of the land, and not limited to a select cadre of research scientists. Indicators should describe the major ecological processes in soil and ensure that measurements made reflect conditions as they exist in the field under a given management system. They should relate to major ecosystem functions such as C and N cycling (Visser and Parkinson, 1992) and be driving variables for process oriented models which emulate ecosystem function. Some indicators, such as soil bulk density, must be measured in the field so that laboratory analyses for soil organic matter and nutrient content can be better related to actual field conditions at time of sampling. Soil bulk density is also required for calculation of soil properties such as water-filled pore space (WFPS) which serves as an excellent integrator of physical, chemical and biological soil properties and aeration dependent microbial processes important to C and N cycling in soil (Doran *et al.*, 1990). Many

Table 1.1. A limited listing of soil attributes or properties which can be estimated from basic input variables using pedotransfer functions or simple models.

Soil attribute or property	Basic input variables	Reference
Cation exchange capacity	Org. C + clay type and content	Larson and Pierce, 1994
Water retension charac. (AWHC)	% sand, silt, clay, + org. C + BD	Gupta and Larson, 1979
Hydraulic conductivity	Soil texture	Larson and Pierce, 1994
Aerobic and anaerobic microbial activity	WFPS as calculated from BD and water content	Linn and Doran, 1984 Doran *et al.*, 1990
C and N cycling	Soil respiration (Soil temperature + WFPS)	Parkin *et al.*, 1996
Plant/microbial activity or pollution potential	Soil pH + EC	Smith and Doran, 1996
Soil productivity	BD, AWHC, pH, EC, and aeration	Larson and Pierce, 1994
Rooting depth	BD, AWHC, pH	Larson and Pierce, 1994
Leaching potential	Soil texture, pH, org. C (hydr. cond., CEC, depth)	Shea *et al.*, 1992

Abbreviations: AWHC, available water holding capacity; BD, soil bulk density; EC, soil electrical conductivity; WFPS, water-filled pore space.

basic soil properties are useful in estimating other soil properties or attributes which are difficult or too expensive to measure directly. A listing of these basic indicators and input variables and the soil attributes they can be used to estimate are given in Table 1.1.

Starting with the minimum data set (MDS) proposed by Larson and Pierce (1991), we have developed a list of basic soil properties (Table 1.2) which meets many of the aforementioned requirements of indicators for screening soil quality and health. Appropriate use of such indicators, however, will depend to a large extent on how well these indicators are understood with respect to the ecosystem of which they are part. Thus, interpretation of the relevance of soil biological indicators apart from soil physical and chemical attributes and their ecological relevance is of little value and, with respect to assessment of soil quality or health, can actually be misleading.

Data presented in a Science article (Reganold *et al.*, 1993) describing soil quality and financial performance of biodynamic and conventional farming management systems in New Zealand, are useful in illustrating this concern (Table 1.3). Our analyses, however, are not intended as criticisms of this published

Table 1.2. Proposed minimum data set of physical, chemical, and biological indicators for screening the condition, quality, and health of soil (after Doran and Parkin, 1994 and Larson and Pierce, 1994).

Indicators of soil condition	Relationship to soil condition and function; Rationale as a priority measurement	Ecologically relevant values/units; Comparisons for evaluation
Physical		
Texture	Retention and transport of water and chemicals; Modelling use, soil erosion and variability estimate	% Sand, silt, and clay; Less eroded sites or landscape positions
Depth of soil, topsoil, and rooting	Estimate of productivity potential and erosion; Normalizes landscape and geographic variability	cm or m; Non-cultivated sites or varying landscape positions
Infiltration and soil bulk density (SBD)	Potential for leaching, productivity, and erosivity; SBD needed to adjust analyses to volumetric basis	minutes per 2.5 cm of water and Mg cm^{-3}; Row and/or landscape positions
Water holding capacity (water retention characteristics)	Related to water retention, transport, and erosivity; Available H_2O: calculate from SBD, texture, and OM	% (Mg cm^{-3}), cm of available H_2O per 30 cm ; Precipitation intensity
Chemical		
Soil organic matter (OM) (total organic C and N)	Defines soil fertility, stability, and erosion extent; Use in process models and for site normalization	kg C or N ha^{-1}–30 cm; Non-cultivated or native control
pH	Defines biological and chemical activity thresholds; Essential to process modelling	Compared with upper and lower limits for plant and microbial activity
Electrical conductivity	Defines plant and microbial activity thresholds; Presently lacking in most process models	dS m^{-1}; Compared with upper and lower limits for plant and microbial activity
Extractable N, P, and K	Plant available nutrients and potential for N loss; Productivity and environmental quality indicators	kg ha^{-1}–30 cm; Seasonal sufficiency levels for crop growth
Biological		
Microbial biomass C and N	Microbial catalytic potential and repository for C and N; Modelling: early warning of management effects on OM	kg N or C ha^{-1}–30 cm; Relative to total C and N or CO_2 produced
Potentially mineralizable N (anaerobic incubation)	Soil productivity and N supplying potential; Process modelling; (surrogate indicator of biomass)	kg N ha^{-1}–30 cm d^{-1}; Relative to total C or total N contents
Soil respiration, water content, and temperature	Microbial activity measure (in some cases plants) Process modelling; estimate of biomass activity	kg C ha^{-1} d^{-1}; Relative microbial biomass actvity, C loss vs. inputs and total C pool

Table 1.3. Reported and ecologically relevant mean values of aggregated soil quality data for 0–20 cm layer of 16 biodynamic and conventional farms in New Zealand (after Reganold *et al.*, 1993).

Soil property	Biodynamic farms	Conventional farms	Ratio Bio./Conv.
Reported units and values			
0–5 cm Bulk density (Mg m^{-3})	1.07	1.15	0.93*
Topsoil thickness (cm)	22.8	20.6	1.11*
Carbon (%)	4.84	4.27	1.13*
Total N (mg kg^{-1})	4840	4260	1.14*
Mineralizable N (mg kg^{-1})	140.0	105.9	1.32*
Respiration (μl O_2 $h^{-1}g^{-1}$)	73.7	55.4	1.33*
Ratio: mineralizable N to C (mg g^{-1})	2.99	2.59	1.15*
Extractable P (mg kg^{-1})	45.7	66.2	0.69*
pH	6.10	6.29	0.97*
Ecologically relevant units and values			
0–20 cm Bulk density† (Mg cm^{-3})	1.2	1.3	0.92
Carbon (Mg C ha^{-1} –20 cm)	116.2	111.0	1.05
Total N (kg N ha^{-1} –20 cm)	11,616	11,076	1.05
Mineralizable N (kg N ha^{-1} –20 cm 14 d^{-1})	336	275	1.22
Respiration in lab (kg C ha^{-1} –20 cm d^{-1})	2275	1850	1.23
Ratio: mineralizable N to C	2.89	2.48	1.17*
Extractable P (excess)‡ (kg P ha^{-1} –20 cm)	110 (50)‡	172 (112)	0.63*
pH units above 6.0 lower limit	0.1	0.3	0.33

* Values differ significantly ($P < 0.01$); † Estimated, since data was only given for 0–5 cm depth; ‡ Threshold value for environmentally sound soil P level set at 60 kg P ha^{-1}.

work as the authors should be commended for their vision in choice of physical, chemical and biological indicators of soil quality. One point of discussion is the importance of expressing the results of soil quality tests on a volumetric rather than a gravimetric basis and in units for which ecological relevance can be readily ascertained. As illustrated in Table 1.3, the magnitude of differences in soil C, total N, respiration, and mineralizable N between management systems for samples expressed by weight of soil are 8–10% greater than where expressed on a volume basis using soil bulk density estimates. In cultivated systems, soil bulk density can vary considerably across the soil surface due to mechanical compaction and throughout the growing season due to reconsolidation of soil after tillage. Soil bulk density is also directly proportional to the mass of any soil component for a given depth of soil sampled. Where samples are taken in the field under management conditions of varying soil densities, comparisons made using gravimetric analyses will err by the difference in soil density at time of sampling. The observed differences due to management in the New Zealand study were statistically significant. However, since results were expressed on a gravimetric basis, they may not be valid nor ecologically relevant. In cases such as this, where values for soil bulk density at time of sampling are not available, the use of soil indicator ratios (in this case mineralizable N to C) can reduce errors of interpretation associated with use of results expressed on a weight basis. Reganold and Palmer (1995) recommend calculating soil measurements on a volume basis per unit of topsoil or solum depth for most accurate assessment of management effects on soil quality.

Choice of units of expression for soil quality indicators can also have an important bearing on determining the ecological relevance of measured values. In the New Zealand study, respiration of laboratory incubated soils from biodynamic farms averaged 73.7 ml O_2 $h^{-1}g^{-1}$, significantly greater (33%) than that from conventional farms. One interpretation of these results could be that the soils of the biodynamic farms are healthier since respiration was greater. However, if one assumes that for aerobic respiration a mole of oxygen is consumed for each mole of carbon dioxide produced, and the results are adjusted for soil density and expressed as kg C released per hectare per day, a different picture emerges. The quantities of C released in one day from both the biodynamic and conventional farms are incredibly high and represent 2.0 and 1.7%, respectively, of the total C pools of these surface soils. While the values for soil respiration from disturbed soils incubated in the laboratory only represent a potential for release of readily metabolizable C (labile C), the results clearly demonstrate that more may not be better and that high rates of respiration may be ecologically detrimental as they represent potentials for depletion of soil organic C with accelerated enrichment of the atmosphere with carbon dioxide. When expressed in ecologically relevant units, it becomes obvious that the respiration rates observed in this study are of limited use in evaluating the status of soil quality and health between these different farming management systems when used as the only indicator. Similar observations can be made for mineralizable N and extractable P. Levels of mineralizable N above that needed for crop production for biodynamic farms and extractable P levels above crop needs for conventional farms could represent a lower level of soil quality and health as a result of greater potential for environmental contamination through leaching, runoff, or volatilization losses. Specific upper limits for environmentally sound levels of soil P and N exist and are determined by local climatic, topographic, soil and management situations (Sharpley *et al.*, 1996). Again, an example that with respect to soil quality and health, more is not necessarily better and ecologically relevant units are needed for proper evaluation. Soil pH is another example of a soil quality attribute that must be referenced to a definable standard for upper and lower limits which are defined by the cropping system or biological processes of greatest ecological relevance. The above discussion serves to highlight the difficulty we have in interpreting the results of laboratory incubations and the need for in-field measurements of respiration and N cycling.

Indicators of soil quality and health are commonly used to make comparative assessments between agricultural management practices to determine their sustainability. However, the utility of comparative assessments of soil quality are limited because they provide little information about the processes creating the measured condition or performance factors associated with respective management systems (Larson and Pierce, 1994). Also, the mere analysis of soils, no matter how comprehensive or sophisticated does not provide a measure of soil quality or health unless the parameters are calibrated against designated soil functions (Janzen *et al.*, 1992).

Quantitative assessments

Quantitative assessments of soil quality and health will require consideration of the many functions that soils perform, their variations in time and space and opportunities for modification or change. Criteria are needed to evaluate the impact of various practices on the quality of air, soil, water and food resources. Soil quality and health can not be defined in terms of a single number, such as the 10 mg l^{-1} NO_3-N standard applied for drinking water, although such quantitative standards will be valuable to overall assessment. Assessments must consider specific soil functions being evaluated in their land use and societal contexts. Threshold values for key indicators must be established with the knowledge that these will vary depending upon land use, the specific soil function of greatest concern and the ecosystem or landscape within which the assessment is being made. For example, soil organic matter concentration is frequently cited as a major indicator of soil quality. Threshold values established for highly weathered Ultisols in the southeastern US indicate that surface soil organic matter levels of 2% (1.2% organic C) would be very good, while the same value for Mollisols developed under grass in the Great Plains, which commonly have higher organic matter levels, would represent a degraded condition limiting soil productivity (Fig. 1.1). As pointed out by Janzen *et al.* (1992) the relationship between soil quality indicators and various soil functions does not always comply to a simple relationship increasing linearly with magnitude of the indicator, as is commonly thought. Simply put, bigger is not necessarily better.

Soil quality and health assessments will have to be initiated within the context of societal goals for a specific landscape or ecosystem. Examples include establishing goals such as enhancing water quality, soil productivity, biodiversity, or recreational opportunities. When specific goals have been established or are known, then critical soil functions needed to achieve those goals can be agreed upon, and the criteria for assessing progress toward achieving those goals can be set. Periodic assessments of soil quality and health with known indicators, thresholds, and other criteria for evaluation will then make it possible to quantify soil quality and health.

To accomplish such goals, several approaches for assessing soil quality have been proposed (Acton and Padbury, 1993; Doran and Parkin, 1994; Karlen *et*

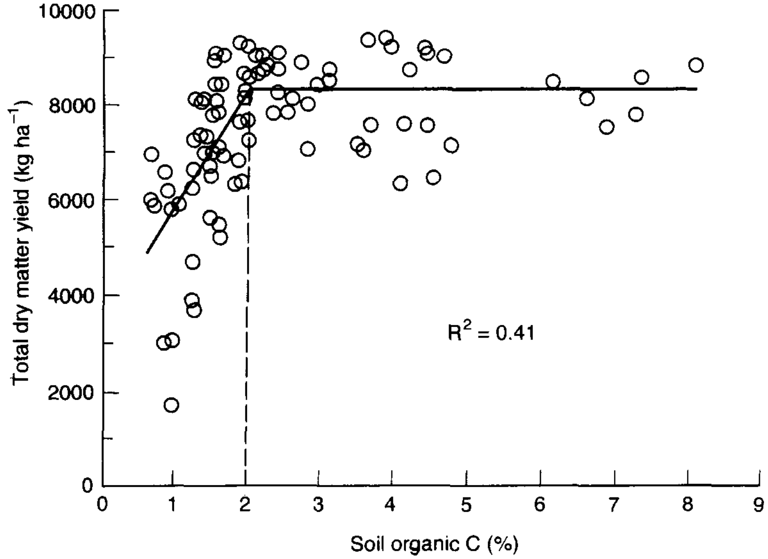

Fig. 1.1. Relationship between organic C concentration in the surface 0–15 cm of soil and soil productivity as determined by total dry matter yield at dryland site in Alberta, Canada in 1991 (after Janzen *et al.*, 1992; with permission).

al., 1994; Larson and Pierce, 1994). A common attribute among all these approaches is that soil quality is assessed with respect to specific soil functions. Larson and Pierce (1994) proposed a dynamic assessment approach in which the dynamics, or change in soil quality, of a management system is used as a measure of its sustainability. They proposed the use of a minimum data set of temporally variable soil properties to monitor changes in soil quality over time. They also proposed the use of pedotransfer functions (Bouma, 1989) to estimate soil attributes which are too costly to measure and to interrelate soil characteristics in evaluation of soil quality (Table 1.1). Simple computer models are used to describe how changes in soil quality indicators impact important functions of soil, such as productivity. An important part of this approach is the use of statistical quality control procedures to assess the performance of a given management system rather than its evaluation by comparison to other systems. This dynamic approach for assessing soil quality permits identification of critical parameters and facilitates corrective actions for sustainable management.

Karlen and Stott (1994) presented a framework for evaluating site-specific changes in soil quality. In this approach they define a high quality soil as one that: (i) accommodates water entry; (ii) retains and supplies water to plants; (iii) resists degradation; and (iv) supports plant growth. They described a procedure by which soil quality indicators which quantify these functions are identified, assigned a priority or weight which reflects relative importance, and are scored using a systems engineering approach for a particular soil attribute such as resistance to water erosion. Karlen *et al.* (1994) also demonstrated the utility of this approach in discriminating changes in soil quality between long-term crop residue and tillage management practices.

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:

$$SQ = f\,(SQE1, SQE2, SQE3, SQE4, SQE5, SQE6)$$

where soil quality elements are: SQE1 = food and fibre production; SQE2 = erosivity; SQE3 = groundwater quality; SQE4 = surface water quality; SQE5 = air quality; and SQE6 = food quality.

One 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 example, yield goals for crop production (SQE1); limits for erosion losses (SQE2); concentration limits for chemicals leaching from the rooting zone (SQE3); nutrient, chemical and sediment loading limits to adjacent surface water systems (SQE4); production and uptake rates for gases that contribute to ozone destruction or the greenhouse effect (SQE5); and nutritional composition and chemical residue of food (SQE6). This list of elements is restricted primarily to agricultural situations but other elements such as wildlife habitat quality could be easily added to expand the applications of this approach.

This approach would result in soil quality indices computed in a manner analogous to the soil tilth index proposed by Singh *et al.* (1990). Weighting factors are assigned to each soil quality element, with relative weights of each coefficient being determined by geographical considerations, societal concerns and economic constraints. For example in a given region, food production may be the primary concern and elements such as air quality may be of secondary importance. If such were the case, SQE1 would be weighted more heavily than SQE5. Thus this framework has an inherent flexibility in that the precise functional relationship for a given region, or a given field, is determined by the intended use of that area or site, as dictated by geographical and climatic constraints as well as socioeconomic concerns.

Assessment of soil quality and health is not limited to areas used for crop production. Forests and forest soils are important to the global C balance as related to C sequestration and atmospheric levels of carbon dioxide. Soil organic matter and soil porosity, as estimated from soil bulk density, have recently been proposed among international groups as major soil quality indicators in forest soils (Richard Cline, personal communication). Criteria for evaluating rangeland health have recently been suggested in a National Research Council (1994) report which describes new methods to help classify, inventory and monitor rangelands. Rangeland health is defined as the degree to which the integrity of the soil and the ecological processes of rangeland ecosystems are sustained. Assessment of rangeland health is based on the evaluation of three criteria: (i) degree of soil stability and watershed function; (ii) integrity of nutrient cycles and energy flows; and (iii) presence of functioning recovery mechanisms.

Value of qualitative/descriptive assessments

The concept of soil health is in many ways farmer-generated and rooted in observational field experiences which translate into descriptive properties such as its look, feel, resistance to tillage, smell, presence of biota, etc. Harris and Bezdicek (1994) conclude that farmer-derived descriptive properties for assessing soil health are valuable for: (i) defining or describing soil quality/health in meaningful terms; (ii) providing a descriptive property of soil quality/health; and (iii) providing a foundation for developing and validating an analytical component of soil health based on quantifiable chemical, physical, and biological properties that can be used as a basis for management and policy decisions. Unfortunately, the potential contributions of indigenous farmer knowledge to management of soil quality/health throughout the world has not been fully utilized (Pawluk *et al.*, 1992).

Descriptive soil information is not commonly used in scientific literature dealing with characterization of soil quality/health. However, Arshad and Coen (1992) indicate that many soil attributes can be estimated by calibrating qualitative observations against measured values and recommend that qualitative (descriptive) information should be an essential part of soil quality monitoring programmes. Visual and morphological observations in the field can be used by both producers and scientists to recognize degraded soil quality caused by: (i) loss of organic matter, reduced aggregation, low conductivity, soil crusting and sealing; (ii) water erosion, as indicated by rills, gulleys, stones on the surface, exposed roots, uneven topsoil; (iii) wind erosion as indicated by ripple marks, dunes, sand against plant stems, plant damage, dust in air, etc. ; (iv) salinization, as indicated by salt crust and salt-tolerant plants; (v) acidification and chemical degradation, as indicated by growth response of acid-tolerant and -intolerant plants and lack of fertilizer response; and (vi) poor drainage and structural deterioration, as indicated by standing water and poor or chlorotic plant stands.

Doran *et al.* (1994a,b) stressed the importance of holistic management approaches which optimize the multiple functions of soil and conserve soil resources and support strategies for promoting soil quality and health. They proposed use of the basic set of soil quality and health indicators (Table 1.2) to assess soil health in various agricultural management systems. However, while many of these key indicators are extremely useful to specialists (i.e. researchers, consultants, extension staff and conservationists) many of them are beyond the expertise of the producer to measure (Hamblin, 1991). In response to this

Table 1.4. Sustainable management strategies for building soil quality and health and associated indicators which are assessable by producers.

Strategy	Indicators
Conserve soil organic matter through maintaining balance in C and N cycles where inputs × outputs	Direction/change in organic matter levels with time; OM potential within soil, climate, and cropping patterns; Both visual and analytical measures; Soil infiltration/water-holding capacity
Minimize soil erosion through conservation tillage and increased soil cover (residue, cover crops, green fallow, etc)	Visual signs (gullies, rills, dust, etc.); Surface soil characteristics: (depth of topsoil, organic matter content/texture, infiltration rate)
Substitution of renewable for non-renewable resources through less reliance on synthetic chemicals, use of conservation tillage, and greater use of natural balance and diversity (crop rotation, legume cover crops, etc.)	Crop growth characteristics (yield, N content, colour, rooting); Soil and water nitrate levels; Soil physical condition/compaction; Input costs
Move toward management systems which coexist more with and less dominate natural systems through optimizing productivity needs with environmental quality	Crop growth characteristics (yield, N content, colour, vigour); Soil and water nitrate levels; Synchronization of N availability with crop needs during year

dilemma, Doran (1995) presented strategies for building soil quality and health which also included generic indicators which are measurable by and accessible to producers within the time constraints imposed by their normally hectic and unpredictable schedules (Table 1.4). Soil organic matter, crop appearance and erosion were ranked by farmers in the Northern US Corn and Dairy Belt as the top three properties for describing soil health (Romig *et al.*, 1995).

Soil Assessment – Need for Producer/Specialist Interaction

Integration of soil health concepts into farm management

At a time when agriculture must address environmental degradation due to certain yield promoting practices against ever increasing demands for both greater and better-distributed food supplies, the concept of soil health can be a useful communication device in meeting present and future world needs. Stewardship of the soil resource that enhances soil quality and health while allowing for acceptable long-term production levels is in everyone's best interest and satisfies what has been called the 'Ecocentric' notion of the Common Good (Stauber, 1994). Soil management practices must now be evaluated for their impacts across the temporal scale – short, middle and long-term, as well as across the landscape, to be truly sustainable (Swift *et al.*, 1991).

Producers around the globe receive advice from many sources about recommended production practices. Unfortunately, much of this advice is often aimed at relatively short-term (1 or 2 years) economic gains to their operation, rather than on long-term resource conservation (Stauber, 1994). Additionally, advice may be value-laden, or linked to agribusiness sales, such as soil tests performed by private companies which may indicate need for unnecessary chemical fertilizers and pesticides (Cramer, 1986; Soule and Piper, 1992). Management recommendations are often developed for regions which may encompass a wide variation in soil type, topography and resource availability. In such cases, practices which are appropriate for experimental conditions may be inappropriate on a large portion of the individual farms to which they are recommended. To begin the move toward site-specific best management practices, tests for soil quality indicators should be developed as meters for gauging both the short and long-term effects of various production practices on soil health. Soil quality tests that yield results uncoupled from value judgments will allow both land stewards and researchers to evaluate production practices objectively under a wide range of conditions, to identify those that are truly improving soil health. Clearly, value judgment is always likely to be necessary to reconcile the need for food production with the need to maintain soil in a near-natural state. Tests which accurately measure impacts on soil quality of various options will help make the consequences of those options more apparent. If tests are made to be used by producers and other land stewards, production practices will not only be efficiently tailored for individual situations, but researchers will have a many fold increase in the information available to better understand soil processes.

The concept of soil health can be a key tool for educating producers about some of the less obvious potentials for soil degradation due to poor management. There is some evidence that a concern for soil health may lead land stewards to production practices that indeed improve some soil characteristics. Van Kooten *et al.* (1990) found in southwestern Saskatchewan that farmer concern for soil quality was in fact correlated to production practices which improved soil physical parameters. The authors found, however, that in areas of deep topsoil, farmers were less likely to be seriously concerned with soil quality, which pinpoints the need to emphasize the long-term vision of soil health.

Technology transfer

Producers and land managers need practical tools which they can use to determine the effectiveness of their management practices on soil health and sustainable production. Traditional research has identified management practices that conserve the soil resource, protect air and water quality, or maximize crop yields. However, development of sustainable management strategies that maintain soil quality and health and balance production needs with environmental concerns require new research approaches and on-site evaluation to confirm the specific applications of general strategies across the range of climatic, soil, economic and social conditions experienced by agriculture. Facilitating producer participation in the research process is essential to the development of practical production systems and assessment approaches which address both the needs of producers and society in general. Indicators of soil health and practical assessment tools are essential to forming this necessary partnership between producers and the technical community. National indicators of some aspects of soil quality and health are likely to be established within the next decade as a means of monitoring the state of our soil resources. It is imperative that these indicators be useful to producers, especially if incentives or regulations based on soil quality or health are enacted.

To include producers as active participants in on-site assessment of soil quality/health, tools and methodologies used by researchers must be adapted to be easily accessible to the producers themselves (Sarrantonio *et al.*, 1996). Tests should be simple to perform, require little in the way of expensive equipment, and give rapid results. Additionally, tests should be able to measure soil indicators that are meaningful to the producers' understanding of soil and its processes, and that give results that are reliable, accurate within an acceptable range, and are easily understood and used. A soil quality kit is currently being developed by USDA-ARS to help producers, researchers, conservationists, environmentalists and consultants assess the health and quality of soil and facilitate technology transfer (Cramer, 1994). The kit provides on-site capability for assessment of many of the potential indicators of soil quality and health (see Table 1.2) such as soil pH, electrical conductivity, soil and water nitrate levels, soil density, water infiltration, water-holding capacity, soil water content, water-filled pore space, soil temperature and soil respiration. The kit provides producers and agricultural specialists with the necessary means for a cursory assessment of the complex suite of physical, chemical and biological factors that comprise soil quality/health. Tests facilitate on-site identification of soil resource condition and its degree of degradation. Currently the cost of the test kit is under $250, yet results obtained with this kit compare well with standard laboratory procedures that are more time consuming and costly (Liebig *et al.*, 1996). The utility of this test kit is currently being evaluated by conservationists, researchers, extension educators, environmental monitors (EPA-EMAP), and producers at locations in Australia, Canada, Cuba, Greece, Honduras, India, New Zealand, Poland, Moldova, Russia and in over 50 locations the United States. Preliminary results suggest the kit is useful to specialists in fostering appreciation for the complexity of soil, in bridging across disciplinary boundaries, and facilitating assessment of soil quality and health. However, the overall procedure for on-site assessment of soil quality and health was found too complicated and time consuming for practical use by producers. The kit is best used by producers as a tool kit from which specific tests can be used as needed to assess soil quality and health. Also, compilation of a practical manual for the test kit, similar to that included with the 'Sustainability Kit' produced in Australia (Powell and Pratley, 1991), would greatly aid utility of this test kit and interpretation of results.

Practical tools for soil quality and health assessment by producers must aid their comprehension of the concept of soil health and be useful to them within the context of their normal work routines (after Nowak in Leopold Letter, 1995). Knowledge of soil for most producers is largely limited to that which they gain through their sensory experiences in working the soil with agricultural implements and watching plant growing conditions during the growing season. Clues producers most often use to differentiate soils include soil colour (largely organic matter), the workability of soil (structure and compaction), wetness or dryness of soil (drainage, storage and infiltration capacity) and topsoil texture and depth (indicators of soil erosion and production potential). Crop yield and input costs are indicators which producers most often rely upon to assess the short-term sustainability of their management practices. Inclusion of other tools for rapid assessment of efficiency of resource use such as quick tests for soil and water nitrate levels, adequacy of plant growth and N content and synchronization of soil nitrogen supplies with crop plant needs will facilitate development of reduced input management systems and management strategies for long-term sustainability (Table 1.4).

Conclusions

Soil is a finite and dynamic living resource that acts as an interface between agriculture and the environment and is vital to global function. Soil health can be defined as the continued capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, promote the quality of air and water environments, and maintain plant, animal and human health. Advantages to giving value to soil health and its assessment include: (i) importance as a resource for evaluation of land-use policy; (ii) use in identification of critical landscapes or management systems; (iii) use in evaluation of practices that degrade or improve the soil resource; and (iv) utility in identifying gaps in our knowledge base and understanding of sustainable management.

To assure the sustainability of agricultural management systems, producers and land managers must be included as active participants in the quantitative and qualitative assessment of soil quality and health. Present research and education needs critical to assessment and enhancement of soil quality/health include:

1. Coordinated development of standards for soil quality/health, by national and local agencies and interest groups involved in agriculture, the environment, resource conservation, and economics, to assess sustainability changes with time. This requires establishment of reference guidelines and thresholds for indicators of soil quality/health that enable identification of relationships between soil measures and soil function which permit valid comparisons across variations in climate, soils, landuse, topography and management systems. This will also require identification of appropriate scales of time and space for assessment of soil quality/health and development of standardized protocols for sampling, processing and analysis.
2. Development of practical approaches and tools for on-site assessment of soil quality/health by farmers, researchers, extension workers, conservationists and environmental monitors that can also be used by resource managers and policy makers to determine the sustainability of land management practices.

We are beginning to realize that soil health, by its broadest definition, is inseparable from issues of sustainability. The challenge before us is to develop holistic approaches for assessing soil quality and health that are useful to producers, specialists, and policy makers in identifying agricultural and land-use management systems which are profitable and will sustain our soil resources for future generations.

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