Australian Government
Australian Centre for
International Agricultural Research

Sustainable Management of Soil in Oil Palm Plantings

ACIAR PROCEEDINGS 144

Research that works for developing countries and Australia

Soil fertility, evolving concepts and assessments

Cécile Bessou[1], Raphaël Marichal[2]

Abstract

Many authors have discussed the concept of soil fertility. Despite some disagreement on the exact terminology, soil fertility retrospectively appeared to focus generally on the use of soil for agriculture. It was defined some 150 years ago, while agricultural sciences mostly focused on soil physical and chemical properties. More recently, with the increasing awareness of environmental issues related to agricultural land use and the development of new knowledge on ecosystems, more comprehensive approaches to soil quality were developed. Since the 1980s, growing knowledge on the roles of soil organic matter and living organisms has emphasised the importance of understanding and assessing the biological components of the soil and their functions alongside the physical and chemical components. Soil is described as a living system that fulfils several functions, such as primary production, environmental filter and climate regulation. Following the metaphor of a complex living 'organism', the term 'soil health' is thus used by some authors instead of soil quality. Soil quality is hence defined as the soil fitness for use, which cannot be measured directly. It must be assessed in a sensitive and holistic way that accounts for both inherent properties and dynamic responses to management and resistance to environmental stress. Several sets of indicators and more integrated methods have been developed. However, further research is still needed to consolidate assessment guidelines that would help to model better the impact of agricultural practices on soil quality and to define strategies for a sustainable management of soil quality.

History of soil fertility and soil quality concepts

The scientific notion of soil fertility originated, around the 1850s, from the focus in agronomy on the use of soil to support production (Patzel et al. 2000) (*ferre* means 'to carry', 'to support' in Latin). It coincided with the beginning of the 'mineralist period' (1840s–1940s) that started with the first scientific demonstration of the origin of plant dry matter from mineral compounds, leading to the conclusion that carbon comes from carbon dioxide, hydrogen from water and other nutrients from solubilised salts in soil and water (Manlay et al. 2007). In this early stage of soil fertility conception, agricultural sciences hence mostly emphasised the role of physical and chemical properties of soil to support plant growth. From there on, soil fertility became a matter for both disciplines of agronomy and soil sciences. The mainstream approach considered soil fertility as dependent on some inherent qualities resulting from the expression of soil-forming factors. This approach led to work on soil classification and survey tables, where a land capability concept overlapped with a soil fertility one.

The concept of soil fertility has been chronically debated as background knowledge and social and political contexts evolved. Its circumscription varies widely, from literature where actual yield or productivity is identical with or fully representative of soil fertility, to literature introducing more or less complex definitions based on the combinations of several factors including soil properties, climate, work and

---

[1] CIRAD, UPR Systèmes de pérennes, F-34398 Montpellier, France. Email: cecile.bessou@cirad.fr

[2] CIRAD, UPR Systèmes de pérennes, F-34398 Montpellier, France. Email: raphael.marichal@cirad.fr

social or cultural parameters (Patzel et al. 2000). Until the 1980s, there was no clear chronological evolution of the concept. The various interpretations co-existed. For instance, one of the earliest definitions stated that 'soil fertility is a product of soil and manpower' (von Wulffen 1847). This focus on work or cultivation can be found again in later definitions (e.g. Blohm 1964). Further definitions have run through the times concomitantly. In their analytical review, the authors concluded that the concept of soil fertility cannot be grasped in one single technical definition. First, it refers to a disposition which is never present at hand. Second, it cannot escape the trade-off relationship between distinctness and completeness due to the plurality of significant aspects transgressing the realm of natural sciences (Patzel et al. 2000).

At the end of the 'mineralist period', concomitant increasing scientific knowledge of soils and rising concern about the environmental impact of inadequate agricultural practices, notably erosion impact, led to a renewed interest in the study of soil organic matter (SOM) (Lewandowski et al. 1999; Manlay et al. 2007). This period marked a turning point in the analysis of soil with a widening of the perception beyond the plant nutrition theories to further ecosystem functions. But it was not until the concerns about the economic and ecological costs of the intensive use of synthetic fertilisers had become more severe following the green revolution, that the soil fertility focus on nutrient storage and productivity was abandoned for a wider vision of soil as a complex living organo-mineral system (Manlay et al. 2007). A political change towards sustainable agriculture was called for (WCED 1987).

In the 1980s, North American authors started to discuss and define a new concept—soil quality—accounting for the multiple dimensions (physical, chemical and biological) and functions of soil (Warkentin and Fletcher 1977 (the authors who introduced the term 'soil quality'); Doran and Parkin 1994; Patzel et al. 2000; Karlen et al. 2003). The first definitions of soil quality were close to those of sustainable agriculture. In essence, preserving or improving soil quality is about maintaining the long-term functions of soils, i.e. it is about sustainability (Doran et al. 1996). The current most common definition is: 'Soil quality is the fitness of a specific kind of soil to function within its surroundings, support plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation' (Karlen et al. 1997). Emphasis is put on both inherent properties of soil ('a specific kind of soil') and dynamic interactive processes (Larson and Pierce 1991). Nowadays, some authors still argue that soil fertility and soil quality may be interchangeable, and the terminology remains relative to the discipline or the application sector. Soil health may be also used instead of soil quality by some authors who want to insist on the metaphoric holistic approach of soil as a living organism (Idowu et al. 2007). Setting aside some ideological considerations linked to the terminology, authors tend to agree that '(1) soils have both inherent and dynamic properties and processes, and that (2) soil quality assessment must reflect biological, chemical, and physical properties, processes and their interactions' (Karlen et al. 2003).

The comprehensive approach

Soil conditions are defined by physical, chemical and biological properties. All these proprieties depend on land-use practices but also inherent soil properties (texture, type of clay, cation exchange capacity). These properties are not independent but linked with complex interactions, and affect soil processes and functions (Larson and Pierce 1991). Physical properties are an important aspect of soil quality; for example, soil storage capacity of plant-available water, bulk density and water infiltration (Grimaldi et al. 2002; Moebius et al. 2007). Chemical properties, such as content of phosphorus and nitrogen and ions of calcium, magnesium and potassium, are essential for plant nutrition and thus contribute to productivity. Soil organic matter is also essential and linked to several soil properties and functions. For example, its composition affects soil structure and porosity, water infiltration, moisture, plant nutrient availability and soil organisms (Bot and Benites 2005). In summary, soil organic matter influences almost all important properties that contribute to soil quality (Bot and Benites 2005).

Another important aspect is living organisms (a component of soil organic matter). Soil organisms can be divided into four metric categories: microorganisms (<100 µm), mesofauna (100 µm – 2 mm), macrofauna (2 mm – 20 mm) and megafauna (>20 mm) (Swift et al. 1979). These organisms contribute to several soil functions: decomposition, nutrient cycling etc. (Lavelle 1997; Lavelle et al. 1994, 2006). Soil organisms can also be divided into functional categories: detritivores, predators/grazers, decomposers, pathogens, herbivores and ecosystem engineers (*sensu* Jones et al. 1994), i.e. organisms that create or significantly modify habitats).

Interactions between chemical, physical and biological properties are strong and complex. Soil organism communities are influenced by soil properties acting like an environmental filter but soil fauna can also impact soil properties—physical or chemical. For example, bioturbation of ecosystem engineers in soil can impact macroporosity and, as a consequence, water infiltration. By the fragmentation and decomposition of litter, soil organisms also affect chemical properties, such as plant-available nitrogen. Earthworms can also help to reduce plant diseases. For example, it has been shown than earthworms improve resistance of rice against pathogen nematodes (Blouin et al. 2005), although the mechanisms remain unclear. For all these reasons, soil organisms are often considered as good indicators of soil quality/fertility, as part of an integrative and holistic approach. Some approaches consider empirically that higher values are better considering biomass, abundance or diversity of soil organisms. Other approaches try to identify organisms or traits responsible for precise functions and try to quantify them.

The different approaches developed to assess soil quality using soil organisms are thus based on quantity, structure or function (Table 1): total biomass of soil micro-organisms (bacteria and fungi) can be evaluated with the classical method of fumigation-extraction (Wu et al. 1990) or, more recently, quantitative polymerase chain reaction (qPCR) (El Azhari et al. 2008). Soil enzymes, produced by micro-organisms, are also good indicators to assess soil quality through soil biochemical functioning (Dick et al. 1997; Alkorta et al. 2003). This approach allows evaluating functions of interest. Molecular methods, like PCR denaturing gradient gel electrophoresis (PCR-DGGE) or phospholipid fatty acid (PLFA) profiling (Bloem et al. 2006) assess soil micro-organism diversity. Nematodes are also used as bio-indicators for soil quality (Neher 2001; Yeates 2003) and indicators using micro-arthropods (e.g. Collembola, Acari) have also been developed (Parisi et al. 2005). Earthworms (biomass, abundance, diversity and proportion of ecological categories—epigeics, anecics, endogeics) are also classically used to assess soil quality (Paoletti 1999; Peres et al. 2008).

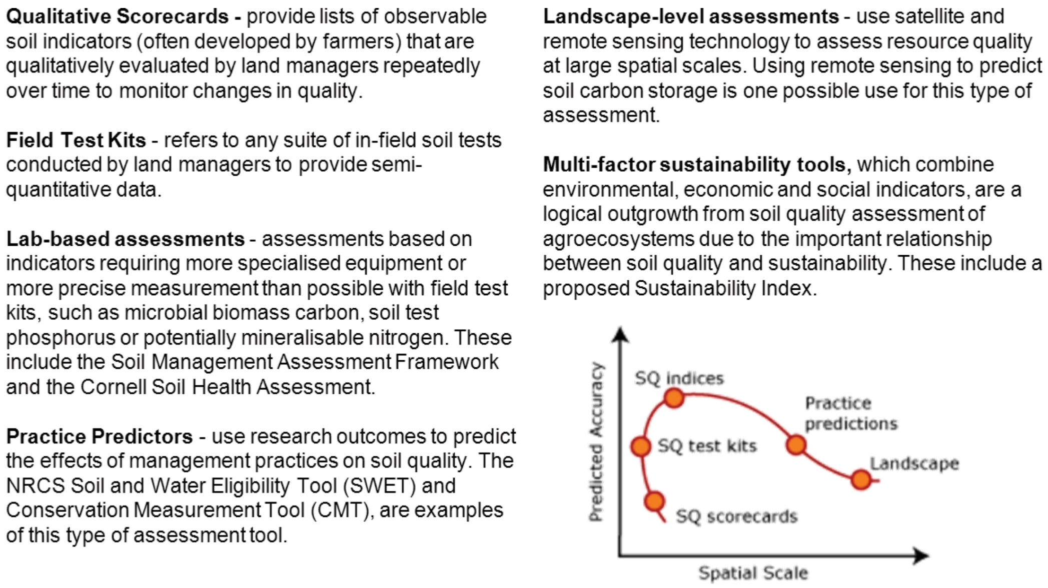
Assessment of soil quality

Since it is a broad, integrative and context-dependent concept, soil quality cannot be measured directly. Instead several proxy measurements, called soil quality indicators, may together provide clues about how the soil is functioning as viewed from one or more soil-use perspectives. There exist various methods based on more or less numerous and integrated indicators (Figure 1), and not much international agreement on a proper harmonised framework (Nortcliff 2002). Nowadays, the most prevalent research theme on soil quality focuses on indicator selection and evaluation (Karlen et al. 2003).

The lack of success in quantifying soil quality through minimum data sets and indexes has highlighted the local and long-term nature of trends in soil quality (Lewandowski et al. 1999). Given some inherent specific properties of each soil and the multiple functions that may be investigated, there cannot be a unique turnkey assessment, or a rating system against which all soils can be compared (Karlen et al. 2003). The selection of appropriate indicators must aim to account for (i) site specificities in terms of both soil type and land-use objectives, and (ii) the dynamic nature of processes and temporal

Table 1. Biological indicators of soil quality: fauna classification and information level

Information level	Micro-flora/fauna	Meso-fauna	Macro/mega-fauna
Quantity (biomass/abundance)	Extraction Fumigation-extraction qPCR	Extraction	TSBF, formalin extraction, mustard extraction
Structure/diversity	PCR-DGGE, PLFA profiling	Richness Biodiversity index	Richness Biodiversity index
Activity/function	Enzyme activities Microrespiration	Functional traits Ecological categories	Functional traits Ecological categories



Qualitative Scorecards - provide lists of observable soil indicators (often developed by farmers) that are qualitatively evaluated by land managers repeatedly over time to monitor changes in quality.

Field Test Kits - refers to any suite of in-field soil tests conducted by land managers to provide semi-quantitative data.

Lab-based assessments - assessments based on indicators requiring more specialised equipment or more precise measurement than possible with field test kits, such as microbial biomass carbon, soil test phosphorus or potentially mineralisable nitrogen. These include the Soil Management Assessment Framework and the Cornell Soil Health Assessment.

Practice Predictors - use research outcomes to predict the effects of management practices on soil quality. The NRCS Soil and Water Eligibility Tool (SWET) and Conservation Measurement Tool (CMT), are examples of this type of assessment tool.

Landscape-level assessments - use satellite and remote sensing technology to assess resource quality at large spatial scales. Using remote sensing to predict soil carbon storage is one possible use for this type of assessment.

Multi-factor sustainability tools, which combine environmental, economic and social indicators, are a logical outgrowth from soil quality assessment of agroecosystems due to the important relationship between soil quality and sustainability. These include a proposed Sustainability Index.

Figure 1. Types of soil quality (SQ) assessment tools and their predicted accuracy. Resource webpage: http://soilquality.org (accessed 30 January 2014)

patterns of soil characteristics. Therefore, proposed indicators must be measured and assessed across a representative set of lands and management practices. As emphasised by Karlen et al. (2003), site-specific expertise may also be needed in order to weight various indicators into an aggregated index (Figure 2). An efficient indicator set should be used to inform land management decisions at specific sites and then be used to monitor trends in soil function after changing practices and over time.

Implementing useful and efficient indicators of soil quality requires robust scientific background combined with reliable practical sense to define consistent and informative indicators. In particular, difficulties arise when assessing interactions between processes and parameters. It is paramount to avoid overlapping indicators and unreliable measurements (Moebius-Clune et al. 2011). More research is needed to better understand and model the links between management – processes – soil quality.

Conclusion and research tracks

Soil quality is itself a field of active research to find fruitful approaches and reliable indicators. For example, new approaches were proposed in soil microbiology, such as taking into account functional ecology concepts, i.e. vigour, organisation, stability, suppressiveness and redundancy (Garbisu et al. 2011), or organisms rarely used, e.g. testate amoebae or diatoms (Heger et al. 2012), which are good bio-indicators (Payne 2013) and sensitive to farming practices (Heger et al. 2012). Functional traits of soil macro-invertebrates are also increasingly used (Yan et al. 2012). Another promising approach is the integration of farmers' knowledge (Barrios et al. 2006; Pauli et al. 2012; Rousseau et al. 2013), including to find indicating species. Finally, modelling can provide interesting perspectives (Torbert et al. 2008; Xue et al. 2010), especially to account for the temporal frame of dynamic processes and their evolution.

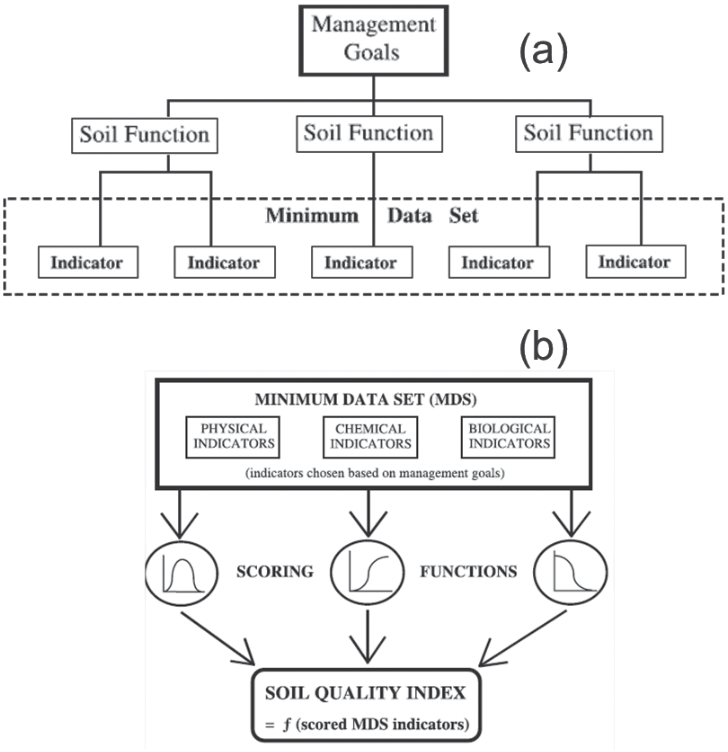


Figure 2. Processes to select and weight soil quality (SQ) indicators, according to functions and management goals (a) and using site-specific expertise to weight scores (b). Adapted from Karlen et al. (2003)

References

Alkorta I., Aizpurua A., Riga P., Albizu I., Amezaga I. and Garbisu C. 2003. Soil enzyme activities as biological indicators of soil health. Reviews on Environmental Health 18(1), 65–73.

Barrios E., Delve R.J., Bekunda M., Mowo J., Agunda J., Ramisch J. et al. 2006. Indicators of soil quality: a South–South development of a methodological guide for linking local and technical knowledge. Geoderma 135, 248–259.

Bloem J., Hopkins D.W. and Benedetti A. 2006. Microbiological methods for assessing soil quality. CAB International: Wallingford.

Blohm G. 1964. Angewandte landwirtschaftliche Betriebslehre. Ulmer: Stuttgart.

Blouin M., Zuily-Fodil Y., Pham-Thi A.T., Laffray D., Reversat G., Pando A. et al. 2005. Belowground organism activities affect plant aboveground phenotype, inducing plant tolerance to parasites. Ecology Letters 8(2), 202–208.

Bot A. and Benites J. 2005. The importance of soil organic matter: key to drought-resistant soil and sustained food and production. Food and Agriculture Organization of the United Nations (FAO): Rome.

Dick R., Pankhurst C., Doube B. and Gupta V. 1997. Soil enzyme activities as integrative indicators of soil health. Pp. 121–156 in ‘Biological Indicators of soil health’, ed. by C. Pankhurst, B.M. Doube and V.V.S.R. Gupta. CAB International: Wallingford.

Doran J.W. and Parkin T.B. 1994. Defining and assessing soil quality. Pp. 3–22 in ‘Defining soil quality for a sustainable environment’, ed. by J.W. Doran and A.J. Jones. SSSA Special Publication No. 35. Soil Science Society of America: Madison, WI.

Doran J.W., Parkin T.B. and Jones A. 1996. Quantitative indicators of soil quality: a minimum data set. Pp. 25–38 in 'Methods for assessing soil quality', ed. by J.W. Doran, D.C. Coleman, D.F. Bezdicek and B.A. Stewart. SSSA Special Publication No. 49. Soil Science Society of America: Madison, WI.

El Azhari N., Bru D,, Sarr A. and Martin-Laurent F. 2008. Estimation of the density of the protocatechuate-degrading bacterial community in soil by real-time PCR. European Journal of Soil Science 59(4), 665–673.

Garbisu C., Alkorta I. and Epelde L. 2011. Assessment of soil quality using microbial properties and attributes of ecological relevance. Applied Soil Ecology 49, 1–4.

Grimaldi M., Schroth G., Teixeira W., Huwe B. and Sinclair F. 2002. Soil structure. Pp. 191–208 in 'Trees, crops and soil fertility: concepts and research methods', ed. by G. Schroth and F.L. Sinclair. CAB International: Wallingford.

Heger T.J., Straub F. and Mitchell E.A.D. 2012. Impact of farming practices on soil diatoms and testate amoebae: a pilot study in the DOK-trial at Therwil, Switzerland. European Journal of Soil Biology 49, 31–36.

Idowu O., van Es H., Schindelbeck R., Abawi G., Wolfe D., Thies J. et al. 2007. The new Cornell Soil Health Test: protocols and interpretation. What's Cropping Up 17(1), 6–7.

Jones C.G., Lawton J.H. and Shachak M. 1994. Organisms as ecosystem engineers. Oikos 69, 373–386.

Karlen D.L., Ditzler C.A. and Andrews S.S. 2003. Soil quality: why and how? Geoderma 114(3–4), 145–156.

Karlen D.L., Mausbach M.J., Doran J.W., Cline R.G., Harris R.F. and Schuman G.E. 1997. Soil quality: a concept, definition, and framework for evaluation. Soil Science Society of America Journal 61(1), 4–10.

Larson W. and Pierce F. 1991. Conservation and enhancement of soil quality. Pp. 15–21 in 'Evaluation for sustainable land management in the developing world: proceedings of the International Workshop on Evaluation for Sustainable Land Management in the Developing World'. International Board Soil Research Management: Chiang Rai, Thailand.

Lavelle P. 1997. Faunal activities and soil processes: adaptive strategies that determine ecosystem function. Advances in Ecological Research 27, 93–132.

Lavelle P., Dangerfield M., Fragoso C., Eschenbrenner V., Lopez-Hernandez D., Pashanasi B. et al.1994. The relationship between soil macrofauna and tropical soil fertility. Pp. 137–169 in 'Tropical soil biology and fertility', ed. by M.J. Swift and P. Woomer. John Wiley-Sayce: New York.

Lavelle P., Decaëns T., Aubert M., Barot S., Blouin M., Bureau F. et al. 2006. Soil invertebrates and ecosystem services. European Journal of Soil Biology 42, S3–S15.

Lewandowski A.M., Zumwinkle M. and Fish A. 1999. Assessing the soil system: a soil quality literature review. Energy and Sustainable Agriculture Program, Minnesota Department of Agriculture: St Paul. Accessible at: http://www.mda.state.mn.us/.

Manlay R.J., Feller C. and Swift M.J. 2007. Historical evolution of soil organic matter concepts and their relationships with the fertility and sustainability of cropping systems. Agriculture Ecosystems and Environment 119(3–4), 217–233.

Moebius B.N., van Es H.M., Schindelbeck R.R., Idowu O.J., Clune D.J. and Thies J.E. 2007. Evaluation of laboratory-measured soil properties as indicators of soil physical quality. Soil Science 172(11), 895–912.

Moebius-Clune B., Idowu O., Schindelbeck R., van Es H., Wolfe D., Abawi G. et al. 2011. Developing standard protocols for soil quality monitoring and assessment. Pp. 833–842 in 'Innovations as key to the green revolution in Africa: exploring the scientific facts', ed. by A. Botiono, B. Waswa, J.M. Okeyo, F. Maina and J.M. Kihara. Springer: Dordrecht, Netherlands.

Neher D.A. 2001. Role of nematodes in soil health and their use as indicators. Journal of Nematology 33(4), 161–168.

Nortcliff S. 2002. Standardisation of soil quality attributes. Agriculture, Ecosystems & Environment 88(2), 161–168.

Paoletti M.G. 1999. The role of earthworms for assessment of sustainability and as bioindicators. Agriculture, Ecosystems & Environment 74(1–3), 137–155.

Parisi V., Menta C., Gardi C., Jacomini C. and Mozzanica E. 2005. Microarthropod communities as a tool to assess soil quality and biodiversity: a new approach in Italy. Agriculture, Ecosystems & Environment 105(1), 323–333.

Patzel N., Sticher H. and Karlen D.L. 2000. Soil fertility—phenomenon and concept. Journal of Plant Nutrition and Soil Science—Zeitschrift fur Pflanzenernahrung ünd Bodenkunde 163(2), 129–142. [In English]

Pauli N., Barrios E., Conacher A.J. and Oberthur T. 2012. Farmer knowledge of the relationships among soil macrofauna, soil quality and tree species in a smallholder agroforestry system of western Honduras. Geoderma 189, 186–198.

Payne R.J. 2013. Seven reasons why protists make useful bioindicators. Acta Protozoologica 52(3), 105–113.

Peres G., Piron D., Bellido A., Goater C. and Cluzeau D. 2008. Earthworms used as indicators of agricultural managements. Fresenius Environmental Bulletin 17(8B), 1181–1189.

Rousseau L., Fonte S.J., Tellez O., van der Hoek R. and Lavelle P. 2013. Soil macrofauna as indicators of soil quality and land use impacts in smallholder agroecosystems of western Nicaragua. Ecological Indicators 27, 71–82.

Swift M.J., Heal O.W. and Anderson J.M. 1979. Decomposition in terrestrial ecosystems. University of California Press: Berkeley and Los Angeles.

Torbert H.A., Krueger E. and Kurtener D. 2008. Soil quality assessment using fuzzy modeling. International Agrophysics 22(4), 365–370.

von Wulffen C. 1847. Entwurf einer Methodik zur Berechnung der Feldsysteme. Verlag Veit & Co.: Berlin.

Warkentin B.P. and Fletcher H. 1977. Soil quality for intensive agriculture. Pp. 594–598 in 'Proceedings of the International Seminar on Soil Environment and Fertility Management in Intensive Agriculture'. Society of Science of Soil and Manure: Tokyo, Japan.

Wu J., Joergensen R.G., Pommerening B., Chaussod R. and Brookes P.C. 1990. Measurement of soil microbial biomass C by fumigation extraction—an automated procedure. Soil Biology and Biochemistry 22(8), 1167–1169.

Xue Y.J., Liu S.G., Hu Y.M. and Yang J.F. 2010. Soil quality assessment using weighted fuzzy association rules. Pedosphere 20(3), 334–341.

Yan S.K., Singh A.N., Fu S.L., Liao C.H., Wang S.L., Li Y.L. 2012. A soil fauna index for assessing soil quality. Soil Biology and Biochemistry 47, 158–165.

Yeates G.W. 2003. Nematodes as soil indicators: functional and biodiversity aspects. Biology and Fertility of Soils 37(4), 199–210.

WCED (World Commission on Environment and Development) 1987. Our common future. Oxford University Press: Oxford.