SUSTAINABLE MANAGEMENT OF SOIL ORGANIC MATTER

Sustainable Management of Soil Organic Matter

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Preface

With the rapidly emerging interest from many sectors of society in sustainable development, there is a realization that an understanding of soil management is of fundamental importance to the debate. Before the latter part of the 20th century, soil was seen as a matrix from which food could be produced and on which wastes could be disposed or buildings constructed. Soils research focused primarily on how an understanding of relevant processes could be applied to optimize food production. Although soil protection has, for many decades, been an issue with which scientists and land managers have been concerned, it has focused primarily on the need to prevent soil loss through erosion rather than to enhance soil quality through management *per se*. During the 1980s and 1990s, a change in attitude to soil began to take place. Concern about environmental issues such as climate change, and the physical and chemical degradation of soils was accompanied by an appreciation of the need to protect soils in their own right in order to underpin efforts to develop society in a way which is sustainable over the long term. Many countries are now developing statutory soil protection policies in an analogous way to those applied to air and water. There is a substantial body of research (some of which is reported in this book) that has defined the importance of understanding soil quality as an issue. Thus a practice of land use that is sustainable needs not only to preserve soil materials but also to maintain or enhance various attributes of its quality. The organic matter content of soils and the components of the organic matter itself play a vital role in defining this quality.

The aim of this book is to examine the role that organic matter plays in soils with a view to understanding the ways in which this contributes to the various functions of soils. The book is based upon papers offered to the annual meeting of the British Society of Soil Science entitled 'The Sustainable Management Of Soil Organic Matter' held in Edinburgh in September 1999. The meeting was host to around 200 delegates from more than 20 different countries. Authors were invited to submit papers for publication, which were then selected on the basis of peer review. The structure of the book follows that of the conference, with keynote papers followed by shorter more focused papers in five main sections;

- Organic matter and sustainability
- Modelling soil organic matter dynamics
- Soil organic matter: the roles of residue quality in C sequestration and N supply
- The role of soil organic matter and manures in sustainable nutrient cycling
- Implications of soil biodiversity for sustainable organic matter management.

After the death of Walter Russell, the British Society of Soil Science decided to honour his contribution to soil science by the creation of a Memorial Lecture, to be given at the Society's Annual Meeting in alternate years. The first of these lectures was by Professor Dennis Greenland at the Society's 50th anniversary meeting in Newcastle in September 1997. The second lecture was given by Professor James Tiedje at the Edinburgh conference in 1999. His intriguing insight into the soil as a habitat of microbial diversity and his vision for the application of new technologies to expand the frontiers of soil science is presented in the penultimate chapter.

We wish to thank all of those involved in helping to organize the conference and prepare the resulting publication. In particular, we are indebted to Sally Burgess, David Green, Jane Lund, John Parker, Rachel Thorman and Adrian Tams for support during the conference. We also wish to thank numerous anonymous referees for their help with the revisions of papers, and Sandra Chalmers, Frances Haldane, Aileen Stewart and Pat Carnegie for help with the preparation of this publication.

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Introduction

Organic Matter – the Sustenance of Soil

The functioning of soils is profoundly influenced by their organic matter content. The abilities of a soil to supply nutrients, store water, release greenhouse gases, modify pollutants, resist physical degradation and produce crops within a sustainably managed framework are all strongly affected by the quality and quantity of the organic matter that it contains. These attributes of organic matter lead it to have a major influence on the quality of soil material itself. As societies throughout the world begin to realize the potential value of the soil resource in contributing to sustainable farming practices, then the need to understand the role that organic matter plays in contributing to soil quality has become more important.

The paradigm of sustainability is one that most scientists subscribe to. However, concepts of sustainable soil management differ widely, and a wide variety of approaches are advocated that all aim to resolve a common problem. As we enter the 21st century, pressure on the world's ecosystems to provide for human needs is at an unprecedented level. It was estimated by Oldeman (1994) that by 1990, some 562 million hectares (38% of the world's cropland) had been degraded by poor agricultural practices. Although some degradation was relatively minor, it was recognized as being sufficient to impair at least some attribute of the soil's function and, in some cases, to lead to complete crop failure. During the 1990s, further damage has occurred, with the annual degradation of 5–6 million hectares, and current trends are not encouraging (UNEP, 1997).

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Losses in the organic matter content of soils during the last 100 years have been substantial, and have been associated with changing patterns of land use that are driven by population increases. The process of cultivation of native soils is nearly always associated with a loss of organic carbon, as previously protected organic matter is oxidized following exposure to the atmosphere (Davidson and Ackerman, 1993; Gregorich *et al.*, 1998). The current global store of organic carbon in agricultural soils is thought to be ~168 Pg (Paustian *et al.*, 1997). Estimates suggest that this has declined from ~209–222 Pg, resulting in a loss of 41–54 Pg (Houghton and Skole, 1990; IPCC, 1996). It is likely that these losses were not evenly distributed across the globe, with disproportionately large losses from upland, organic and wetland soils. Losses of soil organic matter are also associated with land use change other than direct conversion to agriculture, such as deforestation and biomass burning (IPCC, 1996).

Given the importance of soil organic matter in contributing to essential soil functions, these losses are clearly of concern. In some circumstances, organic matter loss will almost certainly have contributed to catastrophic soil damage through soil erosion and loss in productive capacity. However, given the inevitability of some organic matter loss following cultivation, the question arises of whether it is possible to manage systems sustainably on a lower organic matter capital, or whether the losses that have occurred so far are part of a continuing trend towards loss of fertility and productive potential.

One of the key functions of organic matter in soils is that of nutrient supply, and an indication of the pressures that are being placed on cultivated soils to produce crops is provided by nutrient budgeting approaches. The balance between the input and output of nutrients within a given area provides a quantifiable indicator of sustainability. Some analyses carried out in parts of Africa show that nutrients are being depleted at an alarming rate (Smaling *et al.*, 1996). Nutrient budgets can be used at differing scales and, although associated with a high degree of spatial heterogeneity, they can be valuable in identifying regional trends. In Nigeria, Smaling *et al.* (1996) found that the difference between the input and output of N leads to an average net annual loss of 27 kg ha^{-1}, in soils that in many cases are already nutrient poor. This compares with an average nitrogen surplus in Germany of 47 kg ha^{-1}. Although the African situation is clearly not sustainable, the solutions need to be broader than limited attempts at providing additional fertilizer inputs. Policies of integrated fertility management are seen as the most useful approach to overcoming such problems in which increased nutrient supply is provided within a framework of improved land and soil management policies. These must include organic matter management to increase soil nutrient capital and improve the sustainability of production (Smaling, 1998; Scoones and Toulmin, 1999).

In temperate regions, nutrient budgets may be more balanced, as a result of high external inputs of both inorganic and organic nutrients, but can often result in high inputs and high losses (Rosswall and Paustian, 1984). Long-term field trials at Rothamsted in the South East of England have established that the organic matter and nitrogen capital of cultivated soils can increase as a result of long-term cultivations (Powlson *et al.*, 1986; Johnston, 1997). The increased accumulation of organic matter resulting from increased fertilizer applications and the consequent production of more plant material potentially can cause difficulties. Shen *et al.* (1989) found that soils that had received an annual addition of 144 kg N ha^{-1} over 137 years contained more organic matter than those receiving no fertilizer additions. However, this was associated with significantly higher mineralization rates, and potentially higher losses. Positive nutrient balances do not necessarily equate therefore with improved sustainability, as environmental degradation may be linked with nutrient loss in some circumstances. Positive nutrient balances very often will depend on external inputs of nutrients, and are often coupled with external energy inputs to a system that further weakens its sustainability. Pimentel and Heichel (1991) found that the energy output/input ratio of maize grown in Mexico using only human labour was 12.9, with a crop yield of 1944 kg ha^{-1}. In Minnesota, a field under conventional management supported grain yields of 6500 kg ha^{-1}; however, the intensive management meant that the energy output/input ratio was only 3.3. Such systems again must ultimately be unsustainable as they currently depend upon the substantial input of finite non-renewable energy reserves in, for example, fuel and fertilizers. Although technologies requiring reduced inputs are available (Vanlauwe *et al.*, 1996) government policies towards agriculture and the production of commodities need modification (e.g. extensification) if large-scale improvements in energy balances are to be achieved.

Soil Organic Matter and Sustainability

There is much debate about the meaning of the term sustainability; however, a definition that has proved to be useful is that offered by the Bruntland Report (WCED, 1987) and is one that simultaneously ‘Meets the needs and aspirations of the present without compromising the ability of future generations to meet their own needs’. These needs will, amongst other things, require an increased crop production per unit area of land to meet the demands of an increasing population, and therefore a need, as a consequence, to develop a better understanding of the processes that underlie such production.

One of the important contributions of organic matter to sustainability compared with other soil properties is that it influences many soil functions

(Swift and Woomer, 1993). The effects of organic matter in soils interact to influence the biological, chemical and physical properties of the soil material itself. In an attempt to quantify the role of soils in contributing to sustainable land use, the concept of soil quality has proved useful (Carter, Chapter 1). This involves assessing the ability of a soil to undertake a particular function. Thus the quality of a soil which is assessed for the purpose of storing water may be different from the quality of the same soil when assessed for the purpose of growing wheat. Soil organic matter strongly influences the quality of soils when assessed according to these criteria. However, it can be argued that one of the most important features of a soil, and the organic matter that it contains, is the ability to act as a living system. For this reason, Doran and Safley (1997) suggested that the term 'soil health' could usefully be employed to define 'the capacity of a soil to function as a living system within ecosystem and landuse boundaries, to sustain biological productivity, to promote the quality of air and water environments to sustain biological activity, and maintain plant, animal and human health'. Pankhurst (1997) suggested that soil 'health' can be distinguished from soil 'quality' on the grounds that it includes a measure of time and must involve an assessment of biological activity.

In order for the concept of soil health or quality to be useful, these concepts must be based on defined and measurable soil properties. Doran and Safely (1997) argue that the latter should be based on parameters that reflect the dynamics of the physical, chemical and biological functions of soil. The definition of threshold values of organic matter below which the soil cannot be managed sustainably is difficult using this approach. Different soil types contain widely different amounts of organic matter reflecting differences in soil genesis (among other things) at a given site. Loveland *et al.* (Chapter 1.1) carried out an extensive review of the literature that relates organic C to soil physical properties. They found that there was little consistent evidence to define critical thresholds of organic matter below which physical properties change significantly. The inevitable loss of organic matter following cultivation of native soils need not necessarily lead to permanent loss of function. Equilibrium between inputs and outputs can be achieved at a lower level of productivity leading to sustainable soil management, despite changes in land use.

It has been suggested that total soil organic matter may not be a good indicator of soil quality (Carter *et al.*, 1999), particularly as much of the total pool contains relatively inert physically and chemically stabilized fractions. Microbial biomass carbon represents one of the more labile pools and one that makes a critical contribution to nutrient flows, organic matter turnover and the structural stability of soil aggregates. The biomass is also highly responsive over short periods to changes in land management, and measurement of this pool can provide advanced warning of longer term changes to the overall organic matter fraction (Powlson *et al.*, 1987).

Janzen *et al.* (1998) describe a conceptual model in which organic matter accumulates during the process of soil formation and then reaches a steady state at which primary production equals loss of organic C by respiration. Cultivation of the soil results in a rapid but relatively short-lived loss of organic C followed by a new steady state. Further modification to the soils organic matter status may be introduced by deliberate measures taken to sequester carbon (Smith *et al.*, Chapter 4.13).

A new criterion in the sustainable management of organic matter comes from the need to reduce the build up of atmospheric carbon dioxide. The size of the potential sink that may be provided by soils for atmospheric carbon is now of considerable interest to scientists and policy makers. It is argued by Paustian (1997) that this provides a guide to the upper limits of carbon that potentially can be sequestered by agricultural soils. In many cases, this is quite modest, but there are large regional variations. It is probably in temperate regions where sophisticated techniques of agricultural management can be introduced rapidly (as a result of infrastructure and good extension services) where opportunities for further sequestration are greatest (Smith *et al.*, Chapter 4.13). Powlson *et al.* (1998) reported that afforestation of 30% of the current agricultural land in Europe could lead to an increase of 43 Tg C year^{-1} in the storage of carbon in soil, equivalent to 3.8% of anthropogenic emissions. If accumulation in woody biomass is included, the percentage of emissions consumed rises to 15.3%. Soil organic matter storage is also modified by the nature of tillage operations. Some interest has been shown recently in observations that deeper tillage operations resulting from the use of more modern machinery may be contributing to increased organic matter storage at depth (Soane and Ball, 1998). However, in some cases, it seems that tillage may simply lead to a redistribution of organic carbon without leading to an increase in total storage (Yang and Wander, 1999).

References

Carter, M.R., Gregorich, E.G., Angers, D.A., Beare, M.H., Sparling, G.P., Wardle, D.A. and Voroney, R.P. (1999) Interpretation of microbial biomass measurements for soil quality assessment in humid temperate regions. *Canadian Journal of Soil Science* 79, 507–510.

Davidson, E.A. and Ackerman, I.L. (1993) Changes in soil carbon inventories following cultivation of previously untilled soils. *Biogeochemistry* 20, 161–193.

Doran, J.W. and Safley, M. (1997) Defining and assessing soil health and sustainable productivity. In: Pankhurst, C.E., Doube, B.M. and Gupta, V.V.S.R. (eds) *Biological Indicators of Soil Health.* CAB International, Wallingford, UK, pp. 1–28.

Gregorich, E.G., Greer, K.J., Anderson, D.W. and Liang, B.C. (1998) Carbon distribution and losses: erosion and deposition effects. *Soil and Tillage Research* 47, 291–302.

Houghton, R.A. and Skole, D.L. (1990) Carbon. In: Turner, B.L., Clark, W.C., Kates, R.W., Richards, J.F., Mathews, J.T. and Meyer, W.B. (eds) *The Earth as Transformed by Human Action*. Cambridge University Press, Cambridge, pp. 393–408.

Intergovernmental Panel on Climate Change (1996) Climate change 1995: impacts, adaptations and mitigation of climate change. In: Watson, R.T., Zinyowera, M.C. and Moss, R.C. (eds) Cambridge University Press, Cambridge, pp. 745–772.

Janzen, H.H., Campbell, C.A., Izaurralde, R.C., Ellert, B.H., Jumna, N., McGill, W.B. and Zentner, R.P. (1998) Management effects on soil C storage on the Canadian prairies. *Soil and Tillage Research* 47, 181–195.

Johnston, A.E. (1997) The value of long-term field experiments in agricultural, ecological and environmental research. *Advances in Agronomy* 59, 291–333.

Oldeman, L.R. (1994) *Soil Resilience and Sustainable Land Use*. CAB International, Wallingford, UK.

Pankhurst, C.E. (1997) Biodiversity of soil organisms as an indicator of soil health. In: Pankhurst, C.E., Doube, B.M. and Gupta, V.V.S.R. (eds) *Biological Indicators of Soil Health*. CAB International, Wallingford, UK, pp. 297–324.

Paustian, K., Andren, O., Janzen, H.H., Lal, R., Smith, P., Tian, G., Tiessen, H., Van Noordwijk, M. and Woomer, P.L. (1997) Agricultural soils as a sink to mitigate CO_2 emissions. *Soil Use and Management* 13, 230–244.

Pimental, D. and Heichel, G.H. (1991) Energy efficiency and sustainability of farming systems. In: Lal, R. and Pierce, F.J. (eds) *Soil Management for Sustainability*. Soil and Water Conservation Society, Iowa, pp. 113–124.

Powlson, D.S., Pruden, G., Johnston, A.E. and Jenkinson, D.S. (1986) The nitrogen-cycle in the Broadbalk wheat experiment – recovery and losses of ^{15}N labeled fertilizer applied in spring and inputs of nitrogen from the atmosphere. *Journal of Agricultural Science* 107, 591–609.

Powlson, D.S., Brookes, P.C. and Christensen, B.T. (1987) Measurement of soil microbial biomass provides an early indication of changes in total soil organic-matter due to straw incorporation. *Soil Biology and Biochemistry* 19, 159–164.

Powlson, D.S., Smith, P., Coleman, K., Smith, J.U., Glendining, M.J., Körschens, M. and Franko, U. (1998) A European network of long-term sites for studies on soil organic matter. *Soil and Tillage Research* 47, 263–274.

Rosswall, T. and Paustian, K. (1984) Cycling of nitrogen in modern agricultural systems. *Plant and Soil* 76, 3–21.

Scoones, I. and Toulmin, C. (1999) *Policies for Soil Fertility Management in Africa*. DFID Report, Russell Publishing, Nottingham.

Shen, S.M.P., Hart, B.S., Powlson, D.S. and Jenkinson, D.S. (1989) The nitrogen-cycle in the Broadbalk wheat experiment – ^{15}N labelled fertilizer residues in the soil and in the soil microbial biomass. *Soil Biology and Biochemistry* 21, 529–533.

Smaling, E.M.A., Fresco, L.O. and deJager, A. (1996) Classifying, monitoring and improving soil nutrient stacks and flows in African agriculture. *Ambio* 25, 492–496.

Smaling, E.M.A., Nandura, S.M. and Janssen, B.H. (1998) Soil fertility in Africa is at stake. In: Buresh, R., Sanchez, P. and Calhoun, F. (eds) *Replenishing Soil Fertility in Africa*. Soil Science Society of America, Wisconsin, pp. 47–61.

Soane, B.D. and Ball, B.C. (1998) Review of management and conduct of long-term tillage studies with special reference to a 25-yr experiment on barley in Scotland. *Soil and Tillage Research* 45, 17–37.

Swift, M.J. and Woomer, P. (1993) Organic matter and the sustainability of agricultural systems: definition and measurement. In: Mulongoy, K. and Merckx, R. (eds) *Soil Organic Matter Dynamics and Sustainability of Tropical Agriculture*. Wiley, UK, pp. 3–18.

United Nations Environment Programme (UNEP) (1997) *Global Environment Outlook*. Oxford University Press, New York.

Vanlauwe, B., Swift, M.J. and Merckx, R. (1996) Soil litter dynamics and N use in a leucaena (*Leucaena leucocephala* Lam (de Witt)) alley cropping system in south-western Nigeria. *Soil Biology and Biochemistry* 28, 739–749.

WCED (1987) *Our Common Future*. Oxford University Press, Oxford, UK.

Yang, X.M. and Wander, M.M. (1999) Tillage effects on soil organic carbon distribution and storage in a silt loam soil in Illinois. *Soil and Tillage Research* 1–2, 1–9.