THE CONCEPT OF SOIL QUALITY AND ITS APPLICABILITY TO SUGARCANE PRODUCTION

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Abstract

Soil quality can be broadly defined as the sustained capability of a soil to accept, store and recycle nutrients and water, maintain economic yields and maintain environmental quality. Soil organic matter is a key attribute of soil quality since it is a source of nutrients (N, S and P) for plant growth (via mineralisation) and it is important in maintaining soil structural stability. Soil biological indicators of soil quality such as microbial biomass C, soil respiratory rate, soil enzyme activity and soil earthworm population are sensitive to changes in soil C availability caused by changes in soil management practice, and can change markedly before any changes in total soil organic matter content are detected. The use of such soil quality indicators on sugar producing soils of South Africa is advocated to further investigate soil degradation and sustainability. The long term trash management trial at the South African Sugar Association Experiment Station at Mount Edgecombe would be a useful initial study site.

Keywords: soil biological activity, soil organic matter, soil quality, sustainability

Introduction

Concerns regarding soil degradation and agricultural sustainability have kindled interest in assessment of soil quality (Doran and Parkin, 1994; Nannipieri, 1994). Soil quality is broadly defined as the sustained capability of the soil to accept, store and recycle nutrients and water, maintain economic yields and maintain environmental quality. An assessment of soil quality that includes soil biological, chemical and physical properties can provide valuable information for evaluation of the sustainability of land management practices (Doran and Parkin, 1994). Soil chemical properties that define soil fertility (e.g. pH, extractable P, exchangeable cations) are often well documented for agricultural soil since routine soil testing is carried out. Soil physical properties are normally less well documented since they often need to be measured under field conditions and can change markedly during the season (e.g. after cultivation). Soil organic matter content is undoubtedly a key attribute of soil quality (Gregorich *et al.*, 1994). Nevertheless, there is increasing evidence that measures of soil biol-ogical activity (e.g. earthworm activity, microbial biomass C, basal respiratory activity and soil enzyme activity) hold considerable potential as early indicators of soil degradation or improvement. In particular, such parameters are sensitive to changes in soil C availability, caused by alterations in soil management practice, and can change markedly before any changes in total soil organic matter content are detected (Nannipieri, 1994; Haynes and Beare, 1996).

In this paper some of the major indicators of soil quality related to soil organic matter content and soil biological activity are reviewed and discussed. Examples of the effects of long and short term changes in soil management practice on these soil quality indicators are also discussed in detail. In addition, the relevance of such soil quality indicators to the sugar producing soils of South Africa is considered, and suggestions for future research are made.

Importance of soil organic matter

Soil organic matter is a key attribute of soil quality (Doran and Parkin, 1994) and has many important functions. Approximately 95% of soil N and S and about 50% of soil P is present in soil organic matter. This soil organic N, S and P can serve as a source of plant available nutrients following mineralisation. Mineralisation is a biological process mediated by soil microorganisms (soil bacteria and fungi). These microorganisms excrete enzymes into the soil which mediate the conversion of organic forms of N, S and P into inorganic, plant available forms. For example, soil organic N is converted to ammonium N and then to nitrate N. Not all soil organic matter is equally as readily mineralised. As a result, scientists often attempt to separate organic matter into an easily mineralisable (labile) fraction and a more stable fraction. The stable fraction is known as soil humus (Stevenson, 1994).

Soil organic matter has a profound effect on the structure of many soils. When soil organic matter is lost from soils they tend to become harder, more compact and more cloddy. Seedbed preparation and tillage operations are usually easier to carry out and are more effective when soil organic matter levels are adequate. Aeration, water holding capacity and permeability are all favourably affected by a high soil organic matter content. Soil organic compounds bind soil particles into structural units called aggregates (Tisdall and Oades, 1982). These aggregates help maintain a loose, open, granular condition. As a result, water is better able to infiltrate and percolate downward through the soil. Large soil pores also permit better exchange of gases between soil and atmosphere.

Soil organic matter is also of immense importance in affecting the behaviour of pesticides in soils. For example, organic matter content is the soil factor most directly related to the adsorption of most herbicides by soil. Other important functions of organic matter include its ability to hold cations (e.g. calcium, magnesium and potassium) against leaching, its ability to buffer the soil against large changes in pH and its ability to bind with toxic metals (e.g. lead and chromium) which are sometimes added to soils with waste materials.

The most common measures of soil organic matter content are organic C and total N content. The C/N ratio of soil organic matter is generally fairly constant and usually falls in the range of 10 to 12. Soil organic matter content is normally calculated by multiplying soil organic C content by 1,73 or total N content by 17,3.

Trends in soil organic matter content

Soils can vary greatly in organic matter content. A typical temperate grassland may contain 5-6% organic matter in the top 15 cm. Soil organic matter content comes to an equilibrium level under any particular management system. At this level, gains of organic matter equal losses. Long term pastoral management generally results in attainment of a high soil organic matter content. Organic matter inputs under pasture arise from dying plant tops and more particularly roots, exudation of organic compound from roots and return of dung from grazing animals (Haynes and Williams, 1993).

Under arable cropping, the amount of organic material returned to the soil is considerably less than under pasture. This is because crop plants are usually spaced much wider than grass plants (so there is less root and top material produced per unit of ground area) and often much of the above-ground plant material is removed from the field with, or, as the harvested crop. In addition, the soil is often tilled several times per year. Tillage favours decomposition of soil organic matter because the improved aeration resulting from cultivation stimulates microbial activity and decomposition processes. Another major effect of cultivation is exposure of previously inaccessible organic matter to microbial attack. That is, cultivation breaks up soil aggregates and exposes organic matter that was previously physically protected within the aggregate structure, to microbial attack. This also stimulates breakdown of soil organic matter. As a result of the above factors, soil organic matter content characteristically declines when grassland soils are converted to continuous arable cropping (Haynes and Beare, 1996).

Results from a long term trial at Rothamsted Experimental Station in England (Johnston, 1986) demonstrate how management affects soil organic matter content (Figure 1). One site had been under grass for at least 100 years and contained 31 g C/kg. Soil organic C increased to 34 g C/kg during the first 15 years under continuous grass, probably because of improved management and increased dry matter production (and increased organic matter inputs). On an old arable soil initially containing 16 g C/kg organic C, the organic matter content increased steadily under grass management. When the long term grassland site was put under arable cropping there was a rapid decline in soil organic matter content. The organic matter content declined and approached that of the long term arable site. Management of soil organic matter is at the heart of sustainable agriculture. By maximising the amount of organic residues returned to the soil, and by minimising tillage operation, benefits accrue due to reduced erosion, better soil tilth, preservation of stable humus, and improved nutrient cycling through conservation of nutrients.

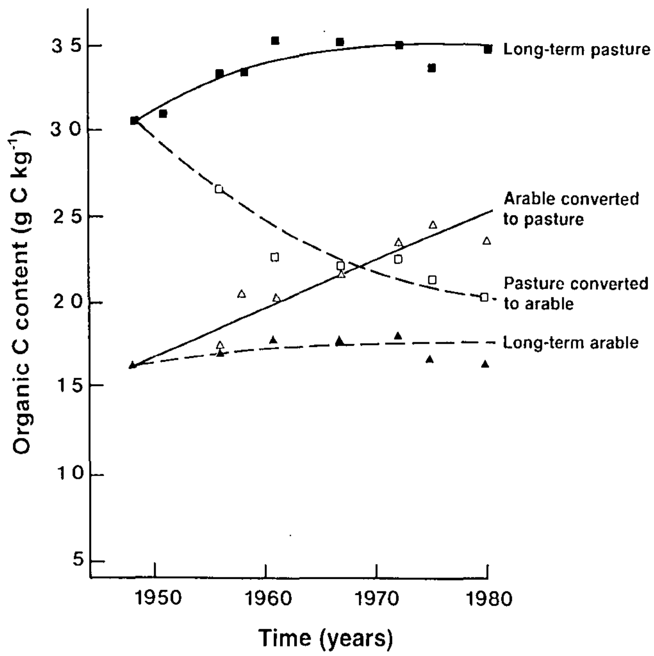

Figure 1. Organic C content of soils from the Rothamsted ley-arable experiment. Treatments consist of long term grassland, long term grassland soil converted to arable and long term arable, and long term arable soil converted to grassland. (Redrawn from Johnston, 1986.)

Soil microbial biomass

Microbial biomass is a measure of the size of the total microbial population in the soil. A vast array of microorganisms live in the soil. Numbers of bacteria are particularly high, often reaching one billion per gram of soil or higher. Numbers of fungi vary widely, with the normal population being 10-20 million per gram. The microbial biomass accounts for 1-3% and 2-6% of soil organic C and total N respectively (Stevenson, 1994). The common methods used for measuring microbial biomass C have been discussed and described by Horwath and Paul (1994).

Microbial biomass is a critical attribute of soil quality (Visser and Parkinson, 1992), and plays a dual role in the soil. Firstly, it is an agent for decomposition of plant residues. Secondly, it serves within the soil as a store of labile organic matter and nutrients. For example, the microbial biomass in the plough layer of a soil can commonly contain 100-200 kg N/ha. When changes in environmental conditions occur (e.g. when soil dries out), much of the microbial population may die and this N is released into the soil.

The soil microbial biomass is also very important in maintaining soil structure (Lynch and Bragg, 1985). The microbes exude carbohydrate material which acts as a glue in soils, thus helping to cement soil aggregates together. As a measure of soil quality, it serves as a sensitive indicator of changes and future trends in soil organic matter content (Carter, 1986; Haynes and Beare, 1996). Due to its dynamic nature, microbial biomass rapidly responds to changes in soil management, such as the incorporation of crop residues or use of a grass sod in rotation. Such inputs of additional organic matter result in a rapid increase in the soil microbial biomass long before any changes in total soil organic matter content are detected.

Soil microbial activity

The determination of microbial biomass C does not by itself provide information on microbial activity (Jenkinson, 1987). The reason for this is that soil microorganisms may be in a state of rest or may be in active, rapidly reproducing stages. The most common method of measuring microbial activity is to measure respiratory activity of the soil. This is done by measuring the rate of CO_2 evolution from the soil over a set period of time. An alternative method of estimating soil microbial activity is to measure soil enzyme activity (Nannipieri, 1994).

Soil enzyme activity

All biochemical action is dependent on, or related to, the presence of enzymes (biological catalysts). Soil enzymes are proteins that are synthesised by plants and more particularly soil microorganisms during metabolism, and are found in living organisms, dead cells and complexed with organic and mineral components of the soil. Soils contain a wide array of enzymes, and each soil has its own characteristic pattern of specific enzymes. Methods that are used for assay of the activity of various enzymes in soils have been outlined by Tabatabai (1994).

Enzyme activities are critical indicators of soil quality since they control nutrient release from soil organic matter and decomposing plant residues (Dick, 1994; Nannipieri, 1994). For example, mineralisation of soil organic N to ammonium N is catalysed by a series of reactions involving enzymes named proteases, deaminases and amidases. Mineralisation of soil organic P is catalysed by phosphatase enzymes. Sometimes, the activity of a range of specific enzymes (e.g. protease and phosphatase) is measured, but in other cases an index of overall enzyme activity is obtained. In the latter case, a compound such as arginine or fluorescein diacetate is added to the soil and its rate of decomposition is measured (Schnürer and Rosswall, 1982; Alef and Kleiner, 1987).

Earthworm activity

The burrowing actions of earthworms have large effects on both nutrient availability and soil structure. Earthworm populations can be high and can commonly reach 1 000/m^2 or greater under temperate pastures. Earthworms ingest large amounts of soil and decaying plant tissues and deposit their casts both above ground and within the surface soil horizon.

The availability of N, P and K in casts is usually greater than that in the surrounding soil (Blair *et al.*, 1995). The increased nutrient levels are the result of preferential feeding of earthworms on decaying plant tissue, which generally has a higher nutrient content than the surrounding soil, and the fact that mineralisation of soil N and P is stimulated during passage of the soil through the earthworm gut. Cast material generally also has a greater stability than surrounding soil aggregates. It has been suggested that 50% of structural aggregates in the upper 15 cm of temperate pasture soils are recognisable as earthworm casts (Haynes and Beare, 1996). Earthworms also contribute greatly to the porosity of soils because they make extensive burrowing systems that ramify through the soil (Tomlin *et al.*, 1995).

Earthworm populations fluctuate greatly in response to environmental as well as soil management factors. Populations are very responsive to the addition of organic matter to soils (e.g. crop residues, manures, grass sod in rotation) and are generally low where inputs of organic matter are low. The size of the earthworm population is often a good indicator of the amount of organic matter being returned to the soil. However, it should be noted that there are many productive, high quality soils that are devoid of earthworm activity (Linden *et al.*, 1994).

Aggregate stability

Soil structure can be defined in relation to the arrangement of solid particles and of the pore space separating them. A well structured soil possesses pores of varying sizes with varying functions. Large (>60 µm diameter) soil pores (macropores) are important for movement of water and air and for root penetration, whereas small pores store water for use by the crop.

An important attribute of soil structure is its stability. It must be able to maintain the pore characteristics mentioned above against various stresses, such as the effects of raindrop impact and contraction and swelling caused by drying and re-wetting. The capacity of a soil to maintain its structure is commonly assessed by measurement of aggregate stability. Aggregate stability is defined as the ability of soil aggregates to withstand the degrading actions of water. It is commonly measured by sieving soil aggregates in water for a fixed period of time and then recovering and weighing the stable aggregates remaining (Kemper and Rosenau, 1965).

As already noted, soil humic material is important in binding soil aggregates together, while carbohydrates produced by the soil microbial biomass also act as cementing agents (Lynch and Bragg, 1985; Haynes and Beare, 1996). In addition, fungal hyphae (thread-like extensions of soil fungi) and fine plant roots can also aid in aggregation by enmeshing and holding aggregates together (Haynes and Beare, 1996).

It is important to note that loss of aggregate stability and breakdown of soil structure can occur in some situations even where soil organic matter content is high. The most common example of this is the influence of soil salinity, where dispersion of soil particles occurs and results in a loss of soil structure.

Long term management effects on soil quality

The effects of long term cultivation on soil quality were investigated in the Pukekohe region of the North Island of New Zealand. The main land use in the area is arable production of vegetables. Parts of the district were first cultivated in 1916 and some fields have been under cultivation ever since. Over the ensuing years an increasing land area has been planted to vegetables, so that fields vary in the number of years they have been under cultivation.

It is evident from the results presented in Figure 2 that cultivation resulted in a decline in soil organic matter content. The decline was most pronounced in the first 10 years and a new equilibrium level was reached after 60-80 years at about 18 g C/kg. The decline in organic matter content resulted in a linear decrease in the size of the soil microbial biomass (Figure 3) and a curvilinear decline in earthworm numbers, FDA hydrolysis rate and aggregate stability. Such results clearly illustrate that, as soil organic matter content declines, so too does soil biological activity and soil physical properties.

The practical significance of these results is that, below an organic C content of about 20 g C/kg on this particular soil type, fields are very difficult to manage. When soils have a low soil organic matter content and low biological activity they also have a low aggregate stability. That is, the soil aggregates are only weakly bound together. Under the disrupting influence of raindrop impact or wetting and drying cycles, the aggregates at the soil surface break down and a surface seal or cap is formed.

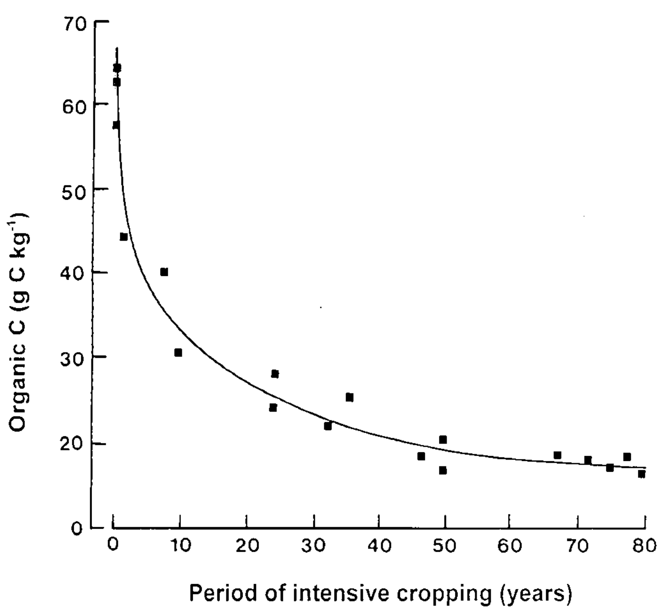

Figure 2. Effect of period of time under intensive arable cultivation on soil organic C content at Pukekohe, New Zealand. (Unpublished data from Haynes and Tregurtha; details available from author.)

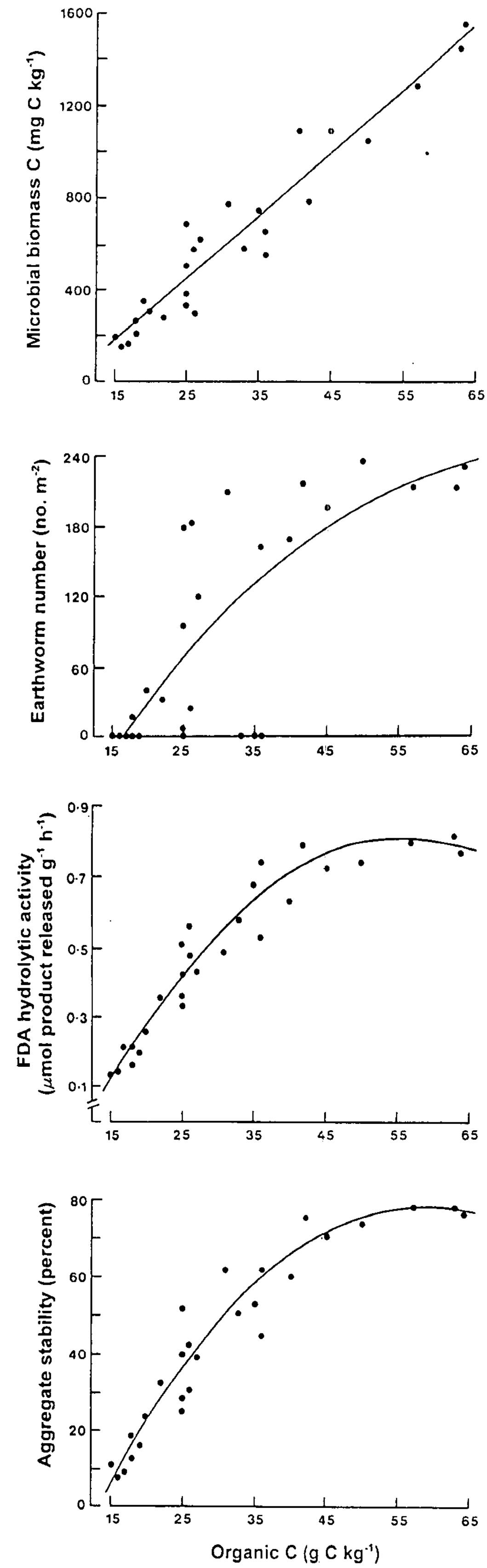

Figure 3. Relationship between organic C content and microbial biomass C, earthworm numbers, FDA hydrolysis rate and aggregate stability. (Unpublished data from Haynes and Tregurtha; details available from author.)

This can impede infiltration of rainfall or irrigation and result in ponding of surface water and/or run-off and surface erosion. If the surface seal dries out it can inhibit seedling germination. The soils also tend to compact easily because of their low organic matter content. Great care must be taken not to work the land when it is wet and particularly susceptible to compaction. The lack of an earthworm population in these long term arable soils means they lack the main natural agent that produces large pores in soils. Thus, compaction (i.e. the loss of large soil pores) is particularly damaging.

The addition of organic material (e.g. crop residues, green manure, grass sod in rotation) to the long term arable soils would have very beneficial effects on soil quality, as is discussed in the following section.

Short term management effects on soil quality

The short term effects of soil management practices on soil quality are often pronounced long before any changes in total soil organic matter content can be detected. Results from the South Island of New Zealand under an eight year rotation (four years of pasture followed by four years of arable crops) illustrates this point (Table 1). For comparison, data from a long term pasture and long term arable site are also shown.

Table 1
Effect of previous cropping history on organic C, microbial biomass C, earthworm numbers and aggregate stability for a soil from the South Island of New Zealand.

Previous cropping history	Organic C (%)	Microbial biomass C (mg C/kg)	Earthworm population (no./m^2)	Aggregate stability (%)
18 year pasture	3,2	1 018	830	82
4 year pasture	2,5	890	760	62
1 year pasture	2,4	801	510	40
1 year arable	2,4	738	380	23
4 year arable	2,4	712	260	22
10 year arable	2,0	610	130	18

The 1 year and 4 year pasture and 1 year and 4 year arable soils come from a cropping rotation of 4 years arable, followed by 4 years pasture. (Data recalculated from Haynes *et al.*, 1991.)

During the pasture phase of the rotation there is the development of a dense ramified root system and, as a result, a large soil microbial biomass also develops. The microbial biomass produces carbohydrate binding agents that result in an increase in aggregate stability. The earthworm population also builds up rapidly under pasture and this too contributes to the increase in aggregate stability.

When the field is returned to arable cultivation, the soil is cultivated and the dense pasture root system is replaced by a more sparse crop root system. As a result there is a rapid decline in soil microbial biomass, earthworm population and aggregate stability. Thus, there is a cyclical improvement in soil quality under the grass phase and a decline under the arable phase although total soil organic matter content remains virtually unchanged during the rotation. The soil quality is maintained in a much better state than under continuous arable production. The regular incorporation of crop residue or cover crops will have a similar cyclical effect on soil quality indices.

Relevance to sugarcane producing soils

Little is known regarding the rate of soil organic matter loss under South African sugarcane producing land (Meyer *et al.,* 1996). Preliminary research in northern KwaZulu-Natal has shown a marked reduction in soil organic matter content under cane production compared with virgin sites (van Antwerpen and Meyer, 1996). Australian research has certainly shown that compared with uncultivated land, there is soil acidification, a loss of soil organic matter and considerable compaction under sugarcane production (MacLean, 1975; Wood, 1985; Bramley *et al.*, 1996). Wood (1985) considered the loss of soil organic matter to be the most important aspect of soil degradation under sugarcane production. This is because soil organic matter improves soil structure, increases soil cation exchange capacity, acts as a store of N, S and P and helps provide an active biological environment (Wood, 1985).

It would be desirable to extend the work of van Antwerpen and Meyer (1996) and compare soil organic matter content and other soil quality indices on a number of paired sites in South Africa. At each site, samples would be taken from long term sugarcane fields and from undisturbed veld on the same soil type. Such a study would give an indication of how soil quality has changed from that of virgin sites. Information of this type is necessary before any judgement can be made as to the effect of sugarcane production on soil quality.

Conservation of crop residues following green cane harvest provides the best opportunity to maintain soil organic matter content under cane (Meyer *et al.*, 1996). Earlier South African research demonstrated that trash incorporation results in an increase in soil organic matter content and aggregate stability (Thompson, 1966) and an initial immobilisation of soil mineral N by the microbial population involved in trash decomposition (Wood, 1966). Recent Australian research (Sutton *et al.*, 1996) has suggested that the higher productivity of green cane harvesting compared with burning is due to higher soil microbial activity, greater soil organic matter turnover and greater storage and release of nutrients. The long term trash management trial at Mount Edgecombe compares (a) trash blanket (100% cover), (b) burnt tops left scattered on plots (69% cover) and (c) burnt tops raked off plots. This would be an ideal site to compare the effects of trash management on soil quality since it is managed under controlled conditions. Other areas of possible future research include studies of soil quality as influenced by fallow green crops and intercropping and the effect of application of filtercake.

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