SOIL ORGANIC MATTER DATA: WHAT DO THEY MEAN?

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Abstract

Soil organic matter influences numerous soil properties and processes, including bulk density, structure, temperature, water relations, nutrient availability and biological activity. With the advent of more efficient and rapid analytical techniques (e.g. near-infrared spectroscopy and automated combustion), most soil testing services now routinely report total carbon or organic matter contents of soils. For these data to be of practical use there must, however, be an appreciation of the factors and processes regulating organic carbon levels in soils, while guidelines on what constitutes optimum or ‘threshold’ carbon levels would also be of great value to field practitioners.

The carbon contents of most agricultural soils in South Africa fall in the range 0.1 to 9%. The two most important factors accounting for variations in carbon contents are soil management practices and soil texture. Tillage leads to decreases in carbon contents due to accelerated oxidation of organic matter. Under no-till cropping or perennial pastures, organic matter is conserved, or may be built up if these systems are established on soils that were previously subjected to intensive tillage. Organic carbon levels increase with increasing clay content, due to clays affording some protection against the oxidation of organic matter. Applications of inorganic fertilisers and lime, where accompanied by increased biomass production, result in increases in soil carbon contents. In the case of sugarcane, long-term experimentation indicates that there is a steady decline in carbon contents with time; however, trashing as opposed to burning has significant beneficial effects in terms of arresting this decline and improving soil quality in the top 100 mm of the profile. Indications are that soil sampling depths currently advocated for routine soil fertility evaluations may be excessive in terms of characterising the contributions of organic matter to soil health.

Keywords: sugarcane, soil organic matter, organic carbon, tillage, soil texture, burning, trashing

Introduction

The central role of soil organic matter (SOM) in the enhancement of soil health has long been recognized. Magdoff and van Es (2000) note that it was the renewed interest in soil health around the turn of the 20th century that led to an appreciation that ‘worn out’ soils, where productivity had drastically declined, resulted mainly from the depletion of soil organic matter. Organic matter has been identified as a key attribute in numerous soil properties and processes, including bulk density, structure, temperature, water relations, nutrient availability and biological activity (Johnston, 1986; Haynes, 2005). The significant advances in the fractionation of SOM which have taken place in recent years have served to promote a vastly improved understanding of the interaction between soil management practices and soil health.

The intensifying interest in SOM has been accompanied by the development of more efficient and rapid analytical techniques for its measurement (e.g. near-infrared spectroscopy and automated combustion). As a result, most agricultural laboratory services now routinely include total carbon (C) or organic matter (OM) contents in soil test reports, and these data are proving of significant value to field practitioners in the ‘fine-tuning’ of various production related recommendations, such as deriving optimum herbicide and fertiliser N application rates. However, as noted by a number of authors (Dick and Gregorich, 2004; Körschens, 2006), a dearth of reliable information on what constitutes ‘capacity’ or ‘threshold’ carbon levels in different soils under varying long-term management regimes is a limitation in terms of the usefulness of OM data. All too often, salesmen, consultants and government officials dabbling in the field of soil health stipulate a universal minimum SOM level which supposedly applies to all soils. In this vein, Körschens (2006) notes that a report tabled in the European Parliament included the statement, “According to the agrarian scientists, soils with a content of organic substance less than 3.6% are in a preliminary state of desert.” That such a standpoint is unscientific and patently flawed will become evident in the ensuing discussion.

In this paper, consideration is given to factors influencing OM accumulation and retention in soils. There is a focus on the impact of soil management on OM levels, as well as on the relationships between soil texture and OM.

Composition and units of measurement

The organic C content of soils can range from less than 0.5% to up to 60% in wetland bogs (Dick and Gregorich, 2004). However, the C contents of most agricultural soils in southern Africa fall in the range 0.1 to 9%.

The chemical composition of SOM may vary depending on its origin and soil conditions; but typically SOM contains about 50% C, 40% oxygen (O), 5% hydrogen (H), 4% nitrogen (N) and 1% sulphur (S) (Dick and Gregorich, 2004). Laboratory determinations of the soil organic fraction generally involve the measurement of organic C (OC). Conversion of measured OC percentage values to OM percentages involves multiplying the C value by a factor, usually 1.72. However, as noted by several workers (Körschens *et al*., 1998; Baldock and Nelson, 1999), the true conversion factor may vary considerably, with values raging from 1.4 and 3.3. Because of this uncertainty, it is preferable to report percentage C, rather than percentage OM.

It has been found that SOM can be divided into at least three fractions (Körschens *et al*., 1998; Magdoff and van Es, 2000):

- A living component, which includes a wide range of micro-organisms and macro-organisms.
- A labile (mineralisable/decomposable) fraction, which consists of recently deceased organisms and decaying plant roots and crop residues.
- An inert component, which comprises stabilised OM or humus.

Magdoff and van Es (2000) aptly named these fractions, ‘the living’, ‘the dead’, and ‘the very dead’, respectively.

The labile fraction (‘the dead’) is of particular interest to scientists. This fraction has been found to be closely associated with short-term C and N dynamics in soils, it is the main supply of food for various organisms living in the soil, and the compounds produced during its decomposition serve to bind soil particles together and thereby contribute to soil structural development (Haynes, 2005).

Factors involved in organic matter accumulation and retention in soils

Organic matter levels in soils are determined by a number of factors. Dick and Gregorich (2004) have proposed the following relationship between various factors and the capacity of a soil to hold (contain) SOM:

$$OM_{\text{soil capacity}} = f\text{ (climate, landscape, texture, inputs, disturbance)} \quad \text{(Equation 1)}$$

It should be noted that the five factors in equation 1 divide into two groups. The first three, climate, landscape and texture, establish limits in capacity that are associated with a particular location and parent material. These factors can not be managed. The last two factors are management-related and are affected by choices made by the farmer; for example, tillage system, trashing or burning, and green manuring. In this brief review, the focus is on firstly, the relationship between soil texture and OM levels, and secondly, the impacts of inputs and disturbance on OM accumulation and retention.

Soil texture

Variations in OM with soil texture have been widely investigated. In a study undertaken on New Zealand soils, Percival *et al.* (2000) noted a poor relationship between OM levels and clay content. These workers found that chemical stabilisation of OM by pyrophosphate-extractable aluminium and allophanes was the key process controlling accumulation in the soils. A lack of relationship between OM and texture was also noted in the studies of Thomsen *et al.* (2001).

In contrast to the above findings, there is much evidence in the literature of well-defined relationships between OM levels and texture in a wide range of soils (Dick and Gregorich, 2004; Dominy *et al*., 2002; Körschens *et al*., 1998; Körschens, 2006). The increased retention of OM with increasing clay content is attributed to the high surface area of clays affording some protection against its oxidation. Relationships between OC and clay contents of cane topsoils in the Midlands of KwaZulu-Natal province, South Africa (Figure 1) provide unequivocal evidence of the close relationship between these components (these data were derived from randomly drawn samples submitted by soil fertility consultants for routine fertility analyses). The strength of this relationship may be considered remarkable, given the diversity of parent materials and soil types occurring in the area from which the samples were drawn. It is worth noting that the inclusion of silt fraction data did not strengthen this correlation.

Management systems: effects of tillage and inputs

Agricultural management systems may impact profoundly on OM retention in soils. It has been repeatedly found that when native soils or soils relatively high in OM are subjected to regular tillage, SOM declines rapidly (Haynes and Tregurtha, 1999; Baldock and Nelson, 1999; Dick and Gregorich, 2004). On the other hand, systems involving little or no soil disturbance coupled with high inputs of organic materials (roots, above-ground plant residues, manures) favour the accumulation and retention of OM in soils. The rapid decline in SOM levels resulting from tillage operations has been ascribed to a number of factors (Dick and Gregorich, 2004). Firstly, there is often less OM being returned to the soil under the new system relative to the previous system. Secondly, tillage results in the rupture of aggregates, and thereby previously ‘protected’ OM is exposed to decomposition processes. Thirdly, a change in soil climatic conditions (temperature and moisture) and improved aeration lead to greater mineralisation of OM relative to uncultivated conditions. Fourthly, under tillage there is accelerated loss of finer soil particles rich in OM due to wind and water erosion.

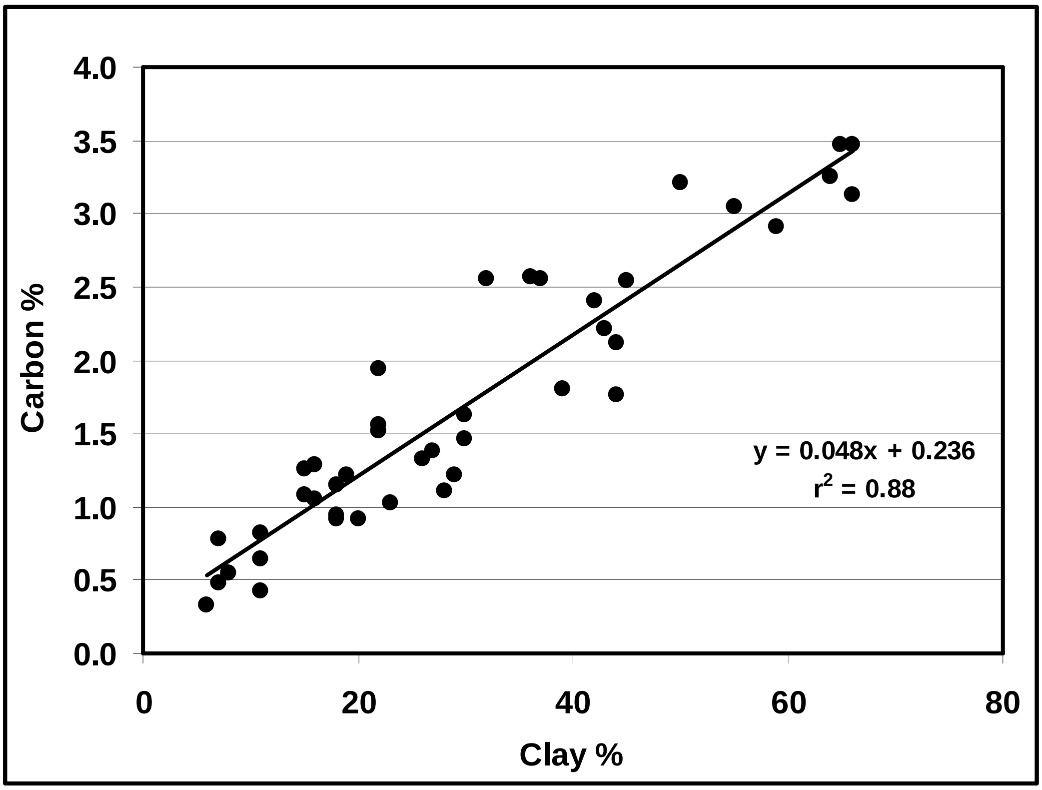

Figure 1. The relationship between soil organic carbon and clay contents in sugarcane topsoils of the Midlands North and South extension regions of KwaZulu-Natal, South Africa (N Miles, unpublished data).

In an attempt to integrate agricultural management practices with the related capacity factors (inputs, disturbance) included in equation 1, Dick and Gregorich (2004) provided a list of 10 major benchmark management systems that affect SOM levels (Table 1). The ranking of these benchmarks is from the management system which serves to maintain or increase SOM levels by optimising C inputs and protecting the soil from disturbances (assigned a value of 100), to the system most likely to cause a decrease (assigned a value of 10). These workers suggest that a management practice not listed can be placed within the framework of the table, inbetween the benchmarks most closely matched by the practice.

Table 1. Management systems that affect soil organic matter levels, from the most aggrading (assigned a value of 100) to the most degrading (assigned a value of 10) (after Dick and Gregorich, 2004).

100	Improved permanent pastures with animal grazing (this basically leaves all material on site).
90	No-tillage rotation with row crops alternating with legumes and soil treated with manure.
80	No-tillage with continuous row crops and manure additions.
70	Conservation tillage with long rotation sequences that include green manures and animal manures.
60	Plough tillage with rotation sequences that include green manures and animal manures.
50	No-tillage with grain and residue (for fuel and feed) harvested.
40	Conservation tillage with continuous row crops.
30	Intensive tillage with continuous row crops.
20	Intensive tillage with continuous row crops on sloping lands (grain and residues harvested).
10	Intensive tillage with mechanical summer fallow in alternate years with little nutrient input.

By way of example, the impact of long-term management systems on SOM levels is reflected by data from Cedara Research Station (Bainsvlei soil, 40% clay) in the KwaZulu-Natal Midlands (Table 2). In terms of the benchmarks listed in Table 1, grazed kikuyu grass would be assigned a value of approximately 100, while 'conventional tillage' maize would have a value of 30. The grazed, annually-tilled ryegrass would be given a value of about 60. The levels of soil C measured under the three management systems appear to be in close accord with the ascribed benchmark values, with that under the kikuyu grass pasture being 2.5 times higher than that under the conventionally tilled maize. The massive differences in N and S levels and in soil density under the three systems provide some indication of the value of OM as a reservoir for plant nutrients, as well its potential impact on soil physical properties.

Table 2. Variations in soil density, and amounts of total carbon, nitrogen and sulphur (0-100 mm) under different long term (>20 years) management systems on a Bainsvlei loam at Cedara Research Station, KwaZulu-Natal, South Africa (N Miles, unpublished data).

System	Soil density* (kg/m^3)	Carbon (kg/ha)	Nitrogen (kg/ha)	Sulphur (kg/ha)
Maize (conventional tillage)	1 070	26 964	2 247	417
Annual pasture (grazed ryegrass)	970	37 345	3 182	475
Perennial pasture (grazed kikuyu grass)	780	68 718	6 919	905

*Measured on sieved (1 mm) samples in the laboratory.

The management system hierarchy listed in Table 1 implies that, for a particular set of conditions which can not be managed (climate, landscape and texture; *cf.* Equation 1), long-term management involving improved permanent pastures under grazing will result in SOM levels which approximate to the soil's capacity to store C. In terms of sugarcane (burned), a management system rating in the region of 40 to 50 is suggested from Table 1. Thus, for a data set for cane such as that presented in Figure 1, it would be useful to have some indication of the capacity of these soils to store C, were a more favourable management system imposed. The availability of limited data from long-term (>20 years) grazed kikuyu pastures in the Midlands provides some indication of this capacity (Figure 2). The line fitted to these kikuyu data reflects a massive increase in SOM relative to the burned cane system, and, as in the case of the cane data, a dominating effect of clay content on the retention of SOM is apparent. Would it be possible to continue producing cane while at the same time implementing management practices that build SOM levels towards the 'capacity' level suggested by the kikuyu data? This may be answered by data from cane fields in the Midlands with a history of manure applications. These data (Figure 2) reflect markedly elevated C levels relative to non-manured fields, and highlight the benefits that are attainable from this improved management practice. The scatter of the points from the manure treated soils may reflect varying rates and durations of application.

Sugarcane management systems

Due largely to concerns related to declining yields, soil C dynamics under sugarcane have in recent years come under intensive scrutiny. The normal practice of burning standing cane prior to harvest leads to massive losses of C via volatilisation (Raison, 1979), while tillage operations accompanying replanting approximately every 7 to 10 years promote further C losses (van Antwerpen and Meyer, 1996). In studies on two soils (18 and 62% clay) which had been under sugarcane monoculture (with burning) for 20 to 40 years, Dominy *et al*.

(2002) found that C levels decreased exponentially with time, with the organic C content maintained in the higher clay soil being almost twice that of the low clay soil. A particularly noteworthy finding in this study was that decreases in C with time were accompanied by a linear decrease in aggregate stability.

The large declines in SOM under conventional sugarcane production practices have led to the promotion of practices more favourable to the conservation of C, such as the addition of organic amendments (van Antwerpen *et al*., 2003), the use of green manure crops (Garside and Bell, 2007), green cane harvesting (also known as 'trashing'), and zero tillage. The beneficial effects of trashing on topsoil C accumulation and associated properties such as nutrient cycling, soil strength and water retention were highlighted in the work of van Antwerpen *et al*. (2002), van Antwerpen and Meyer (1998), and Graham *et al.* (2002). Significant increases in total soil C (45% clay soil), as a result of trashing in a long-term burning versus trashing (63 years) field trial (BT1) at Mount Edgecombe, KwaZulu-Natal, were found to be limited to the surface 100 mm; however, significant increases in microbial biomass were observed to a depth of 300 mm (Graham *et al.*, 2002).

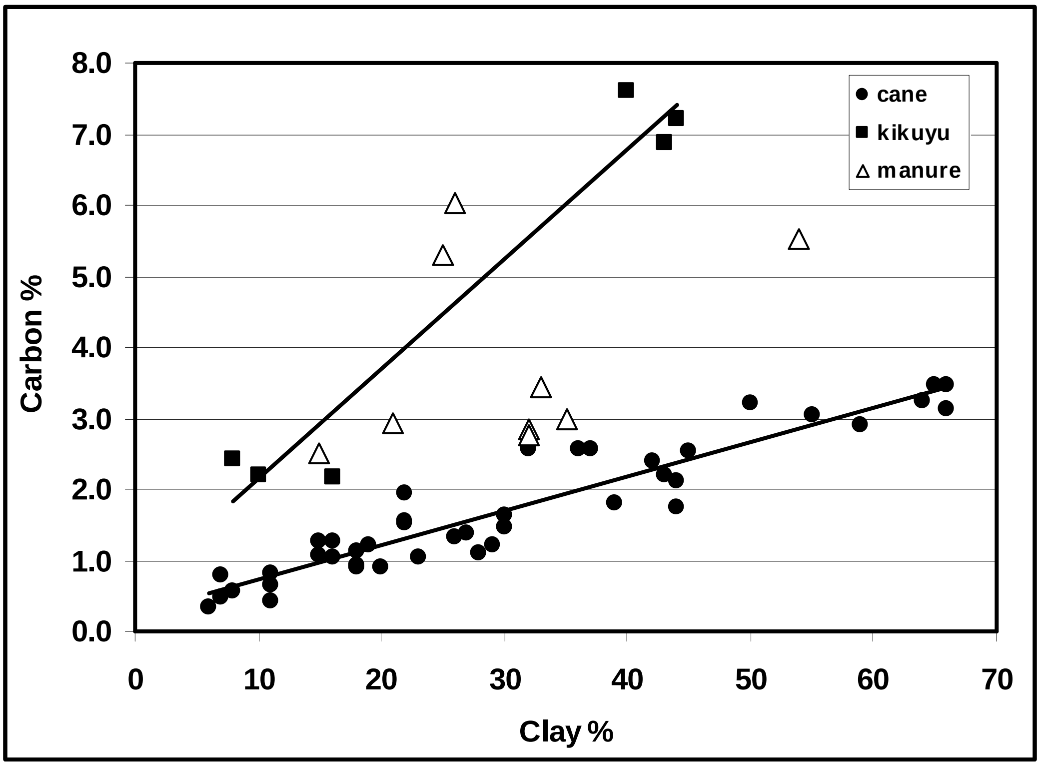

Figure 2. Relationship between soil organic carbon and clay contents in sugarcane and kikuyu grass topsoils of the Midlands North and South extension regions of KwaZulu-Natal, South Africa. Included are the effects of long-term use of animal manures on cane fields in these regions (N Miles, unpublished data).

Impact of fertiliser and lime use on organic matter levels

The impact of fertilisation and liming on SOM levels continues to be a source of contention in agricultural circles. Protagonists of 'green', biological or organic farming, with their often strong views based largely on sentiment, are invariably responsible for fuelling the confusion in this area (Vanlauwe and Giller, 2006).

An increasing body of research, in particular from long-term field trials, shows that fertiliser additions commensurate with crop requirements for optimum yields serve to increase the amount of OM in soils (Dick and Gregorich, 2004; Haynes and Naidu, 1998; Liebig *et al*., 2002; Wiegel *et al*., 1998). Clearly, the increased plant biomass following fertiliser applications results in increased returns of organic material to the soil in the form of decaying roots, litter and crop residues. In terms of sugarcane, information obtained in the long-term BT1 field trial shows clearly that annual fertilisation with N, P and K significantly increased SOM levels (Graham *et al*., 2002).

Reports relating to the impact of lime applications on OM levels in acid soils indicate that there may be short-term effects which differ from the overall long-term effect (Haynes and Naidu, 1998). The short-term effects relate to a temporary increase in microbial activity (‘flush’) immediately following lime additions. This is accompanied by increases in soil respiration rate, enzyme activity and mineralisation of N and S (Haynes, 1984; Haynes and Swift, 1988). The net result of the short-term effects may thus be a decrease in SOM but an increase in microbial biomass C content (Haynes and Naidu, 1998). In the long term, however, liming is predicted to increase SOM levels, due principally to increases in root growth and overall crop yields.

Vertical distribution of soil organic matter and its implications for soil sampling procedures

All productive soils are characterised by decreases in OM content with depth (Haynes and Knight, 1989; Mills, 2003). In soils subjected to regular tillage, there is usually a relatively gradual transition from the surface to the subsoil in terms of OM contents. However, in untilled soils, accumulation of OM in the top 10 to 20 mm of soil is often very marked, with abrupt decreases into deeper layers (Dominy and Haynes, 2002).

Decreases in OM with increasing depth bring into question the optimum soil sampling depth in terms of characterising OM status. At present the recommended topsoil sampling depths for routine soil fertility analyses are 200 mm for sugarcane, 150 mm for other row crops and 100 mm for pastures. However, given the current move towards no-till farming and in the case of cane, trashing, a re-evaluation of these depths may be warranted. In this context, the findings of Mills (2003) on natural range soils are of significance. He found that the accumulation of OM at the soil surface is of major importance in terms of the functioning of the soil ecosystem. Soil C in the 0-10 mm layer on sites protected from burning was 248% greater than that on sites which had been burned regularly. The higher OM in the top 10 to 20 mm of soil exerted profound effects on aggregate stability, water infiltration, aeration and nutrient cycling. These findings suggest that, in samples taken deeper than 100 mm under systems such as trashing, there may be masking of major benefits of OM in terms of soil functioning.

Conclusions

Soil OM is a key attribute of soil quality. A wide range in OM contents is found in soils, and the majority of soil testing services now routinely determine OM or OC in soil samples. For these data to be used optimally, it would appear that there is a need for a better understanding of factors controlling OM levels in soils. The factors listed in equation 1 determine the capacity of a soil to store OM. The integration of management practices with OM capacity factors determine the OM content of a soil at any given time. Soil OM levels generally increase sharply with increasing clay content, with the reason for this being that the large surface areas of clays afford the OM some protection from decomposition. Tillage is particularly inimical in terms of OM retention. Management systems that optimise C inputs and do not involve disturbance (e.g. grazed perennial pastures) serve to maintain or increase C inputs. Organic inputs, such as manures, applied at appropriate rates and on a regular basis, are highly effective in augmenting SOM levels. Optimisation of biomass production through the use of lime and fertilisers generally results in significant increases in soil C. Indications are that soil sampling depths currently advocated for routine soil fertility evaluations may be excessive in terms of characterising the contributions of SOM to soil health.

Information presented in this paper could form the basis for the development of models for the interpretation of OC data in various regions of the South African sugar industry. The relationships between C and clay for different long-term management systems appear to have practical value in terms of:

- predicting the expected OC levels under a particular management system
- estimating maximum C levels that could be sustained in soils (i.e. levels under perennial grazed pasture)
- evaluating the short- and long-term effects of changes in management.

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