LONG-TERM EFFECTS OF SUGARCANE PRODUCTION ON SOIL QUALITY IN THE SOUTH COAST AND THE MIDLANDS AREAS OF KWAZULU-NATAL

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Abstract

The effects of increasing periods under sugarcane monoculture on soil quality on a Glenrosa soil on the south coast and on a Hutton soil in the midlands was investigated. The organic C content at both sites under undisturbed vegetation was 46 g/kg This declined exponentially with increasing years under sugarcane and reached a new equilibrium level of about 34 g/kg for the Hutton soil and 13 g/kg for the Glenrosa soil. The higher organic matter content maintained at the Hutton site was attributed to clay protection of organic matter since the clay content of the Hutton soil was 62% compared with 18% for the Glenrosa one. The loss of soil organic matter resulted in a concomitant decline in soil microbial biomass C, basal respiration and aggregate stability.

Changes in the soil organic matter status in the soil profile to 40 cm depth under various cropping histories were compared at one site in the midlands on a Hutton soil. The known cropping histories were >50y kikuyu pasture, >50y annual ryegrass pasture, >30y continuous maize, >30y continuous sugarcane and undisturbed veld. Compared to veld, kikuyu pasture resulted in a large accumulation of soil organic matter in the surface 10 cm. Soil organic matter was similar under annual pasture and veld but both sugarcane and maize production resulted in a substantial decline in organic matter in the surface 10 cm. Trends in microbial biomass C and basal respiration with treatment and depth were similar to those for organic C except values for sugarcane were less than those for maize. This was attributed to the fallow nature of the sugarcane interrow soil. It was concluded that long-term sugarcane (and maize) causes a marked decline in soil organic matter content and related soil microbial and physical properties. Practices such as retention of crop residues, zero tillage and the use of green crops in rotation should be considered as methods of arresting soil degradation under continuous arable cropping.

Introduction

Concern has recently been raised regarding the degree of soil degradation that can occur under sugarcane production (Garside, 1997; Hartemink and Wood, 1998; Haynes and Hamilton, 1999). Indeed, the plateau or even decline in sugarcane yield per hectare, which has been observed in many countries in recent years, has been linked to soil degradation (Wood, 1985; Garside, 1997). Several workers have suggested that the most serious factor associated with soil degradation under sugarcane is the loss of soil organic matter (Wood, 1985; Meyer *et al.*, 1996; Haynes and Hamilton, 1999). Under sugarcane monoculture, the decrease in organic matter content is appreciable (van Antwerpen and Meyer, 1996; Hartemink, 1998) and sugarcane soils can have less than half the amount of organic matter of virgin sites (Wood, 1985). A loss of soil organic matter has detrimental effects on soil physical, chemical and biological properties (Stevenson, 1994). Indeed, maintenance and improvement of soil organic matter content is generally accepted as being an important objective of any sustainable system of agriculture (Gregorich *et al.*, 1994).

The decrease in soil biological activity that accompanies soil organic matter degradation is of particular concern (Doran and Parkin, 1994; Gregorich *et al.*, 1994). This is because biologically mediated processes in soils are central to their ecological function. Important processes include degradation of organic residues, transformations of organic matter, mineralization of nutrients held in organic form and formation and stabilization of soil aggregates.

Sugarcane monoculture is a major land use on the north and south coasts and even into the midlands of KwaZulu-Natal. Nevertheless, very little is known regarding the effects of sugarcane production on soil biological activity, soil organic matter content and quality. Such information is of particular significance to both sugarcane farmers and to land-use-planners and environmental protection staff who are responsible for management of the land resources of the province. This information would, however, be of little value unless comparisons were made between sugarcane and both undisturbed veld and the other major agricultural land uses in the province.

In this study the effects of increasing periods of time under sugarcane on soil organic matter content, size and activity of the microbial biomass and on aggregate stability were examined in two contrasting regions of the sugar belt. In addition, at one site in the midlands the effects of long-term sugarcane production on the above properties was compared with those of a long-term monoculture of maize, annual and perennial grazed pasture and undisturbed vegetation.

Materials and Methods

Fields with increasing years under sugarcane production were sampled from two separate localities in KwaZulu-Natal. On the south coast the soil was a Glenrosa form (Glenrosa series) (Ochric Cambisol; FAO) with a clay content of about 18% and the clay fraction was predominately kaolinite with some accessory vermiculite also being present. Twenty-four fields were sampled from 'Kinroy' estate (30° 15' 36" S and 30° 30' 00" E) in autumn (March) to a depth of 10 cm (10 samples per field which were bulked). These samples provided a range of cropping histories from undisturbed forest vegetation to about 80 years under sugarcane monoculture. In the midlands region, the soil was a Hutton form (Farmingham series) (Rhodic Ferrasol, FAO) with a clay content of about 62%. Its mineralogy was dominated by kaolinite plus halloysite and there were also appreciable amounts of crystalline sesquioxides, gibbsite and interlayered chlorite. Sixteen fields were sampled from 'Seafield' estate (29° 55' 48" S and 30° 24' 00" E) as described above and these provided a range of histories from undisturbed vegetation to about 30 years under sugarcane.

Changes in organic matter status in the soil profile to 40 cm depth in fields with various cropping histories were compared at one site in the KwaZulu-Natal midlands on a Hutton soil (Farmingham series). The fields were on 'Baynesfield' estate and cropping histories were >50y kikuyu grass pasture, >50y annual ryegrass pasture, >30y continuous sugarcane, >30y continuous maize and undisturbed grassland. Soil samples were taken from three separate randomly chosen areas within each study field. Ten soil samples were taken to a depth of 40 cm from each area, sectioned into 0-5, 5-10, 10-20, 20-30 and 30-40 cm layers and samples from each layer in each area were bulked to give three replicates per field.

Within 48 hours of collection bulk field-moist samples were thoroughly mixed and split into three subsamples. One subsample was sieved (<2 mm) and stored at 2°C prior to biological analysis. Another subsample was air-dried, sieved (< 2 mm) and ground for subsequent analysis of organic C. The third subsample was sieved and the 2-6 mm diameter aggregates were collected and air-dried for subsequent analysis of aggregate stability.

Microbial biomass C was estimated by the fumigation-extraction method based on the difference between C extracted with 0.5 M K_2SO_4 from chloroform fumigated and unfumigated soil samples using a K_c factor of 0.38 (Vance *et al.*, 1987). The microbial quotient was calculated by expressing microbial biomass C as a percentage of total soil organic C. Basal respiration was determined by placing 30g oven-dry equivalent of field-moist soil in a 50 ml beaker and incubating the sample in the dark at 25°C in a one litre air-tight sealed jar together with 10 ml of 1 M NaOH. The CO_2-C evolved was determined after two days, five days and ten days by titration (Anderson, 1982). Organic C was determined by the Walkley and Black dichromate oxidation method (Blakemore *et al.*, 1972).

Aggregate stability was measured using a wet sieving technique (Haynes, 1993). Thirty grams of air-dried 2-4 mm soil aggregates were transferred to a wet sieving apparatus (sieve aperture = 2 mm). The water level was adjusted so that aggregates on the sieve were just submerged at the highest point of oscillation. The oscillation rate was 25 cycles/min, the amplitude of sieving action was 35 mm and the period of wet sieving was 15 min. The results were expressed as the percentage of stable aggregates remaining on the 2 mm sieve following sieving.

Results and Discussion

The loss of organic matter when natural forest (Glenrosa soil) or grassland (Hutton soil) was converted to sugarcane monoculture is evident in Figure 1. Such a loss characteristically occurs when soils under natural vegetation are converted to arable agriculture (Paustian *et al.*, 1997; Fenton *et al.*, 1999). As shown in Figure 1, soil organic C levels typically decline rapidly in the first 10 years after cultivation and then stabilize at a new equilibrium level after 30-100 years. The reason for the decline under arable systems can be traced to (i) a much lower allocation of carbonaceous residues to the soil (due to relatively wide spacing of crop plants, removal of harvested cane and burning of crop residues); (ii) enhancing aggregate disruption and exposure of physically-protected or organic material to microbial action following cultivation and (iii) enhanced rates of decomposition due to more favourable conditions (e.g. aeration, temperature and water content). A decrease in soil organic matter content under long-term sugarcane monoculture is well-documented (van Antwerpen and Meyer, 1996; Hartemink and Wood, 1998; Haynes and Hamilton, 1999).

The new equilibrium organic C content reached was about 34 g/kg for Hutton soil but only about 13 g/kg for the Glenrosa soil (Figure1). In general, the new equilibrium level attained is

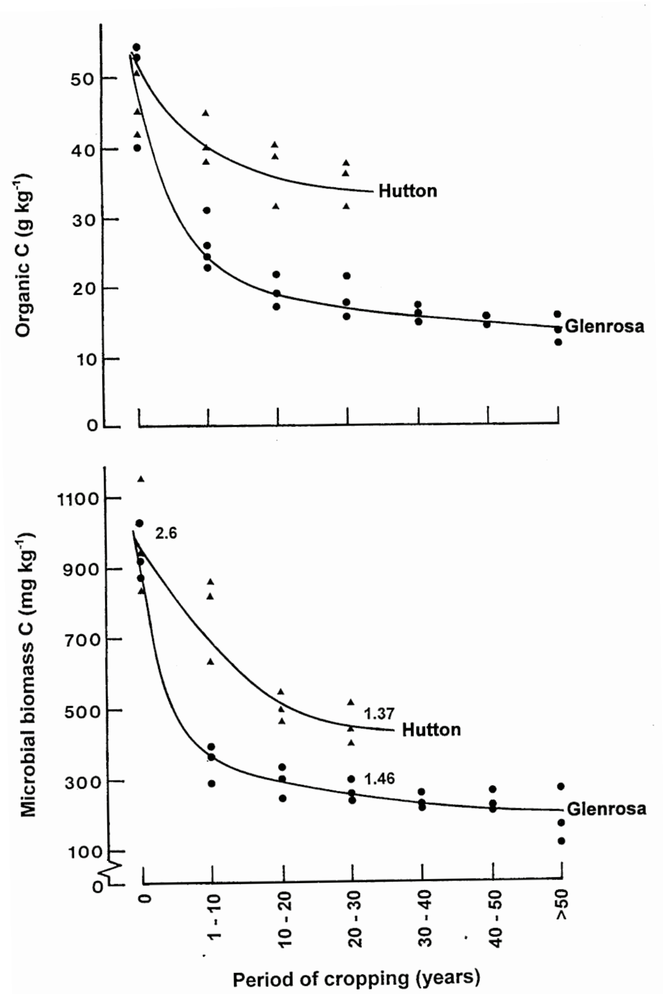

Figure 1. Effect of increasing time under sugarcane monoculture on soil organic C and microbial biomass C content on sites on two soils (Hutton and Glenrosa). Values for microbial quotient after 0 and 20-30 years are shown on the curves for microbial biomass C.

dictated by the ability of the soil to stabilize organic material (e.g. clay content and mineralogy) and the amount, quality and distribution of plant residue inputs (Paustian *et al.*, 1997). The much higher clay content of the Hutton (62%) than Glenrosa (18%) soil is probably the main reason for the higher equilibrium organic matter level attained in the former soil. Indeed, many studies have demonstrated a positive correlation between soil organic C and clay contents (Baldock and Nelson, 2000) due to adsorption of organic matter onto clay mineral surfaces and therefore its protection from microbial attack.

Another important contributing factor to the different equilibrium organic matter levels reached may well be that cultivation of the soil is less frequent on the Hutton than the Glenrosa soil. This is because sugarcane is usually harvested on a one-year cycle on the south coast but on a two-year cycle in the midlands. Thus, the Glenrosa soil is tilled about every eight years (one planted crop and seven ratoons) while for the Hutton soil it is about every 16 years.

Increasing years under sugarcane resulted in a broadly similar pattern of decline in microbial biomass C to that for organic C (Figure 1). The loss of microbial biomass C was, however, more pronounced. This is demonstrated by the fact that the microbial quotient was 2.6% in both the soils under undisturbed vegetation and this decreased to 1.37 for the Hutton and 1.46 for the Glenrosa soil. Such a trend is to be expected since when a soil is put under cultivation it is the labile, readily metabolizable fractions of organic matter that are preferentially lost (Hart *et al.*, 1988). As a result, a long-term cultivated arable soil can support a proportionately smaller microbial community than an undisturbed soil.

The lower microbial quotient in the Hutton than Glenrosa soil is surprising since clay protection of the microbial biomass is well documented (Sparling, 1997). However, in this study, clay protection of organic matter was more pronounced than that for the microbial biomass. Both Sparling (1992) and Haynes (2000) observed a similar effect of increasing clay content in decreasing the microbial quotient. The stabilizing effect of clays probably means that soils with a higher clay content contain a larger proportion of inert organic matter; thus there is a decrease in microbial quotient.

Data for the relationship between organic C and microbial biomass C or aggregate stability and microbial biomass versus basal respiration for the Hutton soil are shown in Figure 2. Trends for the Glenrosa soil were similar and are not presented. It is evident that there was a linear relationship between organic C and microbial biomass C. Although some workers have found that in arable soils, microbial biomass C is linearly related to organic C only up to about 25 g C/kg (Anderson and Domsch, 1989; Wiegand *et al.,* 1995), Haynes and Tregurtha (1999) recorded a linear relationship up to 65 g/C kg. Similarly, in the Hutton soil it was linear up to 50 g C/kg. Basal respiration was linearly related to microbial biomass C (Figure 2) indicating that the size and activity of the microbial biomass decreased concomitantly with decreasing soil organic matter content.

The linear relationship between aggregate stability and organic matter content (Figure 2) has been observed by many workers (Haynes and Beare, 1996). This is because the binding and glueing ability of various fractions of organic matter contributes greatly to the formation and stabilization of soil aggregates. The results demonstrate that with increasing years under sugarcane production, soil aggregates become less strongly bound together. The potential for soil structural breakdown with increased runoff and erosion is therefore greatly increased.

The loss of soil organic matter under both sugarcane and maize in the surface 10 cm, compared with undisturbed grassland, is evident at the Baynsfield estate site in the midlands (Figure 3). By contrast, there was a large accumulation of organic matter

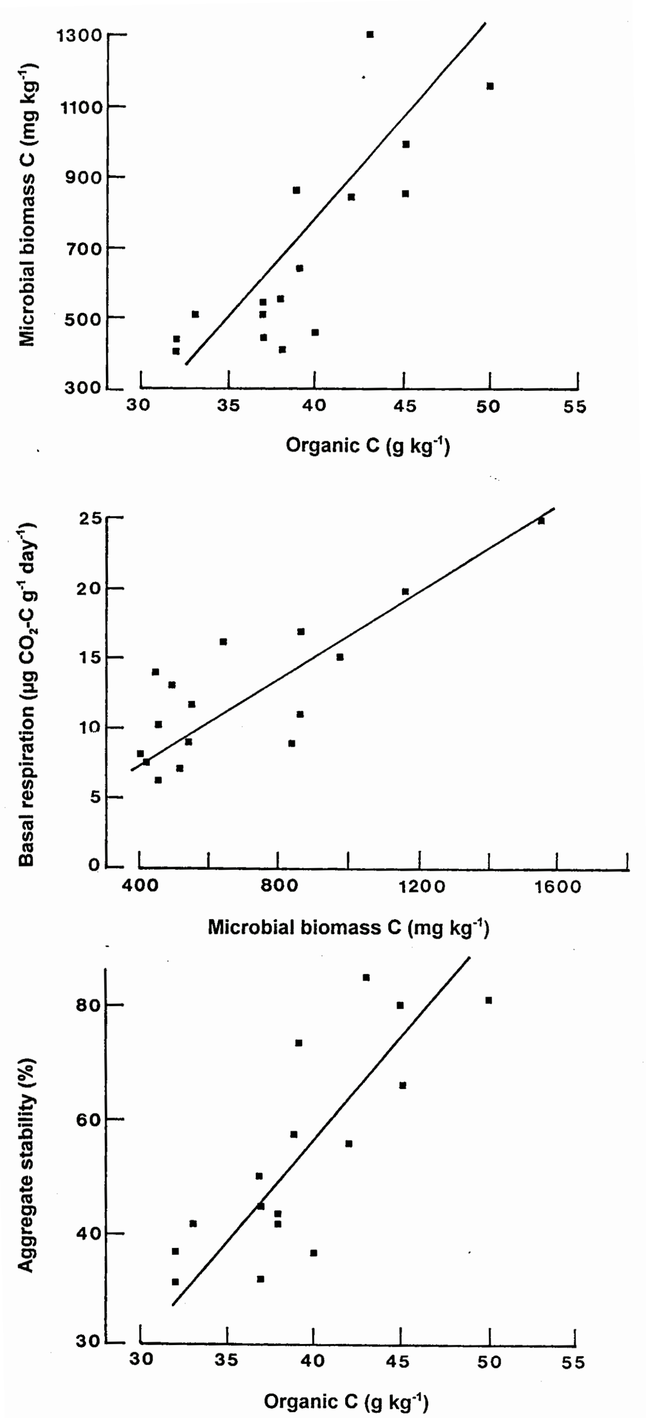

Figure 2. Relationship between organic C and microbial biomass, microbial biomass and basal respiration and organic C and aggregate stability for the Hutton soil.

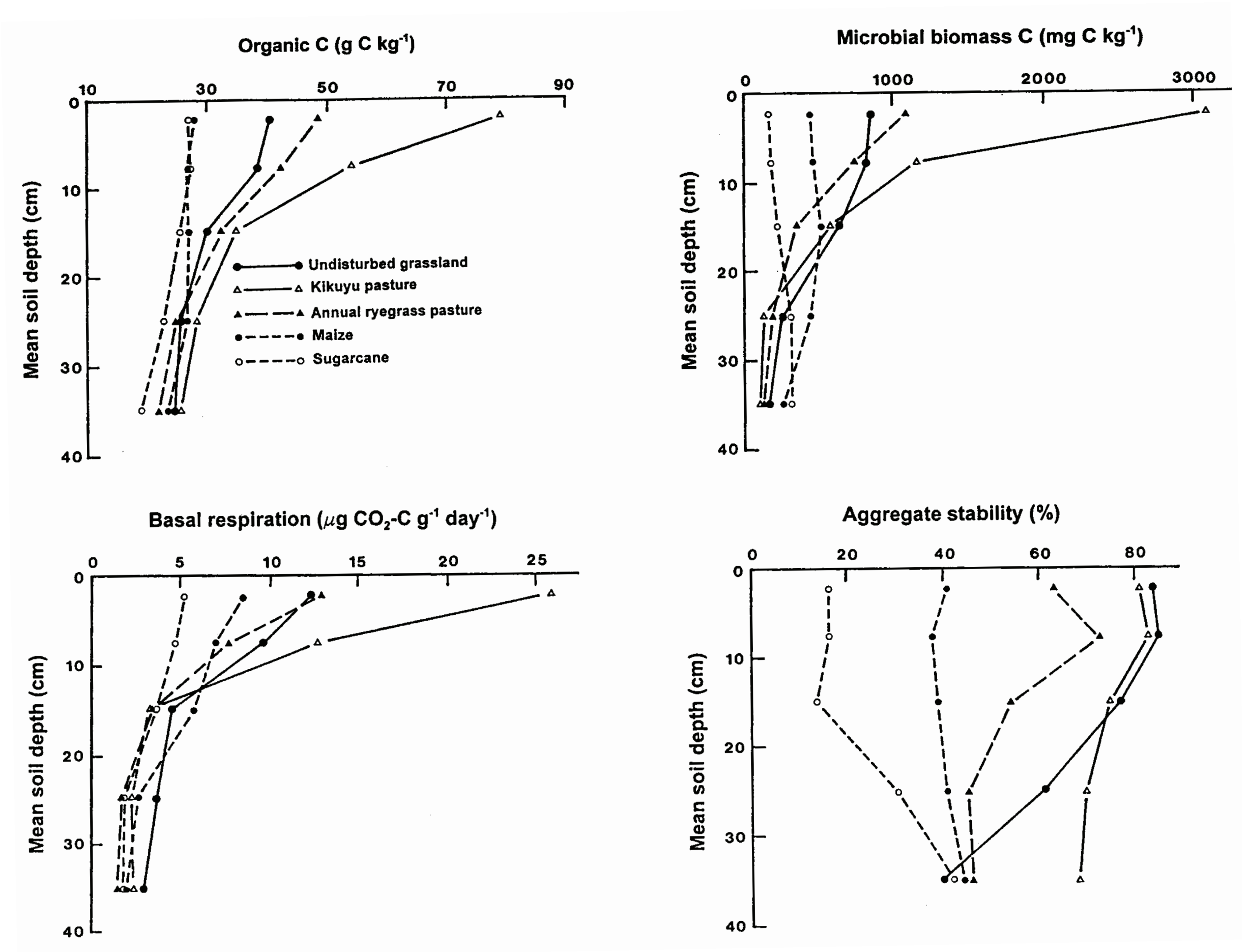

Figure 3. Long-term effect of land use on organic C, microbial biomass C, basal respiration and aggregate stability in the profile to 40 cm on a Hutton soil.

in the surface 10cm of soil under the permanent kikuyu pasture. Accumulation of organic matter when undisturbed land is converted to permanent pasture, with the use of fertilisers, irrigation and high yielding pasture plants, is common (Haynes and Williams, 1993). This accumulation is attributable to increased organic matter inputs, particularly in the form of turnover of the, large ramified root system of pasture grasses.

Soil organic matter content under annual ryegrass pasture was similar to that under undisturbed grassland (Figure 3). This is likely to be the result of a balance between two opposing factors. On the one hand, plant biomass production (above and below-ground) from irrigated annual ryegrass will be much greater than that from undisturbed grassy vegetation, so organic matter inputs to the soil will be increased. Nevertheless, each year annual ryegrass fields are conventionally cultivated and resown with ryegrass and this tillage will promote organic matter decomposition. These two opposing factors apparently balanced out so that there was little overall change in soil organic matter content under annual pasture.

It is, however, interesting to note that annual production of sugarcane and maize is considerably more damaging to soil organic matter content than annual ryegrass. The reason for this is presumably that there is a large removal of organic material from the soil-plant system in the form of harvested cane or maize cobs. In contrast, under grazed pasture no such removal occurs and organic matter inputs to the soil are therefore much greater.

Trends in microbial biomass C and basal respiration with treatment were broadly similar to those for organic C (Figure 3) except that values under sugarcane were lower than those under maize. The lower values under sugarcane are believed to reflect the soil sampling technique used. Soil samples were taken between the rows of the sugarcane and maize. Whilst organic matter inputs (particularly from root material) will be spread over the whole maize field (since the crop is resown each year), for sugarcane the interrow space remains fallow for up to 16 years before replanting occurs. Thus, the lower microbial biomass C and basal respiration under sugarcane reflects the fact that the portion of the field sampled has little C input and labile C pools have become diminished.

The pattern of change in aggregate stability with depth and treatment was dissimilar to that for organic C (Figure 3) in that kikuyu pasture and undisturbed grassland had a similar aggregate stability in the surface 20 cm. Thus, the substantial increase in organic matter content in the surface 10 cm under kikuyu pasture did not cause an increase in aggregate stability. Similarly, it has been shown that soils with widely differing periods under permanent pasture (e.g. 10-50 years) can have similar high aggregate stability values regardless of differences in organic matter content (Haynes and Beare, 1996). This is because the effect of grassland on aggregate stability is only partially an effect of total soil organic matter content. For example, the large microbial community in the pasture rhizosphere produces copious quantities of polysacchoride binding agents and the fine grass roots and associated mycorrhizal hyphae have a strong enmeshing and stabilizing effect (Degens, 1997). The higher aggregate stability in the 30-40 cm layer under kikuyu grass than the other land uses is probably due to the deep rooting nature of kikuyu grass. The annual ryegrass pasture has less of an aggregating effect than undisturbed grassland because tillage and re-seeding of the pasture on an annual basis means there is a less ramified root system and less of a rhizosphere effect.

Aggregate stability was notably low in the sugarcane interrows (Figure 3). As already noted, the sugarcane interrow is effectively fallow soil with little crop root growth and a low microbial activity. As a result, aggregate stability was low particularly in the surface 20 cm. This will mean that the soil is more predisposed to structural breakdown than under the other land uses.

Conclusions

It is concluded that long-term sugarcane (and maize) causes a marked decline in soil organic matter content and related soil microbial and physical properties in the surface 10 cm. A new equilibrium soil organic matter level is reached after 30-50 years and this can be greatly affected by the clay content of the soil. Further research is required to investigate the differences in organic matter status and soil microbial activity between the interrow space and plant row of sugarcane soils since organic matter inputs will occur mainly within the rows.

The low organic matter status in the surface of sugarcane soils will increase the potential for soil structural breakdown, compaction, surface runoff and water erosion. Practices such as retention of trash (rather than burning), zero tillage and the use of green crops in rotation, should be considered as methods of arresting soil degradation.

Acknowledgements

The authors are grateful to the SASEX Extension Officers for identification of suitable sites and the owner / managers of Kinroy, Seafield and Baynesfield estates for allowing us to sample fields on their properties.

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