EFFECT OF LONG-TERM SUGARCANE PRODUCTION ON PHYSICAL AND CHEMICAL PROPERTIES OF SOILS IN KWAZULU-NATAL

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Abstract

Cultivated and virgin (uncultivated) soil samples from two climatically contrasting regions of KwaZulu-Natal were analysed to identify changes in selected soil chemical and physical properties resulting from continuous sugarcane production. The analyses indicated that as the period various fields had been under cultivation increased there was a corresponding decrease in soil pH, cation exchange capacity, exchangeable cations, organic matter, and aggregate stability, with an corresponding increase in bulk density. There was a significant loss of organic matter in the South Coast region due to cultivation but not in the Midlands. In general, the results indicated that cultivated land degraded more rapidly relative to virgin land but degraded soil properties were not consistent across regions. The stepwise regression analysis technique was adopted to determine the set of parameters to be used in the creation of equations to estimate soil degradation indicators such as pH, organic matter and aggregate stability. The resulting equations were robust to the extent that no further subdivision of the data was required after it was combined into a single pool. In order to speed up the collection of data required for these equations all samples were scanned by near infrared reflectance spectroscopy (NIRS) and the captured data were used to calibrate the NIRS instrument for parameters such as pH, cation exchange capacity, organic matter, clay, silt, sand and aggregate stability. Due to the sensitivity of NIRS to the geological composition of the soils, the samples had to be subdivided into two sampling regions. The net result was two NIRS calibrations per parameter.

Keywords: soil degradation, sugarcane, organic matter, soil aggregate stability

Introduction

Recent concerns regarding soil degradation and agricultural sustainability have kindled interest in assessment of soil quality (Gregorich *et al*., 1994). Soil quality has been broadly defined as the capacity of a specific soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, and maintain and enhance air and water quality (Karlen *et al.,* 1997*)*. An assessment of soil quality that includes soil chemical, physical and biological properties can provide valuable information for evaluation of the sustainability of land management practices (Doran and Parkin, 1994). Sugarcane production in South Africa is substantially a monocropping practice with an average cycle of eight ratoon crops before fields are re-established to sugarcane (van Antwerpen and Meyer, 1997). This continuous cropping system often ignores the long-term effects on soil fertility, as long as profitable yields are maintained. Sugarcane and maize are the most common crops in KwaZulu-Natal, and have often been grown on the same land for a prolonged period (more than 50 years).

Industrial sugarcane yields have reached the 'productivity plateau' or even started to decline since the early 1980's, despite the release of many new varieties, all with a yield potential higher than that of the older varieties (Wood, 1985; van Antwerpen and Meyer, 1997). Growers have responded to the falling productivity of their land by applying more nitrogenous fertilisers such as urea and ammonium sulphate and this has resulted in accelerated acidification under sugarcane cultivation. In Hawaii, Humbert (1959) reported that the observed decline in sugarcane yields resulted from a combination of soil compaction, acidification, nutrient depletion and changes in biological properties of soil. Cane machinery, especially harvesters, exerts high ground pressure on soils that are commonly moist or wet with subsequent soil compression and deformation. In South Africa Maud (1960) reported that the tendency for moist sugarbelt soils to become compacted is greatest when their moisture content is near field capacity. Van Antwerpen and Meyer (1997) observed that in trashed plots soils generally had a lower mean bulk density than those in areas that were burnt at harvest.

Soil organic matter is a key attribute of soil quality as it has a profound effect on soil physical, chemical and biological properties (Gregorich *et al*., 1994). Several authors have reported that soil cultivation decreases organic matter content (Wood, 1965; Dalal and Mayer, 1986; Bridges and Bells, 1995; van Antwerpen and Meyer, 1996). Wood (1985) considered the loss of soil organic matter under cane production to be the most important aspect of soil degradation. This is because organic matter promotes soil structure and root development, improves water infiltration and water-use efficiency, increases soil cation exchange capacity, acts as a store for nitrogen, sulfur and phosphorus and helps to provide an active biological environment. Soils with a high clay content, however, are believed to be better able to resist loss of organic matter than sandier soils (Coulombe *et al*., 1996).

In northern KwaZulu-Natal van Antwerpen and Meyer (1996) showed that there was a marked reduction of soil organic matter under sugarcane cultivation compared with virgin soils, and where cane was burnt prior to harvest in both dryland and irrigated conditions. Similarly, McGarry *et al*., (1996) and Wood (1985) found a marked loss of organic matter from the top 100mm soil layer under sugarcane production in Queensland, Australia. The remedy for this decline in organic matter may be the retention of crop residues from green cane harvesting. In a recent study on the 59-year-old burning and trashing trial (BT1) at Mount Edgecombe which is situated on a vertisol, van Antwerpen and Meyer (1998) observed that soil organic matter was significantly higher where green harvesting were compared with the burnt treatment.

An increase in soil acidification was reported for fields under dryland cane production (Schroeder *et al*., 1994; van Antwerpen and Meyer,1996) accompanied by a loss of cations and an increase of Al levels. In their survey of soil fertility trends Meyer *et al*. (1989) found that the sandy soils on the South and lower South Coast had became progressively more acidic between 1980 and 1989. At Mount Edgecombe, van Antwerpen and Meyer (1997) observed increased levels of P and K and a decline in pH and Ca levels in the BT1 trial, which was due to induced acidification from applying nitrogenous fertilisers annually at a rate of 140 kg N ha^{-1} over 58 years.

In Australia, different soil fertility trends have emerged under burnt and trash-blanketed systems and have improved the soil nutrient status of the upper 50mm layer (McGarry *et al*., 1996). It was also shown that compared with uncultivated land, there is soil acidification, a loss of soil organic matter and considerable compaction under sugarcane production (Wood, 1985; Bramley *et al.*1996; McGarry *et al.*1996).

In looking for a more reliable, rapid and non-destructive technique for the determination of selected soil quality indicators, attention was directed to near infrared reflectance spectrophotometry (NIRS). This technique is being used increasingly in a number of countries as a rapid method for simultaneously evaluating several soil properties (Meyer, 1989; Ben-Dor and Banin, 1995). As early as 1965, Bowers and Hanks found that organic matter, moisture content and particle size affected the amount of radiant energy reflected from soils. In the South African sugar industry, the successful application of near infrared reflectance for the determination of organic matter, soil texture, total N content and N-mineralisation rating have been reported by Meyer (1989).

Little is known about long-term effect of sugarcane monoculture on changes in physical, chemical and biological properties of soils (van Antwerpen and Meyer 1996). The success of soil management in maintaining soil quality depends on an understanding of how soils respond to agricultural use and practice over time. The objectives of this paper are to provide information on the effect of long-term sugarcane cultivation on aspects of soil quality and to estimate indicators of soil degradation by (NIRS).

Materials And Methods

Two climatically different dryland sugarcane producing regions were chosen for this study. Granite derived Glenrosa form soil samples were collected from 27 fields from a farm on the South Coast with a mean annual rainfall of 1025mm. In the KwaZulu-Natal Midlands, with a mean annual rainfall of 918mm, soil samples were collected from 38 fields on two farms having dolerite derived Hutton and Inanda form soils. Within each region the samples taken from fields represented various periods under cane cultivation. The fields ranged from zero years under cultivation (virgin veld) to 30 years in the Midlands and more than 50 years on the South Coast. Virgin veld included natural bush and undisturbed roadsides with natural grassland. At all three farms crops are burnt prior to harvest. At each site soil sample slices were taken in duplicate at depths of 0-100 and 100-200 mm using a spade. On cultivated sites, the soil samples were collected from the inter-row area.

Chemical analyses included pH (water), P (Truog), K, Ca, Mg, Na, Al (Meyer *et al*., 1989), cation exchangeable capacity (Sumner and Miller, 1996), and organic matter. Cations (Na, K, Ca and Mg) were extracted using standard 1N ammonium acetate and subsequently determined by atomic absorption spectrophotometry (Meyer *et al*., 1989). Phosphorus was determined by the modified Truog procedure based on 0.02N H_2SO_4. Organic matter was determined using two methods: first, the wet acidified dichromate oxidation, during which organic carbon is oxidized by potassium dichromate in the presence of sulphuric acid with external heating (Nelson and Somner, 1982). Secondly, loss on ignition method, whereby an aliquot of each sample is oven-dried for 24 hours at 105^{o}C and ignited at 650^{o}C or 15 hours, after which weight loss-on-ignition is determined (Ben-Dor and Banin, 1989).

Physical properties measured included textural analysis by the Bouyoucos hydrometer method using sodium hexametaphosphate as dispersing agent (Gee and Bauder, 1986); bulk density by the clod method (Blake and Hartge, 1986); soil aggregate stability by wet sieving (Sumner, 1958) where 50g of soil was placed on a nest of three sieves with apertures of 2.0, 1.0 and 0.5mm respectively. Aggregates are first soaked for 5 minutes in order to prevent breakdown of aggregates by entrapped air and then sieved for 5 minutes. Field-moist samples are used for aggregate stability and the initial water content is measured as it influences stability determinations. Haynes and Swift (1990) observed an increase in soil aggregate stability induced by air-drying before wet-sieving long-term pasture soils and a decrease in stability induced by air-drying long-term arable soils. This is in agreement with the results of other workers such as Churchman and Tate (1987) who found that aggregate stability of air-dried samples, as determined by wet-sieving, was often significantly greater than that of their field-moist counterparts. Munroe and Kladivko (1987), using an arable soil, found that air-drying greatly reduced aggregate stability.

The 120 soil samples from the South Coast were randomly split and one group of 40 samples was scanned with the Perstorp Analytical near infrared reflectance spectrophotometer (model 6500) and used to calibrate the instrument. The remaining 80 samples were then used to validate the subsequent calibration equations. For the Midlands soils 50 samples were used to calibrate the NIRS instrument and the remaining 86 samples were used to validate the calibration equations. Calibration equations for soil parameters were based upon a combination of four wavelengths that gave the best regression correlation coefficients and lowest standard error of estimate in a multiple regression analysis.

Regression analyses were used to search for relationships between the measured soil properties. Particular attention was paid to the relationships between measured properties and soil organic matter, and the length of time fields had been under sugarcane production. The student's t-test of significance was used to test for differences between cultivated and virgin sites. The stepwise regression analysis technique was used to aid the selection of those parameters having the greatest impact on soil quality. All of this was done using the Genstat 5 (release 3.2) computer program.

Results And Discussion

In general pH, Ca, Mg, CEC and SAS all decreased and Al and bulk density increased as the period under sugarcane cultivation increased in both regions (Table 1). In the sandy loam soil of the South Coast plant available P was unchanged while exchangeable K and organic matter decreased over time. By comparison in the Midlands clay soils plant available P increased while exchangeable K and organic matter were unchanged.

The mean pH in the topsoil layer (0-100mm depth) of virgin sites for South Coast sandy loam soils was 5.34 compared with 5.64 for the Midlands clayey soils (Table 1). The mean pH of the South Coast area soils had declined to 4.35 after 50 years of cultivation whereas in the Midlands area it had decreased to 4.97 after 30 years of cultivation and these changes for both areas were statistically highly significant. The rate of decline in pH values for both areas was similar, being 0.025 pH-units per year for the South Coast and 0.024 pH-units per year for the Midlands (Figure 1). This decline in pH might be due to the combined effect of cation leaching (especially from the sandy loam soils of the South Coast where the annual rainfall is 1025mm per annum), increased mineralisation of organic matter which contributes to soil acidification (Rowell and Wild, 1985), and the oxidation of ammonium fertilisers to nitric acid. In contrast

Table 1. Effect of years under cultivation on the chemical and physical properties of soils from two regions in KwaZulu-Natal. All significant determinations were evaluated against 0 years under cultivation (virgin land) within each region.

Soil property	Depth (mm)	South Coast Years under cultivation						Midlands Years under cultivation				
		0 n=7	2 n=3	4 n=3	30 n=6	40 n=4	50 n=4	0 n=7	4 n=5	20 n=8	25 n=4	30 n=7
pH (H_2O)	100	5.34	^{ns}5.26	^{ns}6.52	^{ns}4.94	**4.46	**4.35	5.64	^{ns}5.42	***4.86	**5.06	***4.97
	200	5.21	^{ns}5.21	^{ns}6.65	^{ns}4.67	*4.27	*4.32	5.60	^{ns}5.53	***4.80	*4.98	***5.05
P (mg kg^{-1})	100	32.67	^{ns}22.67	^{ns}53.67	^{ns}41.17	^{ns}31.50	^{ns}16.75	8.00	**31.50	**51.00	*57.25	31.71
	200	33.83	^{ns}21.33	^{ns}52.33	^{ns}33.17	^{ns}19.75	^{ns}12.00	5.86	^{ns}8.75	*34.13	***21.25	*14.14
K (mg kg^{-1})	100	219.67	*101.00	^{ns}155.00	^{ns}120.67	*71.75	*77.75	199.71	^{ns}261.50	^{ns}237.75	^{ns}199.75	^{ns}210.00
	200	154.33	^{ns}76.00	^{ns}112.33	^{ns}75.33	*46.50	*50.25	96.29	^{ns}88.50	^{ns}139.63	^{ns}71.75	^{ns}107.00
Ca (mg kg^{-1})	100	723.00	^{ns}368.67	^{ns}1189.67	*228.17	*235.50	*222.50	1010.86	^{ns}963.25	*491.50	*628.00	**492.14
	200	614.67	^{ns}383.67	*1072.33	^{ns}299.00	*222.00	^{ns}214.25	884.86	^{ns}1027.25	^{ns}491.50	^{ns}618.50	^{ns}591.14
Mg (mg kg^{-1})	100	227.17	^{ns}91.00	^{ns}146.33	*68.33	*82.00	^{ns}77.25	416.00	^{ns}339.75	*99.25	*112.25	**80.29
	200	169.17	^{ns}103.00	^{ns}148.00	*69.33	**61.25	^{ns}65.25	365.86	^{ns}441.00	*74.38	*66.00	*83.57
Na (mg kg^{-1})	100	39.00	*26.33	*26.00	^{ns}37.17	^{ns}36.75	^{ns}28.25	42.86	*27.50	*29.38	**24.50	**25
	200	36.00	^{ns}26.67	^{ns}29.33	^{ns}31.67	^{ns}34.25	^{ns}28.75	46.00	^{ns}32.75	**30.38	**26.27	**28
Al (mg kg^{-1})	100	8.17	^{ns}13.67	^{ns}5.00	*30.00	*35.25	^{ns}38.25	7.71	^{ns}9.00	**96.38	*44.75	*66.57
	200	12.50	^{ns}21.33	^{ns}3.67	^{ns}39.33	^{ns}69.00	^{ns}48.25	12.86	^{ns}4.50	**98.75	^{ns}51.75	*62.14
SOM $_{WB}$ (%)	100	4.68	*2.30	*2.40	*1.94	*2.34	^{ns}2.94	6.06	^{ns}5.50	^{ns}5.51	^{ns}5.775	^{ns}5.80
	200	3.35	^{ns}2.08	^{ns}2.20	*1.95	^{ns}2.27	^{ns}2.53	5.36	^{ns}5.63	^{ns}4.96	^{ns}5.45	^{ns}5.64
SOM$_{LOI}$ (%)	100	9.88	*6.01	^{ns}6.54	*5.67	*6.30	^{ns}6.64	17.96	^{ns}17.58	^{ns}16.24	^{ns}19.03	^{ns}18.32
	200	8.33	^{ns}6.44	^{ns}5.89	^{ns}5.95	^{ns}6.76	^{ns}6.46	17.04	^{ns}16.98	^{ns}16.03	^{ns}18.44	^{ns}18.06
CEC (cmol/kg)	100	7.28	^{ns}6.37	^{ns}6.37	**4.07	*4.45	***2.87	11.26	^{ns}9.00	^{ns}11.13	*6.75	*7.29
	200	7.37	^{ns}6.13	^{ns}6.73	**4.40	**4.60	***2.80	10.91	^{ns}11.14	^{ns}6.50	^{ns}6.837	^{ns}7.11
SAS (%)	100	88.97	*68.17	***53.68	***43.61	***46.32	^{ns}46.69	96.86	^{ns}94.75	***69.75	***85.50	***79.86
	200	77.07	*60.24	**55.93	***48.46	*45.48	^{ns}45.96	97.00	^{ns}97.50	**80.25	**88.50	**88.43
BD (kg m^{-3})	100	1562	*1693	*1716	*1747	**1785	*1772	1184	^{ns}1192	**1301	**1354	**1326
	200	1620	*1754	***1744	**1730	*1736	^{ns}1744	1206	^{ns}1290	^{ns}1272	*1351	*1278
Clay (%)	100	19.00	^{ns}14.00	^{ns}15.00	^{ns}15.67	^{ns}23.25	^{ns}18.00	53.71	^{ns}58.25	^{ns}65.13	^{ns}60.25	^{ns}55.14
	200	20.50	^{ns} 17.67	^{ns}14.67	^{ns}17.33	^{ns}25.25	^{ns}19.50	55.43	^{ns}57.75	*65.13	^{ns} 62.00	^{ns}58.29

SOM $_{WB}$ = soil organic matter by Walkley-Black

SOM$_{LOI}$ = soil organic matter by loss-on-ignition

* P = 0.05

CEC = Cation exchange capacity

SAS = Soil aggregate stability

** P = 0.01

BD = Bulk density

ns = not significant

*** P = 0.001

to the South Coast, the Midlands soils exhibited a significant increase in plant available P, to about the same level as that on the South Coast. Potassium levels on the other hand were maintained in the Midlands but were significantly depleted on the South Coast in soils that had been cultivated for 40 years or more.

Loss of Ca and Mg was greater in the Midlands than on the South Coast (Figure 2) although the Midlands soils contained more clay and organic matter compared with the South Coast soils. Long-term mean rainfall in the Midlands was about 100mm less that that of the South Coast. It was also observed that the Midlands soils had an accumulation of K, while K decreased in the soils of the South Coast. Replacement and leaching of Ca and Mg due to the higher availability of K in the Midlands may account for this on soils that should be well buffered. The rate of soil acidification was found to be similar in both regions (Figure 1).

On the South Coast organic matter levels had declined from 4.7% to a mean value of 2.4% at a rate loss equivalent to 0.04% per year compared with a decline from 6.06% to 5.7% at a rate of 0.01% per annum in the Midlands (Table 1 and Figure 3). The higher organic matter content in the Midlands was attributed to the cooler climate of the mist-belt region and clay-protection (Coulombe *et al*., 1996) of organic matter in the soil. The sharp decline in organic matter in the sandy soils of the South Coast may have been induced by increased soil aeration, thus stimulating microbial activity which accelerates the rate of organic matter mineralisation (Haynes, 1997). A remedy for this decline in organic matter may be the retention of crop residues from green cane harvesting as shown by van Antwerpen and Meyer (1998).

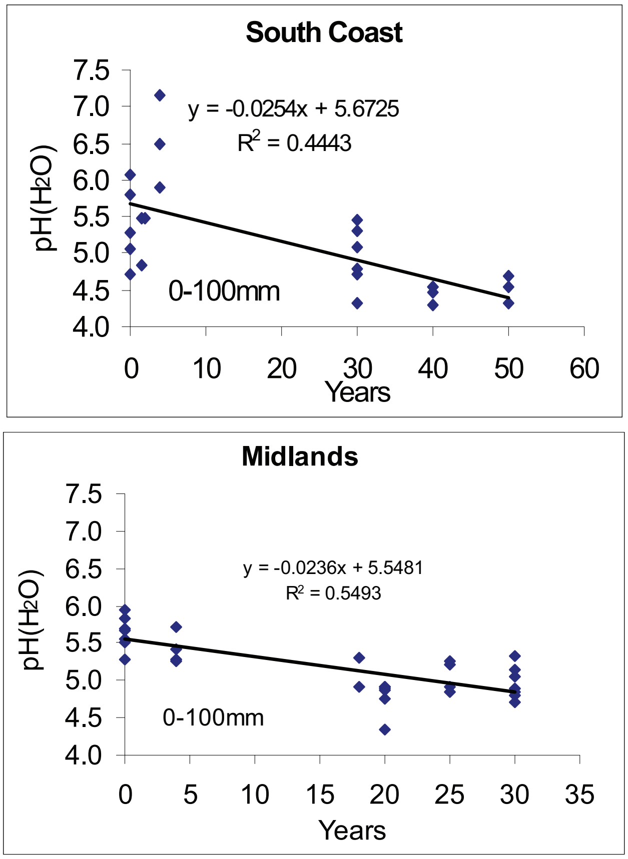

Figure 1. Change in pH with an increase of the period under cultivation for two regions.

Time had a consistent effect on soil physical properties in both regions (Table 2). In the Midlands, no significant change in bulk density had occurred within four years after virgin fields had been cultivated for the first time. However, on the South Coast a significant increase in bulk density was evident after only two years under cane cultivation (Table 1). This may be due to the rapid loss of organic matter (van Antwerpen and Meyer, 1998), structural breakdown (Schjønning *et al*., 1994) and compaction by infield haulage systems (Swinford and Boevey, 1984). Figure 4 shows that on the South Coast, the rate at which bulk density increased was 3.95 kg/m^3 per year and equilibrium was reached after about 30 years of continuous cane cultivation. In the Midlands, the rate of bulk density increase was 5.44 kg/m^3 per year (Figure 4). However, it is acknowledged that if samples had been collected in the row, as

Table 2. Statistical parameters describing the relationship between various soil parameters and the years under sugarcane production.

Soil properties	Depth (mm)	South Coast		Midlands	
		F-value	r^2	F-value	r^2
pH(H_2O)	100 200	*** 17.59 ***15.75	0.44 0.42	***34.13 ***20.94	0.55 0.43
P (mg kg^{-1})	100 200	0.77 2.25	0.03 0.09	**7.90 2.32	0.22 0.08
K (mg kg^{-1})	100 200	**13.91 **11.10	0.39 0.34	0.04 0.03	0.00 0.00
Ca (mg kg^{-1})	100 200	***17.18 **13.22	0.44 0.38	***15.99 **8.35	0.36 0.23
Mg (mg kg^{-1})	100 200	**9.28 ***17.11	0.30 0.44	***27.79 ***26.84	0.50 0.49
Na (mg kg^{-1})	100 200	0.00 0.62	0.00 0.03	***14.34 ***15.63	0.34 0.36
Al (mg kg^{-1})	100 200	***15.38 *6.66	0.41 0.23	**10.28 **8.76	0.27 0.24
SOM $_{WB}$ (%)	100 200	*7.572 *5.717	0.26 0.21	0.30 0.05	0.01 0.01
SOM$_{LOI}$ (%)	100 200	3.062 1.045	0.11 0.04	0.20 0.82	0.01 0.03
CEC (cmol/kg)	100 200	***44.85 ***33.87	0.68 0.61	*4.31 **12.87	0.13 0.32
SAS (%)	100 200	***46.61 ***27.91	0.68 0.56	***16.00 **8.78	0.36 0.24
BD (kg m^{-3})	100 200	***18.22 **10.25	0.45 0.32	***34.13 3.60	0.55 0.11

SOM $_{WB}$ = soil organic matter by Walkley-Black
CEC = Cation exchange capacity
SOM$_{LOI}$ = soil organic matter by loss-on-ignition
SAS = Soil aggregate stability
* P = 0.05   ** P = 0.01   *** P=0.001
BD = Bulk density

opposed to the interrow, the bulk densities obtained could have been much lower. But, it is possible that even here bulk density could have shown an increase due to a probable loss in organic matter and reduced soil structure.

For both the South Coast and Midlands areas, soil aggregate stability (SAS) of the cultivated areas was significantly less stable when compared with SAS for the virgin soils (Table 1). The rate of SAS decrease was 0.87% per year on the sandy loam soils of the South Coast compared with 0.64% per year for the clayey soils of the Midlands (Figure 5). On the South Coast, SAS started to exhibit significant deterioration only two years after cultivation was introduced. This can be attributed to the depletion of organic matter, which is important in binding soil aggregates. Despite the non-significant difference in soil organic matter between cultivated and virgin land in the Midlands, there was a significant linear relationship between organic matter and SAS (see Table 3).

Equations to estimate soil degradation from indicators such as cation exchange capacity (CEC), SAS, bulk density and organic matter were developed using the multi-linear regression analysis technique (Table 4). The multiple correlation coefficient (r) was more than 0.82 for all the equations developed to estimate these soil constituents. The equations still need to be validated for various soil types before they can be used with any confidence.

Table 5 summarises the calibrations developed and validated for easy determination of organic matter, CEC, clay and pH by NIRS, and shows the best correlations obtained between the standard method of determination and NIRS estimates. Calibration equations for these parameters were based upon the selection of the best combination of four wavelengths, which give the lowest standard error of estimate in a multiple regression analysis. Although some useful calibrations were obtained for the various constituents in terms of R-values the validation statistics were a little disappointing. It is clear that NIRS is sensitive to the geological composition of soils and this will need to be considered in future work.

Conclusions

Cultivated land is degraded relative to virgin land because soil chemical and physical properties are significantly changed under continuous sugarcane production. These changes reflect the sensitivity of soils to cultivation and show that soil quality cannot be sustained under the conventional practice of burning before harvest. Soil deterioration in terms of soil acidification, decline in organic matter, nutrient depletion, deterioration of soil aggregate stability and increasing bulk density was observed in both regions. The significant relationships obtained between soil organic matter (SOM) and various other soil constituents illustrate the importance of SOM in maintaining soil quality especially on sandier soils.

Sustainable systems of sugarcane production, which maintain or improve soil quality as well as sugarcane yields, are required in order to ensure a long-term future for the industry. Such systems should include:

- Green cane harvesting with trash blanket retention to replace the conventional system of burning before harvest, which is practiced in both regions.

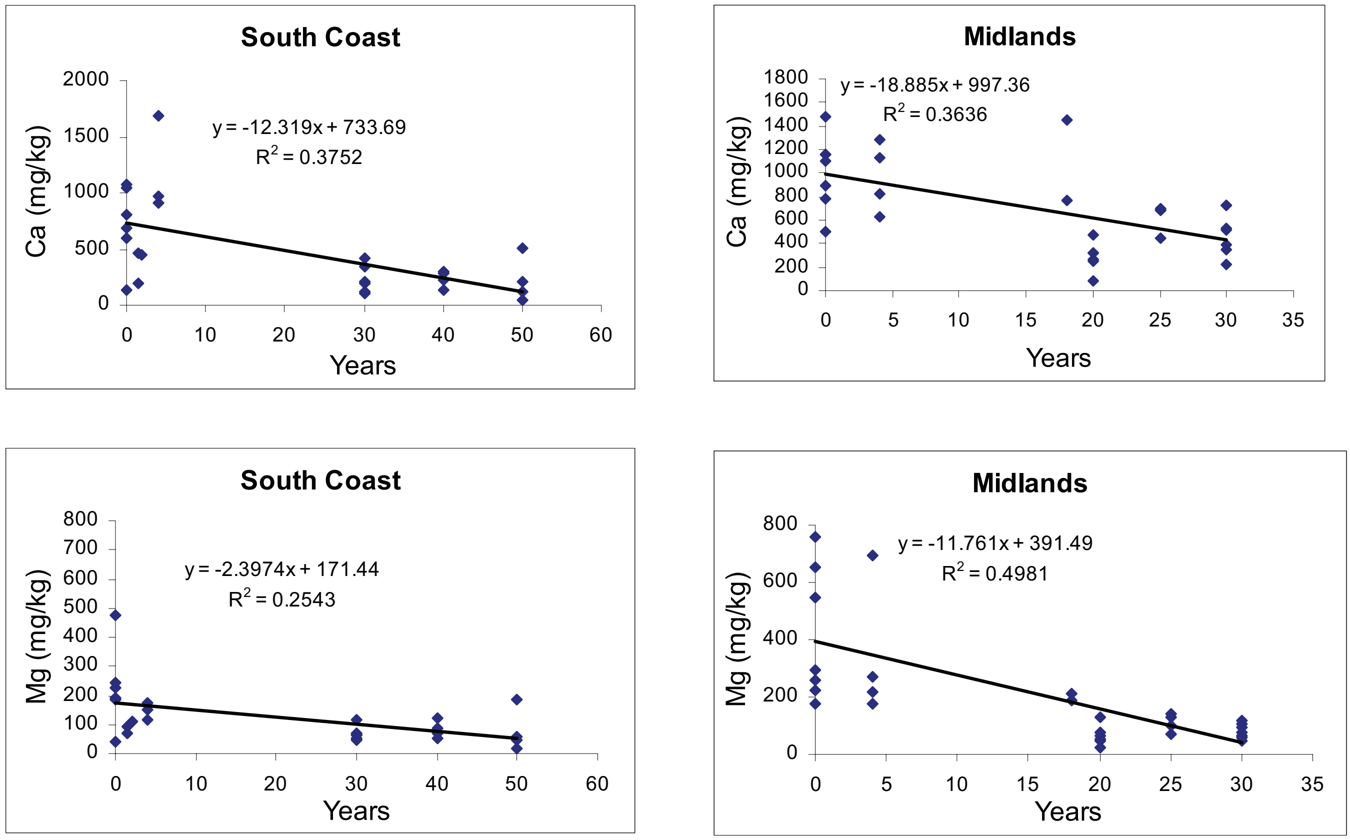

Figure 2. Ca and Mg changes with an increase of the period under cultivation for two regions.

- Also planting of green manure crops, which will return greater amounts of organic matter to the soil.
- Application of lime to increase the base status of soils and to counteract soil acidification.
- Controlled traffic with minimum tillage that can reduce physical damage to the soil.

The equations developed to estimate soil degradation indicators from other soil constituents were promising but warrant further evaluation in order to test whether they are applicable to most soil types. In order to improve the reliability of the NIRS technique, the development of separate calibrations for specific parent materials should be considered because it was apparent that NIRS is sensitive to the geological composition of soils. This necessitates the creation of a NIRS calibration for each region.

Acknowledgements

The authors wish to thank Mr V. Appanna, K. Rasen and S. Moodley for technical assistance, FAS staff for the chemical determinations, Dr A. Schumann for helping with the Genstat statistical package, Mr JH Meyer for guidance with the NIR apparatus and Prof. PNS Mnkeni for helpful suggestions during the preparation of this paper.

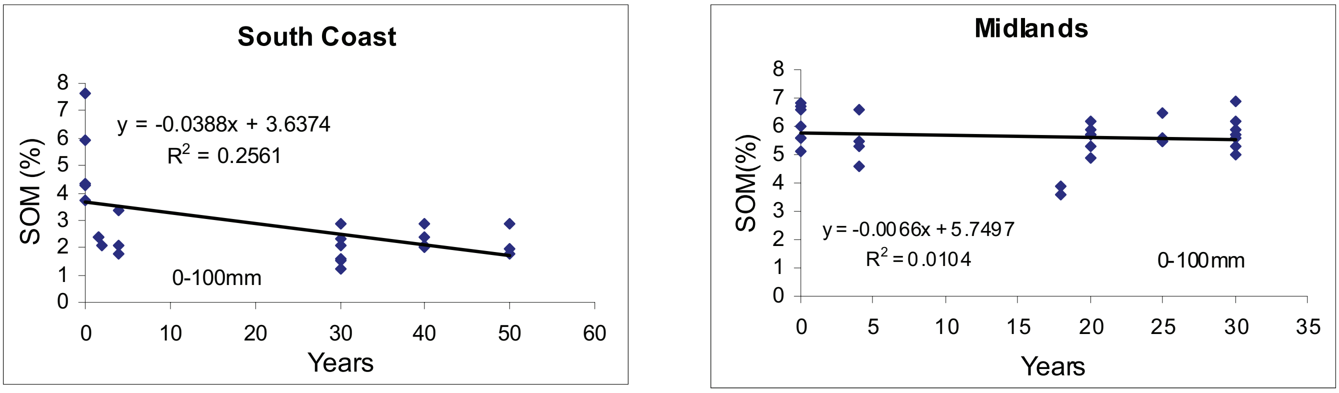

Figure 3. Soil organic matter (SOM) changes with an increase of the period under cultivation for two regions.

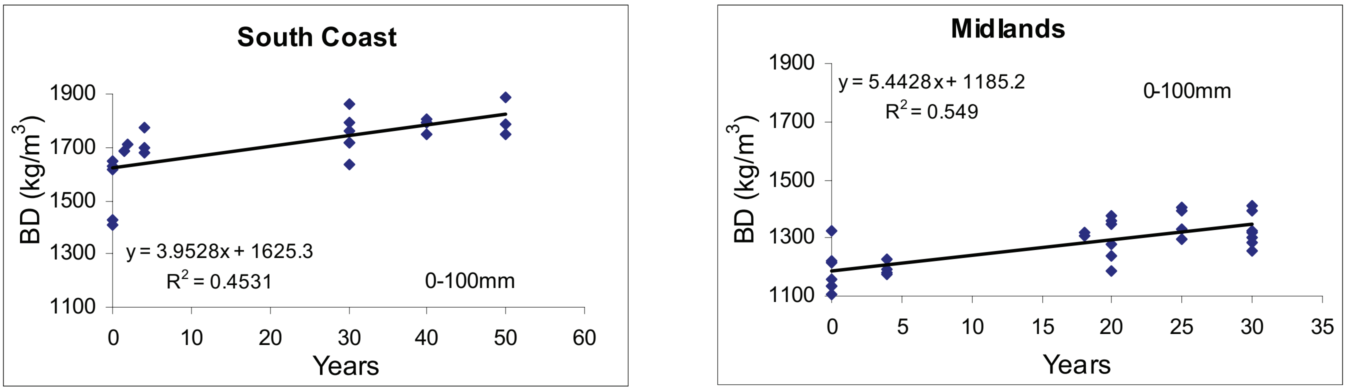

Figure 4. Soil bulk density (BD) changes with an increase of the period under cultivation for two regions

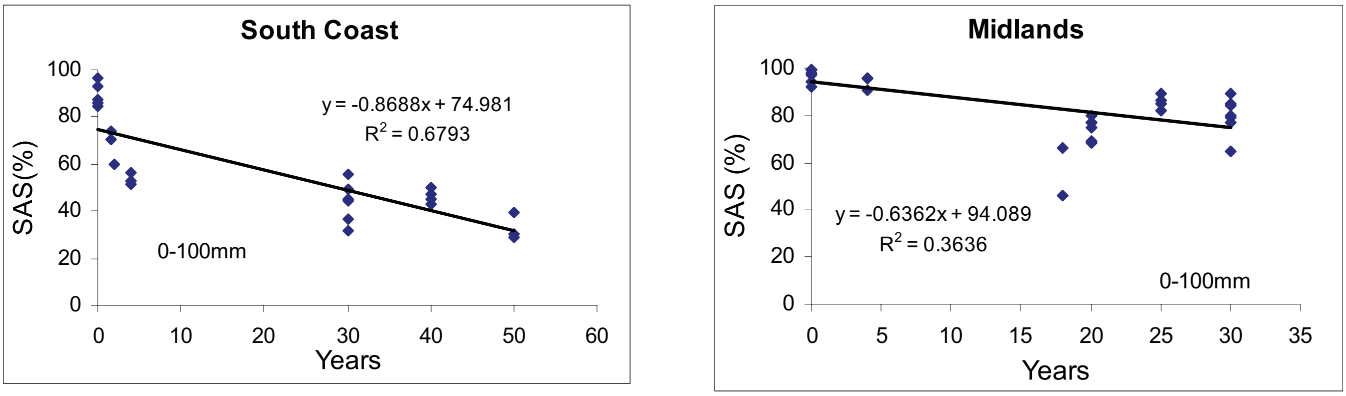

Figure 5. Soil aggregated stability (SAS) changes with an increase of the period under cultivation for two regions.

Table 4. Linear regression equations for the estimation of soil quality indicators from various soil constituents.

Soil parameter	Variables	Coefficient	R
pH	Constant	5.223	0.825
	Silt	-0.041	
	Ca	0.001	
	Na	-0.010	
Organic matter (OM)	Constant	7.393	0.998
	SAS	0.030	
	CEC	0.056	
	BD	-0.004	
Soil aggregate stability (SAS)	Constant	126.223	0.908
	Mg	0.027	
	OM	3.078	
	CEC	-0.282	
	BD	-0.048	
Cation exchange capacity (CEC)	Constant	7.226	0.997
	Clay	-0.457	
	Al	0.113	
	OM	14.463	
	SAS	-0.646	
Bulk density (BD)	Constant	1495.826	0.990
	Sand	5.810	
	K	-0.170	
	Ca	-0.077	
	Mg	-0.182	
	OM	-19.107	
	SAS	-1.559	

Table 3. Statistical parameters describing the relationship between soil organic matter and various other soil parameters.

Soil properties	Depth (mm)	South Coast		Midlands	
		F-value	r^2	F-value	r^2
P (mg kg^{-1})	100 200	1.23 0.45	0.05 0.02	*5.97 ** 8.06	0.18 0.22
K (mg kg^{-1})	100 200	**9.22 2.79	0.30 0.11	1.00 3.20	0.03 0.10
Ca (mg kg^{-1})	100 200	*6.11 1.34	0.22 0.06	0.17 0.62	0.01 0.02
Mg (mg kg^{-1})	100 200	***101.54 ***24.87	0.82 0.53	0.06 0.41	0.00 0.01
Na (mg kg^{-1})	100 200	**11.80 ***16.93	0.35 0.43	0.00 0.19	0.00 0.01
Al (mg kg^{-1})	100 200	3.86 0.39	0.15 0.02	0.38 0.83	0.01 0.03
CEC (cmol kg^{-1})	100 200	***33.73 ***16.43	0.61 0.43	2.76 0.50	0.09 0.02
SAS (%)	100 200	***44.59 ***45.46	0.67 0.67	**12.05 **7.74	0.30 0.22
BD (kg m^{-3})	100 200	***37.79 **11.50	0.63 0.34	*4.24 0.15	0.13 0.01

CEC = Cation exchange capacity SAS = Soil aggregate stability
BD = Bulk density * P = 0.05
** P = 0.01 ***P=0.001

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Table 5. NIRS calibration and validation statistical information for selected soil properties.

Soil parameter	South Coast									
	Wavelengths (nm)				Calibration			Validation		
					n	r	SEC	n	r	SEP
SOM$_{WB}$	1926	546	2046	2236	40	0.88	0.619	80	0.74	0.673
SOM$_{LOI}$	546	2266	2316	796	40	0.87	1.205	80	0.66	1.447
CEC	1336	2236	2176	486	40	0.85	1.054	80	0.68	1.340
Clay	506	2166	2206	1676	40	0.82	2.973	80	0.57	4.233
pH	1346	646	2176	1806	40	0.88	0.307	80	0.72	0.758
	Midlands									
Soil parameter	Wavelengths (nm)				Calibration			Validation		
					n	r	SEC	n	r	SEP
SOM$_{WB}$	1686	1816	2256	2166	50	0.88	0.384	86	0.76	0.623
SOM$_{LOI}$	946	1936	1636	2206	50	0.91	0.875	86	0.91	1.071
CEC	1786	646	426	456	50	0.82	1.360	86	0.72	2.439
Clay	2216	2316	1766	796	50	0.79	5.351	86	0.64	8.426
pH	1826	746			50	0.73	0.268	86	0.68	0.315

n = number of samples
r = regression correlation coefficient
SEC = standard error of calibration
SEP = standard error of prediction

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