CHANGES IN SOIL PROPERTIES AT RAMU SUGAR PLANTATION 1979 - 1996

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ABSTRACT

This paper presents an overview of changes in soil chemical and physical properties that have resulted from continuous sugar cane cultivation at Ramu Sugar plantation since 1979. The majority of the soils at the plantation have developed in alluvial deposits and classify as Fluvisols and Vertisols. Between 1979 and 1996, the soil pH at Ramu Sugar plantation had decreased from about 6.5 to 5.8 and this was accompanied by a decrease in CEC and exchangeable cations. Organic C levels had declined from about 56 g kg^{-1} in 1979 to 32 g kg^{-1} in 1996. The interrow of the sugar cane was compacted and had significantly higher bulk densities and a very slow water intake. Semi-quantitative nutrient budgets showed a shortfall in N, P and K, and levels of these nutrients in the sugar cane leaves had significantly decreased between the mid 1980s and 1990s. Yields at the plantation are largely determined by the insect pests, diseases and weeds. It is concluded that significant soil changes occurred at Ramu Sugar plantation and despite the fact that most soil chemical properties are still favourable for sugar cane cultivation, a change in soil management is required.

Keywords: *soil fertitility decline, soil compaction, soil acidification, soil management.*

INTRODUCTION

Plans for establishing a sugar cane plantation in Papua New Guinea date back to the 1930s when the 'The Singara Sugar Estates Ltd' proposed to establish a plantation near Buna in the Northern Province (Van der Veer 1937). The plantation was never established and in the decades that followed various reports suggested that commercial sugar cane production was technically feasible (e.g. Krishnamurthi 1976). It was emphasized that it would be a great risk because Papua New Guinea is the centre of origin of sugar cane and has therefore a broad range of pests and diseases (Szent-Ivany and Ardley 1962; Li 1985). When by the mid 1970s the demand for sugar increased and world market prices fluctuated strongly, the government decided to establish a national sugar industry. The decision was part of Papua New Guinea Eight Aims that included a more self-reliant economy and the ability to meet the needs of its people through local production. Initial investigations were carried out in the Markham valley for identifying a suitable site, which could produce about 30,000 to 40,000 t sugar annually. Several potential sites were identified but the Gusap-Dumpu area on the north bank of the Ramu river was favoured because it did not need irrigation or flood-protection works and land preparation costs were lower (Chartres 1981). In 1979, a detailed soil survey was undertaken and about 7,000 ha of suitable or moderately suitable land in the Gusap-Dumpu area was identified (Booker Agriculture International 1979). The first sugar cane was planted in 1979 and the plantation was named Ramu Sugar Ltd. The area under cane grew rapidly from 1,592 ha in 1981 to 5,011 ha in 1983 (Eastwood 1990).

There are few plantation crops in the tropics that put such heavy demand on soil resources as sugar cane. Most commercial sugar cane is grown intensively on a large scale and many of the husbandry practices are similar to intensive agricultural systems in temperate regions. Heavy machinery is used for land preparation, planting, spraying and harvesting. Biocides are widely used to control pests

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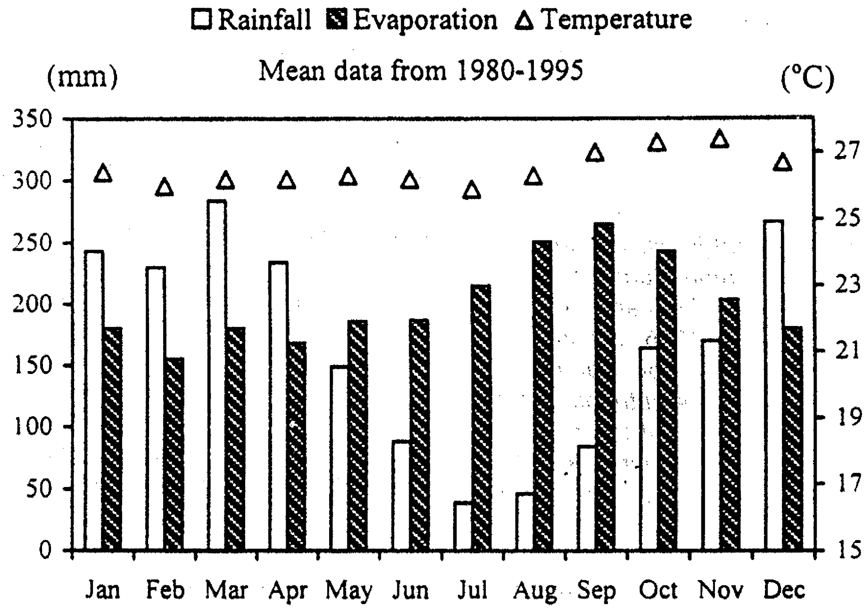
Figure 1. **Mean monthly rainfall, evaporation and temperature at Ramu Sugar Ltd.**



and diseases, herbicides to control weeds, and inorganic fertilizer applications to sustain yields. Sugar cane also makes heavy demands on soil nutrient reserves as large amounts of nutrients are removed with the harvest. Unless replaced either naturally through weathering and bio-geocycling, or artificially through inorganic fertilizers or with for example filter press cake, the soil nutrient pools will decline. In summary, commercial sugarcane cultivation is likely to affect soil conditions.

At Ramu Sugar Ltd, relatively little is known on changes in soil properties resulting from continuous sugar cane cultivation. In 1996 and 1997, we therefore collected all available soil analytical data at the plantation and compared these to changes in leaf nutrient concentration. In order to explain some of the observed trends, semi-quantitative nutrient balances were developed and these were compared to long-term trends in leaf nutrient concentration. This paper summarizes the major research findings including a description of the environmental conditions at Ramu Sugar Ltd.

THE ENVIRONMENT

Ramu Sugar Ltd (6°S, 146°E) is located in the Madang Province. Prior to the planting of sugar cane in 1979, the site was under natural grassland with some forest and swamp vegetation in poorly drained and low-lying areas. The grassland was dominated by *Imperata cylindrica* (kunai) which was found on the deeper and fine textured soils (Booker Agriculture International 1979). Its dominance was probably due to the annual burning as Imperata regenerates rapidly compared with other species (Henty and Pritchard 1988). On shallower and stony soils *Themeda australis* (kangaroo grass) dominated the natural vegetation whereas *Saccharum spontaneum* and *Ophiuros* sp. in the wetter sites along streams and rivers (Chartres 1981).

Climate

The plantation is in an area which is directly affected by the passage of the Inter-Tropical Convergence Zone which occurs twice yearly (Chartres 1981). Consequently, there is a seasonal rainfall pattern (uni-modal) with a dry season from May to November and a rainy season from December to April. The average rainfall at the plantation is 1998 mm y^{-1} but between 1980 and 1995 annual rainfall has varied from 1531 to 2560 mm. June to September are the driest months with an average of less than 90 mm per month (Figure 1). March is the wettest month with an average rainfall of 284 mm. Evaporation (Class A open pan) is about 2281 mm y^{-1} and exceeds rainfall from May to November. Mean annual temperatures are 26.7°C with only minor fluctuations through the year. The climate classifies as Am (Köppen) i.e. a tropical rainy climate with a short dry season.

There is very little relation between total annual rainfall and sugar cane yields. An index often used in the evaluation of water and sugar cane is the production of sugar per mm of rain (Fauconnier 1993). These values were calculated from the yield and climatic data. It was found that in the past fifteen years between 21.2 and 40.9 mm of rain was required to produce 1 t cane ha^{-1} which is equivalent to 2 to 4.2 kg sugar ha^{-1} per mm of rain.

Land management under sugar cane

The first three ha of sugar cane were planted in 1979 but the total area under sugar cane grew rapidly from 1592 ha in 1981, to 5011 ha in 1983 and to 6030 ha in 1995. The plantation was established for rainfed sugar cane production. Feasibility studies for irrigation have been conducted in the past but it was soon realised that other constraints were more important. About 1,800 ha of sugar cane are planted mechanically each year. Up to 1994, planting took place at the beginning of the wet season (September to November) but currently most of the cane is planted from late February to May as it was found to reduce the risk of certain insects pests. The harvesting season lasts from May to October and cutter-chopper-loader harvesters are used with 20 tonnes tractors and trailers transporting the cane to the factory. Most of this equipment has conventional tyres. About half of the sugar cane is trash-harvested (no pre-harvesting burning). Up to five crops (i.e. plant cane + four ratoons) are sometimes obtained after which the land is replanted or sometimes cowpea (*Vigna unguiculata*) is sown which is ploughed under after one year. Prior to 1989, nitrogen fertilizer was applied as urea (46% N) but when trash-harvesting replaced pre-harvesting burning, it was suggested that considerable amounts of urea-N would be lost through volatilization. Therefore nitrogen fertilizer supplied after 1989 was in the form of sulphate of ammonia (21%N) and on average 90 kg N ha^{-1} y^{-1} as applied during the period 1991 to 1995. Nitrogen applications are mostly broadcasted between August and November. Phosphorus and potassium fertilizers are not applied.

Geomorphology

The Ramu valley is drained by the perennial Ramu river and several tributaries with erratic flow characteristics. The valley covers an area of about 7500 km^2 (Bain and Mackenzie 1975) and forms together with the Markham valley a large *graben* which has been a zone of subsidence since the Late Tertiary period (Löffler 1977). At the site of the plantation, the valley is about 10 km wide. The Ramu valley contains about 2000 m of unconsolidated and poorly consolidated Quaternary marine and terrestrial clastic sediments overlying Tertiary sedimentary rocks (Bain and Mackenzie 1975). The valley comprises a series of alluvial fans and some of these fans are incised by their streams forming deep gullies (> 20 m). Slopes are up to 5% on the higher parts of the fans but decrease downslope to less than 0.5%. Altitude at the site of the plantation is about 400 m a.s.l. Since the plantation is situated in a tectonically active area, geomorphologic processes are currently visible. In November 1993, a landslide dammed an important drainage way in the lower part of a catchment area of the Finisterre Mountains. A lake formed behind the dam that collapsed after several days of heavy rain. The massive mudflow that followed filled the deeply incised Gusap and Bora streams and washed out the Lae-Madang road and several hectares of sugar cane. Drainage of soils adjacent to the Gusap stream was then retarded and some sugar cane land had to be abandoned because of poor workability. Although such mudflows quite catastrophically affect the sustainability of sugar cane growing they do not affect large areas and are not further considered in this study.

Soils

The parent material of the soils at the plantation is alluvium. The soils have been developed in clayey, silty and sandy sediments and from the weathering products of the water-worn stones and boulders of varying lithology. The stones and boulders originate from sandstone, siltstone and limestone, but also from basalt and igneous rocks with coarser textures. The coarse material is generally poorly sorted and there is a gradual decrease in grain size from the Finisterre Mountains towards the Ramu River. Although deep and nearly gravel free soils

Table 1. **Soil chemical and physical properties of a Fluvisol and Vertisol at Ramu Sugar plantation.**

Soil type	Sampling depth (m)	pH H_2O 1:2.5	pH KCl 1:2.5	Organic C (g kg^{-1})	Total N (g kg^{-1})	P-Olsen (mg kg^{-1})	CEC pH7 (mmol$_c$ kg^{-1})	Exchangeable cations (mmol$_c$kg^{-1})			Base saturation (%)	Particle size fractions (g kg^{-1})		
								Ca	Mg	K		clay	silt	sand
Fluvisol	0-0.15	6.2	5.0	16.5	1.4	35	311	185	95	7.6	93	300	300	400
	0.15-0.30	6.1	4.9	14.0	1.2	21	302	208	103	4.7	100	280	360	360
	0.30-0.45	6.2	5.1	14.3	1.2	14	435	332	148	3.0	100	480	390	130
	0.45-0.60	6.1	5.0	18.1	1.4	11	530	430	169	2.4	100	750	230	20
Vertisol	0-0.15	5.9	4.7	29.8	1.8	32	540	272	115	9.4	74	550	160	290
	0.15-0.30	6.1	4.6	31.3	1.8	33	517	274	118	12.4	78	530	90	380
	0.30-0.45	6.3	4.8	19.8	1.2	15	546	287	123	3.3	76	590	180	230
	0.45-0.60	6.2	4.8	12.5	1.0	9	531	236	99	2.2	64	530	200	270

Table 2. **Topsoil (0-0.15 m) chemical properties between 1979 and 1996 at Ramu sugar plantation (arithmetic mean ±1 SD).**

Year	Number of Samples[a]	pH H_2O 1:2.5	Organic C (g kg^{-1})	Total N (g kg^{-1})	Available P (mg kg^{-1})	CEC pH 7 (mmol$_c$ kg^{-1})	Echangeable cations (mmol$_c$kg^{-1})			Base saturation (%)
							Ca	Mg	K	
1979[b]	21	6.5 ± 0.3	56.5 ± 13.8	2.8 ± 0.5	n.a.	398 ± 41	246 ± 80	101 ± 42	13.5 ± 4.4	83 ± 18
1982	78	6.2 ± 0.1	n.a.	n.a.	38 ± 5	456 ± 46	268 ± 31	116 ± 19	13.9 ± 2.5	87 ± 2
1983	226	6.3 ± 0.2	n.a.	2.2 ± 0.3	37 ± 11	448 ± 77	267 ± 61	105 ± 23	12.3 ± 2.8	86 ± 6
1984	50	6.2 ± 0.2	n.a.	n.a.	36 ± 14	427 ± 65	260 ± 52	100 ± 23	11.1 ± 3.1	87 ± 3
1985	19	6.1 ± 0.2	n.a.	n.a.	37 ± 15	482 ± 48	293 ± 67	113 ± 31	11.1 ± 3.7	87 ± 3
1986	29	6.1 ± 0.2	n.a.	n.a.	35 ± 19	435 ± 93	262 ± 67	103 ± 32	11.7 ± 7.3	86 ± 4
1991	25	6.2 ± 0.2	n.a.	n.a.	24 ± 14	386 ± 95	326 ± 47	99 ± 52	10.5 ± 3.2	88 ± 10
1994	60	5.9 ± 0.1	33.4 ± 5.2	1.9 ± 0.3	28 ± 10	403 ± 76	248 ± 50	109 ± 28	11.7 ± 3.1	92 ± 11
1996	30	5.8 ± 0.3	32.1 ± 5.5	1.9 ± 0.4	26 ± 11	411 ± 78	263 ± 62	106 ± 27	9.3 ± 3.5	91 ± 7

n.a. not available.
[a] Composite topsoil samples of continuouly cultivated fields, except for 1979.
[b] Soil samples taken prior to the establishment of the plantation.

(>1.2 m depth) occur, extensive areas have gravelly (5 to 15%) topsoils and very gravelly (15 to 40%) or stony subsoils. The pH H_2O values of the soils are around 6.0 indicating no apparent danger from exchangeable aluminium or excess $CaCO_3$ Soil salinity is not a problem in the topsoils but the deeper subsoils are slightly alkaline. Sheet and gully erosion is a threat in some areas but terraces have been dug across the contour to control surface water.

Fluvisols are the dominant Major Soil Grouping at the plantation. At the soil unit level in FAO-Unesco, the Fluvisols are Eutric or Mollic, equivalent to the great group of Tropofluvents (Entisols) in USDA Soil Taxonomy. Some Entisols classify as Tropopsamments (Bleeker 1983). The soil temperature regime is isohyperthermic and the soil moisture regime udic indicating that in most years the soils are dry for less than 90 cumulative days per year. Shrinking and swelling dark clay soils (Vertisols) cover about one quarter of the sugar cane plantation. These soils are dominated by montmorillonite or some other smectite mineral. During the fieldwork (January, August and October 1996, April 1997) cracks were observed in these soils but not to 0.5 m depth as is required for the soils to be classified as Vertisols (FAO-Unesco 1988). The absence of deep cracks may have been caused by frequent tillage and high contents of stable aggregates which commonly occur in Vertisols when the organic matter content is 30 g kg^{-1} or more (Ahmad 1984). The soils are, however, likely to be Vertisols because of the presence of wedge-shaped structural elements, slickensides in the subsoil, the fine texture (> 500 g clay kg^{-1} soil), and the hard consistency and cracks when dry. The soils contain no calcareous concretions which are commonly absent in Vertisols under high rainfall (Blokhuis 1980). At the soil unit level in FAO-Unesco, these soils are Eutric Vertisols, equivalent to the great group of Hapluderts in USDA Soil Taxonomy (Soil Survey Staff 1994). Soil chemical and physical data of a representative Eutric Fluvisol and Eutric Vertisol are given in Table 1.

In some low-lying areas, soils with poor internal drainage occur and these are classified as Gleysols in FAO-Unesco (1988). According to Booker Agriculture International (1987) they cover only a small area of the plantation (ca. 3% or 180 ha) and data from these soils were not included in this study. Some sugar cane is planted at the footslopes of the Finisterre Mountains in soils derived from a mixture of alluvial and colluvial deposits. Very locally, these soils have been enriched with tephra probably originating from Long Island in the Bismarck Sea (Parfitt and Thomas 1975). Such soils may contain up to 10% allophane and have high phosphorus retention capacities (Loveland 1991). Since these soils are confined to a small area and have not received much research attention, they were excluded from this study.

MATERIALS AND METHODS

To investigate changes in soil chemical properties and leaf nutrient concentrations, we collected all available analytical data from 1978 to 1995. In addition we collected sugar cane production data from the whole plantation and divided this by the area under cane to obtain yield figures. Also the total annual fertilizer consumption of Ramu Sugar Ltd was divided by the area under cane to obtain fertilizer applications per hectare. For the changes in soil physical properties, no historical data could be used and we made bulk density and water intake measurements under sugarcane and adjoining grasslands.

Soil chemical data

With the establishment of the plantation in 1979, the area was divided into blocks of 10 to 20 ha. Between 1982 and 1994 soil samples were taken in most sugar cane blocks for routine analysis and the analytical data of 487 topsoil (0-0.15 m) and some 50 subsoil samples was available. Also the chemical data of 21 soil profiles (15 Fluvisols, 6 Vertisols) from the initial soil survey report was available (Booker Agriculture International 1979). The topsoil samples between 1982 to 1994 were commonly taken after the last ratoon when the sugar cane was ploughed-out. Samples were bulked from 20 to 50 locations in a sugar cane block using an Edelman auger. The samples taken in 1996 were composites from 10 to 15 locations in a sugar cane block and mini-pits were used for the 0-0.15 soil horizons. All soil samples of 1996 were taken in the interrow of the sugar cane.

Airdried, ground and sieved samples (2 mm) were analyzed at the Cambridge Laboratory in Cambridge (New Zealand) or at the National Analytical Chemistry Laboratory in Port Moresby (Papua New Guinea). The procedures for soil analysis were identical at both laboratories, and as follows: pH H_2O in 1:2.5 or 1:5 suspension of soil and water; pH KCl in a 1:2.5 soil and 1*M* KCl solution; organic carbon by $K_2Cr_2O_7$ and H_2SO_4 oxidation (Walkley & Black); total N by Kjeldahl; available P by $NaHCO_3$ extraction (Olsen); exchangeable cations Ca, Mg, K, Na and CEC percolation by 1*M* NH_4OAc followed by spectrophotometry (K, Na), AAS (Ca, Mg) and titration (CEC); particle size analysis by hydrometer. The soil samples of the initial soil survey (Booker Agriculture International 1979) were analyzed at the laboratories of Hunting Technical Services Ltd in England. Except for available P, all other methods were identical to the ones described above.

Soil physical data

Infiltration measurements were made using the double ring (cylinder) method with measurements confined to the inner-ring. Four sugar cane blocks (2 Eutric Fluvisols, 2 Eutric Vertisols) were selected bordering a natural grassland area with the same soil profile as under sugar. The sugar cane at the infiltration sites was in the second or third ratoon. In each sugar cane block, infiltration measurements were made in triplicate at about 10 m from each other. Measurements were made between the sugar cane rows (interrow), and within the rows (between two stools). At about 75 m from the sugar cane block, infiltration measurements were made in natural grassland and also these measurements were triplicated. Although the infiltration measurements were made in periods with ample rain, particularly during the night (November 1996 and April 1997), most infiltration sites were prewetted 24h prior to the measurements using borehole water. Infiltration readings were made every min for the first 10 min, every 2 min between 10 and 20 min, and every 15 min between 20 and 320 min. Mean infiltration rates (mm h^{-1}) were calculated for the first 10 min (10 readings) and between 20-80 min (5 readings), 140-200 min (5 readings) and 245-305 min (5 readings) after the rings were filled with water. In total 36 infiltration measurements were made of at least 5h each but in most measurements the steady state was reached within 4h.

At the same sites where the infiltration measurements were made, soil pits were dug (± 1 m depth) for bulk density measurements. At each site, one soil pit was dug in the sugar cane block and one in the adjoining natural grassland area. In total 8 soil pits were sampled using cores (100 mL) which were gently pushed into the soil at four depths: 0-0.15, 0.15-0.30, 0.30-0.50, 0.50-0.70 m. Because of abundant gravel in the 0.50-0.70 soil horizon of the Fluvisols, the bulk density could not be accurately determined with 100 mL cores as their volume is much too small. In the soil pits under sugar cane, both the interrow and the soil horizons between the rows were sampled. Three cores were used for each depth and they were ovendried at 105°C for 72h. In total 126 core samples were taken at the infiltration sites and an additional 18 cores were taken in 2 other soil pits at the plantation.

Leaf nutrient data

About 600 foliar samples for the analysis of macronutrients (N, P, K, Ca, Mg, S) were taken between 1982 to 1996. Leaf samples at Ramu Sugar Ltd were commonly taken after the onset of the rainy season (December-February) when growth rates are high. For the leaf sampling, 21 rows were selected randomly within a block. At 30 to 40 paces the fourth leaf was sampled from a nearby stool; the first leaf was the unfurl leaf. About 400 to 600 leaves of which the midrib was removed, were composited of which a subsample was taken. Leaf samples were dried at 80°C for 48 hours. All leaf samples were analyzed at the Cambridge laboratory in New Zealand following standard analytical procedures.

RESULTS

Soil chemical properties

Between 1979 and 1996, the topsoil pH_w (pH H_2O) decreased from about 6.5 to 5.8 (Table 2). The initial decrease in pH_w from grassland (1979) to sugar cane (1982) may have been caused by the increased mineralisation of organic matter which is a common cause for soil acidification (Rowell and Wild 1985). The rapid pH_w decline observed in the 1990s coincides with the change in fertilizer policy from urea to sulphate of ammonia which has twice the potential acidity. It may also be due to the large addition of organic matter with the trash-harvesting as in some studies such additions were found to decrease the soil pH (Pocknee and Sumner 1997). The soil acidification was accompanied by a change in the levels of exchangeable bases. Particularly

Table 3. **Changes in soil chemical properties (0-0.15 m) of Fluvisols and Vertisols under sugarcane between the 1980s 1990s.**

	Fluvisols (n=7 pairs)			Vertisols (n=5 pairs)		
	1982 -1983	1991 -1994	difference	1982 -1983	1991 -1994	difference
pH H_2O (1:2.5 w/v)	6.3	5.9	P<0.001	6.4	6.0	P<0.001
available P (mg kg^{-1})	37.2	29.0	P=0.04	35.4	24.6	n.s.
CEC ($mmol_c$ kg^{-1})	412	354	P<0.001	450	403	n.s.
exchangeable Ca ($mmol_c$ kg^{-1})	229	213	n.s.	269	250	n.s.
exchangeable Mg ($mmol_c$ kg^{-1})	100	94	n.s.	109	95	n.s.
exchangeable K ($mmol_c$ kg^{-1})	11.0	9.5	n.s.	13.0	10.1	n.s.
base saturation (%)	83	88	P=0.02	87	88	n.s.

n.s. not significant

Table 4. **Bulk density[a] (kg dm^{-3}) of Fluvisols and Vertisols under sugar cane and natural grassland.**

Major soil Groupings	Sampling depth (m)	Land-use: Sugar cane within the rows	Land-use: Sugar cane interrows	Land-use: Natural grassland	SED[c]
Fluvisols[b]	0-0.15	1.10	1.29	1.07	0.04
	0.15-0.30	1.18	1.34	1.17	0.06
	0.30-0.50	1.35	1.39	1.26	0.05
Vertisols	0-0.15	0.98	1.18	1.00	0.03
	0.15-0.30	1.08	1.19	1.02	0.05
	0.30-0.50	1.14	1.21	1.12	0.06
	0.50-0.70	1.13	1.22	1.17	0.06

[a] values reported are the arithmetic mean of 6 core samples of 100 mL taken in 2 soil pits.
[b] the 0.50-0.70 m soil horizons could not be sample accurately with 100 mL cores because of abundant gravel.
[c] standard error of the difference in means (10 *df*).

the levels of exchangeable K declined possibly due to a combination of the large K removal by the sugar cane (Yates 1978) and leaching losses. Organic C levels declined by about 40% between 1979 and 1996. For high yielding sugar cane, however, maintenance of favourable organic matter levels is important (Yadav and Prasad 1992). Levels of available P declined but variation was large. Topsoil data of the same sugar cane block but from different times revealed a significant decline in pH_w, available P, CEC and base saturation in Fluvisols (Table 3). In the Vertisols, a highly significant decline of 0.4 pH_w units was found whereas changes in other soil chemical properties were not significant.

Soil physical properties

Bulk densities under natural grassland and within the sugar cane rows were similar for all depths of both Fluvisols and Vertisols (Table 4). The bulk densities in the interrow were, however, significantly higher in the two Major Soil Groupings and in all soil pits it was observed that roots were absent in the interrow which commonly is found in compacted soils under sugar cane (Trouse and Humbert 1961). The compaction in the interrow of the sugar cane was caused by wheel traffic during harvesting and other field operations. In the Vertisols, there was no difference below 0.3 m depth whereas in the

Fluvisols the bulk density of the interrow was also higher in the 0.30-0.50 m soil horizon. The absolute increase in the topsoil bulk density of the interrow as compared to natural grassland was 0.22 kg dm^{-3} (+21%) in the Fluvisols and 0.18 kg dm^{-3} (+18%) in the Vertisols. Overall, Fluvisols had significantly higher bulk densities than the finer textured Vertisols.

Cumulative water intake of natural grassland and within the sugar cane rows was very high in both Major Soil Groupings (Figure 2). The high water intake of the Vertisols is puzzling as it is commonly found that such soils have a low water intake when wet (Ahmad 1983). There may have been some lateral flow which is common in double-ring infiltrometers (Lal 1979) and this may be enhanced in crops grown on ridges like sugar cane. Variation in cumulative water intake was larger in the Fluvisols than in Vertisols possibly due to the non-uniformity of the Fluvisol profile with layers having different hydraulic conductivities (Bouwer 1986). Within the sugar cane rows, cumulative infiltration rates after 5h were 1322 mm in the Fluvisols compared to 1200 mm in the Vertisols. Water intake in the interrow was very low and had not exceeded 105 mm in Fluvisols and 59 mm in Vertisols after 5h. Amongst others, the slow water intake in the interrows may result in soil erosion which can be particularly high on Vertisols (Unger and Stewart 1988) and under sugar cane (Prove *et al.* 1995) but there were no data available to verify this.

Table 4 and Figure 2 provide evidence for significantly higher bulk densities and lower infiltration rates in the interrow of sugar cane. To investigate the relation between the two, mean infiltration rates were plotted against topsoil bulk densities for Fluvisols and Vertisols (Figure not shown). A negative exponential relation was observed i.e. a rapid decrease in water intake with increasing bulk densities. For both Fluvisols and Vertisols, a high correlation (r^2>0.8) was found between bulk density and mean infiltration rates. Bulk densities at which mean infiltration was above 100 mm h^{-1} after 4h, were 1.15 kg dm^{-3} for Fluvisols and 1.04 kg dm^{-3} for Vertisols. Bulk densities at which infiltration rates were 50 mm h^{-1} during the first 10 min, were 1.20 kg dm^{-3} for Fluvisols and 1.16 kg dm^{-3} for the Vertisols.

***Figure 2.* Cumulative infiltration of Fluvisols and Vertisols at Ramu sugar Ltd. Vertical bars represent the largest standard deviation for measurements at an infiltration interval.**

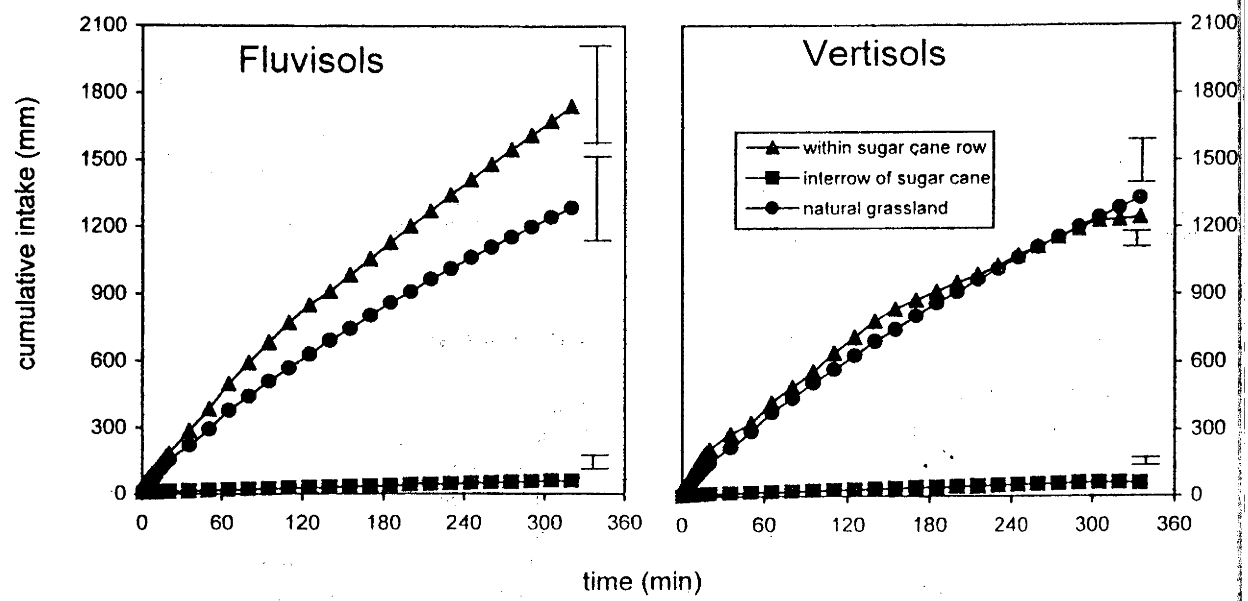


Table 5. **Nutrient removal (range) and nutrient input with fertilizers between 1991 and 1995.**

	Nutrient removal (kg ha^{-1})						Fertilizer applications (kg ha^{-1})			Difference (kg ha^{-1})					
	N		P		K		N	P	K	N		P		K	
	low	high	low	high	low	high				low	high	low	high	low	high
1991	27	57	8	17	48	119	34	12	0	7	-23	4	-5	-48	-119
1992	33	71	9	21	59	148	115	4	0	82	44	-6	-17	-59	-148
1993	28	60	8	17	50	124	105	1	0	77	46	-7	-16	-50	-124
1994	35	75	10	22	62	156	81	0	0	47	7	-10	-22	-62	-156
1995	35	75	10	22	63	156	83	3	0	48	8	-7	-19	63	-156

[a] highest and lowest removal values as given by Hunsigi (1993) multiplied by the sugarcane yield from the plantation

Table 6. **Mean difference (kg ha^{-1}) between nutrient removal and nutrient input.**

	N	P	K
1991	-8	-1	-84
1992	+63	-12	-104
1993	+62	-12	-87
1994	+27	-16	-109
1995	+28	-13	-110

Nutrient budgets

Changes in soil chemical properties indicated a decline in plant nutrient availability. In this section, we shall look at a possible explanation based on a comparison between nutrient inputs and nutrient outputs. Yield data (t ha^{-1}) from 1991 to 1995 were multiplied with a range of nutrient removal data (kg nutrient per t ha^{-1}). These were compared with the nutrients applied in the fertilizers and the difference was calculated for the low and high range (Table 5). It appeared that the difference between N removal and N applied was positive whereas for P and K a negative difference between removal and fertilizer application was found. Table 6 presents the mean differences for the three major nutrients. However, this assumes a 100% efficiency of the fertilizers, which never occurs, and in reality, the balance is therefore much more negative.

Leaf nutrients

Median nitrogen contents in the cane leaves at Ramu Sugar Ltd varied from 19.3 to 22.0 g kg^{-1} between 1983 to 1994 (Table 7). The lowest figure was the median of the 27 leaf samples taken in 1994. There appears to be a declining trend in the phosphorus contents of cane leaves but the median value of 2.4 g kg^{-1} in 1994 is still above the optimum concentration of 1.8 g kg^{-1} as given by Anderson and Bowen (1990) and 2.1 g kg^{-1} as given by De Geus (1973). The apparent trend in leaf phosphorus decline coincides with the decrease observed in the levels of available P in the topsoils (Table 3). Leaf potassium contents were favourable from 1983 to 1989 but the median value in 1994 is at the lower border of the optimum range of 12.5 g kg^{-1} (Anderson and Bowen 1990; De Geus 1973). Levels of sulphur, calcium and magnesium show no apparent trend and all medians values are in the optimum range.

Table 7. **Macronutrient concentrations (g kg⁻¹) of sugar cane leaves at Ramu Sugar plantation (mediam values with CV %).**

Year	no. of samples	N	P	K	S	Ca	Mg
1983	481[a]	22.0 (11%)	3.5 (16%)	15.0 (14%)	1.3 (12%)	2.9 (16%)	1.8 (12%)
1987	69	20.0 (13%)	2.7 (9%)	16.0 (15%)	1.8 (14%)	4.4 (16%)	2.5 (14%)
1989	24	21.0 (12%)	2.9 (17%)	16.1 (15%)	1.8 (30%)	3.5 (21%)	1.7 (17%)
1994	27	19.3 (10%)	2.4 (7%)	12.5 (11%)	n.a.	3.1 (20%)	1.3 (17%)

[a] there were only 11 samples of sulphur, calcium and magnesium in 1983.
n.a. not available

Table 8. **Macronutrient concentrations (g kg⁻¹) of sugar cane leaves in the 1980s and 1990s.**

Period	no. of Samples	N	P	K	Ca	Mg
1985-1987	93	20.3	2.8	14.7	4.4	2.4
1994-1996	160	19.4	2.6	13.8	2.8	1.6
Difference		$p<0.001$	$p<0.01$	$p<0.001$	$p<0.001$	$p<0.001$

Table 9. **Critical nutrient concentration (g kg⁻¹) and % samples below this level in the 1980s and 1990s.**

	N	P	K	Ca	Mg
Critical nutrient concentration[a]	19.0	2.0	13.0	1.5	1.0
% sample <critical level in mid 1980s	17	1	23	0	0
% sample <critical level in mid 1990s	40	17	47	1	3

[a] based on data for +4 leaf in: De Geus (1973), Orlando Filho (1985), Anderson and Bowen (1990), Srivastava (1992), and Malavolta (1994).

All major nutrients in the sugar cane leaves had decreased significantly between the mid 1980s and 1990s (Table 8). The largest decrease was found in the Ca and Mg concentrations, which had decreased with 36 and 33%, respectively. Small but highly significant differences were found between the P concentrations of the mid 1980s and 1990s. Several keys to the interpretation of leaf nutrients concentration for sugar cane exist, but much depends on the age of the plant at sampling, the sugar cane variety, the plant part sampled, soil conditions and fertilizer applications. The first row in Table 9 summarizes the critical nutrient concentration for the fourth leaf as compiled from several sources. The mean nutrient concentrations in both the mid 1980s and 1990s (Table 8) were exceeding the critical level. However, the percentage samples below the critical level increased dramatically between the mid 1980s and 1990s (Table 9). The increase was particularly high for N and K, and the data showed that in the mid 1990s about 40% of the samples was below the critical N concentration whereas 47% of the samples was below the critical K concentration. Although Ca and Mg

***Table 10.* Estimated average yield loss (t ha^{-1} y^{-1}) by insect pests, diseases and weeds (Hartemink and Kuniata 1996).**

year	insects pests and diseases				weeds	total estimated loss	actual yield
	moth stem borer	cicadas	white grubs	Ramu stunt			
1984	-	-	7	-	-	-	65
1985	-	-	7	15	-	-	50
1986	18	-	4	27	-	-	27
1987	31	-	0	1	5	-	64
1988	12	-	0	0	1	-	86
1989	8	4	0	0	20	32	53
1990	11	22	0	0	22	55	49
1991	4	16	0	0	18	38	48
1992	3	3	0	0	24	30	59
1993	0	1	0	0	26	27	50
1994	2	0	1	0	17	20	61
1995	10	1	<1	0	5	17	62

- means unknown or not quantified

concentrations had decreased dramatically (Table 8), there were only very few values in the mid 1990s below the critical levels.

Sugar cane yields

Mean sugar cane yields at Ramu Sugar Ltd have varied in the past fifteen years from 28 to 88 t ha^{-1} y^{-1} and sugar yield varied from 2.0 to 8.2 t ha^{-1} y^{-1}. Regression analysis of cane and sugar yield showed a strong linear relationship and the sugar content of the cane is about 9% (sugar yield = 0.09 * cane yield - 0.29; r^2 =0.942). Much of the variation in sugar cane yields can be explained by pests and diseases, some of which can have a high impact on yield if poorly controlled (Table 10).

Ramu stunt was first observed in 1985 and in 1986, the disease was widespread in the sugar cane variety Ragnar that occupied most of the plantation. The rapid decrease between 1982 and 1986 can therefore be explained by the incidence of Ramu stunt disease. The disease was so severe that it could have caused the closure of the plantation (Eastwood 1990). Also the white grub was present in 1984 and 1985 but its effects were not very obvious although potential losses of up to 36 t cane ha^{-1} y^{-1} can be expected if the infestation is severe (L.S. Kuniata unpublished data). As a result of the Ramu stunt, most of the sugar cane was replanted in 1986 with the resistant variety Cadmus. However, Cadmus appeared to be very susceptible to the moth stem borer and in 1987, a severe outbreak was observed damaging up to 60% of the crop resulting in 18% reduction in sugar production (Kuniata and Sweet 1994). Average cane yields in 1988 were substantial higher because of the prolonged droughts in 1987 that significantly reduced the number of stem borers. Also larvae of the moth stem borers were controlled by applications of carbofuran insecticides in 1988. Yield dropped again sharply in 1989 due to the outbreak of cicadas, reducing yields to about 50 t cane ha^{-1}. The cicadas were controlled by ploughing-out followed by a fallow period of two to four months. This was effectively practised from 1989 onwards. Since the late 1980s yields have stabilized at around 55 to 60 t cane ha^{-1} y^{-1}. Such low yields can be explained through the planting of varieties resistant to pests and diseases, but these varieties have generally a low yield potential. Highly productive varieties were considered again in 1993 resulting in higher yields but also a higher population of moth stem borers in 1995 and 1996. Yields are also limited by the competition between sugar cane and weeds. Dominant weeds at Ramu Sugar Ltd are itchgrass (*Rottboellia* sp.) and nutgrass *Cyperus rotundus* and weed competition trials have shown that itchgrass can give yield reductions of up to 54 t cane ha^{-1} (L.S. Kuniata unpublished). In commercial fields, an average loss of 26 t cane ha^{-1} was observed in 1993 but losses were reduced to 5 t cane ha^{-1} in 1995 as a result of improved weed control measures (Table 10). It confirms the general belief that sugar cane does not tolerate competition for water and nutrients.

Table 10 shows that between 1982 and 1995 sugar cane yields were largely determined by insect pests, diseases and weeds. These factors are likely to mask the effects of the changes in soil properties on sugar cane yields.

DISCUSSION AND CONCLUSIONS

In the past 17 years significant changes in soil chemical and physical properties occurred at Ramu Sugar plantation. These changes reflect the way in which the soils were managed including continuous cultivation with acidifying N fertilizers, the absence of P and K fertilizers, and the use of heavy machinery. Soil chemical and physical properties have changed but did they reach levels that affect the sugar cane?

The pH levels in 1996 were about 5.8. Although the optimum pH for sugar cane is about 6.5 (Yates 1978), sugar cane is successfully grown on soils with pH 4 as in Guyana to soils with pH over 7 as in many parts of Barbados. It is therefore unlikely that the current pH levels affect sugar cane production. Levels of available P (Olsen) were on average over 25 mg kg^{-1} which are high levels for sugar cane (Blackburn 1984). Also the exchangeable cations remained at favourable levels for sugar cane cultivation. It suggests that the soil chemical properties had not reached threshold values for sugar cane cultivation despite their significant decline. Threshold values in bulk density were, however, reached because in all soil pits it was observed that roots were absent in the interrow. These values are about 1.3 kg dm^{-3} for the Fluvisols and 1.2 kg dm^{-3} for the Vertisols topsoils and they are only slightly higher for the subsoils. Absolutely seen, they are low (<1.4 Mg m^{-3} and most studies with sugar cane have indicated critical bulk densities up to 1.8 and 1.9 Mg m^{-3} for rooting (Blackburn 1984).

Although P and K levels in the soil were still favourable (Table 4 and 5), the increase in leaf nutrient deficiencies provides circumstantial evidence that nutrient availability was reduced in the 1990s as compared to the 1980s. This may be the result of the soil compaction and acidification.

Changes in soil chemical properties continue if current management strategies remain unchanged but it is not possible to predict at what pace that will happen. It is likely that the P and K content of the soil continue to decrease since they are not replenished by inorganic fertilizers. Applying these nutrients to maintain favourable levels is, however, only useful if the soil compaction is dealt with. Some lime, when the sugar cane is ploughed-out, may be required to keep the pH at favourable levels (i.e. pH> 5.5). It was found that since 1979 organic matter levels had decreased by about 40% but currently trash-harvesting is practised which is likely to increase soil organic matter (Wood 1991). Such increase affects many soil properties. For example, the pH buffering capacity may increase reducing the acidifying effects of sulphate of ammonia (Hartemink 1998), but it may also reduce the compactibility of the soil by increasing resistance to deformation. The trash-harvesting is therefore an important step to achieve sustainable land management and favours sugar cane yields (Yadav and Prasad 1992).

The risk of soil compaction at the plantation could be reduced if the overhaul equipment had high flotation instead of conventional (small) tyres. Also strip tillage involving smaller tractors and reduced tillage is helpful (de Boer 1997). The topsoil compaction is alleviated when the sugar cane is ploughed out but deep tillage or sub-soiling is required for the subsoil. It is recommended for the Fluvisols but sub-soiling cannot be recommended for the Vertisols as it is likely to result in more compaction (Ahmad 1996). The subsoil compaction in the Vertisols (up to 0.3 m) is possibly one of the only changes in soil properties which is hard to reverse.

There is a cost to these measures that may not directly be compensated for by extra sugar cane. However, the costs to restore degraded soils may be substantially higher than those required maintaining the soil in favourable conditions for sugar cane production.

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