Sustainable Land Management at Ramu Sugar Plantation: Assessment and Requirements

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Abstract

Ramu Sugar Plantation was established in 1979. This paper presents an overview of changes in soil chemical and physical properties that have resulted from continuous sugarcane cultivation since that time. Between 1979 and 1996, the soil pH decreased from about 6.5 to 5.8 and this acidification was accompanied by a decrease in cation exchange capacity and exchangeable cations. Organic carbon levels declined from about 56 grams per kilogram in 1979 to 32 grams per kilogram in 1996. The inter-row of the sugarcane was compacted and had significantly higher bulk densities and a very slow water intake. Semiquantitative nutrient budgets showed a shortfall in nitrogen, phosphorus and potassium, and levels of these nutrients in the sugarcane leaves significantly decreased between the mid-1980s and 1990s. Yields at the plantation are largely determined by insect pests, diseases and weeds. It is concluded that significant soil changes occurred that may affect the sustainability of sugarcane growing in the long term if such trends continue.

THE term 'sustainable land management' is difficult to define, but in essence refers to the combination of production and conservation of the natural resources on which the production depends (Young 1997). The soil is the most important component in sustainable land management as indicated by pedologists (Bouma 1994), soil fertility experts (Scholes et al. 1994) and soil biologists (Swift and Sanchez 1984). Assessing sustainable land management is as difficult as defining it. Key problems are choosing the spatial and temporal borders for assessment (Fresco and Kroonenberg 1992) and the indicators for evaluating sustainability in a given locality (Smyth and Dumanski 1995). Long-term data are imperative to evaluate the sustainability of land management practices but they are scarce for tropical regions (Greenland 1994).

Most studies dealing with sustainable land management have focused on subsistence agriculture. Relatively little attention has been given to high external input or plantation agriculture, which constitutes a major segment of the national economies in many tropical countries (Hartemink 1998b). An important plantation crop is sugarcane (interspecific hybrids of *Saccharum* spp.), which is mostly monocropped. Sugarcane production has dramatically increased in the past few decades. In the 1960s, sugar production in the world was about 64 million tonnes, of which half was produced in developing countries (FAO 1996). By the mid-1990s, production had increased to 119 million tonnes. About 76 million tonnes was produced in developing countries, of which 40 million tonnes was produced in Asia and the Pacific. Between the mid-1960s and 1990s, the largest expansion of

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sugar production occurred in India (from about 3 to 15 million tonnes) and Brazil (from 5 to 10 million tonnes). In some sugarcane-producing countries like Cuba and Barbados there has, however, been a decline in production in the past decades (Anderson et al. 1995). Part of the increase in sugar production has resulted from improved agronomic practices, but in many countries increased production has resulted from having a larger area under sugarcane.

There are few plantation crops in the tropics that put such heavy demand on soil resources as sugarcane. Most commercial sugarcane is grown intensively on a large scale, and many of the husbandry practices are similar to intensive agricultural systems in temperate regions (Hartemink and Wood 1998). Heavy machinery is used for land preparation, planting, spraying and harvesting. Biocides are widely used to control pests and diseases and herbicides are used to control weeds. Sugarcane also makes heavy demands on soil nutrient reserves, because large amounts of nutrients are removed with the harvest. Unless replaced, either naturally through weathering and biogeocycling or artificially through inorganic fertilisers with, for example, filter press cake, the soil nutrient pool will decline. In summary, commercial sugarcane cultivation is likely to affect soil conditions.

Sugarcane is indigenous in PNG. Plans for establishing a sugarcane plantation in PNG date back to the 1930s when Singara Sugar Estates Ltd proposed to establish a plantation near Buna in what is now called Oro (Northern) Province (van der Veer 1937). The plantation was never established. In the decades that followed, various reports suggested that commercial sugarcane production was technically feasible. It was emphasised that it would be a great risk because of a broad range of pests and diseases (Li 1985). In the mid-1970s the demand for sugar increased, world market prices fluctuated strongly, and the PNG Government decided to establish a national sugar industry. Initial investigations were carried out in the Markham Valley to identify a suitable site. 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 7000 hectares (ha) of suitable or moderately suitable land in the Gusap–Dumpu area was identified. The first sugarcane was planted in 1979 and the plantation was named Ramu Sugar Ltd.

Initially, most attention was paid to the establishment of the plantation and factory, but in 1987 a soil management plan was developed based on expert knowledge (Booker Agriculture International 1987). The plan has received only lip-service by the plantation management because they mainly focused on the control of insect pests and diseases, which severely affected sugarcane production. Hence, soils were not regarded as a limiting factor in sugarcane production. Such differences in perception between the users of the soil and soil experts is common (Bouma 1993) and not unique to plantation agriculture.

In this paper, an assessment is made of the sustainability of land management at Ramu Sugar Plantation. The hypothesis tested was simple. If it could be proven that soil properties have changed significantly and that such changes could be attributed to the effect of continuous sugarcane cultivation, sugarcane cultivation at the plantation would not be sustainable. Although the term 'sustainable land management' is used throughout this paper, it usually refers only to soil aspect. Indicators of sustainable land management were based on the availability of historical soil data from the plantation, supplemented with data that could be relatively easily collected. Soil survey data of 1979 were also used, providing useful information to assess changes in soil properties (Young 1991). No historical data were available for the soil physical properties, and changes were assessed by comparing measurements in sugarcane plantations with those on uncultivated land.

The Environment at Ramu Sugar Plantation

Ramu Sugar Plantation (6°S, 146°E) is located in Madang Province. Before sugarcane was planted in 1979, the site was 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 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. occurred in the wetter sites along streams and rivers (Chartres 1981).

Climate

The plantation is in an area that 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 (unimodal) with a dry season from May to November and a rainy season from December to April. The average rainfall at the plantation is 1998 millimetres (mm) per year, but between 1980 and 1995 annual rainfall varied from 1531 to 2560 mm. June to September are the driest months, with an average of less than 90 mm of rain per month. March is the wettest month, with an average rainfall of 284 mm. Evaporation (class A open pan) is about 2281 mm per year and exceeds rainfall from May to November. Mean annual temperatures are 26.7°C, with only minor fluctuations through the year. The climate is classified as Am (Köppen system)—tropical rainy climate with a short dry season.

There is very little relation between total annual rainfall and sugarcane yield (Hartemink et al. 1998). An index often used in the evaluation of water and sugarcane is the production of sugar per millimetre of rain (Fauconnier 1993). These values were calculated from yield and climatic data. In the past 15 years, between 21.2 and 40.9 mm of rain was required to produce 1 tonne of sugarcane per hectare(ha), which is equivalent to 2–4.2 kilograms (kg) sugarcane/ha/mm of rain (Hartemink et al. 1998).

Land management under sugarcane

The first 3 ha of sugarcane were planted in 1979 but the total area grew rapidly from 1592 ha in 1981, to 5011 ha in 1983 and to 6030 ha in 1995. The plantation was established for rainfed sugarcane production. Feasibility studies for irrigation have been conducted in the past but it was soon realised that other constraints were more important. About 1800 ha of sugarcane 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 this reduces the risk of certain insect pests. The harvesting season lasts from May to October and cutter–chopper–loader harvesters are used, with 20-tonne tractors and trailers transporting the cane to the factory. Most of this equipment has conventional tyres. About half of the sugarcane is trash harvested (no burning before harvesting). Up to five crops (i.e. plant cane plus four ratoons) are sometimes obtained, after which the land is replanted; at other times, cowpea (*Vigna unguiculata*) may be sown and ploughed under after one year. Before 1989, nitrogen (N) fertiliser was applied as urea (46% N), but when trash harvesting replaced pre-harvest burning it was suggested that considerable amounts of urea-N would be lost through volatilisation. Therefore N fertiliser supplied after 1989 was in the form of sulfate of ammonia (21% N); on average, 90 kg N/ha/year was applied during the period 1991–95. N applications are usually broadcast between August and November. Phosphorus (P) and potassium (K) fertilisers 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 square kilometres and forms, together with the Markham Valley, a large *graben* that has been a zone of subsidence since the Late Tertiary period (Löffler 1977). At the site of the plantation, the valley is about 10 kilometres wide. The Ramu Valley contains about 2000 metres (m) of unconsolidated and poorly consolidated Quaternary marine and terrestrial clastic sediments overlying Tertiary sedimentary rocks (Hartemink 1998b). The valley comprises a series of alluvial fans, some of which 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%. The plantation is about 400 m above sea level. 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, with a lake formed behind the dam. The dam 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 sugarcane. Drainage of soils adjacent to the Gusap stream was then retarded and some sugarcane land had to be abandoned because of poor workability. Although such mudflows catastrophically affect the sustainability of sugarcane 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 (> 1.2 m depth) occur, and extensive areas have gravelly (5–15%) topsoils and very gravelly (15–40%) or stony subsoils. The pH_w (pH in water) indicates no apparent danger from exchangeable aluminium (Al) or excess calcium carbonate ($CaCO_3$). Soil salinity is not a problem in the topsoils but the deeper subsoils are slightly alkaline. Sheet and gully erosion are a threat in some areas but terraces have been dug across the contour to control surface water (Hartemink 1998b).

Fluvisols are the dominant major soil grouping at the plantation. At the soil unit at the Food and Agriculture Organization–United Nations Educational, Scientific and Cultural Organization (FAO–UNESCO), the Fluvisols are Eutric or Mollic, equivalent to the great group of Tropofluvents (Entisols) in United States Department of Agriculture (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 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 the high content of stable aggregates that commonly occur in Vertisols when the organic matter content is 30 grams (g)/kg 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, a fine texture (> 500 g clay/kg soil), a 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 of FAO–UNESCO, these soils are Eutric Vertisols, equivalent to the great group of Hapluderts in USDA Soil Taxonomy. 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 at FAO–UNESCO (1988). According to Booker Agriculture International (1987), they cover only a small area of the plantation (about 3% or 180 ha) and data from these soils were not included in this study. Some sugarcane is planted on 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 P retention capacities (Hartemink 1998b). 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

Data types

The literature describes two methods to study changes in soil properties under cropping. Firstly, soil dynamics can be monitored over time on the same site. This is called chronosequential sampling (Tan 1996) or type I data (Sanchez et al. 1985). Differences in soil properties are hence attributable to the management of the soil during the period of observation. Although type I data are extremely useful to assess the sustainability of land management practices, few such data sets exist for tropical regions (Greenland et al. 1994).

In the second method, soils under adjacent different land-use systems are sampled at the same time and compared. These are called type II data (Sanchez et al. 1985), biosequential sampling (Tan 1996) or 'sampling from paired sites' in the literature from Australia (e.g. Garside et al. 1997; McGarry et al. 1996). The main underlying assumption is that the soils of the cultivated and uncultivated land are similar and that differences observed in soil properties are attributed to the cultivation. Obviously, this is not always the case, as the uncultivated land may have been of inferior quality. Such situations are likely to occur when land pressure is low, so that areas with poorer soils (e.g. patches which are waterlogged, stony or with low fertility) remain uncultivated. When carefully taken, however, biosequential samples provide useful information, and such a sampling strategy has been followed in much of the literature reviewed on soil changes under sugarcane cultivation.

To investigate changes in soil chemical properties and leaf nutrient concentrations, all available analytical data from 1978 to 1995 were collected (type I data). For the changes in soil physical properties, no historical data could be used and we made bulk density and water intake measurements in areas under sugarcane and adjoining grasslands (type II data).

Table 1. Soil chemical and physical properties of a typical Fluvisol and Vertisol at Ramu Sugar Plantation.

Soil type	Sampling depth (m)	pH_w 1:2.5	pH KCl 1:2.5	Organic C (g/kg)	Total N (g/kg)	P (Olsen) (mg/kg)	CEC pH7 ($mmol_c$ /kg)	Exchangeable cations ($mmol_c$/ kg)			Base saturation (%)	Particle size fractions (g/kg)		
								Ca	Mg	K		Clay	Silt	Sand
Fluvisol	0–0.15	6.2	5.0	16.5	1.4	34	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

Soil chemical data

With the establishment of the plantation in 1979, the area was divided into blocks of 10–20 ha. Between 1982 and 1994, soil samples were taken in most sugarcane blocks for routine analysis, and the analytical data of 487 topsoil (0–0.15 m) and some 50 subsoil samples were available (type I data). Also, the chemical data of 21 soil profiles (15 Fluvisols, 6 Vertisols) from the initial soil survey report of 1979 were available. The topsoil samples between 1982 and 1994 were commonly taken after the last ratoon when the sugarcane was ploughed out. Samples were bulked from 20 to 50 locations in a sugarcane block using an Edelman auger. The samples taken in 1996 were composites from 10 to 15 locations in a sugarcane block and mini-pits were used for the 0–0.15 m soil horizons. All soil samples of 1996 were taken in the inter-row of the sugarcane. In addition, soil samples were taken in natural grassland bordering sugarcane fields (type II data). Figure 1 summarises the work plan for the soil chemical data.

Airdried, ground and sieved samples (2 mm) were analysed at the Cambridge Laboratory, Cambridge, New Zealand or at the National Analytical Chemistry Laboratory, Port Moresby, PNG. The procedures for soil analysis were identical at both laboratories, and were as follows: pH_w in 1:2.5 or 1:5 suspension of soil and water; pH_{KCl} in a 1:2.5 soil and 1 molar (M) KCl solution; organic carbon by $K_2Cr_2O_7$ and H_2SO_4 oxidation (Walkley and Black); total N by Kjeldahl; available P by $NaHCO_3$ extraction (Olsen); exchangeable cations Ca, magnesium (Mg), K, sodium (Na) and cation exchange capacity (CEC) percolation by 1M NH_4OAc followed by spectrophotometry (K, Na), atomic absorption spectrometer (Ca, Mg) and titration (CEC); particle size analysis by hydrometer. The soil samples of the initial soil survey in 1979 were analysed at the laboratories of Hunting Technical Services Ltd in England. Except for available P, all 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 sugarcane blocks (two Eutric Fluvisols, two Eutric Vertisols) were selected bordering a natural grassland area with the same soil profile as the area under sugar (type II data). The sugarcane at the infiltration sites was in the second or third ratoon. In each sugarcane block, infiltration measure-

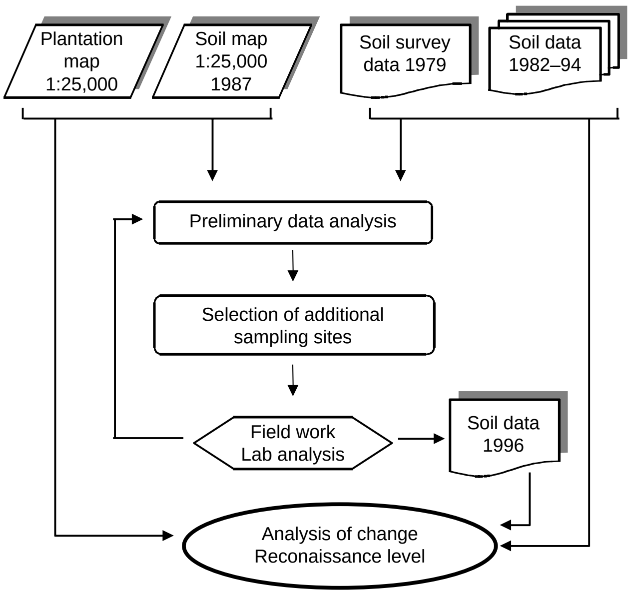

Figure 1. Work plan for the collection and data analysis of soil chemical information at Ramu Sugar Plantation.

ments were made in triplicate at about 10 m from each other. Measurements were made between the sugarcane rows (inter-row), and within the rows (between two stools). At about 75 m from the sugarcane block, infiltration measurements were made in natural grassland, and 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 pre-wetted 24 hours prior to the measurements using borehole water. Infiltration readings were made every minute for the first 10 minutes, every 2 minutes between 10 and 20 minutes, and every 15 minutes between 20 and 320 minutes. Mean infiltration rates (mm/hour) were calculated for the first 10 minutes (10 readings) and between 20 and 80 minutes (5 readings), 140–200 minutes (5 readings) and 245–305 minutes (5 readings) after the rings were filled with water. In total, 36 infiltration measurements were made of at least 5 hours each but in most measurements the steady state was reached within 4 hours.

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 sugarcane block and one in the adjoining natural grassland area. In total, eight soil pits were sampled using cores of 100 millilitres (mL) that 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 m soil horizon of the Fluvisols, the bulk density could not be accurately determined with 100 mL cores, because their volume is much too small. In the soil pits under sugarcane, both the inter-row and the soil horizons between the rows were sampled. Three cores were used for each depth and they were oven dried at 105°C for 72 hours. In total, 126 core samples were taken at the infiltration sites and an additional 18 cores were taken in two 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 and 1996 (type I data). Leaf samples at Ramu Sugar Plantation 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 30–40 paces the fourth leaf was sampled from a nearby stool; the first leaf was the unfurl leaf. After removal of the midrib, about 400–600 leaves were combined (composited) and a subsample taken. Leaf samples were dried at 80°C for 48 hours. All leaf samples were analysed at the Cambridge Laboratory in New Zealand following standard analytical procedures.

Results

Soil chemical properties

Between 1979 and 1996, the topsoil pH_w decreased from about 6.5 to 5.8 in both Fluvisols and Vertisols (Table 2). The soil acidification was accompanied by a change in the levels of exchangeable bases. In particular, the levels of exchangeable K declined, possibly due to a combination of the large K removal by the sugarcane (Yates 1978) and leaching losses. Organic C levels declined by about 40% between 1979 and 1996. For high-yielding sugarcane, it is important to maintain favourable organic matter levels (Yadav and Prasad 1992). Levels of available P declined but variation was large. Topsoil data from the same sugarcane block but at 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 acidification

The data in Tables 2 and 3 show that soil acidification was the most significant change in soil chemical properties. Acidification was not restricted to the topsoil. Chronosequential paired samples (type I data) from different depths showed a significant decrease of 0.2–0.4 pH_w units to a depth of 0.60 m after 10 years of continuous sugarcane cultivation (Table 4). Also, the biosequential samples (type II data) showed a significant decrease of 0.5 pH_w units in the topsoil, and a decrease of 0.2 pH_w units to a depth of 0.5 m.

The initial decrease in pH_w from grassland to sugarcane (1979–82) may have been due to the increased mineralisation of organic matter, which is a common cause of soil acidification (Rowell and Wild 1985). There were no organic C data available from the early 1980s, but the levels declined from about 56 g C/kg in 1979 to 30 g C/kg in 1994 (Table 2). The significant pH_w decline observed in the 1990s coincided with a change in fertiliser policy resulting from a change in harvesting technique. Since 1989, Australian cutter–chopper–loader harvesters were used instead of preharvest burning. These harvesters may leave up to

Table 2. Topsoil (0–0.15 metres) chemical properties of Fluvisols and Vertisols (arithmetic mean ±1 SD) (type I data), 1979–96.

Major soil groupings	Year	Number of samples[a]	pH_w 1:2.5	Organic C (g/kg)	Available P (mg/kg)	CEC pH 7 ($mmol_c$ /kg)	Exchangeable cations ($mmol_c$/ kg)			Base saturation (%)
							Ca	Mg	K	
Fluvisols	1979[b]	15	6.5 ± 0.4	58 ± 15	na	389 ± 43	228 ± 78	93 ± 41	13.0 ± 5.0	79 ± 17
	1982	14	6.2 ± 0 1	na	36 ± 4	459 ± 55	275 ± 35	113 ± 24	12.9 ± 2.0	87 ± 2
	1983	44	6.3 ± 0.1	na	37 ± 10	435 ± 48	256 ± 35	100 ± 16	12.4 ± 2.8	85 ± 3
	1984	9	6.1 ± 0.1	na	42 ± 10	437 ± 52	266 ± 45	102 ± 21	12.9 ± 3.8	87 ± 4
	1994	12	5.9 ± 0.1	35 ± 6	28 ± 9	384 ± 65	232 ± 47	101 ± 22	10.8 ± 2.3	90 ± 5
	1996	8	5.8 ± 0.2	31 ± 7	28 ± 12	374 ± 33	220 ± 30	99 ± 13	8.0 ± 2.0	88 ± 8
Vertisols	1979[b]	6	6.6 ± 0.1	52 ± 9	na	421 ± 21	293 ± 69	123 ± 39	15.5 ± 2.7	93 ± 17
	1982	17	6.2 ± 0.1	na	43 ± 5	490 ± 29	286 ± 22	131 ± 16	16.1 ± 2.9	89 ± 2
	1983	40	6.3 ± 0.2	na	40 ± 13	477 ± 94	290 ± 83	114 ± 33	12.9 ± 2.3	87 ± 9
	1986	7	6.2 ± 0.2	na	37 ± 18	490 ± 108	307 ± 77	112 ± 37	12.3 ± 5.6	88 ± 3
	1994	12	5.9 ± 0.1	32 ± 3	32 ± 11	452 ± 79	273 ± 50	129 ± 34	13.4 ± 3.9	92 ± 5
	1996	12	5.8 ± 0.2	32 ± 6	28 ± 11	421 ± 102	276 ± 73	115 ± 38	9.0 ± 3.0	92 ± 8

na = not available

[a] Composite topsoil samples of continuously cultivated fields, except for 1979.

[b] Soil samples taken prior to the establishment of the plantation; sampling depths varied from 0–0.12 m to 0–0.28 m (mean 0.18 m).

Table 3. Changes in soil chemical properties (0–0.15 metres) of Fluvisols and Vertisols under sugarcane (type I data), 1980s and 1990s.

	Fluvisols (n = 7 pairs)			Vertisols (n = 5 pairs)		
	1982–83	1991–94	Difference	1982–84	1991–94	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)	37.2	29.0	$P = 0.04$	35.4	24.6	ns
CEC ($mmol_c$/kg)	412	354	$P < 0.001$	450	403	ns
Exchangeable Ca ($mmol_c$/kg)	229	213	ns	269	250	ns
Exchangeable Mg ($mmol_c$/kg)	100	94	ns	109	95	ns
Exchangeable K ($mmol_c$/kg)	11.0	9.5	ns	13.0	10.1	ns
Base saturation (%)	83	88	$P = 0.02$	87	88	ns

ns = not significant

Table 4. Change in pH_w with depth, based on samples from the same site at different times (chronosequential), and from different land use sampled at the same time (biosequential).

Chronosequential samples (Type I data)					Biosequential samples (Type II data)				
Sampling depth (m)	Number of sample pairs	1986	1996	Difference	Sampling depth (m)	Number of sample pairs	Natural grassland	Continuous sugarcane[a]	Difference
0–0.15	9	6.2	5.8	$P < 0.001$	0–0.15	5	6.3	5.8	$P = 0.02$
0.15–0.30	9	6.2	5.9	$P < 0.001$	0.15–0.30	5	6.3	6.1	$P = 0.02$
0.30–0.45	7	6.5	6.1	$P = 0.02$	0.30–0.50	5	6.6	6.4	$P = 0.05$
0.45–0.60	7	6.6	6.4	$P = 0.01$	0.50–0.70	5	6.7	6.6	ns
					0.70–0.90	5	6.9	6.8	ns

ns = not significant
[a] Soils were continuously cultivated with sugarcane for at least 10 years.

10 tonnes/ha of crop residues or trash (Ng Kee Kwong et al. 1987). In Australia, it has been found that, when urea is applied to trash-covered fields, ammonia losses of 40% can be expected (Freney et al. 1992). Accordingly, in the early 1990s, urea was replaced by sulfate of ammonia, which is less vulnerable to ammonium ion volatilisation. The theoretical acidity produced by sulfate of ammonia is, however, twice that from urea-N, and that may explain the significant increase in soil acidity observed in the 1990s. Contributing causes are possibly the end of burning, by which no more pH-increasing ashes are returned to the soil, and the yearly addition of sugarcane trash, which increases the organic matter content, resulting generally in a lowering of the pH (Dalal 1989; Moody and Aitken 1997). Although the trash harvesting method may favour the organic matter content (Vallis et al. 1996), in the young alluvial soils of Ramu Sugar Plantation it is likely to have resulted in significant acidification.

As mentioned, an important cause for the soil acidification trend is the yearly application of urea, sulfate of ammonia and diammonium phosphate. Since these fertilisers contain N in the ammonium form, nitrification reactions result in acid residues. The acid residue of urea is 71 g protons (H^+)/kg N, which is at its maximum equivalent to about 3.6 kg $CaCO_3$ (Adams 1984). For sulfate of ammonia, the potential soil acidity produced through nitrification is equivalent to 143 g H^+/kg N. Diammonium phosphate has intermediate levels.

Data on fertiliser application rates from the plantation were available only for 1991–95. Records were incomplete for other years and could not be used. Based on the fertilisers applied at the plantation, the theoretical produced acidity in kilomoles (kmol) per hectare was calculated for each year from 1991 to 1995 (Table 5). Up to 1991, urea was the main fertiliser applied (L.S. Kuniata, Ramu Sugar Ltd., pers. comm.) but most of the N fertilisers in the mid-1990s were applied as sulfate of ammonia. Diammonium phosphate was applied only in a very few sugarcane blocks where P deficiency was suspected.

The total theoretical acidity produced between 1991 and 1995 was 57.8 kmoles H^+/ha, of which 88% was produced by sulfate of ammonia. The average annual addition of protons with the N fertilisers was 11.6 kmol H^+/ha. Net changes in soil acidity during this period were calculated from the antilog differences between the pHs in 1991 and 1996. The changes in soil pH_w were found to be only a small fraction of the acidity added with the fertiliser (Table 6).

The resistance of a soil to pH changes after the addition of acid or base is the buffer capacity (pH BC), which generally increases with increasing clay and organic matter content. The pH BC is a measure of the number of protons required to decrease the soil pH, and it is commonly expressed in kmol H^+/ha/unit pH or millimoles (mmol) H^+/litre (L) soil/unit pH (Helyar et al. 1990). For alluvial soils under sugarcane, pH BC can be estimated by dividing the acidity added by the net changes in soil pH_w. Between 1991 and 1996, the soils had received 57.8 kmol H^+/ha (Table 5) whereas the mean pH_w decreased from 6.2 to 5.7. From this, the approximate pH BC for topsoil (0–15 centimetres depth) was estimated to be 125 kmol H^+/ha/unit pH, which is equivalent to 84 mmol H^+/L/unit pH, or 96 mmol H^+/kg/unit pH, with a topsoil bulk density of 1.15 tonnes/cubic metre (m^3). This value (125 kmol H^+/ha/unit pH) agrees well with values calculated for similarly textured soils in New South Wales, Australia (Helyar et al. 1990).

The pH BC allows some estimates of future soil pH_w levels to be made. If the current application rates of 90 kg N/ha in the form of sulfate of ammonia continue, 12.8 kmol/ha/year are added to the soil and the pH_w may decrease by one unit in 10 years. This implies that the mean pH_w of the soils will have decreased to 4.7 by the year 2006. However, with the change to trash harvesting and the expected increase in soil organic matter levels, the pH BC may increase and rates of soil acidification are therefore hard to predict.

In addition to the pH BC, the uptake of nitrate in excess of cations may also have neutralised some of the acidity produced by nitrification (Pierre 1928). Furthermore, it was found that significant acidification occurred up to 0.60 m depth (Table 4), which explains

Table 5. Mean annual fertiliser applications at the sugarcane plantation and their theoretical acidity produced.

Year	kg N/ha				kmoles H^+/ha			
	Urea	Diammonium phosphate	Sulfate of ammonia	Total	Urea	Diammonium phosphate	Sulfate of ammonia	Total
1991	23	8	0	31	1.6	0.9	0	2.5
1992	27	3	92	122	1.9	0.3	13.2	15.4
1993	10	1	87	98	0.7	< 0.1	12.4	13.1
1994	7	< 0.5	89	96	0.5	< 0.1	12.7	13.2
1995	5	3	90	98	0.4	0.3	12.8	13.5

Source: modified from Hartemink (1998a)

Table 6. Applied acidity and actual changes in soil pH_w, 1991–95.

Period	Applied acidity kmoles H^+/ha/y	Annual decrease in topsoil pH_w	Increase in soil acidity moles H^+/ha/y
1991–93	10.4	0.10	0.328
1994–95	13.4	0.08	0.398
Mean	11.6	0.09	0.356

Source: modified from Hartemink (1998a)

some of the calculated difference between the theoretical and net acidity of the topsoils. The decrease in subsoil pH was, however, lower than in the topsoil. Apparently, the acidification front is slowly descending (Hartemink 1998a).

The decline in topsoil and subsoil pH has a number of unwanted consequences. Although sugarcane tolerates a pH range of 5 to 8 (Blackburn 1984), some studies have shown that optimum yields are obtained when the pH is about 6.0 (Coale and Schueneman 1993). In some of the soils under sugarcane, the pH_w had decreased below 5.5, the point at which Al becomes soluble. Although sugarcane is relatively more tolerant to Al in solution than, for example, maize (Hetherington et al. 1988), a decline in productivity may be expected. Cation availability is decreased at a lower pH because the increase in protons displaces cations from the exchange sites, which are subsequently leached (Haynes and Swift 1986).

Rates of change in soil chemical properties

From 30 sugarcane blocks (13 Fluvisols, 17 Vertisols), soil chemical data (pH_w, CEC, exchangeable Ca, Mg, K and base saturation %) were available from different sampling times. These data were used to calculate the rates of change. The difference in years between the initial soil sample at t_0 and the second sample at t_1 was plotted against the difference in the measured value for each soil chemical property. Different functions (linear, logarithmic, polynomial) were fitted through the data, and the function with the highest correlation coefficient (R) was used to calculate the rates of change. Clear trends with time were found for pH_w, available P, CEC and exchangeable K.

In Fluvisols and Vertisols, the pH_w decreased with time (pH_w at t_1 minus pH_w at $t_0 < 0$), and from a linear equation fitted through the data it was calculated that the pH_w decrease was about 0.5 and 0.3 units after 10 years (t_1–t_0=10), and 0.7 and 0.4 units after 15 years (t_1–t_0=15) in the topsoils of Fluvisols and Vertisols, respectively (Table 7). Rates of change for P were higher in Fluvisols (–20 mg/kg after 15 years) than in Vertisols (–11 mg/kg after 15 years) and also the decline in CEC was larger in Fluvisols. Changes in exchangeable K were, however, larger in Vertisols (–6.6 mmol charge ($mmol_c$) /kg after 15 years) than in Fluvisols (–2.6 $mmol_c$ /kg after 15 years).

Field scale heterogeneity

Samples were taken in sugarcane fields in the inter-row and within the rows, and in adjoining natural grassland areas that had never been cultivated (Table 8). A pH_w difference of 0.6 units was observed between topsoils (0–0.15 m) under natural grassland and within the sugarcane rows. The pH_w values of the inter-row were slightly higher than within the sugarcane rows. Below 0.3 m depth, there were only slight differences between sugarcane and natural grassland.

Organic C levels in the topsoils within the sugarcane rows were about 8 g/kg lower than under natural grassland but on average 2.1 g/kg higher than within the sugarcane rows. Although the difference between the inter-row and within the rows is small, it may significantly affect the susceptibility of the soil to compaction

Table 7. Approximate rates of changes in some topsoil (0–0.15 metres) chemical properties of Fluvisols and Vertisols.

Major soil groupings	Soil chemical property	Line fitted[a]	r^2	Approximate change after		
				5 years	10 years	15 years
Fluvisols	pH_w 1:2.5	pH_w = -0.048x	0.301	–0.2	–0.5	–0.7
(13 pairs)	Available P (mg/kg)	P = –0.098x^2 + 0.159x	0.607	–2	–8	–20
	CEC ($mmol_c$/kg)	CEC = –0.531x^2 + 0.374x	0.212	–11	–49	–114
	Exchangeable K ($mmol_c$/kg)	K = –0.172x	0.182	–0.9	–1.7	–2.6
Vertisols	pH_w 1:2.5	pH_w = –0.029x	0.471	–0.1	–0.3	–0.4
(17 pairs)	Available P (mg/kg)	P = –0.734x	0.914	–4	–7	–11
	CEC ($mmol_c$/kg)	CEC = –4.553x	0.265	–23	–46	–68
	Exchangeable K ($mmol_c$/kg)	K = –0.439x	0.224	–2.2	–4.4	–6.6

[a]Line fitted through: t_1 minus t_0 (x-axis) vs value at t_1 minus value at t_0 (y-axis).

Table 8. Soil fertility status under sugarcane (within and inter-row) and natural grassland. Values are the arithmetic mean of five samples ± 1 SD (type II data).

	Sampling depth (m)	Sugarcane within rows	Sugarcane inter-rows	Natural grassland
pH_w (1:5)	0–0.15	6.1 ± 0.3	6.2 ± 0.4	6.7 ± 0.2
	0.15–0.30	6.4 ± 0.2	6.6 ± 0.2	6.8 ± 0.3
	0.30–0.50	6.8 ± 0.1	6.8 ± 0.3	6.9 ± 0.2
	0.50–0.70	6.9 ± 0.1	7.0 ± 0.2	7.1 ± 0.2
	0.70–0.90	6.9 ± 0.6	7.0 ± 0.2	7.1 ± 0.2
Organic C (g/kg)	0–0.15	34.1 ± 3.6	32.0 ± 2.4	41.9 ± 9.1
	0.15–0.30	29.0 ± 2.8	22.0 ± 7.4	28.7 ± 1.9
	0.30–0.50	18.7 ± 4.6	14.6 ± 7.4	17.2 ± 3.3
	0.50–0.70	12.7 ± 6.6	10.1 ± 6.6	10.5 ± 4.2
	0.70–0.90	9.0 ± 5.1	8.1 ± 4.2	7.9 ± 4.2
Total N (g/kg)	0–0.15	2.3 ± 1.6	1.8 ± 0.3	2.4 ± 0.7
	0.15–0.30	1.4 ± 0.2	1.2 ± 0.5	1.6 ± 0.1
	0.30–0.50	0.9 ± 0.3	0.7 ± 0.4	0.9 ± 0.2
	0.50–0.70	0.6 ± 0.3	0.4 ± 0.4	0.6 ± 0.2
	0.70–0.90	0.3 ± 0.3	0.3 ± 0.1	0.3 ± 0.2
Available P (mg/kg)	0–0.15	22 ± 10	22 ± 11	27 ± 10
	0.15–0.30	17 ± 10	11 ± 7	16 ± 11
	0.30–0.50	7 ± 5	6 ± 4	7 ± 6
	0.50–0.70	6 ± 4	6 ± 4	5 ± 3
	0.70–0.90	4 ± 2	4 ± 1	5 ± 2
Exchangeable Ca ($mmol_c$/kg)	0–0.15	278 ± 73	280 ± 49	283 ± 48
	0.15–0.30	280 ± 61	249 ± 74	246 ± 34
	0.30–0.50	283 ± 71	262 ± 70	257 ± 33
	0.50–0.70	275 ± 52	274 ± 57	263 ± 24
	0.70–0.90	251 ± 21	250 ± 17	270 ± 66
Exchangeable Mg ($mmol_c$/kg)	0–0.15	104 ± 16	91 ± 12	92 ± 15
	0.15–0.30	104 ± 19	93 ± 26	83 ± 18
	0.30–0.50	116 ± 13	94 ± 21	97 ± 18
	0.50–0.70	119 ± 28	101 ± 19	109 ± 21
	0.70–0.90	103 ± 9	93 ± 14	106 ± 40
Exchangeable K ($mmol_c$/kg)	0–0.15	10.8 ± 4.9	10.3 ± 5.5	12.8 ± 6.3
	0.15–0.30	6.4 ± 5.8	4.1 ± 1.8	5.8 ± 4.4
	0.30–0.50	2.5 ± 1.2	2.9 ± 1.2	4.5 ± 4.6
	0.50–0.70	2.5 ± 0.7	2.5 ± 0.9	4.3 ± 4.8
	0.70–0.90	2.0 ± 0.4	2.5 ± 0.6	4.6 ± 5.1

Source: Hartemink (1998c)

as resistance to deformation and soil elasticity is decreased (see below). The inter-row had a lower organic C content in the subsoil, whereas organic C in natural grassland and within the row was comparable with depth. For the total N content, a similar pattern was followed, with lower content in the topsoils of the sugarcane inter-row as compared to within the rows.

Levels of available P in the topsoils were similar in the inter-row and within the rows but were lower in the subsoil of the inter-row. Soils under natural grassland had higher levels of available P in the topsoil (+5 mg/kg), but small differences were found with depth between grassland and within the sugarcane rows. The considerably higher exchangeable Mg content within the sugarcane rows was striking, compared with the inter-row and natural grassland. Also, exchangeable Ca levels appeared to be slightly higher within the sugarcane rows. Exchangeable K was highest under natural grassland and similar in the topsoils within and between the rows of sugarcane. Overall, the data suggest a similar degree of soil acidification and fertility decline as was found with the data from different sampling times (type I data, see Tables 2, 3 and 4).

Soil compaction

Bulk densities under natural grassland and within the sugarcane rows were similar for all depths of both Fluvisols and Vertisols (Table 9). The bulk densities in the inter-row were, however, significantly higher in the two major soil groupings, and in all soil pits it was observed that roots were absent in the inter-row, a common observation in compacted soils under sugarcane (Hartemink and Wood 1998). The compaction in the inter-row of the sugarcane 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 inter-row was also higher in the 0.30–0.50 m soil horizon. The absolute increase in the topsoil bulk density of the inter-row as compared to natural grassland was 0.22 tonnes/m^3 (+21%) in the Fluvisols and 0.18 tonnes/m^3 (+18%) in the Vertisols. Overall, Fluvisols had significantly higher bulk densities than the finer textured Vertisols.

Water infiltration

Cumulative water intake of natural grassland and within the sugarcane rows was very high in both major soil groupings (Fig. 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 like sugarcane that are grown on ridges. 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 sugarcane rows, cumulative infiltration rates after five hours were 1322 mm in the Fluvisols compared to 1200 mm in the Vertisols. Water intake in the inter-row was very low and had not exceeded 105 mm in Fluvisols and 59 mm in Vertisols after five hours. Among other consequences, the slow water intake in the inter-rows may result in soil erosion, which can be particularly high on Vertisols (Unger and Stewart 1988) and under sugarcane (Prove et al. 1995) but there were no data available to verify this.

Table 9 and Figure 2 provide evidence for significantly higher bulk densities and lower infiltration rates in the inter-row of sugarcane. To investigate the relation between the two parameters, 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/hour after 4 hours were 1.15 tonnes/m^3 for Fluvisols and 1.04 tonnes/m^3 for Vertisols. Bulk densities at which infiltration rates were 50 mm/hour during the first 10 minutes were 1.20 tonnes/m^3 for Fluvisols and 1.16 tonnes/m^3 for Vertisols.

Nutrient budgets

Changes in soil chemical properties indicated a decline in plant nutrient availability. In this section a comparison is made between nutrient inputs and nutrient outputs. Yield data (tonnes/ha) from 1991 to 1995 were multiplied with a range of nutrient removal data (kg nutrient/tonnes/hectare). These were compared with the nutrients applied in the fertilisers and the difference was calculated for the low and high range (Table 10). It appeared that the difference between N removal and N applied was positive, that is, more N was applied than removed. However, for P and K a negative difference between removal and fertiliser application was found. Table 11 presents the mean differences for the three major nutrients. However, this assumes a 100% recovery of the fertilisers, which never occurs. In reality, the balance is therefore much more negative, that is, more nutrients were lost than the data suggest.

Table 9. Bulk density of Fluvisols and Vertisols under sugarcane and natural grassland land use (type II data).

Major soil groupings	Sampling depth (m)	Bulk density (tonnes/m^3)[a]			
		Sugarcane within the rows	Sugarcane inter-row	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 sampled accurately with 100 mL cores because of abundant gravel.
[c] Standard error of the difference in means (10 degrees of freedom).

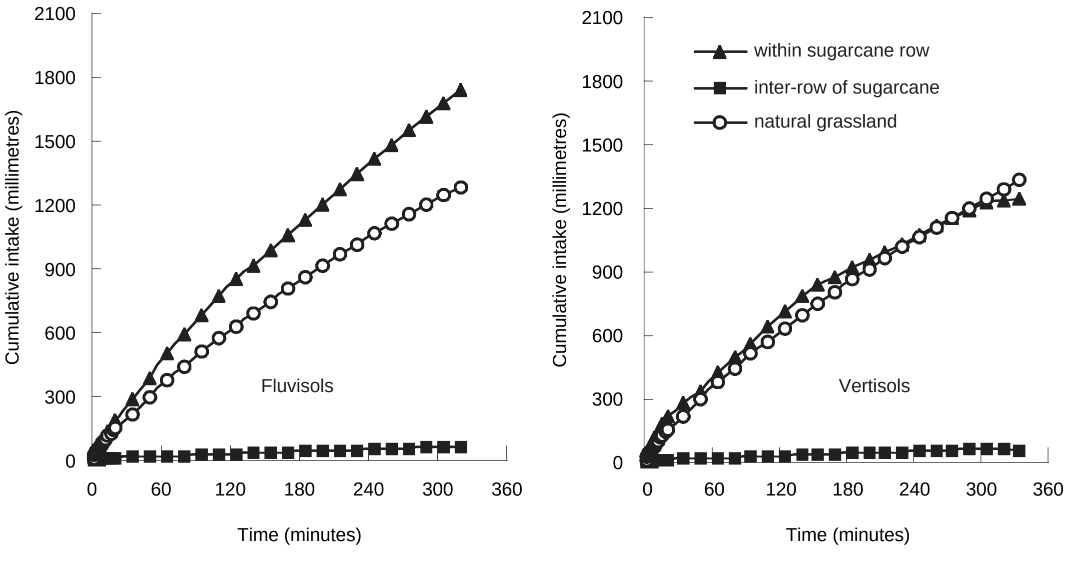

Figure 2. Cumulative infiltration of Fluvisols and Vertisols at Ramu Sugar Plantation (modified from Hartemink 1998b).

Leaf nutrients

Median N content in the cane leaves at Ramu Sugar Plantation varied from 19.3 to 22.0 g/kg between 1983 and 1994 (Table 12). The lowest figure was the median of the 27 leaf samples taken in 1994. There appears to be a declining trend in the P content of cane leaves but the median value of 2.4 g/kg in 1994 is still above the optimum concentration of 1.8 g/kg as given by Anderson and Bowen (1990) and 2.1 g/kg as given by de Geus (1973). The apparent trend in leaf P decline coincides with the decrease observed in the levels of available P in the topsoils (Table 2). Leaf K content was favourable in the 1980s but the median value in 1994 was at the lower border of the optimum range of 12.5 g/kg. Levels of S, Ca and Mg show no apparent trend and all median values are in the optimum range.

All major nutrients in the sugarcane leaves decreased significantly between the mid-1980s and 1990s (Table 13). The largest decrease was found in the Ca and Mg concentrations, which had decreased by 36% and 33%, respectively. Small but highly significant differences were found between the P concentrations of the mid-1980s and 1990s.

There are several keys to the interpretation of leaf nutrient concentration for sugarcane, but much depends on the age of the plant at sampling, the sugarcane variety, the plant part sampled, soil conditions and fertiliser applications. The first row in Table 14 summarises the critical nutrient concentration for the fourth leaf as compiled from several sources. The mean nutrient concentration in both the mid-1980s and the 1990s (Table 13) exceeded the critical level. However, the percentage samples below the critical level increased dramatically between the mid-1980s and 1990s (Table 14). The increase was particularly high for N and K, and the data showed that in the mid-1990s about 40% of the samples were below the critical N concentration, whereas 47% of the samples were below the critical K concentration. In the mid-1990s, although Ca and Mg concentrations had decreased dramatically (Table 13), there were very few values below the critical levels.

Sugarcane yields

Mean sugarcane yields at Ramu Sugar Plantation have varied between 1980 and 1995 from 28 to 88 tonnes/ha/year; sugar yield varied from 2.0 to 8.2 tonnes/ha/year. Regression analysis of cane and sugar yield showed a strong linear relationship; the sugar content of the cane was about 9% (sugar yield = 0.09 x cane yield – 0.29; $r^2 = 0.942$). Much of the variation in sugarcane yields can be explained by pests and diseases, some of which can have a high impact on yield if poorly controlled. Ramu stunt was first observed in 1985; in 1986 the disease was widespread in the sugarcane variety Ragnar that occupied most of the plantation. The rapid decrease in yield 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 (Hartemink and Kuniata 1996). Also, the white grub was present in 1984 and 1985 but its effects were not very obvious, although potential losses of up to 36 tonnes sugarcane/ha/year can be expected if the infestation is severe (L.S. Kuniata, pers. comm.). As a result of the Ramu stunt infestation, most of the sugarcane 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 and resulting in an 18% reduction in sugar production (Hartemink and Kuniata 1996). Average cane yields in 1988 were substantially 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 that reduced yields to about 50 tonnes sugarcane/ha. 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 stabilised at around 55–60 tonnes sugarcane/ha/year. Such low yields can be explained through the planting of varieties resistant to pests and diseases, since 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 sugarcane and weeds. Dominant weeds at Ramu Sugar Plantation are itchgrass (*Rottboellia* sp.) and nutgrass (*Cyperus rotundus*); weed competition trials have shown that itchgrass can give yield reductions of up to 54 tonnes sugarcane/ha (L.S. Kuniata, pers. comm.). In commercial fields, an average loss of 26 tonnes sugarcane/ha was observed in 1993 but losses were reduced to 5 tonnes sugarcane/ha in 1995 as a result of improved weed control measures. It confirms the general belief that sugarcane does not tolerate competition for water and nutrients.

Table 10. Nutrient removal (range[a]) and nutrient input with fertilisers, 1991–95.

	Nutrient removal (kg/ha)						Fertiliser applications (kg/ha)			Difference (kg/ha)					
	N		P		K					N		P		K	
	low	high	low	high	low	high	N	P	K	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 11. Mean difference between nutrient removal and nutrient input (kg/ha).

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

Table 12. Macronutrient concentrations (g/kg) of sugarcane leaves at Ramu Sugar Plantation (median values with CV%) (type I data).

Year	Number 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 (13%)
1994	27	19.3 (10%)	2.4 (7%)	12.5 (11%)	na	3.1 (20%)	1.3 (17%)

na = not available

[a] There were only 11 samples of sulfur, calcium and magnesium in 1983.

Table 13. Macronutrient concentrations (g/kg) of sugarcane leaves in the 1980s and 1990s (type I data).

Period	Number 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		$P < 0.001$	$P < 0.01$	$P < 0.001$	$P < 0.001$	$P < 0.001$

Source: Hartemink (1998c)

Table 14. Critical nutrient concentration (g/kg) and percentage samples below this level, 1980s and 1990s.

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

Source: Hartemink (1998c)

Discussion

In the previous section, evidence was presented for changes in young alluvial soils under sugarcane cultivation since 1979. Figure 3 summarises the major changes brought about by continuous sugarcane cultivation at Ramu Sugar Plantation. Soil erosion and surface sealing were not measured but soil compaction and reduced water infiltration suggest that they may be occurring.

What do these changes in soil properties indicate for the sustainability of sugarcane cultivation at the plantation? Discussion of this question includes sections on indicators of sustainable land management, threshold values in soil properties, and requirements for sustainable land management under sugarcane.

Indicators of sustainability

Sustainability, although a dynamic concept, implies some sort of equilibrium or steady state (O'Callaghan and Wyseure 1994). Indicators, defined as attributes that measure or reflect conditions of sustainability (Smyth and Dumanski 1995), should therefore not show a significant declining trend (Larson and Pierce 1994). Zinck and Farshad (1995) have argued that a good indicator is free of bias, sensitive to temporal changes and spatial variability, and is predictive and referenced to threshold values. In addition, a useful indicator is a clear measure of a cause having a well understood effect that can be measured and expressed in numerical terms (Smyth and Dumanski 1995). One of the best indicators of sustainable land management is crop yield. Yields at the plantation were largely determined by insect pests, diseases and weeds (Hartemink and Kuniata 1996). These caused large variation, and overall no declining yield trend could be observed.

The significant decrease in soil chemical properties at Ramu Sugar Plantation indicates, however, that soil management has not been sustainable. Changes in soil physical properties give a similar indication. These changes reflect the way in which the soils were managed including continuous cultivation with the use of acidifying N fertilisers, the absence of P and K fertilisers, and the use of heavy machinery. The long-term data on soil chemical properties indicate a gradual decline, but the rates of change in soil physical properties are unknown. They may have been brought about much faster, although it could not be ascertained whether the soil compaction had accumulated with time (Bakker and Davis 1995) or resulted from one field operation when the soils were too wet. Moreover, the seasonal effect on bulk density and water intake is unknown. Therefore, soil chemical properties are easier to use as indicators of sustainable land management than are soil physical properties.

There were only a limited number of soil chemical properties available from the plantation's records that could be used as indicators. Other data would have been helpful — total N content of the soil or

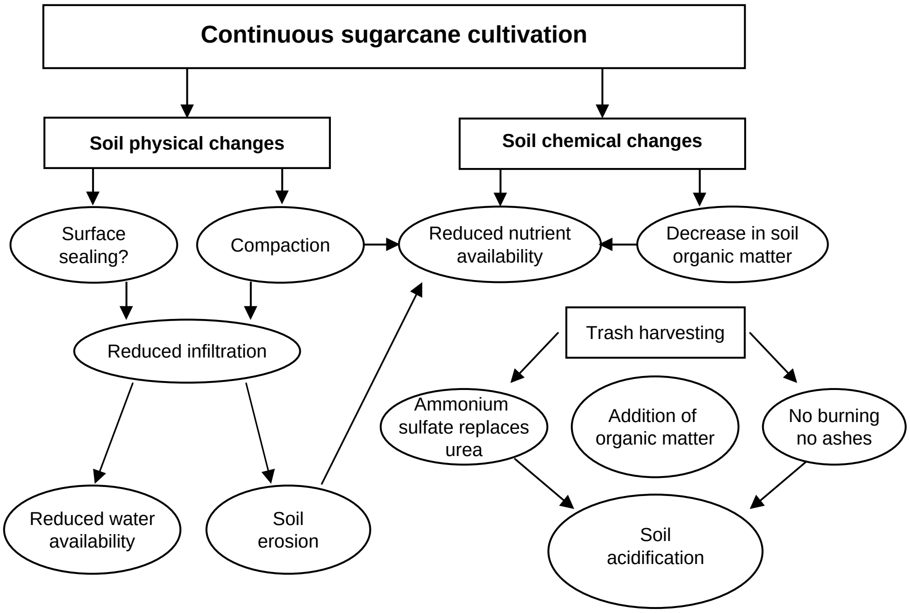

Figure 3. Changes in soil properties under continuous sugar cultivation at Ramu Sugar Plantation (see text for explanation).

microbial biomass, to list two examples (Doran and Parkin 1996). In addition, data on surface sealing and water erosion would have been helpful. There is, however, a cost to collect such data, and for the general assessment presented here the extra cost is unlikely to have been justified by the extra information obtained. For plantation management, obtaining spatial information on the changes in soil properties is probably more useful.

Threshold values

Soil chemical and physical properties have changed, but did they reach levels (thresholds) which affect the sugarcane? The pH levels in 1996 were about 5.8. Although the optimum pH for sugarcane is about 6.5 (Yates 1978), sugarcane is successfully grown on soils with pH 4, as in Guyana, andils with pH over 7, as in many parts of Barbados. It is therefore unlikely that the current pH levels adversely affect sugarcane production. Levels of available P (Olsen determination) were on average over 25 mg/kg, which is a high level for sugarcane (Blackburn 1984). Also, the exchangeable cations remained at favourable levels for sugarcane cultivation. This suggests that the soil chemical properties had not reached threshold values for sugarcane 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 inter-row. These values are about 1.3 tonnes/m^3 for the Fluvisol topsoils and 1.2 tonnes/m^3 for the Vertisol topsoils, and only slightly higher for the subsoils. Absolutely seen, they are low (< 1.4 tonnes/m^3) and most studies with sugarcane have indicated critical bulk densities of up to 1.8 and 1.9 tonnes/m^3 for rooting (Blackburn 1984).

A surrogate but more quantitative way to investigate whether threshold values were reached is by the analysis of tissue samples from the sugarcane, reflecting the nutrient availability. It was shown that all major nutrients were significantly lower in the sugarcane leaves in the 1990s (n = 160) compared to the 1980s (n = 93) (Table 9). The number of samples below the critical nutrient concentration increased dramatically in the 1990s: more than two-thirds of the leaf samples were deficient in N, about one-fifth were deficient in P, and nearly one-half were deficient in K (Table 10). Although P and K levels in the soil were still favourable (Tables 2 and 3), 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 soil compaction and acidification.

Requirements for sustainable land management

Changes in soil chemical properties will 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 will continue to decrease, since they are not replenished by inorganic fertilisers. Applying these nutrients to maintain favourable levels is, however, only useful if the soil compaction is dealt with. The regular application of small quantities of lime prevents the development of topsoil and subsoil acidity. Liming is usually economical, but may depress the sucrose content of the sugarcane (Kingston et al. 1996). Application rates of 1–2 tonnes of lime/ha when the cane is ploughed out may be sufficient to maintain favourable pH levels. Another possibility is to apply non-acidifying fertilisers such as calcium–ammonium nitrate, which will not reverse the decrease in $pH_{w,}$ but may prevent further soil acidification.

Since 1979, organic matter levels have been shown to have decreased by about 40%, but the current practice of trash harvesting is likely to increase soil organic matter (Wood 1991). Such an increase would affect many soil properties. For example, the pH BC may increase, reducing the acidifying effects of sulfate of ammonia (Hartemink 1998a) but also reducing the compactibility of the soil by increasing resistance to deformation (Soane 1990). Trash harvesting is therefore an important step to achieve sustainable land management and is likely to improve sugarcane 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 are helpful (de Boer 1997). The topsoil compaction is alleviated when the sugarcane is ploughed out, but deep tillage or subsoiling is required for the subsoil. It is recommended for the Fluvisols, but subsoiling 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 that is hard to reverse.

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

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