ELSEVIER

Geoderma 85 (1998) 283–306

GEODERMA

Soil chemical and physical properties as indicators of sustainable land management under sugar cane in Papua New Guinea

Alfred E. Hartemink *

University of Technology, Department of Agriculture, PO Box 82, Lae, Papua New Guinea

Received 24 June 1997; accepted 20 April 1998

Abstract

The sustainability of land management was assessed for a sugar cane plantation using soil chemical and physical properties as indicators. The plantation (6000 ha) was established in 1979 on a broad alluvial plain and the majority of the soils are classified as Eutric and Mollic Fluvisols (73%) and Eutric Vertisols (23%). Average annual rainfall is about 2000 mm with a dry season from May to November. The sugar cane is not irrigated and receives only N fertilizer (90 kg N ha^{-1} yr^{-1}). Detailed soil maps were used to make a selection (186 samples) of the existing soil chemical database (1979–1994) and for selecting sample sites in 1996. The pH of the topsoils had decreased from about 6.5 to 5.8 in both Fluvisols and Vertisols accompanied by a decrease in CEC and exchangeable K. Between 1979 and 1996, organic C contents declined from about 5.5 to 3.2 g kg^{-1}. A significant decline in available P was found in Fluvisols (40 to 32 mg kg^{-1}) and Vertisols (37 to 25 mg kg^{-1}). Significant changes in soil chemical properties were mostly confined to the topsoil and differences between Fluvisols and Vertisols were relatively small. Changes in soil physical properties were assessed by measuring bulk density and infiltration under sugar cane and adjoining natural grassland areas. Bulk density and water intake were similar under natural grassland and within the sugar cane rows. The interrow had a significantly higher bulk density due to wheel traffic, which caused very low water intake. Bulk densities at which infiltration rates were severely reduced were slightly higher in Fluvisols than in Vertisols but for both Major Soil Groupings an increase of only 0.2 Mg m^{-3} was critical. Changes in soil chemical and physical properties indicated that land management is not sustaining the resource base for sugar cane cultivation in the long-term. Threshold values in soil chemical properties were not reached and they were in 1996 still favourable for sugar cane cultivation. The soil compaction, however, directly affect the sugar cane as it seriously reduce rooting. It is concluded that routine

* Fax: +675-4757380; E-mail: ahartemink@ag.unitech.ac.pg

0016-7061/98/$19.00 © 1998 Elsevier Science B.V. All rights reserved.
PII S0016-7061(98)00048-2

soil analytical data combined with data that can be easily collected suffices to make a general assessment of sustainable land management at a plantation scale. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: soil fertility decline; acidification; compaction; infiltration; sustainability; indicators; Fluvisols; Vertisols; sugar cane

1. Introduction

Since the Bruntland report of 1987 on 'Our Common Future' and the 'Earth Summit' in Rio de Janeiro in 1992, there has been a wide debate on the issue of sustainability, particularly in relation to soils, land and agriculture. Much attention has been given to tropical regions where an increasing population is competing for limited natural resources which may result in land degradation (Greenland, 1981; Larson, 1986; El-Swaify, 1991; Lal, 1995; Eden, 1996). Although regional differences in the population increase are large (Fischer and Heilig, 1997) as are the soil resources (Eswaran et al., 1992), methods of sustainable land management are needed in many parts of the tropics (Stewart et al., 1990; Gryseels et al., 1992; FAO, 1994). Their development represents a widely recognized challenge (Ewel, 1986; Okigbo, 1990; Ragland and Lal, 1993; Greenland and Szabolcs, 1994; Eger et al., 1996).

Various definitions exist for sustainable land management (Greenland, 1994) but in essence, it 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 which has been indicated by pedologists (Bouma, 1994), soil fertility experts (Scholes et al., 1994) as well as soil biologists (Swift and Sanchez, 1984). Assessing sustainable land management is as difficult as defining it. Key problems are the spatial and temporal borders which need to be chosen for its assessment (Fresco and Kroonenberg, 1992; Heilig, 1997) and the selection of indicators to evaluate sustainability in a given locality (Pieri et al., 1995; 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. An important plantation crop is sugar cane (interspecific hybrids of *Sachharum* spp.) which is mostly monocropped with husbandry practises similar to cropping systems of the temperate regions (Hartemink and Wood, 1998). Sugar cane is indigenous to Papua New Guinea but it was not until 1979 that a commercial plantation was developed. 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 sugar cane production. Hence, soils were not regarded as a limiting factor in sugar cane production. Such differences in perception between the users of the soil and the experts is common (Bouma, 1993) and possibly not unique to plantation agriculture.

In this paper, an assessment is made of the sustainability of land management on a sugar cane plantation in Papua New Guinea. The hypothesis tested was simple. If it could be proven that soil properties have changed significantly and such changes can be attributed to the effect of continuous sugar cane cultivation, than sugar cane cultivation at the plantation is not sustainable. Although the term sustainable land management is used throughout this paper, it mostly refers to the soil aspect only. 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 which commonly provides useful information to assess changes in soil properties (Young, 1991; Hartemink, 1996). No historical data were available for the soil physical properties and changes were assessed from measurements in sugar cane and uncultivated land.

2. Materials and methods

2.1. The plantation

The research was conducted on a sugar cane plantation in the Ramu valley in the Madang Province of Papua New Guinea (Fig. 1). 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* on the deeper and fine textured soils, *Themeda australis* on stony and shallow soils, and *Saccharum spontaneum* and *Ophiuros sp*. along streams and rivers (Chartres, 1981). All grassland areas were chisel-ploughed and trees were clear-felled for the planting of sugar cane.

The first 3 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 and overhead-irrigation is only applied at nurseries. About 1800 ha of sugar cane are planted mechanically each year from late February to May. The harvesting season lasts from May to October and cutter–chopper–loader harvesters are used with 20 Mg tractors and trailers transporting the cane to the factory. The majority of the transport equipment has conventional tyres. Most of the sugar

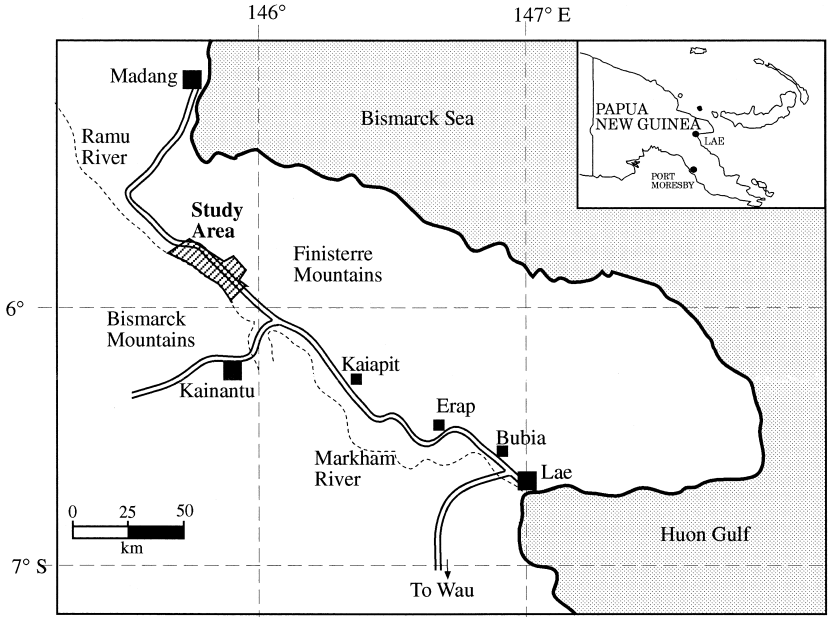

Fig. 1. Location of the sugar cane plantation in Papua New Guinea.

cane is trash-harvested (no pre-harvesting burning) which may leave up to 10 Mg ha^{-1} of crop residues or trash on the ground after harvesting (Ng Kee Kwong et al., 1987). Up to five crops (i.e., plant cane + four ratoons) are sometimes obtained after which the land is ploughed and replanted. Prior to 1989, N fertilizer was applied as urea but when trash-harvesting replaced pre-harvesting burning, volatilization losses of urea-N were expected (Freney et al., 1992). Nearly all N fertilizer applied after 1989 was therefore in the form of sulphate of ammonia and on average 90 kg N ha^{-1} yr^{-1} was applied between 1991 to 1995. Nitrogen applications are mostly broadcasted between August and November. Phosphorus and potassium fertilizers are not applied.

2.2. 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 (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 mm yr^{-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. March is the wettest month with an average rainfall of 284 mm. Evaporation (Class A open

pan) is about 2281 mm yr^{-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).

2.3. Geomorphology and soils

The Ramu valley is drained by the perennial Ramu River and several tributaries with erratic flow characteristics. The valley forms together with the Markham valley a large *graben* which has been a zone of subsidence since the Late Tertiary period (Löffler, 1977). The margins of the depression are marked by steep, fault scarps of the Bismarck mountains in the Southwest and the tectonically unstable Finisterre mountains in the Northeast (Chartres, 1981). At the site of the plantation, the valley is about 10 km wide (Fig. 2). 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 fans which are fluvial in origin 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.

The parent material of the soils at the plantation is alluvium. The soils are pedologically very young although their exact age is unknown. Organic material collected from the lower part of the Erap fan in the Markham valley gave a C^{14} age of 610 ± 150 years BP but the soils in the Ramu area are possibly older based upon the degree of weathering (Löffler, 1977). The soils have been developed in clayey, silty and sandy sediments and from the weathering products of the water-worn rock fragments. Common rock types are sandstone, siltstone and limestone, but also basalt and igneous rocks with coarser textures occur. Although deep and nearly gravel free soils occur, extensive areas have

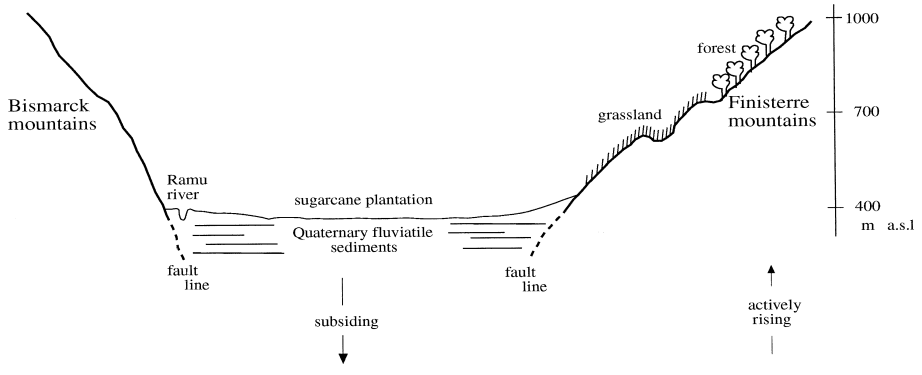

Fig. 2. Cross-section through the Ramu valley (not to scale).

slightly gravelly topsoils and gravelly or stony subsoils. Sheet and gully erosion is a threat in some areas but contour furrows have been dug to control surface water.

Fluvisols are the dominant Major Soil Grouping at the plantation (Table 1). The majority of the Fluvisols are Eutric or Mollic (FAO-UNESCO), equivalent to Tropofluvents (Entisols) in USDA Soil Taxonomy and very locally as Tropopsamments (Bleeker, 1983). Stratification is common in most Fluvisols but in some it is less clear possibly due to the combined activity of soil fauna and sugar cane roots in the solum (Edelman and Van der Voorde, 1963). A pedofeature of many Fluvisols is their thick (>0.25 m), dark-coloured A-horizon with a base saturation exceeding 50%, which qualifies as a Mollic epipedon. Chartres (1981) and Bleeker (1983) classified these soils as Mollisols (Hapludols) but in FAO-UNESCO classification they key out as Mollic Fluvisols and not as Phaeozems ($=$ Mollisols) because of the dominant fluvic properties. The Fluvisols have an irregular organic matter distribution and large changes in particle size with depth inherited from the parent material deposition (Table 2).

Table 1
Major soil groupings (FAO-UNESCO, 1988) of the sugar cane plantation

Major soil groupings	Main diagnostic properties	USDA soil taxonomy equivalent[a]	Approximate extent (ha)[b]	Cane yield estimate (Mg ha^{-1})[c]
Fluvisols	Very young, alluvial soils with weak horizon differentiation. The soils are developed in sediments, and are stratified with often an irregular organic matter profile.	Fluvents (Entisols)	4100	58–74
Vertisols	Fine textured soils with poor internal drainage. When dry, the soils crack to at least 50 cm depth and have slickensides and wedge-shaped structural elements in the subsurface soil.	Vertisols	1320	70
Gleysols	Soils with clear signs of excess wetness within 50 cm depth. The soils are formed in unconsolidated materials and are usually found in depressed areas with shallow groundwater.	Aquic suborders	180	45

[a] From Soil Survey Staff (1994).
[b] Calculated from the 1:25 000 soil map (Booker Agriculture International, 1987).
[c] Modified after Booker Agriculture International (1987).

Table 2
Soil chemical and physical properties of an Eutric Fluvisol and Eutric Vertisol at the sugar cane plantation

Major soil groupings	Sampling depth (m)	pH_w 1:2.5	pH KCl 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})	Exchangeable cations ($mmol_c$ kg^{-1})			Base saturation (%)	Particle size fractions (g kg^{-1})		
								Ca	Mg	K		Clay	Silt	Sand
Fluvisol[a]	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[b]	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

[a]Samples taken in a soil pit in August 1996; sugar cane cultivation since 1982.
[b]Samples taken in a soil pit in January 1996; sugar cane cultivation since 1981.

Vertisols cover about one quarter of the sugar cane plantation. 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 soils are, however, likely to be Vertisols because pedofeatures include wedge-shaped structural elements, slickensides in the subsoil, fine texture (>500 g clay kg^{-1} soil), and hard consistency and cracks when dry. In the FAO-UNESCO classification, these soils are Eutric Vertisols, equivalent to the great group of Hapluderts (Soil Survey Staff, 1994). The Vertisols have a high CEC due to smectite clays with a high permanent charge (Ahmad, 1983) and favourable cation levels (Table 2). Like most Vertisols in the humid tropics, they have fairly high organic carbon contents and contain no calcareous concretions (Coulombe et al., 1996).

In some low-lying areas, soils with poor internal drainage occur and these are classified as Gleysols (Table 2). They cover only a small area of the plantation 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. 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 (Loveland, 1991). Since these soils are confined to a small area, they were also excluded from this study.

2.4. Soil chemical data

With the establishment of the plantation, 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. In addition, the chemical data of 21 soil profiles from the initial soil survey report was available (Booker Agriculture International, 1979).

The detailed soil maps (1:10,000 and 1:25,000) of the plantation were used to list sugar cane blocks which were located within one mapping unit only, i.e., Fluvisol or Vertisol. This list was combined with the existing data set ($n = 487$) of the plantation whereafter analytical data from sugar cane blocks with more than one mapping unit was eliminated. A reduced data set remained of sugar cane blocks which had either Fluvisols ($n = 94$) or Vertisols ($n = 92$) as a Major Soil Grouping. The soil maps and the reduced data set were then used to select 20 sugar cane blocks of which samples were taken in 1996.

2.5. Soil sampling and analysis

Between 1982 and 1994, topsoil samples were commonly taken after the last ratoon when the 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; mini-pits were used for the 0–0.15 and 0.15–0.30 m soil horizons and an Edelman auger for the lower horizons. All soil samples of 1996 were taken in the interrow of the sugar cane.

Air-dried, 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 (1:2.5 w/v); pH KCl (1:2.5 1 M KCl w/v); organic C by Walkley and Black; total N by Kjeldahl; available P by Olsen; exchangeable cations and CEC by 1 M NH_4OAc percolation; particle size analysis by hydrometer. The soil samples of the initial soil survey (1979) were analyzed at the laboratories of Hunting Technical Services in England. Except for available P, all other methods were identical to the ones described above.

2.6. Soil physical measurements

Infiltration measurements were made using the double ring (cylinder) method with measurements confined to the inner-ring. Four sugar cane blocks (two Eutric Fluvisols, two 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, measurements were made in natural grassland and these were also triplicated. Although the infiltration measurements were made in periods with ample rain, particularly during the night (November 1996 and April 1997), the sites were prewetted 24 h 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. In total 36 infiltration measurements were made of at least 5 h.

At the same sites where the infiltration measurements were made, soil pits were dug ($\pm$1 m depth) for bulk density measurements. A total of eight soil pits were sampled using cores (100 ml) at four depths: 0–0.15, 0.15–0.30, 0.30–0.50 and 0.50–0.70 m. Three cores were used for each depth and they were oven-dried at 105°C for 72 h. In total 126 core samples were taken at the infiltration sites and an additional 18 cores were taken in two other soil pits. Due to moist conditions at the time of sampling, cracks were absent in the Vertisols which largely affects the denseness (Ahmad, 1983). In the Fluvisols there was abundant gravel below 0.5 m depth and therefore the bulk density could not be

accurately determined with 100 ml cores as their volume is too small (Vincent and Chadwick, 1994).

2.7. Statistical analysis

Student's *t*-test was applied for paired top- and subsoil samples of Fluvisols and Vertisols from the 1980s and 1990s. Differences in topsoil chemical properties between Fluvisols and Vertisols were also tested for the 1980s and 1990s. The number of samples from the Fluvisols was, however, not equal to the Vertisols (67 vs. 64 in 1980s; 20 vs. 24 in 1990s). The statistical analysis for groups of unequal sizes follows, however, almost exactly the pattern for groups of equal sizes (Snedecor and Cochran, 1989). The pooled variance for the data of each Major Soil Grouping was calculated from the sum of squared deviations within the population. This was followed by the calculation of the *t*-value taking into consideration the unequal sample size. For the soil physical data, standard error of the differences in mean infiltration rates and soil bulk density were calculated for the sugar cane interrow, within the rows, and the natural grassland. All statistical analysis was conducted using Statistix for Windows software.

3. Results and discussion

3.1. Soil chemical properties

Between 1979 and 1996, the topsoil pH_w (pH H_2O) decreased from about 6.5 to 5.8 in both Fluvisols and Vertisols (Table 3). 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 a two-times larger 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 decrease in exchangeable bases and CEC. Particularly 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. The loss occurred in both Major Soil Groupings despite the high clay contents of the Vertisols, which is an asset against loss of organic matter (Coulombe et al., 1996). A similar rate of decrease in organic C was reported for Vertisols by Skjemstad et al. (1986). Levels of available P declined in Fluvisols and Vertisols but variation was large.

Table 3
Topsoil (0–0.15 m) chemical properties of Fluvisols and Vertisols between 1979 and 1996 (arithmetic mean ± 1 SD)

Major soil groupings	Year	Number of samples[a]	pH_w 1:2.5	Organic C (g kg^{-1})	Available P (mg kg^{-1})	CEC pH 7 ($mmol_c$ kg^{-1})	Exchangeable cations ($mmol_c$ kg^{-1})			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

[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 to 0–0.28 m (mean 0.18 m).
na = not available.

Table 4
Changes in soil chemical properties of Fluvisols

Sampling depth (m):	0–0.15 (10 pairs)		0.15–0.30 (2 pairs)		0.30–0.45 (2 pairs)		0.45–0.60 (2 pairs)	
Sampling period[a]:	1980s	1990s	1986	1996	1986	1996	1986	1996
pH_w 1:2.5	6.3	5.9***	6.4	6.1*	6.4	6.0	6.6	6.1
Available P (mg kg^{-1})	40	32*	23	25	14	12	12	9
CEC ($mmol_c$ kg^{-1})	422	372*	470	344	505	390	450	422
Exchangeable Ca ($mmol_c$ kg^{-1})	238	225	281	196	314	232	288	281
Exchangeable Mg ($mmol_c$ kg^{-1})	105	101	135	98	139	109	119	123
Exchangeable K ($mmol_c$ kg^{-1})	11.9	9.6*	5.2	5.4	4.0	2.3	2.9	2.0
Base saturation (%)	84	89	90	87	91	80	91	84

[a]For the 0–0.15 m soil horizon paired samples from the 1980s (1983–1986) and 1990s (1994–1996) were used; for the lower horizons paired samples from 1986 and 1996 were used.

***, * indicate that the values in the 1990s were significantly lower from the 1980s at $p < 0.001$ and $p < 0.05$, respectively.

Table 5
Changes in soil chemical properties of Vertisols

Sampling depth (m):	0–0.15 (12 pairs)		0.15–0.30 (6 pairs)		0.30–0.45 (6 pairs)		0.45–0.60 (5 pairs)	
Sampling time[a]:	1980s	1990s	1986	1996	1986	1996	1986	1996
pH_w 1:2.5	6.3	5.9***	6.2	6.1	6.4	6.1	6.4	6.2
Available P (mg kg^{-1})	37	25*	36	21	17	10	12	6
CEC ($mmol_c$ kg^{-1})	478	437	505	463	488	451	524	472
Exchangeable Ca ($mmol_c$ kg^{-1})	296	271	325	286	320	307	354	324
Exchangeable Mg ($mmol_c$ kg^{-1})	111	109	116	114	119	128	128	132
Exchangeable K ($mmol_c$ kg^{-1})	13.3	9.2*	8.6	5.9	5.0	2.8*	3.8	2.2
Base saturation (%)	88	89	89	86	91	92	94	93

[a]For the 0–0.15 m soil horizon paired samples from the 1980s (1982–1986) and 1990s (1994–1996) were used; for the lower horizons paired samples from 1986 and 1996 were used.

***, * indicate that the values in the 1990s were significantly lower from the 1980s at $p < 0.001$ and $p < 0.05$, respectively.

Table 6
Difference in topsoil (0–0.15 m) chemical properties between Fluvisols and Vertisols in the 1980s and 1990s

Sampling time:	1982–1986			1994–1996		
Major soil groupings:	Fluvisols ($n = 67$)	Vertisols ($n = 64$)	Difference	Fluvisols ($n = 20$)	Vertisols ($n = 24$)	Difference
pH_w 1:2.5	6.3	6.3	ns	5.9	5.9	ns
Organic C (g kg^{-1})	na	na		33	32	ns
Total N (g kg^{-1})	na	na		1.9	1.9	ns
Available P (mg kg^{-1})	38	40	ns	28	30	ns
CEC ($mmol_c$ kg^{-1})	440	479	$p < 0.001$	382	437	$p < 0.05$
Exchangeable Ca ($mmol_c$ kg^{-1})	260	288	$p < 0.01$	227	275	$p < 0.01$
Exchangeable Mg ($mmol_c$ kg^{-1})	104	118	$p < 0.01$	101	122	$p < 0.05$
Exchangeable K ($mmol_c$ kg^{-1})	12.5	13.4	ns	9.7	11.0	ns
Base saturation (%)	86	87	ns	89	92	ns

ns = not significant.
na = not available.

Topsoil data of the same sugar cane block but from different times revealed a significant decline in pH_w, available P, CEC and exchangeable K in Fluvisols (Table 4). The pH_w in the 0.15–0.30 m soil horizon declined significantly but other soil chemical properties had not changed although many of the changes were nearly significant ($0.10 < p < 0.05$). In the Vertisols, a highly significant decline of 0.4 pH_w units was found in the topsoils but no changes were found in the lower horizons (Table 5). Available P and exchangeable K had decreased significantly in the topsoils whereas changes in other soil chemical properties at lower depths were not significant. Changes were mostly confined to the topsoil confirming the observations that sugar cane at the plantation is shallow rooted (< 0.3 m) with apparently little or no nutrient removal from deeper soil horizons.

Differences in soil chemical properties between Fluvisols and Vertisols were investigated for grouped data from the 1980s and 1990s (Table 6). In both periods, Vertisols had significantly higher levels of exchangeable Ca and Mg and a higher CEC than Fluvisols. Levels of exchangeable K, base saturation and other soil chemical properties were not different between the Fluvisols and Vertisols.

3.2. Soil physical properties

Bulk densities under natural grassland and within the sugar cane rows were similar for all depths of both Fluvisols and Vertisols (Fig. 3). The bulk densities

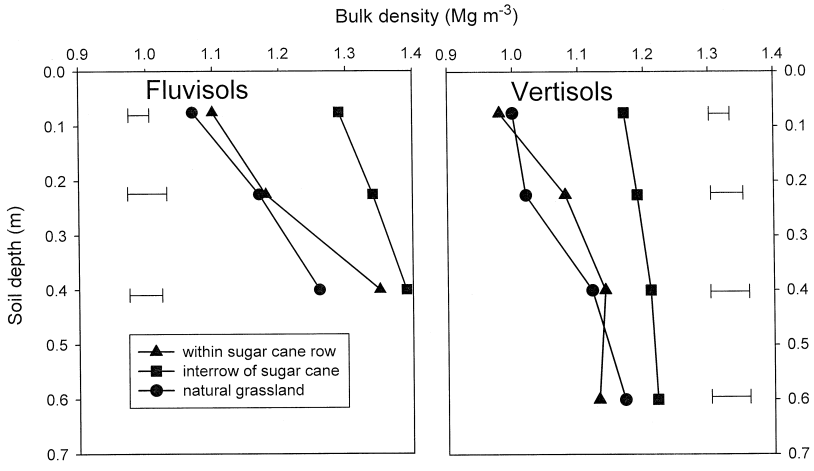

Fig. 3. Bulk density of Fluvisols and Vertisols under sugar cane and natural grassland. Each value is the arithmetic mean of six core samples. Vertical bars represent 1 SED (df)

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; Juang and Uehara, 1971). 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 Mg m^{-3} (+21%) in the Fluvisols and 0.18 Mg m^{-3} (+18%) in the Vertisols. Overall, Fluvisols had significantly higher bulk densities than the finer textured Vertisols (Table 7).

Cumulative water intake of natural grassland and within the sugar cane rows was very high in both Major Soil Groupings (Fig. 4). The high water intake of

Table 7
Difference in bulk density between Fluvisols and Vertisols under sugar cane and natural grassland

Sampling depth (m)	Sugar cane[a]			Natural grassland[b]		
	Fluvisols	Vertisols	Difference	Fluvisols	Vertisols	Difference
0–0.15	1.19	1.09	$p < 0.05$	1.07	1.00	ns
0.15–0.30	1.28	1.15	$p < 0.01$	1.17	1.02	$p < 0.05$
0.30–0.50	1.37	1.18	$p < 0.001$	1.26	1.12	$p < 0.05$

[a]Thirty core samples per sampling depth per MSG; mean data from interrows and within the rows.
[b]Twelve core samples per sampling depth per MSG.
ns = not significant.

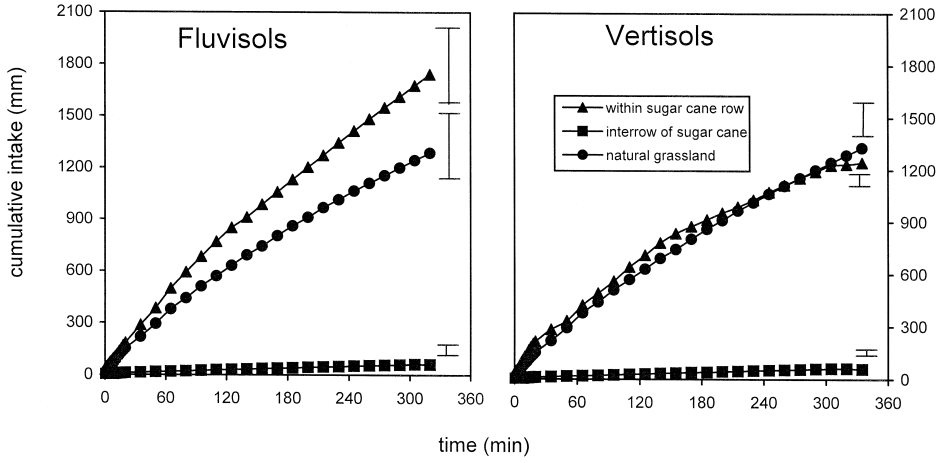

Fig. 4. Cumulative infiltration of Fluvisols and Vertisols. Vertical bars represent the largest standard deviation for measurements at an infiltration interval.

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).

Table 8
Mean infiltration rates[a] (mm h^{-1}) of Fluvisols and Vertisols under sugar cane and natural grassland

Major soil groupings	Infiltration time (min)	Number of readings	Land-use			SED[b]
			Sugar cane within the rows	Sugar cane interrow	Natural grassland	
Fluvisols	0–10	10	744	10	625	86
	20–80	5	484	8	418	55
	140–200	5	374	21	303	49
	245–305	5	334	20	271	42
Vertisols	0–10	10	901	37	616	176
	20–80	5	462	22	374	72
	140–200	5	310	14	284	43
	245–305	5	247	12	247	35

[a]Values reported are the arithmetic mean of six infiltration measurements from two sites.
[b]Standard error of the difference in means (10 *df*).

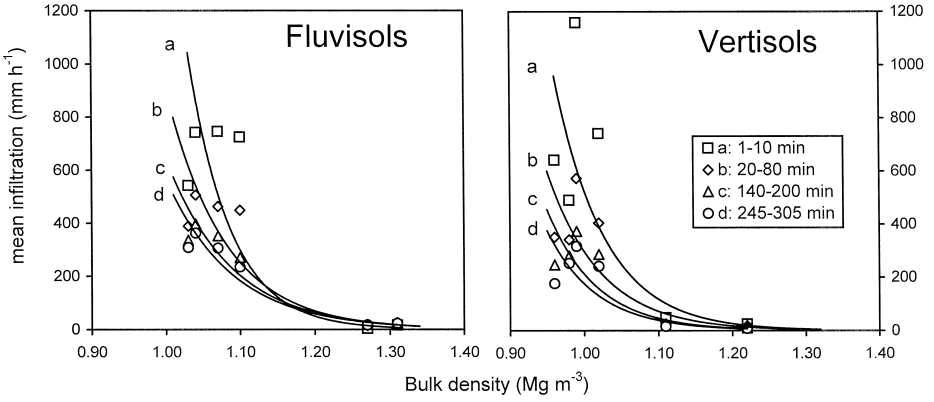

Fig. 5. Relation between topsoil bulk density and mean infiltration rates of Fluvisols and Vertisols.

Within the sugar cane rows, cumulative infiltration rates after 5 h 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 5 h. 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.

Mean infiltration rates in the interrow were very low compared to within the sugar cane rows at any time interval (Table 8). No differences were found between the natural grassland and within the sugar cane rows. Variation in water infiltration was particularly high in the Vertisols during the first 10 min but decreased thereafter.

Fig. 3 and Table 8 provide evidence for significantly higher bulk densities and lower infiltration rates in the interrow of sugar cane. To investigate the

Table 9
Exponential equations relating mean infiltration rates and the bulk density of the topsoil (0–0.15 m)

Major soil groupings	Infiltration time (min)	Equation[a]	r^2
Fluvisols	0–10	$MI = 1\times10^{11}e^{-17.9\times\rho_b}$	0.823
	20–80	$MI = 3\times10^{8}e^{-12.8\times\rho_b}$	0.912
	140–200	$MI = 7\times10^{7}e^{-11.6\times\rho_b}$	0.949
	245–305	$MI = 5\times10^{7}e^{-11.3\times\rho_b}$	0.952
Vertisols	0–10	$MI = 2\times10^{9}e^{-14.9\times\rho_b}$	0.867
	20–80	$MI = 4\times10^{8}e^{-14.0\times\rho_b}$	0.852
	140–200	$MI = 8\times10^{8}e^{-15.2\times\rho_b}$	0.887
	245–305	$MI = 6\times10^{8}e^{-15.1\times\rho_b}$	0.882

[a] MI = mean infiltration (mm h^{-1}); ρ_b = bulk density (Mg m^{-3}).

relation between the two, mean infiltration rates were plotted against topsoil bulk densities for Fluvisols and Vertisols. A negative exponential relation was observed, i.e., a rapid decrease in water intake with increasing bulk densities (Fig. 5). For both Fluvisols and Vertisols, a high correlation ($r^2 > 0.8$) was found between bulk density and mean infiltration rates (Table 9). Bulk densities at which mean infiltration was above 100 mm h^{-1} after 4 h, were 1.15 Mg m^{-3} for Fluvisols and 1.04 Mg m^{-3} for Vertisols. Bulk densities at which infiltration rates were 50 mm h^{-1} during the first 10 min, were 1.20 Mg m^{-3} for Fluvisols and 1.16 Mg m^{-3} for the Vertisols.

4. Discussion—sustainable land management

In Section 3, evidence was presented for changes in young alluvial soils under sugar cane cultivation since 1979. The question now arises what these changes in soil properties indicate for the sustainability of sugar cane cultivation at the plantation. That is discussed here including sections on indicators of sustainable land management, threshold values in soil properties, and requirements for sustainable land management under sugar cane.

4.1. Indicators

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). A good indicator of sustainable land management is crop yield. In the past 17 years, 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 indicates, however, that in the past 17 years 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 acidifying N fertilizers, the absence of P and K fertilizers, and the use of heavy machinery. The long-term data on soil chemical properties indicate a gradual decline (Table 3), 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 cumulated 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 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 such as total N contents of the soil or microbial biomass, to list a few (Doran and Parkin, 1996; Lal, 1997). 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, it is improbable that the extra costs would have been justified by the extra information obtained. For the plantation management, obtaining spatial information on the changes in soil properties is probably more useful.

4.2. Threshold values

Soil chemical and physical properties have changed but did they reach levels (thresholds) which affect the sugar cane? This question is comparable to qualitative land evaluation procedures in which land qualities are matched with crop requirements. 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 Mg m^{-3} for the Fluvisols and 1.2 Mg m^{-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).

A surrogate but more quantitative way to investigate whether threshold values were reached is by the analysis of tissue samples from the sugar cane reflecting the nutrient availability. Hartemink (1998b) showed that all major nutrients were significantly lower in the sugar cane leaves in the 1990s ($n = 160$) compared to the 1980s ($n = 93$). The number of samples below the critical nutrient concentration increased dramatically in the 1990s and more than two-thirds of the leaf samples were deficient in N, about one-fifth deficient in P, and nearly one-half were deficient in K. Although P and K levels in the soil were still favourable (Tables 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.

4.3. Some requirements

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; Vallis et al., 1996). Such increase affects many soil properties. For example, the pH buffering capacity may increase reducing the acidifying effects of sulphate of ammonia (Hartemink, 1998a), but it may also reduce the compactibility of the soil by increasing resistance to deformation (Soane, 1990). 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.

5. Conclusions

Between 1979 and 1996, soil chemical and physical properties had significantly changed on young alluvial soils under continuous sugar cane. These changes reflect the way in which the soils are being managed and indicate that in the past 17 years the soil resource base for sugar cane cultivation has not been sustained. The effects of the changes on sugar cane yield are masked by other factors (pests, diseases, weeds) and the fact that threshold values in most soil properties had not been reached. It was found that long-term data supplemented with data that can be easily collected suffice to make a general assessment of the

sustainability of land management at a plantation scale. The study suggests that sustainable land management should also be a matter of concern in high-external input agriculture in tropical regions where maximisation of profit is perhaps more important than sustaining the resources on which the profit in the long-term depends.

Acknowledgements

I am greatly indebted to Mr. L.S. Kuniata and Mr. J. Nero of Ramu Sugar for their assistance during data collection and fieldwork and to Mr. O. Ngere for the help in water infiltration measurements. I also would like to acknowledge Dr. E.M. Bridges for his comments on the draft, and Prof. J. Bouma, Prof. J.K. Syers and an anonymous reviewer for their constructive suggestions to modify this paper.

References

Ahmad, N., 1983. Vertisols. In: Wilding, L.P., Smeck, N.E., Hall, F.G. (Eds.), Pedogenesis and Soil Taxonomy, Vol. II: The Soil Orders. Elsevier, Amsterdam, pp. 91–123.

Ahmad, N., 1996. Management of Vertisols in rainfed conditions. In: Ahmad, N., Mermut A. (Eds.), Vertisols and Technologies for Their Management. Elsevier, Amsterdam, pp. 363–428.

Bain, J.H.C, Mackenzie, D.E., 1975. Explanatory notes geological series 1:250,000. Ramu, Papua New Guinea. Australian Government Publishing Service, Canberra.

Bakker, D.M., Davis, R.J., 1995. Soil deformation observations in a Vertisol under field traffic. Aust. J. Soil Res. 33, 817–832.

Blackburn, F., 1984. Sugar-Cane. Longman, Harlow.

Bleeker, P., 1983. Soils of Papua New Guinea. Australian National Univ. Press, Canberra.

Booker Agriculture International, 1979. Ramu Sugar Soil survey report. BAI, London.

Booker Agriculture International, 1987. Soil management at Ramu Sugar. Final report. BAI, London.

Bouma, J., 1993. Soil behavior under field conditions: differences in perception and their effects on research. Geoderma 60, 1–14.

Bouma, J., 1994. Sustainable land use as a future focus for pedology (a guest editorial). Soil Sci. Soc. Am. J. 58, 645–646.

Bouwer, H., 1986. Intake rate: cylinder infiltrometer. In: Methods of Soil Analysis, Part 1, Physical and Mineralogical Methods, 2nd edn. ASA-SSSA, Madison, pp. 825–844.

Chartres, C.J., 1981. Land resource assessment for sugar-cane cultivation in Papua New Guinea. Appl. Geogr. 1, 259–271.

Coulombe, C.E., Dixon, J.B., Wilding, L.P., 1996. Mineralogy and chemistry of Vertisols. In: Ahmad, N., Mermut, A. (Eds.), Vertisols and Technologies for Their Management. Developments in Soil Science 24. Elsevier, Amsterdam, pp. 115–200.

de Boer, H.G., 1997. Strip tillage in sugar cane agriculture: techniques and challenges. Zuckerindustrie 5, 371–375.

Doran, J.W., Parkin, T.B., 1996. Quantitative indicators of soil quality: a minimum data set. In:

Doran, J.W., Jones, A.J. (Eds.), Methods for Assessing Soil Quality. SSSA, Madison, pp. 25–37.
Edelman, C.H., Van der Voorde, P.K.J., 1963. Important characteristics of alluvial soils in the tropics. Soil Sci. 95, 258–263.
Eden, M.J., 1996. Land degradation: environmental, social and policy issues. In: Eden, M.J., Parry, J.T. (Eds.), Land Degradation in the Tropics—Environmental and Policy Issues. Pinter, London, pp. 3–18.
Eger, H., Fleischhauer, E., Hebel, A., Sombroek, W.G., 1996. Taking action for sustainable land-use: results from the 4th ISCO Conference in Bonn, Germany. Ambio 25, 480–483.
El-Swaify, S.A., 1991. Land-based limitations and threats to world food production. Outlook Agric. 20, 235–242.
Eswaran, H., Kimble, J., Cook, T., Beinroth, F.H., 1992. Soil diversity in the tropics: implications for agricultural development. In: Lal, R., Sanchez, P.A. (Eds.), Myths and Science of Soils in the Tropics. SSSA-ASA, Madison, pp. 1–16.
Ewel, J.J., 1986. Designing agricultural ecosystems for the humid tropics. Annu. Rev. Ecol. Syst. 17, 245–271.
FAO-UNESCO, 1988. Soil Map of the World, revised legend. World Soil Resources Report 60. Reprinted as technical paper 20. ISRIC, Wageningen.
FAO, 1994. Cherish the earth—soil management for sustainable agriculture and environmental protection in the tropics (text by Greenland, D.J.). FAO Land and Water Development Division, Rome.
Fischer, G., Heilig, G.K., 1997. Population momentum and the demand on land and water resources. In: Greenland, D.J., Gregory, P.J., Nye, P.H. (Eds.), Land Resources: On the Edge of the Malthusian Precipice? Philos. Trans. R. Soc. London, 869–889.
Freney, J.R., Denmead, O.T., Wood, A.W., Saffigna, P.G., Chapman, L.S., Ham, G.J., Hurney, A.P., Stewart, R.L., 1992. Factors controlling ammonia loss from trash covered sugarcane fields fertilized with urea. Fertilizer Res. 31, 341–349.
Fresco, L.O., Kroonenberg, S.B., 1992. Time and spatial scales in ecological sustainability. Land Use Policy 9, 155–168.
Greenland, D.J., 1981. Soil management and soil degradation. J. Soil Sci. 32, 301–322.
Greenland, D.J., 1994. Soil science and sustainable land management. In: Seyers, J.K., Rimmer, D.L. (Eds.), Soil Science and Sustainable Land Management in the Tropics. CAB International, Wallingford, pp. 1–15.
Greenland, D.J., Szabolcs, I. (Eds.), 1994. Soil Resilience and Sustainable Land Use. CAB International, Wallingford.
Gryseels, G., de wit, C.T., McCalla, A., Monyo, J., Kassam, A., Craswell, E., Collison, M., 1992. Setting agricultural research priorities for the CGIAR. Agric. Syst. 40, 59–103.
Hartemink, A.E., 1996. Using soil survey data for the assessment of nutrient depletion. In: Australian and New Zealand National Soils Conference. ASSSI, Melbourne, pp. 103–104.
Hartemink, A.E., 1998a. Acidification and pH buffering capacity of alluvial soils under sugarcane. Exp. Agric. 34, 231–243.
Hartemink, A.E., 1998b. Changes in soil fertility and leaf nutrient concentration at a sugar cane plantation in Papua New Guinea. Commun. Soil Sci. Plant Anal. 29, 1045–1060.
Hartemink, A.E., Kuniata, L.S., 1996. Some factors influencing yield trends of sugar cane in Papua New Guinea. Outlook Agric. 25, 227–234.
Hartemink, A.E., Wood, A.W., 1998. Sustainable land management in the tropics: the case of sugar cane plantations. Proceedings of the 16th World Congress of Soil Science. ISSS, Montpellier.
Heilig, G.K., 1997. Sustainable development—ten arguments against a biologistic ‘slow-down’ philosophy of social and economic development. Int. J. Sustainable Dev. World Ecol. 4, 1–16.

Juang, T.C., Uehara, G., 1971. Effects of ground-water table and soil compaction on nutrient element uptake and growth of sugarcane. Int. Soc. Sugarcane Technol. 14, 679–687.

Lal, R., 1979. Physical characteristics of soils of the tropics: determination and management. In: Lal, R., Greenland, D.J. (Eds.), Soil Physical Properties and Crop Production in the Tropics. Wiley, Chichester, pp. 7–44.

Lal, R., 1995. Trend in world agricultural land use: potential and constraints. In: Lal, R., Stewart, B.A. (Eds.), Soil Management—Experimental Basis for Sustainability and Environmental Quality. CRC Press, Boca Raton, FL, pp. 521–536.

Lal, R., 1997. Soil quality and sustainability. In: Lal, R., Blum, W.H., Valentin, C., Stewart, B.A. (Eds.), Methods for Assessment of Soil Degradation. CRC Press, Boca Raton, FL, pp. 17–30.

Larson, W.E., 1986. The adequacy of soil resources. Agron. J. 78, 221–225.

Larson, W.E., Pierce, F.J., 1994. The dynamics of soil quality as a measure of sustainable management. In: Doran, J.W., Coleman, D.C., Bezdicek, D.F., Stewart, B.A. (Eds.), Defining Soil Quality for a Sustainable Management. SSSA-ASA, Madison, pp. 37–51.

Löffler, E., 1977. Geomorphology of Papua New Guinea. Australian National Univ. Press, Canberra.

Loveland, P.J., 1991. Phosphorus sorption in some tropical soils. Consultancy report to Ramu Sugar. Cranfield Institute of Technology, Silsoe.

Ng Kee Kwong, K.F., Deville, J., Cavalot, P.C., Riviere, V., 1987. Value of cane trash in nitrogen nutrition of sugarcane. Plant Soil 102, 79–83.

O'Callaghan, J.R., Wyseure, G.C.L., 1994. Proposals for quantitative criteria in the management of sustainable agricultural systems. In: Syers, J.K., Rimmer, D.L. (Eds.), Soil Science and Sustainable Land Management in the Tropics. CAB International, Wallingford, pp. 27–39.

Okigbo, B.N., 1990. Sustainable agricultural systems in tropical Africa. In: Edwards, C.A., Lal, R., Madden, P., Miller, R.H., House, G. (Eds.), Sustainable Agricultural Systems. SWCS/St. Lucie Press, Florida, pp. 323–352

Parfitt, R.L., Thomas, A.D., 1975. Phosphorus availability and phosphate fixation in Markham Valley soils. Sci. New Guinea 3, 123–130.

Pieri, C., Dumanski, J., Hamblin, A., Young, A., 1995. Land quality indicators. World Bank Discussion Paper 315. Washington, DC.

Pocknee, S., Sumner, M.E., 1997. Cation and nitrogen contents of organic matter determine its soil liming potential. Soil Sci. Soc. Am. J. 61, 86–92.

Prove, B.G., Doogan, V.J., Truong, P.N.V., 1995. Nature and magnitude of soil erosion in sugarcane land on the wet tropical coast of north-eastern Queensland. Aust. J. Exp. Agric. 35, 641–649.

Ragland, J., Lal, R. (Eds.), 1993. Technologies for sustainable agriculture in the tropics. ASA special publication no. 56. ASA-CSSA-SSSA, Madison.

Rowell, D.L., Wild, A., 1985. Causes of soil acidification: a summary. Soil Use Manage. 1, 32–33.

Scholes, M.C., Swift, M.J., Heal, O.W., Sanchez, P.A., Ingram, J.S.I., Dalal, R.C., 1994. Soil fertility research in response to the demand for sustainability. In: Woomer, P.L., Swift, M.J. (Eds.), The Biological Management of Tropical Soil Fertility. Wiley, Chichester, pp. 1–14.

Skjemstad, J.O., Dalal, R.C., Barron, P.F., 1986. Spectroscopic investigations of cultivation effects on organic matter of Vertisols. Soil Sci. Soc. Am. J. 50, 354–359.

Smyth, A.J., Dumanski, J., 1995. A framework for evaluating sustainable land management. Can. J. Soil Sci. 75, 401–406.

Snedecor, G.W., Cochran, W.G., 1989. Statistical Methods, 8th edn. Iowa State Univ. Press, Ames.

Soane, B.D., 1990. The role of organic matter in soil compactibility: a review of some practical aspects. Soil Tillage Res. 16, 179–201.

Soil Survey Staff, 1994. Keys to Soil Taxonomy, 6th edn. U.S. Department of Agriculture. Pocahontas Press, Blacksburg, Virginia.

Stewart, B.A., Lal, R., El-Swaify, S.A., Eswaran, H., 1990. Sustaining the soil resource base of an expanding world agriculture. Proceedings of the 14th International Congress on Soil Science, Vol. VII. Kyoto, Japan, pp. 296–301.

Swift, M.J., Sanchez, P.A., 1984. Biological management of tropical soil fertility for sustained productivity. Nat. Resour. 20, 2–10.

Trouse, A.C., Humbert, R.P., 1961. Some effects of soil compaction on the development of sugar cane roots. Soil Sci. 91, 208–217.

Unger, P.W., Stewart, B.A., 1988. Conservation techniques for Vertisols. In: Wilding, L.P., Puentes, R. (Eds.), Vertisols: Their Distribution, Properties, Classification and Management. SMSS/Texas A&M University, TX, pp. 165–181.

Vallis, I., Parton, W.J., Keating, B.A., Wood, A.W., 1996. Simulation of the effects of trash and N fertilizer management on soil organic matter levels and yields of sugarcane. Soil Tillage Res. 38, 115–132.

Vincent, K.R., Chadwick, O.A., 1994. Sythesizing bulk density for soils with abundant rock fragments. Soil Sci. Soc. Am. J. 58, 455–464.

Wood, A.W., 1991. Management of crop residues following green harvesting of sugarcane in north Queensland. Soil Tillage Res. 20, 69–85.

Yadav, R.L., Prasad, S.R., 1992. Conserving the organic matter contents of the soil to sustain sugarcane yield. Exp. Agric. 28, 57–62.

Yates, R.A., 1978. The environment for sugarcane. In: Land Evaluation Standards for Rainfed Agriculture. World Soil Resources Report No. 49. FAO, Rome, pp. 58–72.

Young, A., 1991. Soil monitoring: a basic task for soil survey organizations. Soil Use Manage. 7, 126–130.

Young, A., 1997. Agroforestry for Soil Management, 2nd edn. CAB International, Wallingford.