

ACIDIFICATION AND pH BUFFERING CAPACITY OF ALLUVIAL SOILS UNDER SUGARCANE

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SUMMARY

Changes in soil pH water (pH_w) were investigated on a sugarcane plantation in the Ramu Valley of Papua New Guinea. The plantation was established in 1979 from natural grassland and the dominant soils were Fluvents and Vertisols. Statistical analysis of the topsoil pH_w data ($n = 541$) showed a significant ($\alpha = 0.01$) decrease from 6.5 to 5.7 between 1979 and 1996. Based on samples from 80 fields at different sampling times, the average decrease in topsoil pH_w was calculated to be 0.4 units after 10 years of continuous sugarcane cultivation ($r^2 = 0.481$). Between 1986 and 1996, subsoil pH_w also decreased significantly ($\alpha \leq 0.05$) by 0.4 and 0.3 units in the 0.30–0.45 and 0.45–0.60 m horizons respectively. The acidification trend accelerated in the 1990s when trash-harvesting replaced pre-harvesting burning and sulphate of ammonia became the dominant nitrogen fertilizer. Between 1991 and 1995, average nitrogen application rates were $90 \text{ kg N ha}^{-1} \text{ a}^{-1}$ which resulted in an annual addition of $11.6 \text{ kmol H}^+ \text{ ha}^{-1}$. The soil buffer capacity was estimated to be $125 \text{ kmol H}^+ \text{ ha}^{-1} \text{ pH}^{-1}$ which implied that the pH_w could further decrease by 0.5 unit after five annual applications of $90 \text{ kg N ha}^{-1} \text{ pH}^{-1}$ as sulphate of ammonia. Although these soils were young in pedological terms and they had been cultivated for less than 20 years, they had acidified significantly and this could affect sugarcane production adversely if such trend were to continue.

INTRODUCTION

About 70% of the world's 17 million ha under sugarcane cultivation has soils which are acid (Uexküll and Mutert, 1995). Many of these soils were already acid before they were planted with sugarcane, but in other soils cultivation has enhanced acidity through acid input and alkali removal. For most agricultural soils, addition of ammonium-nitrogen (N) through chemical fertilizers has been the main cause of acidification (Rowell and Wild, 1985). Both the oxidation by nitrification and the direct uptake of ammonium-N by plants results in acidification. This relation was first studied by Pierre in Alabama (USA) in the 1920s (Pierre, 1928) and several studies thereafter quantified the relation between N fertilizers and acidification. Abruña *et al.* (1958), who worked with napier grass species on a fertile alluvial soil, found a large decrease in the topsoil pH from 7.0 to 4.1 after three annual applications of 300 kg N ha^{-1} as NH_4NO_3 . Pierre *et al.* (1971) found a decline in topsoil pH from 6.6 to 5.7 after 13 annual applications of

200 kg $\text{NH}_4\text{NO}_3\text{-N ha}^{-1}$, and Jolley and Pierre (1977) found a significant decrease of 0.9 pH units after 17 annual applications of 168 kg $\text{NH}_4\text{NO}_3\text{-N ha}^{-1}$.

Soil acidification has also been reported from various areas of the world where sugarcane (*Saccharum* sp.) is grown. One of the earliest reports on soil acidification under sugarcane came from Hawaii where it was found that the use of sulphate of ammonia over a period of 20 years decreased the topsoil pH by 1.0 unit (Humbert, 1959). In the Herbert Valley in Queensland, Australia, Wood (1985) compared sugarcane and uncultivated land and found a significant difference of 0.3 pH units in the soil horizon at a depth of 0.2–0.3 m. The difference was attributed to the annual application of 200 kg N ha^{-1} . Moody and Aitken (1995), also working in Queensland, found a topsoil pH water of 4.5 after 15 years of sugarcane cultivation compared with a pH water of 5.5 in uncultivated land. Soil acidification was also reported from the sugarcane areas in Puerto Rico, USA (Abruña-Rodriguez and Vincente-Chandler, 1967), Fiji (Masilaca *et al.*, 1986), The Philippines (Alaban *et al.*, 1990), Florida, USA (Coale and Schueneman, 1993) and South Africa (Schroeder *et al.*, 1994).

In this paper soil acidification under commercial sugarcane cultivation on young alluvial soils in Papua New Guinea is discussed. The objectives of the research were (i) to quantify pH changes in the topsoils and subsoils, (ii) to estimate the soil buffering capacity, (iii) to discuss possible causes for the pH changes and (iv) to discuss soil management strategies which maintain favourable pH levels for the cultivation of sugarcane.

MATERIALS AND METHODS

Site

The research was conducted on a commercial sugarcane plantation in the Ramu Valley (lat 6°S, long 146°E) of Papua New Guinea. Prior to planting sugarcane 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* and *Themeda australis* (Chartres, 1981). All grassland areas were chisel-ploughed and trees were clear-felled for the planting of sugarcane.

The plantation has unimodal rainfall with a dry season from May to November and a rainy season from December to April. The average annual rainfall at the plantation is 1998 mm but between 1980 and 1995, annual rainfall varied from 1531 to 2560 mm (Hartemink and Kuniata, 1996). 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 a^{-1} and exceeds rainfall from May to November. Mean annual temperatures are 26.7°C with only minor fluctuations through the year. The Köppen climatic classification for the area is Am.

Soils

The Ramu Valley is drained by the perennial Ramu River and several tributaries. The valley comprises a series of fluvial fans and some of these 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 altitude at the plantation is about 400 m above sea level and the parent material of the soils is alluvium. The soils are pedologically young and have been developed in clayey, silty and sandy sediments and from the weathering products of the water-worn stones and boulders of varying lithology (Hartemink, 1998). The stones and boulders originate from sandstone, siltstone and limestone, but also from basalt and igneous rocks with coarser textures.

Fluvents are the dominant soil types equivalent to Fluvisols in the FAO–UNESCO revised legend (FAO–UNESCO, 1988). Many Fluvents are classified as Mollic and Typic Udifluvents and very locally as Tropopsamments (Bleeker, 1983). The soil temperature regime is isohyperthermic and the soil moisture regime is udic. Shrinking and swelling dark clay soils (Vertisols) cover about one-quarter of the sugarcane plantation. At the soil unit level in FAO–UNESCO, these soils are Eutric Vertisols, equivalent to the great group of Hapluderts in USDA Soil Taxonomy (Soil Survey Staff, 1994). Soil chemical and physical data of a representative Fluvent and Vertisol are given in Table 1.

Data collection

The pH_w data presented in this paper are from (i) the 1979 soil survey report of the plantation area, (ii) plantation records of soil analysis covering the period 1982–1994 and (iii) soil samples collected and analysed in 1996.

The initial soil survey (Booker Agriculture International, 1979) was conducted in 1979 before the plantation was established and the report provides physical and chemical data for 21 soil profiles. Samples were taken in grassland areas which were used for extensive grazing by beef cattle. Sampling depths varied from 0–0.12 m to 0–0.28 m. The average depth of the 21 topsoil samples was 0.18 m, and the samples were analysed for pH_w (1:2.5, w/v) at the laboratories of Hunting Technical Services Ltd in England.

Upon establishment, the plantation was divided into blocks of 10–20 ha. During the past fifteen years, samples were taken in nearly every sugarcane block and the pH_w was available for 487 topsoil samples (0–0.15 m depth). The samples were usually taken after the last ratoon when the cane was ploughed-out. Between 20 and 50 samples were taken in each block using an Edelman auger and these were bulked (L. S. Kuniata, Ramu Sugar Ltd, personal communication 1996). Samples which were air-dried, ground and passed through a 2-mm sieve were analysed at the Cambridge Laboratory in New Zealand and the pH was determined in distilled water (1:2.5, w/v).

In addition to the existing pH_w data set, 33 topsoil and 23 subsoil samples were taken in 1996 from sugarcane blocks that were also sampled in 1986. Mini-pits

Table 1. Soil chemical and physical properties of a Fluvent and a Vertisol† at the sugarcane plantation.

Soil type†	Sampling depth (m)	pH H ₂ O (1:2.5, w/v)	pH KCl (1:2.5, w/v)	Organic carbon (g kg ⁻¹)	Total nitrogen (g kg ⁻¹)	Phosphorus (P-Olsen, mg kg ⁻¹)	Exchangeable cations (mmol _c kg ⁻¹)				Base saturation (%)	Particle size fractions (g kg ⁻¹)		
							Ca	Mg	K	CEC pH7‡ (mmol _c kg ⁻¹)		clay	silt	sand
Fluvent	0-0.15	6.2	5.0	16.5	1.4	34	185	95	7.6	93	300	400		
	0.15-0.30	6.1	4.9	14.0	1.2	21	208	103	4.7	100	280	360		
	0.30-0.45	6.2	5.1	14.3	1.2	14	332	148	3.0	100	480	130		
	0.45-0.60	6.1	5.0	18.1	1.4	11	430	169	2.4	100	750	230		
Vertisol	0-0.15	5.9	4.7	29.8	1.8	32	272	115	9.4	74	550	160		
	0.15-0.30	6.1	4.6	31.3	1.8	33	274	118	12.4	78	530	90		
	0.30-0.45	6.3	4.8	19.8	1.2	15	287	123	3.3	76	590	180		
	0.45-0.60	6.2	4.8	12.5	1.0	9	236	99	2.2	64	530	200		

†Fluvents and Vertisols (Soil Survey Staff, 1994) are equivalent to Fluvisols and Vertisols (FAO-UNESCO, 1988); ‡CEC pH7 = cation exchange capacity at pH7.

were used for the soil horizons at depths of 0–0.15 and 0.15–0.30 m and an Edelman auger was used for the lower horizons. Samples were composited from 10 locations within each sugarcane block. In 1996 10 soil pits were also dug in natural grasslands and in adjacent sugarcane blocks which had been under continuous cultivation for at least 10 years. At each site the soil pits were approximately 50 m apart and samples were collected from five depths. The soil samples collected in 1996 were air-dried, ground and passed through a 2-mm sieve, and the pH was determined in distilled water (1:2.5, w/v) at the soil laboratories of the University of Technology in Lae.

For the analysis of trends in soil pH_w , the data were aggregated at three levels: the whole plantation at different sampling times (chronosequential unplanned), individual sugarcane fields at different sampling times (chronosequential paired samples) and sugarcane fields and natural grassland (biosequential paired samples).

Statistical analysis of chronosequential topsoil pH_w data

Descriptive statistics were calculated for the pH_w data of each year. Since the number of topsoil samples varied from 19 to 225 per year (Table 2), a conventional multiple comparison test was not appropriate. However, the strategy to follow when multiple comparisons between means of unequal sample sizes have to be made has not yet been settled (Sokal and Rohlf, 1995). In this paper, the GT-2 method of Hochberg was used and this employed the studentized maximum modulus distribution m (Sokal and Rohlf, 1995). This method was preferred to other methods (such as the 'T' method) when sample sizes were very unequal as in the case of the pH_w data of the sugarcane plantation. In this method, the pooled variance was calculated and this was the weighted average variance (MS_{within}) of the entire sample population:

Table 2. Descriptive statistics of topsoil pH water data for the sugarcane plantation between 1979 and 1996.

Year	Number of samples	Mean	Maximum	Minimum	Coefficient of variation (%)
1979†	21	6.49	7.2	5.7	5
1982	79	6.19	6.6	6.0	2
1983	225	6.33	7.1	5.9	3
1984	50	6.20	6.7	5.9	3
1985	19	6.13	6.6	5.9	3
1986	29	6.14	6.6	5.7	3
1991	25	6.20	6.5	5.6	3
1994	60	5.89	6.2	5.6	2
1996	33	5.74	6.3	5.3	4

†Samples taken in natural grassland prior to the establishment of the sugarcane plantation.

$$MS_{\text{within}} = \frac{\sum_{i=1}^a (n_i - 1) s_i^2}{\sum_{i=1}^a (n_i - 1)}$$

whereby n_i is the number of samples and s_i^2 is the variance in year i . The minimum significant difference (MSD) required to detect a significant difference between the pH_w means, can then be calculated as the critical value (m) multiplied by the standard error (SE_{ij}):

$$MSD = m_{\alpha[k^*, v]} \times SE_{ij}$$

whereby α is the experimental error ($p = 0.05, 0.01$), k^* is a coefficient, and v the degrees of freedom. The m -value can be obtained from statistical tables (Rohlf and Sokal, 1995) whereas the standard error is calculated as:

$$SE_{ij} = \sqrt{s \frac{2}{Y_i} + s \frac{2}{Y_j}} = \sqrt{\frac{MS_{\text{within}}}{n_i} + \frac{MS_{\text{within}}}{n_j}}$$

Statistical analysis of chronosequential and biosequential profile data

In 1986, soil samples were taken from four depths in nine sugarcane blocks and the blocks were resampled from the same depths in 1996. Statistical analysis was carried out for each depth by paired comparison with a Student's t -test using Statistix 1.0 for Windows software. A t -test was also used for detecting statistical differences in the pH_w data of paired samples under natural grassland and adjoining sugarcane blocks.

RESULTS

Chronosequential topsoil pH_w data

Under natural grassland prior to the establishment of the plantation in 1979 the mean pH_w value was 6.5 (Table 2). Under sugarcane cultivation, the pH_w decreased to around 6.2 between 1982 and 1991. In 1994 the mean pH_w was 5.9, and in 1996 it had decreased further to 5.7. Up to the mid-1980s there were no pH_w values below 5.9 whereas in the 1996 samples the lowest value recorded was 5.3. The pattern of change in mean pH_w is depicted in Fig. 1. Linear regression (line not shown) showed a decline of about 0.4 pH units per 10 years ($pH_w = -0.035x + 76.1, r^2 = 0.78$).

Statistical analysis showed that the topsoil pH_w had decreased significantly ($\alpha = 0.01$) by 0.8 units between 1979 and 1996 (Table 3). The pH_w in 1994 and 1996 was also significantly ($\alpha = 0.01$) lower than between 1983 and 1991. Between the mid-1980s and 1996, the pH_w of the topsoils declined by approximately 0.5 units. The analysis also showed that the pH_w of the topsoils in 1996 had decreased by nearly 0.2 units when compared with 1994.

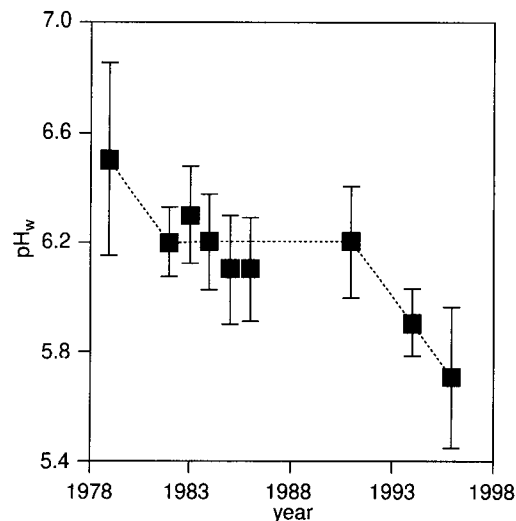


Fig. 1. Changes in pH water (pH_w) (median values \pm 1 s.d.) between 1979 and 1996. Dotted line indicates approximate trend.

For 80 sugarcane blocks, pH_w data were available for different sampling times (chronosequential paired samples). The difference in years between the initial sample at t_0 and the second sample at t_1 was plotted against the difference in the measured pH_w values. It appeared that the decline in pH_w was related to the initial pH_w value (Fig. 2a). Although the data were scattered, they suggested that a larger decline occurred when the initial pH_w was high. This relation does not, however, take into account the time elapsed between the pH_w measurements. Based on the 80 sample pairs the decline in pH_w with time was calculated whereby t_0 was the initial value and t_1 the pH_w value of the second sampling (Fig. 2b). Only in a few samples did the pH_w increase or stay unchanged (that is, pH_w at t_1 minus pH_w at $t_0 \geq 0$), but in the majority of the sample pairs there was a decline in pH_w (that is, pH_w at t_1 minus pH_w at $t_0 < 0$). The largest decrease in pH_w occurred

Table 3. Changes[†] in topsoil pH water between different years.

	1982	1983	1984	1985	1986	1991	1994	1996
1979	-0.292**	-0.155*	-0.290**	-0.354**	-0.348**	-0.282**	-0.596**	-0.747**
1982		+0.137	+0.002	-0.062	-0.056	+0.010	-0.304**	-0.455**
1983			-0.135**	-0.199**	-0.193**	-0.127*	-0.441**	-0.592**
1984				-0.064	-0.058	+0.008	-0.306**	-0.457**
1985					+0.006	+0.072	-0.242**	-0.393**
1986						+0.066	-0.248**	-0.399**
1991							-0.314**	-0.465**
1994								-0.151**

[†]*, **different at $\alpha = 0.05$ and 0.01 respectively.

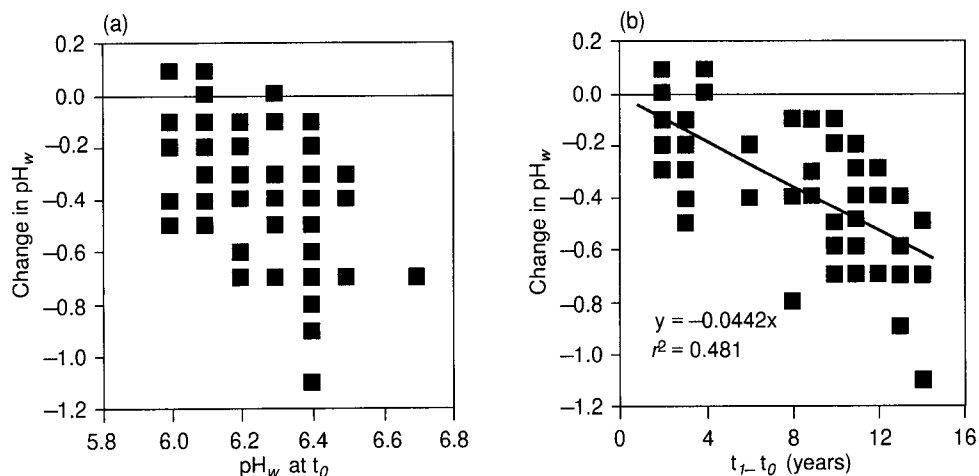


Fig. 2. Change in topsoil pH water (pH_w) in relation to (a) the initial pH_w at t_0 and (b) the change in topsoil pH_w with time. Figure is based on 80 sample pairs.

after 10 years ($t_j - t_0 \geq 10$) and nearly 50% of the variation was explained by the linear function: $\Delta\text{pH}_w = -0.044 \times (t_j - t_0)$.

Chronosequential and biosequential profile data

Acidification was not restricted to the topsoil. Chronosequential paired samples from different depths showed a significant decrease of 0.2–0.4 pH_w units to a depth of 0.6 m after 10 years of continuous sugarcane cultivation (Table 4). In addition the biosequential samples 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.

Soil acidification and nitrogen fertilizer applications

Both the chronosequential and the biosequential samples showed that the soils had acidified under continuous sugarcane cultivation. The cause of this acidifica-

Table 4. Changes in pH water with depth based on samples from the same site at different times (chronosequential) and from different land uses sampled at the same time (biosequential).

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

†Soils were cultivated continuously with sugarcane for at least 10 years; ns = not significant

Table 5. Mean annual fertilizer applications (kg N ha^{-1}) at the sugarcane plantation and their theoretical acidity produced ($\text{kmol H}^+ \text{ha}^{-1}$).

Year	Fertilizer			Acidity				
	Urea	Diammonium phosphate	Sulphate of ammonia	Total	Urea	Diammonium phosphate	Sulphate of ammonia	Total
1991	23	8	0	31	1.6	0.9	0.0	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

tion trend could have been the annual applications of urea, sulphate of ammonia and diammonium phosphate since these fertilizers contain nitrogen in the ammonium form and nitrification reactions result in acid residues. The acid residue from urea is $71 \text{ g H}^+ (\text{kg N})^{-1}$ which is, at its maximum, equivalent to about 3.6 kg CaCO_3 (Adams, 1984). For sulphate of ammonia the potential soil acidity produced through nitrification is twice as high as that from urea and equivalent to about $143 \text{ g H}^+ (\text{kg N})^{-1}$. Diammonium phosphate has intermediate levels.

Data on fertilizer application rates from the plantation were available only from 1991 to 1995. For other years, records were incomplete and could not be used. Based on the fertilizers applied at the plantation, the theoretical acidity produced, expressed as kmol ha^{-1} , was calculated for each year from 1991 to 1995 (Table 5). Up to 1991 urea was the main fertilizer applied (L. S. Kuniata, Ramu Sugar Ltd, personal communication 1996) but most of the nitrogen fertilizers in the mid-1990s were applied as sulphate of ammonia. Diammonium phosphate was applied only in a few sugarcane blocks where phosphorus deficiency was suspected.

The total theoretical acidity produced between 1991 and 1995 was $57.8 \text{ kmol H}^+ \text{ha}^{-1}$ of which 88% was produced by sulphate of ammonia. The average annual addition of protons with the nitrogen fertilizers was $11.6 \text{ kmol H}^+ \text{ha}^{-1}$. Net changes in soil acidity during this period were calculated from the antilog differences between the pH in 1991 and the pH in 1996. It was found that the changes in soil pH_w were only a small fraction of the acidity added with the fertilizer (Table 6).

Table 6. Applied acidity and actual changes in soil pH water between 1991 and 1995.

Period	Applied acidity ($\text{kmol H}^+ \text{ha}^{-1} \text{a}^{-1}$)	Annual decrease in topsoil pH water	Increase in soil acidity $\text{mol H}^+ \text{ha}^{-1} \text{a}^{-1}$
1991–1993	10.4	0.10	0.328
1994–1995	13.4	0.08	0.398
Mean	11.6	0.09	0.356

Soil pH buffering capacity (pH BC)

The resistance of a soil to pH changes after the addition of an acid or base is the buffer capacity (pH BC) and this generally increases with increasing clay and organic matter contents. The pH BC is a measure of the amount of protons required to decrease the soil pH and it is usually expressed in $\text{kmol H}^+ \text{ha}^{-1} \text{pH}^{-1}$ or $\text{mmol H}^+ \text{l}^{-1} \text{soil pH}^{-1}$ (Helyar *et al.*, 1990). For the alluvial soils under sugarcane, an estimation of the pH BC can be made by dividing the acidity added by the net changes in soil pH_w . Between 1991 and 1996 the soils had received $57.8 \text{ kmol H}^+ \text{ha}^{-1}$ (Table 5) whereas the mean pH_w decreased from 6.20 to 5.74 (Table 2). From this the approximate pH BC was estimated to be $125 \text{ kmol H}^+ \text{ha}^{-1} (0-0.15 \text{ m}) \text{ pH}^{-1}$, which is equivalent to $84 \text{ mmol H}^+ \text{l}^{-1} \text{pH}^{-1}$, or $96 \text{ mmol H}^+ \text{kg}^{-1} \text{pH}^{-1}$ with a topsoil bulk density of 1.15 Mg m^{-3} .

DISCUSSION

Variation in topsoil pH_w data was observed between and within years. Of the 541 pH_w measurements, the maximum value recorded was 7.2 while the lowest value was 5.3. Coefficients of variations (2–5%) and standard deviations (0.12–0.35) were lower than those reported by Dobermann and George (1994) but similar to those of Rowell (1988). Despite the variation there is a clear declining trend in the topsoil pH_w which can be summarized as follows: a sharp and significant decrease of 0.3 pH_w units between 1979 and 1982, little changes between 1982 and 1991 and a significant linear decrease between 1991 and 1996.

The initial decrease in pH_w from grassland to sugarcane (1979–1982) may have been due to the increased mineralization of organic matter, which is a common cause of soil acidification (Rowell and Wild, 1985). There were no organic carbon (C) data available from the early-1980s but the levels declined from about 56 g C kg^{-1} in 1979 to 30 g C kg^{-1} in 1994 (Hartemink, 1998). The significant pH_w decline observed in the 1990s coincided with the change in fertilizer policy resulting from a new harvesting technique. Since 1989, Australian cutter-chopper-loader harvesters have been used, replacing pre-harvesting burning. These harvesters may leave crop residues or trash in quantities up to 10 Mg ha^{-1} (Ng Kee Kwong *et al.*, 1987) and in Australia when urea was applied to fields covered in residues, ammonia losses of 40% could be expected (Freney *et al.*, 1992). Accordingly in the early 1990s, urea was replaced by sulphate of ammonia which is less vulnerable to NH_4 -volatilization. The theoretical acidity produced by sulphate of ammonia nitrogen is, however, twice that from urea nitrogen and that may explain the significant increase in soil acidity observed in the 1990s. Contributing causes are possibly the end of burning which caused pH-increasing ashes to be returned to the soil, and the annual additions of sugarcane residues which may increase the organic matter content of the soil and lower of the pH (Dalal, 1989; Moody and Aitken, 1997). Although the trash-harvesting method may favour the organic matter content of the soil (Vallis *et al.*, 1996), in the young

alluvial soils of the Ramu Valley it is likely to have resulted in significant acidification.

Net acidity changes in the topsoils were only a fraction of the acidity added by the fertilizer nitrogen applications and the difference is explained by the pH buffering capacity of the soils. The pH BC was estimated to be $125 \text{ kmol H}^+ \text{ ha}^{-1}$ (0–0.15 m) pH^{-1} which agreed well with values calculated for similar textured soils in New South Wales, Australia (Helyar *et al.*, 1990). The pH BC allows some estimates of future soil pH_w levels. If the current applications of sulphate of ammonia continue at rates of 90 kg N ha^{-1} , $12.8 \text{ kmol ha}^{-1} \text{ a}^{-1}$ 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 neutralized some of the acidity produced by nitrification (Pierre, 1928). Furthermore, it was found that significant acidification occurred to a depth of 0.60 m which explains 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 descending slowly as was reported elsewhere by Abruña *et al.* (1958), Pierre *et al.* (1971) and Stumpe and Vlek (1991).

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 were obtained when the pH is about 6 (Coale and Schueneman, 1993). In some of the soils under sugarcane, the pH_w had decreased to below 5.5 at which level aluminium becomes soluble. Although sugarcane is relatively more tolerant of aluminium 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; Rowell, 1988). The regular application of small quantities of lime prevent the development of topsoil and subsoil acidity. Liming is usually economical but may, however, depress the sucrose content of the sugarcane (Kingston *et al.*, 1996). Application rates of 1–2 Mg lime ha^{-1} when the cane is ploughed-out may be sufficient to maintain favourable pH levels. Another possibility is to apply non-acidifying fertilizers such as calcium ammonium nitrate, which will not reverse the decrease in pH_w , but may prevent further soil acidification.

CONCLUSIONS

Significant soil acidification occurred under continuous sugarcane cultivation in the Ramu Valley of Papua New Guinea despite these soils being young and

cultivated for less than 20 years. The pH_w decrease was accelerated in the 1990s coinciding with the change to trash-harvesting and the increased use of sulphate of ammonia. The buffering capacity of the soils was estimated to be $125 \text{ kmol H}^+ \text{ ha}^{-1} \text{ pH}^{-1}$ which implied that, with the current fertilizer practices, the mean pH_w may decrease below 5.0 in ten years. Although the mean soil pH_w in 1996 was still favourable for sugarcane cultivation, a change in soil management is required to avoid further acidification.

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