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Amelioration of subsoil acidity in an Oxisol of the humid tropics

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Summary. This work investigated the effects of amendments of fertilizer N and lime on subsoil acidity and maize rooting depth in an acid soil of the central Amazon basin. A split-plot designed field experiment was conducted on a clayey Oxisol (Typic Acrudox) during a 16-month period. Main plots received 0 or 4 Mt ha^{-1} of lime. Subplots were four crop sequences: (1) Maize-green manure (*Canavalia ensiformes*); (2) maize-green manure (*Mucuna aterrima*); (3) maize-bare fallow, with the maize receiving 300 kg ha^{-1} of urea-N; and (4) bare fallow, with an application of 300 kg ha^{-1} of urea-N at the same time as sequence 3. Plots were periodically sampled to 1.2 m. The experimental site received 4265 mm of precipitation during 16 months; approximately 60%–90% of this rain percolated through the profile. Substantial amounts of Ca were leached from the 0–30 cm horizon during the experimental period, but only limited amounts accumulated in the subsoil. Base saturation below 45 cm was less than 50% at the end of the experiment regardless of lime treatment. Roots of maize were concentrated in the 0–30 cm layers in limed plots and the 0–20 cm layers in unlimed plots. In all treatments less than 5% of the roots was found below 50 cm. An acidity balance indicated that considerable acidity was leached below the plow layer and out of the profile.

Key words: Calcium – Maize – Nitrogen – Brazilian Amazon – Cation leaching – *Canavalia ensiformes* – *Mucuna aterrima*

Upland soils of the central Amazon basin are predominantly clayey Oxisols; characteristically they are highly acidic, low in plant nutrients, and contain an abundance of Al and Fe oxides. Previous research demonstrated that periodic additions of lime ameliorated acidity and that additions of N, K, P, and micronutrients corrected nutrient deficiencies in the plow layer, resulting in increased yields of grain crops (Cravo et al. 1987; Cravo and Smyth 1987a, b; Smyth et al. 1987; Smyth and Cravo 1990).

In order for intensive agriculture to succeed in Amazonia, subsoil acidity must be reduced to allow deep penetration of crop roots. A large excess of precipitation over evapotranspiration in Amazonia leads to a high leaching potential and consequent reduction of the benefit of fertilizer applications. Melgar (1989) concluded that leaching reduced the N uptake and yield of maize cultivated on an Oxisol in the Amazon basin, even when N fertilizer was split-applied. Cahn (1991) observed that after 14 days without rain maize suffered from water stress because its roots were not able to reach subsoil water reserves.

Bouldin (1979) has summarized a substantial amount of research done at the research station near Brasilia, Brazil, on the effects of subsoil acidity on crop yields, water uptake, root growth, and amelioration of subsoil acidity. The results illustrated that liming the surface soil was usually successful in reducing subsoil acidity within 2–4 years. Incorporation of lime into the plow layer has not always been successful in reducing subsoil acidity (Bouldin et al. 1987). Cravo and Smyth (1987b), who conducted their work near Manaus, Brazil, where the average annual rainfall is 2500 mm, found that 1 year after applying 4 Mt ha^{-1} of $CaCO_3$, acidity saturation [assessed as the percentage of total extractable cations ($cmol_c\ kg^{-1}$ Al+Ca+H+Mg+K) that are acidic ($cmol_c\ kg^{-1}$ Al+H)] was greater than 60% below 50 cm. Other studies conducted in the humid tropics also have shown that applications of lime have limited effects on subsoil acidity. For example, the application of lime at 5 Mt ha^{-1} did not reduce acidity saturation at the 40 cm depth to less than 60% in a Typic Haplorthox (Gill 1988). Freisen et al. (1982) reported significant leaching of Ca from the surface horizon of a kaolinitic Ultisol of Nigeria, but little Ca accumulation and amelioration of acidity in the subsoil. In an Ultisol of the Peruvian Amazon, Sanchez et al. (1983) reported that after liming during a 7-year period, acidity saturation was about 60% below 30 cm.

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Table 1. Chemical and physical properties of the unlimed plots at the initiation of the experiment

Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Bulk density (g cc^{-1})	pH	Exchangeable cation (cmol kg^{-1})				
						Ca	Mg	K	Al	ECEC
0–15	81	10	9	1.19	4.7	1.98	0.31	0.16	0.67	3.12
15–30	88	3	9	1.17	4.4	1.03	0.12	0.08	0.85	2.08
30–45	91	4	5	1.13	4.4	0.59	0.07	0.03	0.79	1.48
45–60	91	4	5	1.09	4.5	0.36	0.04	0.03	0.77	1.20
60–75	91	4	5	1.09	4.5	0.17	0.03	0.02	0.78	1.00
75–90	91	4	5	1.06	4.5	0.10	0.03	0.02	0.77	0.92
90–105	91	4	5	1.03	4.5	0.06	0.03	0.01	0.78	0.88
105–120	91	4	5	1.04	4.5	0.04	0.02	0.01	0.71	0.78

Textural data from Melgar (1989). ECEC, effective cation exchange capacity

Table 2. Rates of Ca (dolomite and legume sources) and N (urea and legume sources) incorporated into the surface layer (0–30 cm) at the initiation of the maize crops

Treatment	n	Crop 1		Crop 2		Crop 3		Total	
		Ca	N	Ca	N	Ca	N	Ca	N
		(kg ha^{-1})							
No lime									
Mucuna	4	0	300	56	283	18	142	74	657
Canavalia	4	0	300	71	164	50	142	121	606
Urea	4	0	300	0	300	0	300	0	900
Bare + urea	4	0	300	0	300	0	300	0	900
Lime									
Mucuna	4	1600	300	59	279	26	182	1685	761
Canavalia	4	1600	300	86	172	109	206	1795	678
Urea	4	1600	300	0	300	0	300	1600	900
Bare + urea	4	1600	300	0	300	0	300	1600	900

Values for the mucuna and canavalia treatments of the 2nd and 3rd maize crop represent the amount of nutrient contained in the aboveground biomass of the legume crop at the time of incorporation into the plow layer. n, Number of replicates

The amelioration of subsoil acidity depends on transport of bases from the surface horizon and the reaction of these bases with the acidity in the subsoil horizons. Transport is dependent on the amount of water and the concentration of cations in the leaching water; presumably the latter is dependent on concentrations of anions such as sulfate, nitrate, chloride, and bicarbonate. The reaction of subsoil acidity depends upon the ability of the cations in solution to displace or react with the acidity in the subsoil; presumably this will be determined by the ratio of acidity to bases in the incoming leachate. Still another factor is the "buffering capacity" of the subsoils.

In acid soils, receiving an annual rainfall of less than 1500 mm, the transport of bases to the subsoil may be relatively slow (Lathwell 1979; Friesen et al. 1982; Messick et al. 1984; Pavan et al. 1984; Conyers and Scott 1989). Amelioration of subsoil acidity was accelerated in the red Oxisols of the Cerrados region of Central Brazil (Lathwell 1979) by applying amendments containing mobile anions such as sulfate, nitrate, or chloride, which facilitated the leaching of bases into the subsoil (Pleysier and Juo 1981; Pavan et al. 1984).

In the humid tropics the potential for transport of bases is high but the soils appear to be buffered by Al minerals somewhat better than in savanna regions. Thus 4 Mt ha^{-1} of lime may not increase the pH of the surface soil enough for the acidity: base ratio in the leachate to have much if any capacity to displace and/or react with the subsoil acidity, which may also be well buffered.

The cropping system is an additional factor that may affect the amelioration of subsoil acidity. Few studies have examined the interactions among cropping system, surface-placed lime, and amelioration of subsoil acidity. Yet, crop transpiration reduces the amount of drainage through the soil profile, and root absorption of NO_3^- and SO_4^{2-} reduces the amount of mobile anions available to promote cation leaching.

The objectives of the present work were (1) to determine why lime applications have had limited success in ameliorating subsoil acidity in the humid tropics, and (2) to find a cropping system that would enhance the amelioration of subsoil acidity with lime.

Materials and methods

Description of experimental site

The field experiment was conducted at the Centro de Pesquisa Agroflorestal da Amazonia (CPAA), 30 km northeast of Manaus, Brazil, on the Manaus-Itacoatiara road, 3 °S 60 °E. CPAA is the national research station for agroforestry of the Amazon and is operated by the Empresa Brasileira de Pesquisa Agropecuaria (EMBRAPA). The soil is classified by US. Soil Taxonomy (Soil Survey Staff 1990) as a very-fine, kaolinitic, isohyperthermic Typic Acrudox, or by Brazilian Taxonomy as a yellow Latosol (Melgar 1989). The site is typical of terra firme soils, which are not inundated by flood waters. The soil is highly weathered, acid, and poor in nutrients. The chemical and physical characteristics of the soil before the initiation of the experiment are summarized in Table 1.

Meteorological data collected at the field station (Melgar 1989) show that about 80% of the 2461 mm average annual precipitation occurs between October and May and the mean annual air temperature is 25.7 °C (Melgar 1989). During the present experiment (November 1 1988 to March 12 1990), precipitation totalled 4265 mm and pan evaporation 1128 mm. Mean temperature was 25.0 °C.

Experimental design

The field experiment was a random block, split-plot, factorial design, consisting of eight treatments (two lime levels × four crop sequences)

and four replications (blocks). The main plots received 0 or 4 Mt ha^{-1} of $CaCO_3$ equivalents of lime (33% Ca, 0.8% Mg, 73% $CaCO_3$) on October 24 1988. The lime was broadcast and disked to a 15-cm depth. The subplots were four crop sequences, comprising (1) maize-legume green manure (*Canavalia ensiformes*)-maize-green manure-maize; (2) maize-legume green manure (*Mucuna aterrima*)-maize-green manure-maize; (3) maize-bare fallow-maize-bare fallow-maize; (4) continuous bare fallow. In early October 1988 (before the initial crop) all treatments received applications of 300 kg ha^{-1} of urea-N, but subsequently, the green manure treatments were not supplied with additional N. In the bare fallow treatments, 300 kg ha^{-1} of urea N was applied before each maize crop. The urea was immediately incorporated to 15 cm to prevent ammonia volatilization. Leguminous material was incorporated to the same depth within 1 day after cutting, also to prevent ammonia volatilization. Applications of chemical and legume sources of Ca and N to the topsoil are summarized for each treatment in Table 2.

Supplementary soil amendments

All treatments received an initial application of 87 kg ha^{-1}of P (triple superphosphate) and 75 kg ha^{-1}of K (KCl). For subsequent maize crops, triple superphosphate was applied in bands at a rate of 22 kg ha^{-1} of P and an equivalent rate was broadcast on the bare-fallow plots. KCl was broadcast again at a rate of 75 kg ha^{-1} of K on all plots before the third maize crop was planted.

Maize cultivation

The maize cultivar BR 5110, an open pollinated line recommended by EMBRAPA, was used throughout the experiment. Maize was planted on November 7 1988, May 24–25 1989, and November 20–21 1989 in rows with 1 m spacing. Two weeks after germination the plants were thinned to a density of 100000 plants ha^{-1} and 2 weeks later to a density of 50000 plants ha^{-1}. Each crop was sprayed several times with Dipteryx at recommended dosages to prevent infestation of corn borer, *Spodoptera frugiperda.*

Root profile study

Four pits 1 m deep were dug between plots when the third maize crop reached tasseling stage. From each pit roots of two adjacent plots were counted. Profiles were dug to 10 cm from the base of a maize plant and oriented to show a symmetrical cross-section of rows. The soil profile was scarified with a knife and soil was washed away from the roots with water, applied with a herbicide sprayer. A 10-cm grid was laid over a 1 m×0.7 m area of the soil profile, and the number of roots per 10 cm square was counted. Only roots protruding from the soil were counted (i.e., branch roots originating from a root beyond the grid were not counted).

Soil samples

Soil was sampled six times during the course of the experiment. Plots (5 m×8 m) were sampled from an area 0.5 m from the borders, using dutch augers, generally at intervals of 0.15 m, to 1.2 m in depth. The outer edge and the top of auger borings were discarded to guard against contamination from other soil layers. For each replicate a composite sample from three holes was collected for analysis. Ca, Mg, and acidity were extracted from soil samples with 1 *N* KCl at a 1 : 10 soil solution ratio. Ca and Mg were analyzed by atomic absorption and acidity by titration with 0.025 *N* NaOH. Soil K was extracted with a Mehlich 1 solution analyzed by flame photometry. Bulk density was determined on undisturbed cores sampled adjacent to the plots to 1.2 m in depth.

Calculations

Acidity saturation was calculated as follows:

$$\text{Acidity saturation} = \frac{\text{Al}+\text{H}}{\text{Ca}+\text{Mg}+\text{K}+\text{Al}+\text{H}} \times 100 \qquad (1)$$

where the extractable cations, Ca, Mg, K, Al, and H were expressed in units of $\text{cmol}_c\,\text{kg}^{-1}$.

Changes in Ca and acidity levels at 0–30 cm and 30–120 cm in depth during the experimental period were calculated by the following equation:

$$\Delta M = A + \sum_{j=m}^{n} D_j \times (C_j^{\text{i}} - C_j^{\text{f}}) \qquad (2)$$

where ΔM is the change in nutrient M, C^{i} and C^{f} are the initial and final concentrations of M respectively, in layer j, m is the top layer and n is the bottom layer, D is the bulk density, and A is the amount of M added after the initial sampling. Nutrients removed by harvesting maize crops were not included in the above calculation because they were generally insignificant relative to leaching losses.

Climatic data

Rainfall was measured at the field site with a pluviograph (Wilh. Lambrecht GmbH, 3400 Göttingen, Germany), elevated to intercept rainfall 1.5 m above ground level. Pan evaporation, relative humidity, and mean air temperature were obtained from the weather station at the EMBRAPA station in Manaus.

Statistical analyses

The experimental data were statistically analyzed with a split-plot or nested model by analysis of variance using Statistical Analysis software (SAS Institute Inc. 1985). For the analysis of treatment, depth, and time effects a three-level split-plot model was used where "subplot treatment" was nested within "main-plot treatment", "depth" was nested within "subplot treatment", and "time" was nested within "depth". Snedercor and Cochran (1980) discuss the use of a nested model for analysis of repeated measures (time effects), and similar reasoning justifies treating "depth" as a factor nested within "subplot treatment". All block interactions at the same nested level were pooled into a single error term (Snedecor and Cochran 1980).

Results

Subsoil acidity and depth of maize rooting

The distribution of acidity saturation in the soil profile is shown in Fig. 1. No differences in the amelioration of subsoil acidity were observed between the lime and unlimed treatments. In both treatments acidity saturation was reduced to about 55% at depths below 45 cm during the 16-month experimental period. In the surface 0–40 cm the soil in the unlimed plots became more acidic with time while acidity in the limed plots remained relatively constant with time. We speculate that the lime neutralized acidity produced by nitrification.

The results of the root studies of maize are shown in Fig. 2 together with acidity saturation profiles at the time the root observations were made. In the 0–10 cm layer, the unlimed plots had the highest percentage of roots but the lowest actual count of roots. Despite applying 4 Mt ha^{-1} of $CaCO_3$ to the limed treatment, the depth of penetration of appreciable numbers of roots was increased only by about 15 cm relative to the unlimed treatment. In neither case were there many roots below 30 cm and 90% or more of the roots counted were in the 0–30 cm layer. This restricted distribution reduced the ability of the maize to use subsoil water during the second crop when several 5–10 day periods without rainfall caused severe wilting and a 50% reduction in grain yields (Cahn 1991).

Leaching and accumulation of Ca in subsoil

Large amounts of Ca were redistributed in the profiles of treated soils during the experimental period (Table 3). Losses from the topsoil were balanced by accumulations in the subsoil for the urea and mucuna treatments but were not balanced in the canavalia and bare fallow treatments; however, the coefficient of variance for changes in Ca levels in the topsoil and subsoil layers ranged as high as 277% (Table 3). Large coefficients variance may be expected for the calculations because errors associated with each variable (initial and final Ca levels at each depth and bulk density) are additive. Nevertheless, losses of Ca from the topsoil (0–30 cm) were statistically different within the lime and N treatments, demonstrating that cropping systems may significantly affect cation leaching. The highest Ca losses occurred in bare fallow plots treated with urea-N, where the most drainage occurred and the highest rate of N was applied. Plots fallowed with canavalia had the lowest losses of Ca from the plow layer. A high rate of transpiration and deep root proliferation may be the mechanisms by which canavalia reduced Ca leaching. Deep root proliferation may have been the most important since losses of Ca were greater in plots fallowed with mucuna, though they accumulated 17% more biomass than the canavalia plots (data not presented).

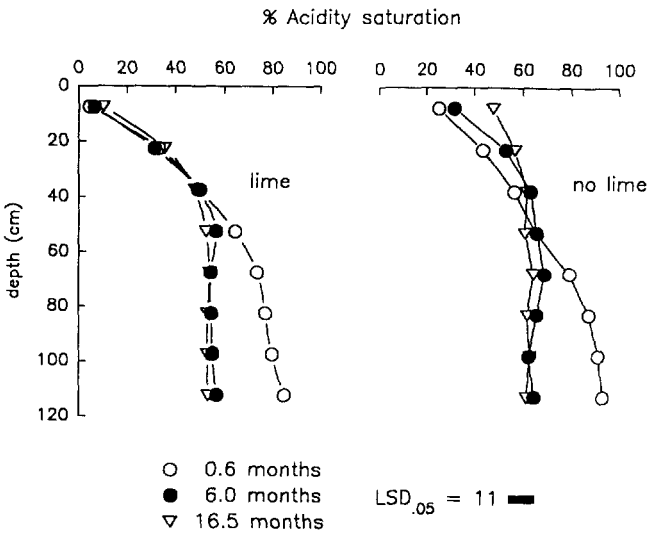

Fig. 1. Acidity saturation in the profiles of limed and unlimed treatments, 0.6, 6.0, and 16.5 months after the initiation of the experiment (crop sequence treatments pooled). Acidity saturation is the percentage of total extractable cations ($cmol_c\ kg^{-1}$ of Al+Ca+H+Mg+K) that are acidic ($cmol_c\ kg^{-1}$ of Al+H)

Table 3. Changes in levels of Ca and soil acidity (Al and H) in the profile of an Oxisol after 16 months of cropping

	n	Ca ($kg\ ha^{-1}$)		Al+H ($kmol_c\ ha^{-1}$)	
		0–30 cm	30–120 cm	0–30 cm	30–120 cm
Lime-N treatment comparison					
No lime					
Mucuna	4	−405 (367)	416 (397)	6.8 (2.7)	10.7 (13.7)
Canavalia	4	−65 (180)	481 (330)	−5.8 (8.9)	−10.7 (26.3)
Urea	4	−351 (342)	503 (182)	14.6 (9.2)	16.7 (8.2)
Bare+urea	4	−827 (261)	451 (266)	15.1 (10.6)	22.3 (7.1)
Lime					
Mucuna	4	−617 (789)	597 (536)	−1.8 (4.1)	−7.9 (9.7)
Canavalia	4	−454 (139)	551 (136)	1.8 (6.6)	19.3 (14.6)
Urea	4	−1182 (172)	944 (419)	−5.2 (11.4)	−14.8 (11.4)
Bare+urea	4	−1516 (187)	465 (645)	1.4 (5.9)	2.8 (16.0)
LSD (0.05)		509	557	13.5	22.5
N treatment comparison					
Mucuna	8	−511 (881)	507 (447)	2.5 (5.6)	1.4 (14.8)
Canavalia	8	−260 (255)	521 (217)	−2.0 (8.3)	4.3 (25.4)
Urea	8	−767 (510)	723 (380)	4.7 (14.2)	1.0 (19.2)
Bare+urea	8	−1171 (424)	458 (457)	8.2 (10.8)	12.5 (15.5)
LSD (0.05)		360	394	9.5	15.9
Lime treatment comparison					
No lime	16	−412 (387)	461 (462)	7.7 (11.5)	9.7 (19.1)
Lime	16	−942 (580)	639 (463)	−0.9 (7.3)	−0.1 (17.7)
LSD (0.05)		254	278	6.7	11.3

SD in parentheses; n, number of replicates . Negative values are calculated losses while positive values are calculated accumulations within a soil layer. Values with differences greater than least significant difference (LSD) values are significantly different at the 95% confidence level

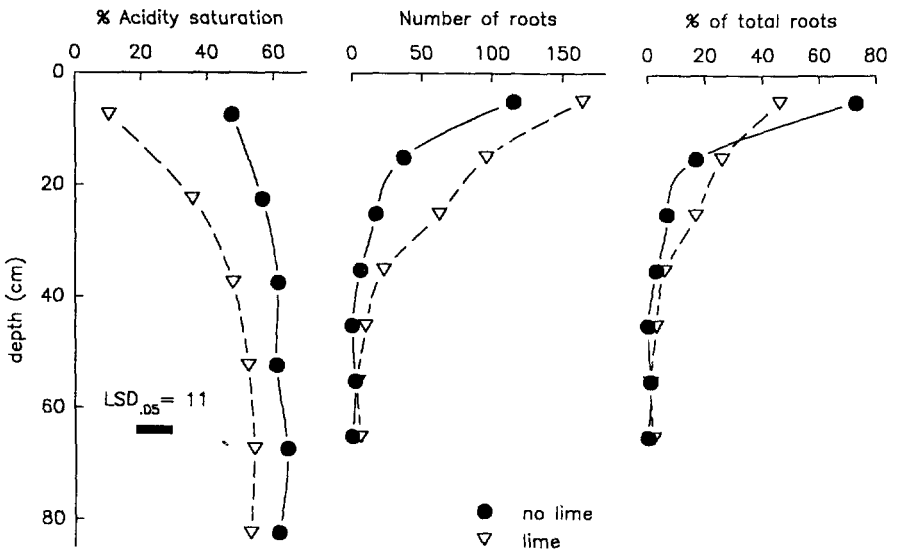

Fig. 2. Acidity saturation and root distribution of a mature maize crop, showing profiles of limed and unlimed plots in the maize-bare fallow sequence 16.5 months after initiation of the experiment. Acidity saturation is the percentage of total extractable cations ($cmol_c\ kg^{-1}$ of Al+Ca+H+Mg+K) that are acidic ($cmol_c\ kg^{-1}$ of Al+H). Root data are expressed as the actual number of roots counted and as a percentage of the total roots counted in an individual profile

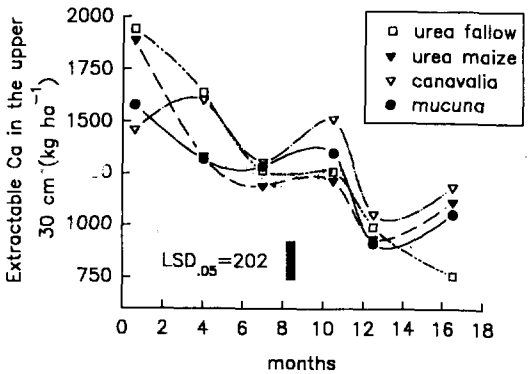

Fig. 3. Extractable Ca levels in the 0–30 cm layer during the experimental period. Comparison of crop sequence treatments: maize-mucuna, maize-canavalia, maize-bare fallow, and bare fallow (urea-fallow). The two lime levels were averaged; main-plot treatments were pooled)

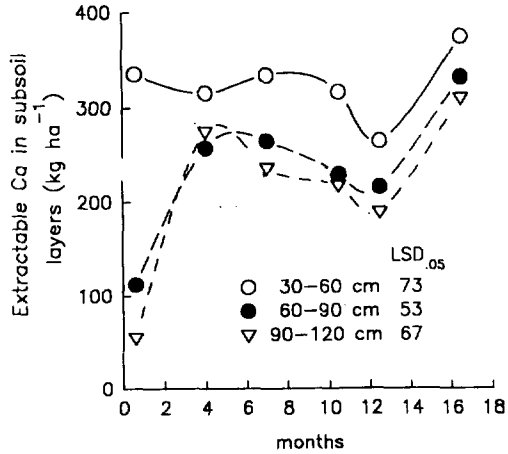

Fig. 4. Extractable Ca levels in subsoil layers during the experimental period averaged over all treatments (main-plot and subplot treatments pooled)

Although the amount of Ca lost from the surface soil differed among treatments, the amount of Ca accumulated in the subsoil was not statistically different among treatments. In urea-bare fallow plots, where large amounts of Ca were leached from the plow layer, only about half of the leached Ca accumulated in the subsoil. These results suggests that in treatments with large losses of Ca, a major portion of the Ca was leached to points beyond the lowest sample depth (120 cm).

The dynamics of the redistribution of Ca and the acidity in the profile also indicate that Ca was leached to points below 120 cm. Ca was lost continuously from the 0–30 cm layer throughout the experiment period (Fig. 3); however, it did not accumulate in the lower subsoil horizons (60–120 cm) after 4 months (Fig. 4). Similarly, acidity saturation in the subsoil decreased during the first 6 months and then remained constant (Fig. 1). Finally, in the bare fallow-cropping sequence, Ca decreased in the soil profile (0–90 cm) as a linear function of cumulative drainage during the experimental period, where drainage was defined as precipitation − 0.37 × pan evaporation (Fig. 5). Such a relationship would occur if Ca was leached below 90 cm.

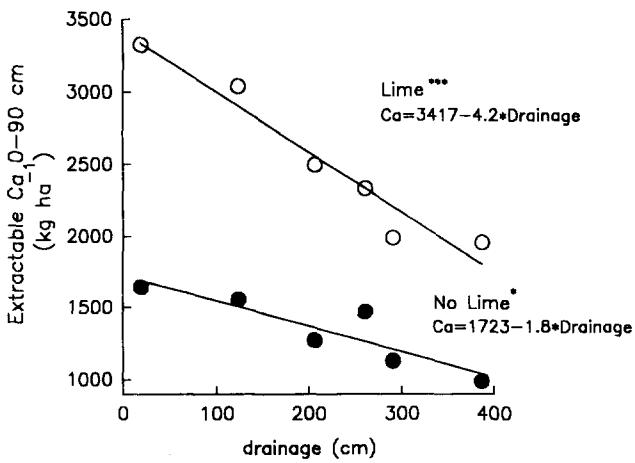

Fig. 5. Linear regression of extractable Ca on estimated drainage through the profiles (0–90 cm) of the fallow plots; comparison of limed and unlimed treatments. Drainage was calculated as precipitation −0.37 × (pan evaportation)

Leaching of acidic cations

The question of whether acidic cations were leached in unlimed plots was examined by measuring changes in acidity over time at various depths in the profile, and by comparing these values with the acidity theoretically generated by the mineralization and nitrification of urea fertilizer applied to the plow layer.

In the maize + urea and bare fallow + urea treatments a total of 900 kg ha^{-1} of urea-N was added to the 0–30 cm layer over 16 months. Since hydrolysis of urea N creates 1 mol OH^- per mol NH_4^+ and nitrification of 1 mol NH_4^+ generates 2 mol acid, the net effect of 900 kg ha^{-1} of urea N is the generation of 64.3 kEq ha^{-1} of acidity. In addition, mineralization of soil organic N generated an unknown amount of acidity, but this is likely to be small in relation to that generated by the urea.

The net increase in extractable acidity was calculated from the difference between final and initial extractable acidity multiplied by soil bulk density. In this manner the increase in extractable acidity in the surface horizons (0–30 cm) was calculated to be 14.6 kEq ha^{-1} for the maize-bare fallow sequence and 15.1 kEq ha^{-1} for the bare fallow sequence during 16 months (Table 3), approximately 1/4 of the theoretical acidification. During the same period, in these same plots, acidity in the 0–120 cm depth increased by 31.2 and 37.4 kEq ha^{-1}, respectively. This is about 1/2 the theoretical acidification.

Discussion

Applications of 4 Mt ha^{-1} of $CaCO_3$ has a limited effect on extractable acidity in the subsoil and a relatively small influence on the proliferation of maize roots below 30–45 cm. The yields of the maize crops were reduced during the dry season, presumably because the crop

could not use subsoil water (Cahn 1991). Bases were readily leached from the surface of the profile (0–30 cm), owing to an ample supply of a mobile anion (NO_3^-) and annual rainfall that exceeded evapotranspiration by 1.5 m. In contrast to work conducted in Oxisols of savanna climates, this leaching was not effective in ameliorating subsoil acidity.

The cropping treatments affected the leaching of Ca from the topsoil, but did not significantly influence the accumulation of Ca in the subsoil. Since drainage and nitrate leaching were the main factors differing among these cropping systems, they probably had little influence on the accumulation of Ca in the subsoil.

The actual accumulation of acidity in the unlimed maize+urea and bare fallow+urea treatments was less than the theoretical accumulation. Three possibilities may account for the missing acidity: (1) Some of the acidity was leached beyond 120 cm; (2) some of the acidity was converted to non-extractable forms within the profile; and (3) some of the acidity was neutralized by denitrification. We cannot allocate the missing acidity to these sinks on the basis of the data we collected. If 2 and 3 were small, then 1/4 of the acidity accumulated in the subsoil and 1/2 was leached below 120 cm.

If a substantial amount of the acidity was leached through the profile then this is a likely explanation for the limited amelioration of subsoil acidity. The solution being leached out of the surface horizon may have contained enough acidity (primarily Al) to be nearly in equilibrium with the soil in the lower horizons. The net effect of the acidity accompanying the bases was to reduce the ability of the leaching solution to neutralize the subsoil acidity.

Other studies have demonstrated that soil leachates may contain significant amounts of acidic cations. Pleysier and Juo (1981) measured significant amounts of acidity ($Al^{3+}+H^+$) in the leachate of an Ultisol given a surface application of $Ca(NO_3)_2$. Pierre et al. (1971) reported migration of acidic cations to 45 cm under high rates of N fertilizer. Pavan et al. (1984) did not find large amounts of acidity in the leachate from a Brazilian Oxisol given surface applications of $CaSO_4$. However, SO_4^{2-} may have the ability to desolubilize exchangeable Al so that Al ions are not leached (Alva et al. 1990).

Because of the high acidity in the leachate, there was no effective base exchange with acidic cations in the subsoil and the bases were leached deeper into the soil profile. Therefore we conclude that adding anions (such as NO_3^-) in order to enhance leaching of bases such as Ca is not a sufficient to ameliorate subsoil acidity in the humid tropics. The finding also suggests that an essential condition for amelioration of subsoil acidity with $CaCO_3$ is that the surface horizons be limed to pH 6.0–6.5. Presumably at this pH there will be very small amounts of Al^{3+} in the leachate from the limed surface soil; as these bases are leached into the lower soil horizons the bases will replace some of the exchangeable soil Al, which will be leached to lower horizons. In addition the higher pH together with elevated CO_2 in the soil gases will furnish some additional neutralizing capacity to the leachate by the following reaction:

$$3H_2O+Al^{3+}+3HCO_3^- = Al(OH)_3+3H_2CO_3 \ .$$

Another way of ameliorating subsoil acidity is to incorporate gypsum into the surface soil. Cravo and Smyth (1987b) reported that gypsum, applied with lime, ameliorated subsoil acidity more successfully than lime, applied alone, at the Manaus experimental site. Likewise, other researchers have lessened subsoil acidity with gypsum and phosphogypsum amendments (Pavan et al. 1984, Sumner et al. 1986, Alva and Sumner 1990).

An advantage of using gypsum over lime is that the sulfate in gypsum may have an important effect in accumulating Ca and alleviating Al toxicity in the subsoil. Marcano-Martinez and McBride (1989) found that the Ca sorption in an Oxisol was far higher from a $CaSO_4$ solution than from a $CaCl_2$ solution. They hypothesized that the sorption of SO_4^{2-} to positively charged sites would provide ligand exchange sites for Ca^{2+}. Other studies indicate that SO_4^{2-} may precipitate or polymerize Al (Adams and Rawajfih 1977, O'Brien and Sumner 1989, Alva et al. 1990).

Conclusions

The best way to use lime to consistently ameliorate subsoil acidity has yet to be developed. The present results indicate that Ca may be readily leached into the subsoil with ample drainage and applications of NO_3^-, but Ca may not accumulate in the subsoil to a level that will reduce acidity and promote root growth. Indirect evidence suggests that leaching of acidity from the plow layer interferes with the accumulation of bases in the subsoil.

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