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Cation and Nitrate Leaching in an Oxisol of the Brazilian Amazon

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ABSTRACT

High rates of N fertilizers are often necess... .o achieve yield goals in the humid tropics, where subsoil acidity prevents deep crop rooting. However, leaching of fertilizer nitrate may accelerate the leaching of bases from the crop rooting zone, leading to an acidification of the topsoil and a reduction in crop yields. Our ojective was to investigate the influence of urea and legume green manure sources of N on crop yields, leaching of cations, and the fertility of the plow layer of a clayey Oxisol (Typic Acrudox) of the central Amazon basin. We established a split-plot field experiment near Manaus, Brazil where main plots received 2 levels of lime (0 and 4 Mt/ha $CaCO_3$) and sub-plots were cropped with (i) a legume green manure (*Canavalia ensiformes* L. or *Mucuna aterrima* L.) followed by maize (*Zea mays* L.); (ii) maize receiving 300 kg ha^{-1} of urea–N, or (iii) left bare-fallow with an application of 300 kg ha^{-1} of urea–N. Plots were periodically sampled to 1.2 m during three cropping seasons. The field site received 4265 mm of rain during the experiment (16 mo). Legume crops accumulated between 142 and 280 kg ha^{-1} of N. The distribution of NO_3 in the soil profile changed in a pattern consistent with leaching. All treatments lost Ca and Mg from the plow layer during the experimental period. Losses were greatest (500–1000 kg ha^{-1} for Ca and 50 kg ha^{-1} for Mg) in plots treated with urea and lime. Leaching of bases and the generation of acidity decreased base saturation in the plow layer of all treatments, but was minimized in plots receiving legume green manure N, perhaps because less inorganic N was applied and/or the legume crops recycled leached bases. Unlimed plots receiving urea, had the highest increase in acidity in the 0 to 30-cm layer and a corresponding 44% reduction in grain yield between the first and third maize crops.

MUCH OF THE UPLAND SOILS of the central Amazon basin, regionally known as *terra firme*, are clayey Oxisols (Acrudox and Hapludox), predominantly kaolinitic with few primary minerals, and abundant in Fe and Al oxides. These soils have favorable physical properties, such as good drainage and a high water holding capacity, but chemical properties, specifically, high acidity, low base saturation, and low effective cation exchange capacity (ECEC), limit their use for agriculture.

Several studies demonstrated that additions of lime, N, K, P and micronutrient amendments ameliorated acidity and nutrient deficiency in the plow layer of these Oxisols and increased yields of grain crops (e.g. Cravo et al. 1987; Cravo and Smyth, 1987a; Smyth and Cravo, 1990; Smyth et al. 1987). However, in these well drained soils, abundant rainfall may quickly leach nutrients from the amended plow layer into the acid subsoil, where crop roots are sparse (Melgar 1989). Leaching of bases acidifies the plow layer and reduces crop yields. Cravo and Smyth (1987b) reported that base saturation of less than 70% of the ECEC of an Amazonian Oxisol limited maize yields.

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A number of studies measured leaching of the basic cations, Ca, Mg, and K, in the humid ' ›ics (Conyers and Scott, 1989; Friesen et. al. 1982; Gillman et al. 1989; Juo and Ballaux, 1977; Omoti et al. 1983; Peason et al. 1962; Pleysier and Juo, 1981). Leaching losses varied as a function of the amount of mobile, or leachable, anions present. For example, Ritchey et al. (1980) and Pavan et al. (1984) demonstrated that the presence of SO_4 or Cl accelerated Ca leaching in soil columns. The influence of SO_4 and Cl on the movement of Ca is attributable to the mobilities of the anions and the maintenance of charge neutrality. In the soil solution, the movement of all anions is accompanied by an equivalent movement of cations.

Nitrogen fertilizers are likely to accelerate the leaching of bases from the plow layer. If NO_3, a mobile anion, is leached beyond the crop rooting zone it will carry along an equivalent of cations. Nitrification of fertilizers containing amide or ammonium-N produces protons, which can dissolve Al minerals in acidic soils. The Al cations, or the protons, may displace exchangeable bases, such as Ca, Mg, and K, into the soil solution. Once displaced into solution, bases may be leached.

Few studies have investigated the influence of fertilizer-N on the leaching of bases. Gonzalez et al. (1985), using suction lysimeters, collected the highest levels of Ca, Mg, and K in leachates when urea or $NH_4 NO_3$ fertilizers were applied to plots. Jones (1976) reported that increasing rates of N increased losses of Ca, Mg, and K from the plow layer. As well, Aduayi (1984) and Gillman and Bristow (1990) found N fertilizers to accelerate cation leaching. Few of these studies have also investigated the effects of NO_3 leaching on crop yield. Jones (1976) found some evidence that high N fertilizer rates accelerated soil acidification and reduced crop yields, but his results were confounded by drought stress.

Legume green manures, used as a N source for subsequent non-legume crops, have much potential in the central Amazon as a partial or total substitute for N fertilizers (Melgar 1989), and they may also translocate nutrients in the subsoil back to the surface. Nevertheless, this N management practice could potentially promote cation leaching because tropical legumes are capable of accumulating large quantities of N in the above ground biomass which often decomposes rapidly (Bowen et al., 1988). Consequently, if N is oversupplied to a succeeding non-legume crop, it may accelerate cation leaching. Unlike chemical fertilizers, legume green manures cannot be split applied to reduce NO_3 leaching.

Our objective was to investigate the influence of urea and legume green manure sources of N on maize and legume yields, leaching of cations, and the fertility of the plow layer of a clayey Oxisol (Typic Acrudox) of the central Amazon basin.

MATERIALS AND METHODS

Description of Experimental Site

The field experiment was conducted at the CPAA, located 30 km northeast of Manaus, Brazil on the Manaus-Itacoatiara road, latitude 3 ° S, longitude 60 ° W. Centro de Pesquisa Agroflorestal da Amazonia is the national research station for agroforestry of the Amazon and is operated by the Empresa Brasileira de Pesquisa Agropecuaria. The soil is classified by U. S. Soil Taxonomy (Soil Survey Staff, 1990) as a very-fine, kaolinitic, isohyperthermic Typic Acrudox, or by Brazilian Taxonomy, a Yellow Latosol (Melgar, 1989). The site is typical of *terra firme* soils, which are not inundated by flood waters. The native soil is highly weathered, acid, and poor in nutrients with almost no primary minerals remaining.

Meteorological data collected at the field station (EMBRAPA-UEPAE de Manaus, 1987) show that about 80% of the 2461-mm average annual precipitation occurs between October and May and mean annual air temperature is 25.7 °C. During the period of this experiment (1 Nov. 1988 – 12 Mar. 1990) precipitation and pan evaporation totaled 4265 and 1128 mm, respectively. Soil infiltration rates were sufficiently high such that puddling and run-off were uncommon except for the most intense storms (80 mm hr^{-1} lasting 1 hr or more) which occurred only several times during the experiment. Mean temperature was 25.0 °C.

Experimental Design

The field experiment was a randomized block, split-plot factorial design, consisting of eight treatments (two lime levels by 4 N treatments) with four replications (blocks). The main plots received 0 or 4 Mg ha^{-1} of $CaCO_3$ equivalents of lime (33% Ca, 0.8% Mg, 83% $CaCO_3$) on 24 Oct. 1988; the subplots were cropped with one of four cropping sequences, illustrated in Fig. 1. All sub-plots received an initial application of 300 kg ha^{-1} of urea-N. The legume crops, *M. aterrima* and *C. ensiformes* of sub-plot Treatments 1 and 2, respectively, were incorporated into the soil as sources of N for the second and third maize crops. Treatments 3 and 4 received 300 kg ha^{-1} of N-urea when legumes were incorporated. Main-plot treatments are referred to as "lime" and sub-plot treatments are referred to as "nitrogen" in subsequent text. Bare-fallow plots were maintained bare with applications of herbicide and frequent cultivation. Other plots were maintained free of weeds by hand cultivation.

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). In 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. Potassium (KCl) was broadcast again at a rate of 75 kg ha^{-1} of K on all plots before planting the third maize crop.

Maize Cultivation

The maize cultivar BR5110, an open pollinated line recommended by EMBRAPA, was planted 7 Nov. 1988, 24 to 25 May 1989, and 20 to 21 Nov. 1989 in 1-m rows. Two weeks after germination plants were thinned to a density of 100 000 plants/ha and two weeks later to a density of 50 000 plants ha^{-1}. Each crop was sprayed with Dipteryx at recommended rates to prevent insect damage. Ears were harvested from the middle 6 m of the center three rows approximately 120 days after planting (DAP), when kernels formed a black layer. Moisture and nutrient contents were determined on samples of grain. Stover was left standing in sub-plot Treatment 1 as structural support for the subsequent mucuna crop.

Legume Cultivation

Legumes were grown as green manure sources of N for a subsequent corn crop and as a means to recycle nutrients leached into the subsoil. The legumes used, mucuna preta (*M. aterrima*) and canavalia (*C. ensiformes*) were selected for their contrasting root and top growth habits. Mucuna is a climber

subplot treatments	Nov. '88	Feb. '89	June '89	Sept. '89	Dec. '89
1	maize + urea	mucuna	maize + green manure	mucuna	maize+green manure
2	maize + urea	canavalia	maize+green manure	canavalia	maize+green manure
3	maize + urea	fallow	maize + urea	fallow	maize + urea
4	fallow + urea	fallow	fallow + urea	fallow	fallow + urea

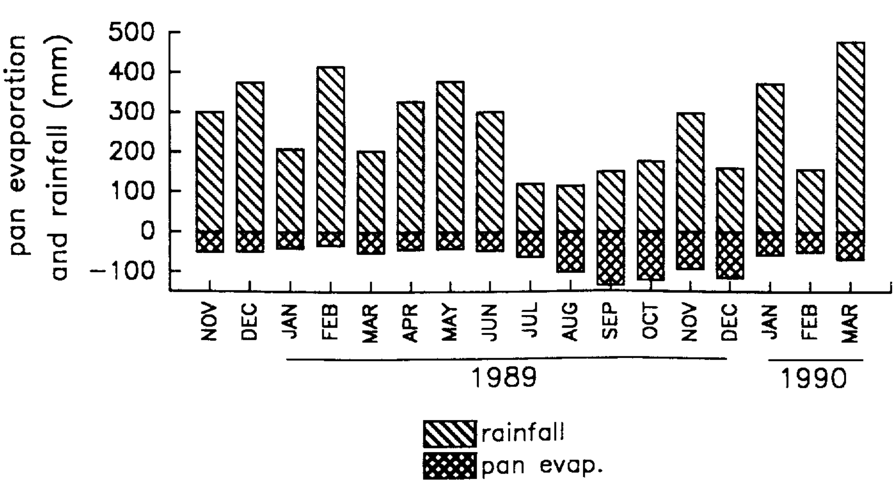

Fig. 1. Pan evaporation and rainfall distribution and subplot cropping sequences. Treatments 1 and 2 received legume green manure sources of N during the June and Dec. maize crops. Treatments 3 and 4 were clean tilled (bare) during fallow periods.

with a fine, but deep root system. Canavalia grows as a bush and has a tap root system. Both species have shown potential in the Amazonian region as partial or total substitutes for N fertilizers.

Legume crops were relay planted among 80-d-old maize plants (about 5 wk before harvest of maize), with the exception of the first canavalia crop, which was planted after maize. Both legumes were planted with 15-cm spacing in rows 0.5 m apart. Legume seed was not inoculated with rhizobia, but nodules, presumably caused by native rhizobia, were observed on roots of seedlings. The first and second legume crops were harvested 20 May 1989 and 14 Nov. 1989, respectively, approximately 120 DAP. Leguminous material from each plot was weighed and sampled for determination of moisture and nutrient content. The material was evenly spread over the plots and manually chopped with a machete. In the case of the first legume crop, the material of Blocks 1 and 2 was manually hoed into the soil and material of Blocks 3 and 4 was rototilled into the soil with a small tractor. The second legume crop was incorporated into the soil solely by rototilling.

Soil Samples

Soil was sampled 11 times during the course of the experiment. Plots were sampled from an area 0.5 m from the borders, with dutch augers, generally at intervals of 15 cm to a 120–cm depth. A composite sample from three holes was collected for nutrient analysis. A portion of the sample was analyzed for inorganic N by extraction with 1*M* KCl and steam distillation as described by Keeney and Nelson (1982). Calcium, Mg, and acidity were extracted from soil samples with 1*M* KCl and K with Mehlich 1 at a 1:10 soil:solution ratio. Calcium and Mg were analyzed by atomic absorption, K by flame photometry, and acidity by titration with 0.025 *M* NaOH. Soil pH was measured with 1:2.5 soil-water ratios (vol. basis) using a pH meter. Acidity saturation was calculated as follows:

$$\text{Acidity Saturation} = \frac{\text{Al} + \text{H}}{\text{Ca} + \text{Mg} + \text{K} + \text{Al} + \text{H}} \times 100$$

where the extractable cations Ca, Mg, K, Al and H are expressed in units of $\text{cmol}_c\ \text{kg}^{-1}$. Bulk density was determined on undisturbed cores sampled from pits dug adjacent to plots to a 1.2-m depth.

Climatic Data

Rainfall was measured at the field site with a pluviograph, 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 (located 0.2 km from field site).

Statistical Analyses.

The experimental data were statistically analyzed with a split-plot or nested model using the ANOVA procedures of the Statistical Analysis Software (SAS Institute Inc., 1985). The hierarchy of the nested model was as follows: "nitrogen treatment" was nested within "lime treatment," depth was nested within "nitrogen treatment," and "time" was nested within "depth." Snedecor and Cochran (1980) have discussed the nested model for analysis of repeated measures (time effects). All block interactions of the same nested level were pooled into a single error term (Snedecor and Cochran, 1980).

RESULTS

Leaching of Nitrate

During the first and the third maize crops, large amounts of NO_3 were lost from the topsoil, but during the second crop, grown in the dry season, there were no significant NO_3 losses (<10 kg NO_3^--N ha^{-1}) from the plow layer. Therefore, only data of the first and third crops are discussed in this NO_3 leaching section.

Nitrate losses from the soil profile (0–120 cm) were similar for all N and lime treatments during the first crop (Fig. 2). In contrast, urea treatments had greater losses of NO_3 from the plow layer than legume treatments during the third crop (Fig. 3), presumably because more N was applied under the urea treatments than the legume treatments. In addition, the mucuna treatment appeared to have had a second flush of mineralization between 60 and 120 DAP.

In many cases, major amounts of inorganic N were lost from the surface horizon during the first 60 d of a maize crop, probably before the period of N uptake was completed. These losses were determined by taking into account bulk density values and the difference between initial and 60-d concentrations of inorganic-N (NH_4, NO_2, and NO_3) in the 0- to 30-cm layer. During the first crop, plots cropped with maize lost an average of 316 kg ha^{-1} of inorganic-N and bare-fallow plots lost an average of 386 kg ha^{-1} of inorganic-N from the 0- to 30-cm layer by 60 DAP. During the third maize cycle, cropped plots treated with urea lost an average of 210 kg ha^{-1} of inorganic-N from the 0- to 30-cm layer by 60 DAP. Total accumulated N in the maize crops was not greater than 100 kg N ha^{-1} at harvest; therefore, a large portion of the N was likely leached as NO_3 or denitrified. Considering the humid regime of the region and that a large portion of the applied N accumulated in the subsoil with time (Fig. 2 and 3), much NO_3 was probably leached and could have had a strong influence on cation leaching.

Soil Acidification

Plots treated with lime showed no significant changes in KCl extractable acidity in the plow layer after 16 mo. However, unlimed plots, with the exception of the can-

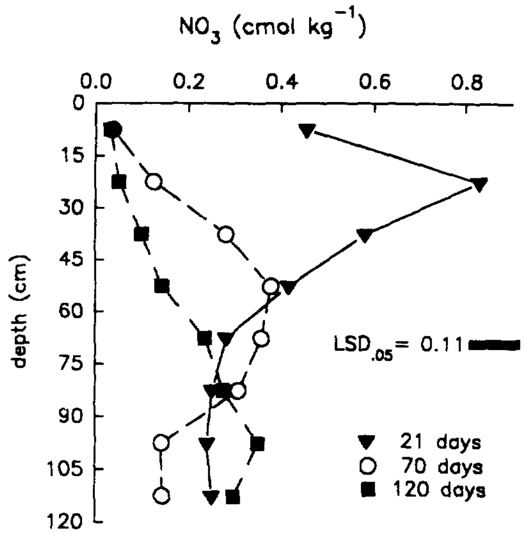

Fig. 2. Soil NO_3 content plotted against soil depth at three sampling intervals during the first maize crop, before establishing the legumes. Nitrate values were pooled for all treatments. Cumulative precipitation 21, 70, and 120 d after N application was 155 mm, 718 mm, and 1296 mm, respectively.

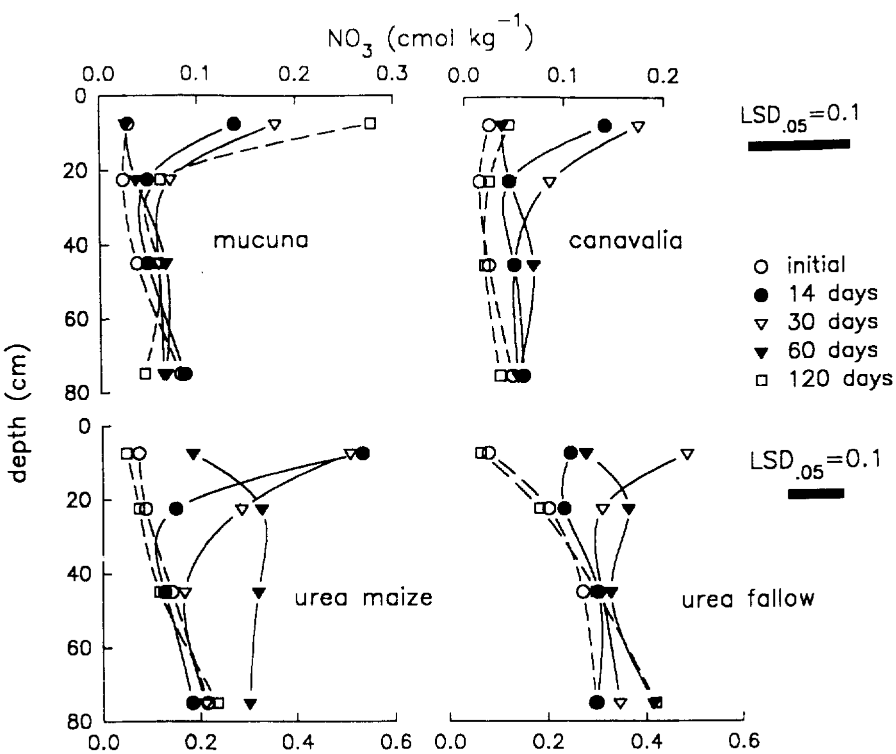

Fig. 3. Soil NO_3 content plotted against soil depth at five sampling intervals during the third maize crop; comparison among sub-plot treatments (lime treatments pooled). Cumulative precipitation 14 d after N application was 120 mm, 30 d = 199 mm, 60 d = 538 mm, and 120 d = 1128 mm.

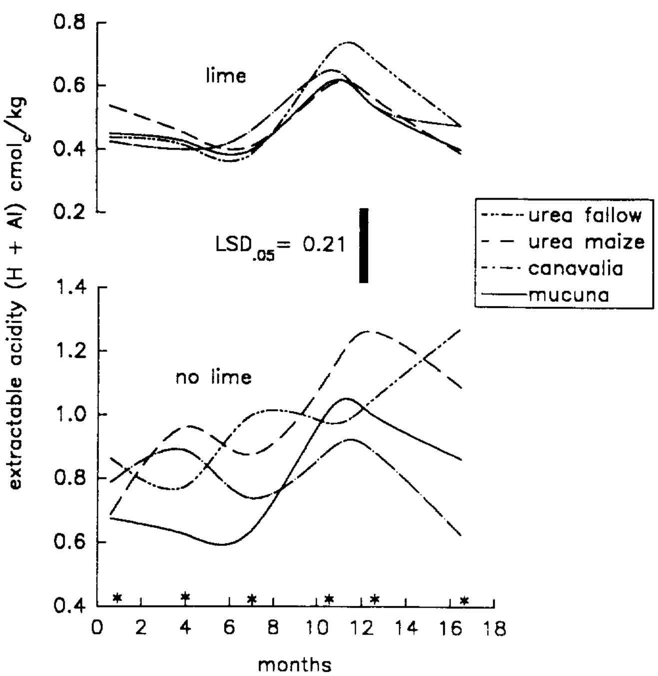

Fig. 4. Extractable soil acidity (H + Al) in the 0- to 30-cm soil layer for two lime rates plotted against time. Asterisks (*) indicate time of sampling.

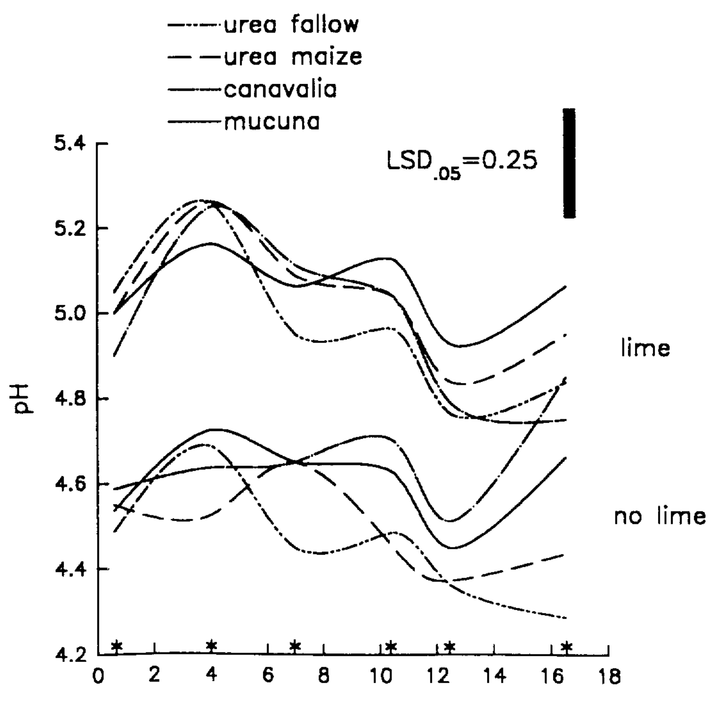

Fig. 5. Soil pH plotted against time in the 0- to 30-cm soil layer of sub-plot treatments. Asterisks (*) indicate time of sampling.

avalia treatment, had significant increases of KCl extractable acidity in the plow layer during the experiment (Fig. 4). Plots receiving the highest rates of N (urea-fallow and urea-maize) were most acidic. The pH of the plow layer changed little in these plots during 16 mo (Fig. 5), perhaps because these soils were well buffered by Al hydrous oxides.

Losses of Ca and Mg from the plow layer were influenced by the rate of lime applied. Approximately 1000 kg ha^{-1} and 500 kg ha^{-1} of Ca (equivalent to 2500 kg ha^{-1} and 1250 kg ha^{-1} of $CaCO_3$) were lost from the

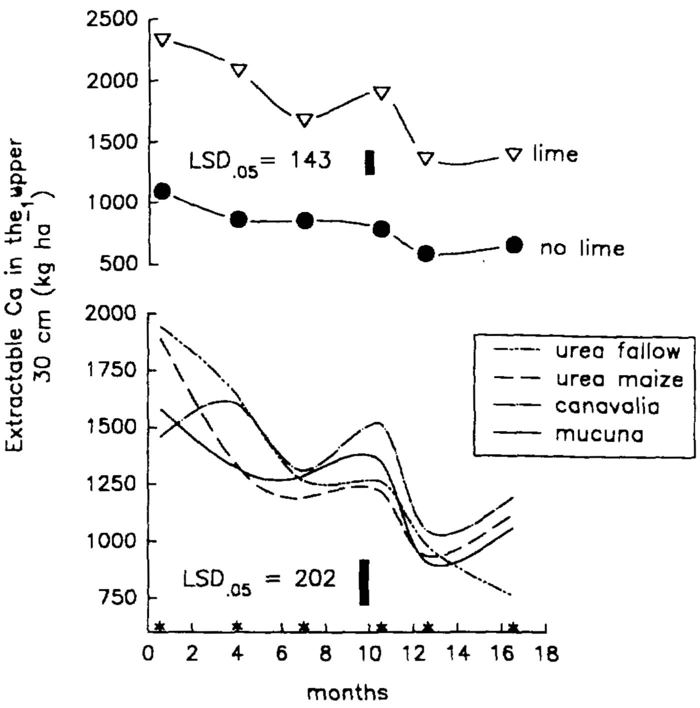

Fig. 6. Extractable Ca in the 0- to 30-cm soil layer plotted against time. Comparison among lime treatments (nitrogen treatments pooled) and nitrogen treatments (lime treatments pooled). Asterisks (*) indicate time of sampling.

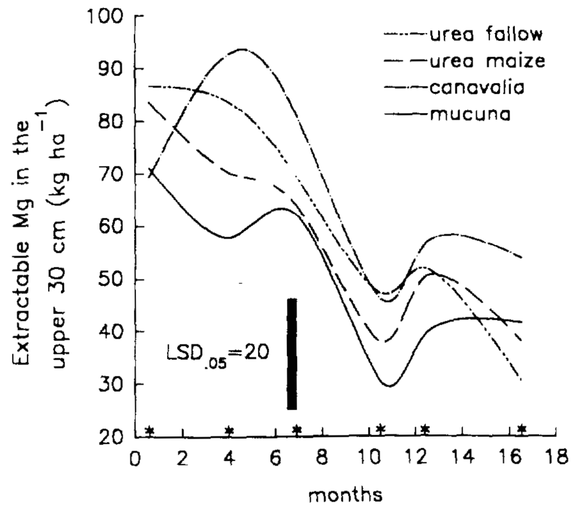

Fig. 7. Extractable Mg in the 0- to 30-cm soil layer plotted against time. Comparison among nitrogen treatments (lime treatments pooled). Asterisks (*) indicate time of sampling.

plow layer (0 to 30 cm) of limed and unlimed plots, respectively, during 16 mo (Fig. 6). Presumably, most of these losses were due to leaching, since removal of grain from the three maize crops accounted for less than 30 kg ha^{-1} of Ca. Magnesium losses from the plow layer were about 50 kg ha^{-1}. Less than half of these losses were due to crop removal (Table 1).

Nitrogen treatments also influenced the leaching of Ca and Mg from the plow layer (Fig. 6 and 7). Similar to the acidity data, the greatest loss of Ca and Mg in the plow layer occurred in the fallow-urea plots and the least occurred in the canavalia plots. Although the canavalia root system may have translocated leached bases from the subsoil to the surface, this treatment received the

Table 1. Nutrients removed from soil by harvesting maize during the experimental period.†

Treatment	Ca	Mg	N	K
	kg ha^{-1}			
No lime				
mucuna	23	20	153	85
canavalia	23	19	141	80
urea	16	15	109	62
Lime				
mucuna	24	21	161	90
canavalia	27	23	194	97
urea	29	25	202	100
LSD (0.05)‡	14	3	36	18

† Values estimated as the sum of nutrients contained in the grain of the first and second crops and the above ground dry matter of the third crop. Values represent the means of 4 replicates.
‡ Values within columns with differences greater than the LSD are significantly different at the 0.05 level.

lowest N rate during the experimental period, and therefore, would have had the least acidification.

In general, acidity saturation (percentage of extractable cations that are acidic) in the plow layer increased by about 50% of initial values during 16 mo (Fig. 8). In unlimed plots, acidity saturation was initially greater than 30%, the level which Cravo and Smyth (1987b) found reduced maize yields. In plots receiving urea, acidity saturation increased to levels which would severely limit maize root growth, while plots cropped with legumes, had minimal changes in acidity saturation. Although limed plots did not attain acidity saturation of 30%, at these rates of acidification they would need additional lime in another 1 to 2 yr to maintain maize yields.

Crop Response

Legume crops accumulated between 142 to 238 kg of N ha^{-1} in the above ground dry matter (Table 2). Probably the main factors influencing N content of the green manures were (i) the development of acidity in the unlimed plots which reduced N-yields of both legumes and (ii) relay planting legumes in maturing maize, which extended the legume cropping period, thereby increasing N accumulation.

The maize yields are presented in Table 3. The first and third maize crops yields were increased by lime. The second crop yields were about one-half the first crop yields, presumably because of water stress. Figure 1 shows low levels of rainfall and high rates of pan evaporation during the second maize crop (July through September). Water stress caused leaf wilting during the reproductive and grain filling stages of the second crop.

Acidity in the plow layer appeared to reach levels critical to maize yields in only the unlimed plots. Maize yields of the urea-limed treatments were not significantly different between Crops 1 and 3; however, maize yields of urea-unlimed treatments decreased by a 1/3 between the first and third crops (Table 3).

In the third crop, nitrogen treatments had contrasting effects on maize yield in limed and unlimed plots. Among limed plots the highest yields occurred in those receiving

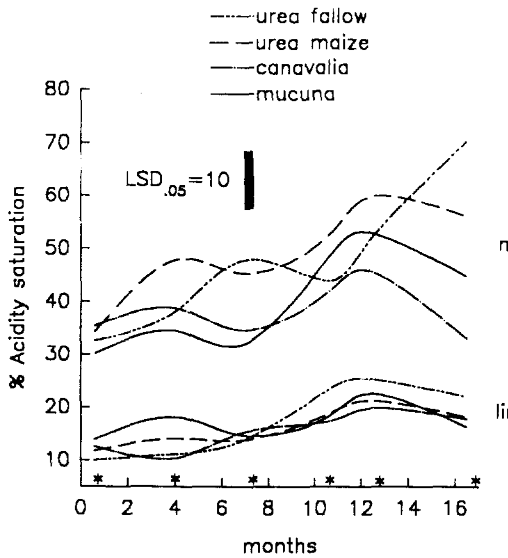

Fig. 8. Acidity saturation plotted against time in the 0- to 30-cm soil layer for two lime rates. Acidity saturation was calculated as the % of extractable cations (Ca, Mg, K, Al, and H) that are acidic (H + Al). Asterisks (*) indicate time of sampling.

urea, which received the highest rates of N fertilizer. As illustrated in Fig. 3, much NO_3 was quickly lost from the 0 to 30 cm layer of plots treated with green manures during the first 60 d, and hence these crops may have suffered N deficiencies in later stages of growth. Among unlimed plots the highest yields occurred in the legume treatments, which had the lowest acidity . The amount of N furnished by the three sources of N in these plots was considerably different and hence differential acidity may have developed during the cropping period.

DISCUSSION

The yield and soil chemical data showed that, during 16 mo, the additions of 900 kg ha^{-1} of urea-N and 4265 mm of rainfall acidified unlimed plots to a level that reduced maize yields. Once NO_3 from legume and urea sources leached beyond the amended plow layer where maize roots were concentrated, it was destined to leach further together with an equivalence of cations. Hence, the management of N would be important in maintaining the overall fertility of this Oxisol.

The urea applications were not correctly timed because one of the objectives was to measure the acidifying effects of excessive N fertilizers in a reasonable time and to compare the urea with legume green manures. We know that the effectiveness of the urea can be improved by proper timing of the correct amount of N. On the other hand, legume green manures are notably more difficult to manage than chemical fertilizers. Legume green manures cannot be easily applied in split applications to reduce NO_3 leaching nor can we always match the N supplied with the crop uptake. Because the amount of N mineralized from legume materials is affected by many factors, such as species, management, soil fertility, season, etc. (Costa, 1988), predicting the amount of green manure required to achieve a desired nonlegume yield, but minimize N leaching, is difficult.

Table 2. Above ground dry matter yields and nutrients contained in the legume crops.†

Treatment	Dry matter	N	P	K	Ca	Mg
	kg ha^{-1}					
Crop 1						
Lime						
mucuna	6824	279	15	67	59	9
canavalia	4017	172	8	60	86	5
No lime						
mucuna	7677	283	15	61	56	9
canavalia	3727	164	8	41	71	5
Crop 2						
Lime						
mucuna	3459	182	11	39	26	4
canavalia	5110	206	11	49	109	7
No lime						
mucuna	2945	142	9	32	18	3
canavalia	3473	142	7	35	50	5
LSD (0.05)‡	823	42	3	13	27	2

† Values represent the means of four replicates.
‡ Values within columns with differences greater than the LSD are significantly different at the 0.05 level.

Evidence that legumes were effective in recycling leached bases from the subsoil was limited. Acidification (loss of bases and generation of acidity) in the 0- to 30-cm horizon of the unlimed treatments was lowest in the legume green manure plots. Although this result may be due to the ability of legume crops to translocate bases from the subsoil to the surface, it does not exclude the possibility that (i) less N was added from green manure sources and hence less leaching may have occurred, (ii) denitrification may have been enhanced by energy derived from the green manures, and (iii) increased organic matter in the green manure plots may have buffered some of the acidity.

Nitrogen management for non-legume crop production in situations similar to those studied here is difficult. First, matching N supply to crop needs requires careful timing of more than one fertilizer application; technology for using legume green manures is not yet adequate because N mineralizes more rapidly from incorporated green manure than the young maize crop can absorb N. Three factors could improve the prospects for utilizing legume green manures. One would be the discovery of ways to delay by about a month the rapid mineralization

Table 3. Grain yields of maize from 1st (1989 wet season), 2nd (1989 dry season), and 3rd (1990 wet season) crops.†

Treatment	Crop 1	Crop 2	Crop 3
	Mg ha^{-1}		
No lime			
mucuna	--	1.96	3.12
canavalia	--	1.52	2.75
urea	3.18	1.09	1.78
Lime			
mucuna	--	1.54	3.20
canavalia	--	2.48	3.88
urea	4.51	2.23	4.47
LSD (0.05)‡	0.78	0.78	0.78

† Values represent the means of 4 replicates.
‡ Values with differences greater than 0.78 are significantly different at the 0.05 level (independent of row or column).

of legume N. A second would be the amelioration of subsoil acidity. Since anion exchange capacity tends to cause NO_3 to accumulate in the subsoil (Cahn et al. 1992), N leached beyond 30 cm might be recovered later in the season. A third factor would be the discovery of legume green manures that would recover N and cations from the deeper portions of the soil and trans. .ate them to the surface.

CONCLUSIONS

Nitrogen management significantly affected the fertility of an Oxisol during a 16-mo period. In plots treated with urea-N, high rates of NO_3 leaching accelerated the loss of Ca and Mg, leading to the acidification of the plow layer. In plots receiving urea-N without lime, maize yields decreased by 44% between the first and second wet seasons. Leaching of NO_3 and acidification was minimized in plots receiving legume green manure sources of N, perhaps because less inorganic N was applied than in urea plots and/or the legume crops recycled leached bases.

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