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Fertilizer nitrogen movement in a Central Amazon Oxisol and Entisol cropped to corn

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Abstract

Nitrogen fertilization experiments were conducted on a Oxisol and Entisol in the Central Amazon to evaluate the influence of soil properties and rainfall distribution on soil inorganic N movement and N recovery by corn (*Zea mays* L.). One corn crop was grown during the wet season on each site. A second crop was planted in the Oxisol during the dry season. Inorganic N was monitored in urea-N treatments (0 to 160 kg ha^{-1}) to a depth of 0.60 m by periodic soil sampling during each crop. During the wet season large N losses by leaching occurred in both soils with 120 or 160 kg ha^{-1} of applied N. Differences in soil permeability and corn rooting depth between soils contributed to a greater movement of N into subsoil layers in the Oxisol than the Entisol. However, N leaching beyond 0.60 m in the Oxisol was delayed, apparently because of NO_3^- adsorption in the net positively charged subsoil layers. Corn yields and N recovery in the Entisol were higher than in the Oxisol, during the wet season. During the dry season N leaching in the Oxisol was greatly reduced, relative to the previous wet season, by split applications of fertilizer N and lower cumulative rainfall (300 vs. 1012 mm). Management practices which promote root growth into acid subsoil layers of the Oxisol would increase plant access to soil N, improve crop N recovery and reduce fertilizer N requirements.

Introduction

Nitrogen losses by leaching are often reported for humid tropical environments, where rainfall during crop growth exceeds evapotranspiration and soil water holding capacity [1] [17] [24]. The rate of N leaching in soils in proportional to the rate of water movement below the crop rooting zone and the NO_3^- concentration in solution [23]. When acid tropical soils are limed, complete hydrolysis and nitrification of urea can occur within three days [25]. Downward water movement depends on soil physical parameters such as pore solute velocity, diffusivity and pore size distribution [7] [14]. Field experiments have demonstrated that N leaching is reduced under cropped conditions [17]. In a sandy kaolinitic Ultisol under high rainfall conditions, Arora and Juo [1] found that bare fallow plots contained more inorganic N and higher N losses by leaching than cropped plots.

Rainfall in the Central Amazon basin occurs in a monomodal distribution over a period of six to seven months, often exceeding 2000 mm. Large areas of the Central Amazon are occupied by Oxisols with high subsoil Al saturation levels which act as a chemical barrier to deep root growth [4]. Although clay content of Oxisols near Manaus often exceeds 80%, the predominance of kaolinite and strong aggregation results in medium water holding capacities [2]. Entisols along the white water rivers of the Amazon basin represent a second major land resource. Their high base status, adequate water supply and an eight month flood-free period provide appropriate conditions for intensive crop production in a region dominated by low fertility Oxisols and Ultisols [20]. In contrast to the Oxisols, availability of subsoil water in the Entisols is not restricted by high subsoil acidity.

Significant yield responses to applied N were reported for corn in a clayey Acrudox and a silty Tropofluvent of the Manaus region [22]. At equivalent N supply grain yields in the Acrudox were lower than in the Tropofluvent, suggesting that N recovery and potential N losses by leaching differed between soils. As a continuation of these field experiments in the Oxisol and Entisol, the objectives of this investigation were to evaluate the influence of soil properties and rainfall distribution on soil inorganic N movement and apparent N recovery corn (*Zea mays* L.) under variable rates of fertilizer N.

Material and methods

Site characterization

Two experiments were conducted at the Empresa Brasileira de Pesquisa Agropecuaria/ Centro de Pesquisa Agroflorestal da Amazônia research stations, near Manaus, Amazonas, Brazil: one on an upland soil and the other on an Amazon River terrace. The upland soil is classified as a very fine, kaolinitic, isohyperthermic, Typic Acrudox. The terrace soil is classified as silty fine-loamy, mixed, nonacid isohyperthermic, Typic Tropofluvent. Both sites are on flat topography (1–2% slope) with no appreciable micro-relief. Long term climatic data at the experiment station indicated a mean annual temperature of 25.7°C and an annual rainfall of 2461 mm, with 80% of the rainfall occurring during the months of October to May [6]. Corn yield response to five levels of fertilizer N (0–120 kg urea-N ha^{-1}), applied in three equal split-applications, was evaluated in the same field plots at both sites during the two cropping cycles preceding the present investigation. Fertilizer N requirements for corn increased progressively with each crop cycle at both sites [13].

Field experiments

One corn crop was planted in the Oxisol and Entisol during the wet season. A second crop that matured during the dry season was grown in the Oxisol. During the wet season crops treatments were arranged in a randomized complete block design, with three and four replications in the Entisol and Oxisol, respectively. Treatments consisted of five rates of urea-N (0, 40, 80, 120 and 160 kg ha^{-1}) broadcast and incorporated in a single application at planting. A locally adapted open pollinated corn cultivar (BR-5102) was planted on 27 November, 1986 in the Entisol, and on 12 January, 1987 in the Oxisol.

The dry season crop in the Oxisol was planted 16 June, 1987 and contained six treatments arranged in a randomized complete block design with four replications. Four urea-N rates (0, 40, 80 and 120 kg ha^{-1}) were broadcast and incorporated to the same corn cultivar, splitting the N rates into three equal parts applied at planting, and at 28 and 58 days after planting (DAP). Additional treatments included two N rates (0 and 80 kg ha^{-1}) split-applied to bare plots in the same manner as treatments with corn. The bare treatments were kept clean by periodic weeding. Each plot contained five 8 m length rows spaced at 1 m. Plant population at the silking stage averaged 4.2, 5.6, and 6.5 plants m^{-2} for the Entisol, and wet- and dry-season Oxisol crops, respectively.

For the two trials in the Oxisol, 45 kg P ha^{-1} as triple superphosphate and 30 kg K ha^{-1} as KCl were applied broadcast to all plots at planting. Lime was initially applied to the Oxisol two years prior to the present investigation. A second application of 2 t of calcitic lime ha^{-1} plus 50 kg ha^{-1} of $MgSO_4$ was made before planting the dry season crop in the Oxisol to maintain Al saturation below 20% and supply adequate Mg. Soil pH and nutrient levels in the Entisol precluded the need for fertilizer applications other than N. Fertilizers at all sites were incorporated with a rotovator before planting. Nitrogen applications after planting were immediately incorporated with a hoe. Although N volatilization was not measured, this step was taken to minimize such N losses. Weeds were controlled with a pre-plant herbicide and manually whenever necessary.

Soil sampling

Prior to planting the wet season crops soils at both sites were characterized by sampling profiles to a 0.6 m depth in 0.15 m increments. Particle size distribution was evaluated by the pipette method, using 0.1 *M* NaOH as the dispersing agent [5]. Three cores per depth increment were extracted using metallic cylinders ($96.4\ cm^3$) to determine bulk density. Saturated hydraulic conductivity values were determined with the constant head method [11] using three cores per depth collected with larger metallic cylinders ($347.5\ cm^3$).

Water retention curves for all depths were constructed with three undisturbed soil cores ($96.4\ cm^3$) per depth increment for the low tension range (saturation to −0.1 MPa) and disturbed samples for the high tension range (0.1 to 1.5 MPa). For this study microporosity was assumed to be equivalent to the volumetric water content of the undisturbed cores equilibrated at −0.01 MPa tension. Macroporosity was determined as the difference between the volumetric water content of the saturated cores and microporosity.

Total inorganic soil N determinations were made on samples taken at several dates during crop growth. Samples for the top 0.15 m depth of each plot contained 20 subsamples taken from the final harvest area. All other sampling depths (0.15 to 0.30, 0.30 to 0.45, and 0.45 to 0.60 m) contained three subsamples per plot. Each sample hole was refilled with soil and marked to avoid subsequent sampling in the immediate vicinity. Sampling was carried out in the Entisol at 0, 26, 42, 54, 70 and 109 DAP. During the wet season crop in the Oxisol, samples were taken at 0, 23, 32, 42, 56, 71 and 105 DAP. During the dry season crop samples were taken at 0, 15, 28, 42, 58, 70 and 109 DAP. These sampling dates corresponded approximately to the V6 (except on the Entisol experiment), V8, V12, R1 and R3 and R6 (harvest) growth stages [16]. Samples at day zero in each trial and at 28 and 58 DAP in the Oxisol dry season crop were taken prior to fertilizer N application.

Plant sampling

Total aboveground dry matter and N uptake were determined at physiological maturity, which occurred at 109, 105 and 109 DAP for the Entisol and wet and dry season Oxisol crops, respectively. Yields were estimated from a $12\ m^2$ area in each plot, consisting of the central 4 m on each of the three middle rows. Crop residues were weighed in the field, and subsamples were collected for N analysis and moisture content. Ears were separated into husks, cobs and grain, and weighed. Subsamples were taken to determine moisture and N concentration. Apparent fertilizer N recovery was determined as the difference in N uptake between a given N rate and the zero-N treatment, and expressed as a percentage of the applied fertilizer N. It was assumed that 1) N uptake by the zero N treatments corresponded to the N supplied by native soil reserves, and 2) that this soil N supply was constant across all N treatments [3].

During the wet season crops, root distribution was evaluated in each site at the silking stage using the trench-profile method [12]. Pits were dug perpendicular to a plot row in three replications of the 0, 80 and 160 $kg\ N\ ha^{-1}$ treatments. A 0.1×0.1 m square grid was then placed on a 1 m wide pit wall, 0.05 m from a plant stem, to a depth of 0.8 m. In each grid square, live roots were exposed by washing away 5 mm of soil and counted. For each treatment, root numbers from all replicates were averaged by depth and expressed as a percentage of the total roots counted in the profile.

Laboratory determinations

Chemical soil characterization for all depths was performed on samples taken at planting. Samples were extracted with *M* KCl for Ca, Mg and acidity and with the Mehlich-1 solution for K and P. Soil pH was determined in a 1:2.5 soil:H_2O suspension. Exchangeable acidity in the extracts was measured by titration with NaOH to the phenolphthalein endpoint. Calcium, Mg, and K were determined by atomic absorption spectrophotometry and P by colorimetry. Positive and negative soil charge was determined in all sampling depths for the zero-N plots according to the procedure described by Smyth and Sanchez [21].

Preliminary soil N determinations on samples collected from various depths and N treatments, during the four initial weeks of the wet season trials, showed negligible amounts of NH_4^+ relative to NO_3^- in the fresh soil extracts (data not shown). It was thus decided to measure total inorganic nitrogen (N_i) without distinction to ionic form. Soil samples for N_i were analyzed as soon after sampling as possible; otherwise, they were kept frozen. Soil extracts were obtained by shaking 13 g of fresh soil with 50 mL of *M* KCl for 30 min. After allowing the suspension to settle for two hours, 15 mL aliquots of the clear supernatant solution were subjected to steam distillation with MgO and Devarda alloy according to procedures described by Keeney and Nelson [10]. Fresh soil samples were converted to an oven dry soil basis by determinations of gravimetric water content. Values were transformed to a kg ha^{-1} basis using bulk density data. Changes in soil N resulting from fertilizer N at each sampling date were determined as the difference in profile (0 to 0.60 m) N_i between any given fertilizer N treatment and the treatments without applied N. These values are referred to as delta N_i. Nitrogen in plant tissues was determined by standard semi-micro Kjeldahl procedures [10] after wet digestion with H_2SO_4 and H_2O_2.

Model simulations

Nitrate movement was simulated using the model developed by Nofziger and Hornsby [15]. The model creates a homogeneous soil profile by averaging bulk density and soil water content at matrix potentials of -0.01 and -1.5 MPa at each sampling depth. Rainfall water redistributes between matrix potentials of -0.01 and -1.5 MPa and is withdrawn by evapotranspiration from the wettest part of the root zone, or uniformly from all depths when the water content is constant. All soil water participates in the transport process. Solute losses by plant uptake or soil adsorption are not considered.

Three climatic files were created with daily precipitation and evapotranspiration records from the growing periods of each crop (Fig. 1). Evapotranspiration values were calculated by subroutines included in the CERES-Maize model [9], using daily records of rainfall, solar radiation, maximum and minimum temperatures, crop growth and physical soil properties by sampling depth. Downward NO_3^- movement was simulated for both soils under the three weather files, resulting in three matched and three crossed simulations.

Statistical analyses

Treatment, time (as subplots) and treatment by time effects were evaluated by analysis of variance procedures in the Statistical Analysis System [18]. Homogeneity of variance was tested prior to combining sampling dates. Planned single-degree-of-freedom comparisons were used to partition treatment sums of squares in the dry season trial on the Oxisol.

Results and discussion

Physical and chemical soil properties

Soil profile physical and chemical characteristics are shown in Tables 1 and 2, respectively. Average microporosity for the Entisol profile was 20% greater than the Oxisol whereas mean hydraulic conductivity for the Oxisol was six times greater than the Entisol. These physical characteristics suggested that the Entisol would require more rainfall and a longer time to displace a pore volume of profile water than the Oxisol. Ion exchange capacity was essentially constant for all depths in the Entisol, with mean values of 12.28 and 0.26 $cmol_c\ kg^{-1}$ for negative and positive charge, respectively (Table 2). In the Oxisol cation exchange capacity decreased by 79% and anion exchange capacity increased by 141% with increasing soil depth. Below the surface 0.15 m there was a sevenfold difference in mean positive charge between the Oxisol and Entisol.

Crop weather

Accumulated rainfall and evapotranspiration during the three crop growth cycles are shown in

Table 1. Selected physical properties for soil profiles at the two experimental sites

Depth	Clay	Silt	Sand	BD[a]	Porosity		HD[b]
					Micro	Macro	
cm	%			$Mg\ m^{-3}$	m^3		$cm\ h^{-1}$
				Oxisol			
0–15	82	7	11	1.04	516	278	28.12
15–30	82	9	9	1.12	703	132	8.12
30–45	84	8	8	1.11	731	136	9.60
45–60	92	1	7	1.04	685	127	10.44
				Entisol			
0–15	21	64	15	1.18	636	204	5.47
15–30	18	60	22	1.52	853	270	0.57
30–45	16	56	28	1.61	822	340	1.54
45–60	13	53	34	1.65	842	348	0.59

[a] Bulk density
[b] Hydraulic conductivity

Table 2. Selected chemical properties for soil profiles at the two experimental sites

Depth	pH	Exchangeable				Effective CEC	Charge	
		Ca	Mg	K	Acidity		Negative	Positive
cm		$cmol_c\ kg^{-1}$						
					Oxisol			
0–15	4.7	1.15	0.15	0.17	0.89	2.36	2.06	0.88
15–30	4.5	0.60	0.07	0.05	1.52	2.24	0.77	1.55
30–45	4.5	0.38	0.05	0.04	1.18	1.65	0.82	1.82
45–60	4.4	0.34	0.04	0.04	1.14	1.56	0.43	2.12
					Entisol			
0–15	6.1	7.97	1.67	0.31	0.23	10.18	13.75	0.27
15–30	6.1	7.57	1.64	0.15	0.20	9.56	11.24	0.25
30–45	6.0	7.74	1.63	0.20	0.24	9.81	12.59	0.24
45–60	5.8	7.36	1.63	0.17	0.19	9.35	11.54	0.28

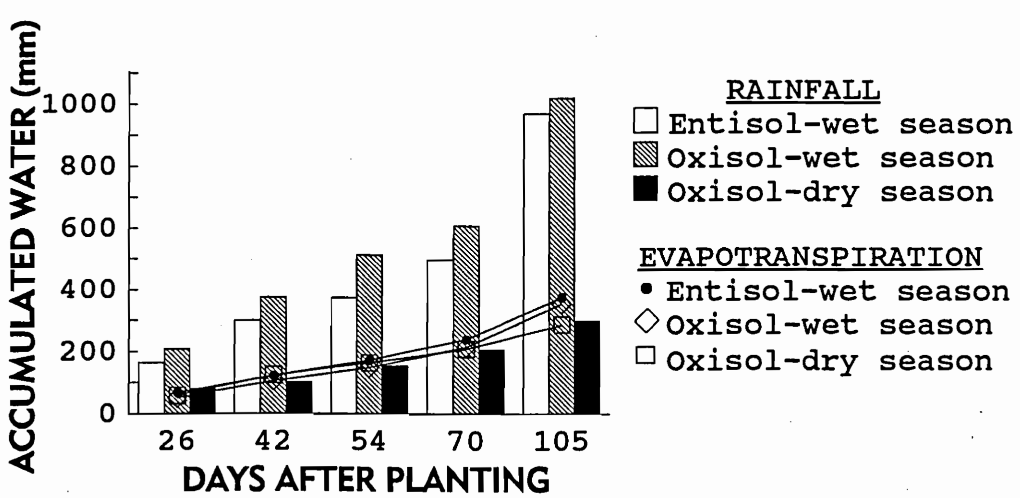

Fig. 1. Whether scenarios that prevailed during the crop growth cycles of the three experiments.

Figure 1. Rainfall for the Oxisol wet season was consistently greater than for the Entisol with a cumulative difference of 50 mm. Quantity and distribution of rainfall during the dry season in the Oxisol contrasted with the former wet season. Number of days with rain and total rainfall, relative to the wet season, were one-half and one-third, respectively. During the final growth stages in the dry season visual symptoms of water deficiency were evident. Rainfall exceeded evapotranspiration by 617, 644 and 11 mm for the Entisol and wet- and dry-seasons of the Oxisol, respectively. Cumulative rainfall during the wet and dry season crops in the Oxisol deviated from the previous 15-year average [6] by +6 and −9%, respectively.

Soil N_i distribution

Set season crops. Nitrogen treatment and time effects were significant at all sampling depths in both soils (Table 3). Significant N by time interactions were limited to the top 0.30 and 0.45 m in the Oxisol and Entisol, respectively. For each sampling depth changes in soil N_i as a function of time after fertilizer N was applied are shown in Figures 2 for the Oxisol and figure 3 for the Entisol. Prior to applying N (0 d) mean soil N_i levels in the Entisol profile (0 to 0.60 m) exceeded the Oxisol by 100 kg ha^{-1}. Futhermore, initial N_i decreased with depth in the Oxisol and increased with depth in the Entisol. Native soil N_i at the time of N fertilization, therefore, differed in quantity and distribution between profiles at the two sites.

Table 3. Analysis of variance summary of soil N_i at each sampling depth during the wet season crops in the Oxisol and Entisol

Soil	Source of Variation	df	Profile depth, cm			
			0–15	15–30	30–45	45–60
			F-value			
Oxisol	Replication	3	0.3	0.5	0.5	0.3
	N Rates	4	12.2**	10.8**	15.1**	18.4**
	Time	6	15.3**	20.4**	13.1**	5.4**
	Rate × Time	24	2.7**	2.8**	1.4	1.1
Entisol	Replication	2	0.4	5.7*	1.7	9.9**
	N Rates	4	7.4**	8.1**	7.0**	21.8**
	Time	5	23.0**	3.3*	3.0	3.9*
	Rate × Time	20	5.6**	2.6**	2.5**	1.5

*, **: Significant at $p \leq 0.05$ and 0.01, respectively.

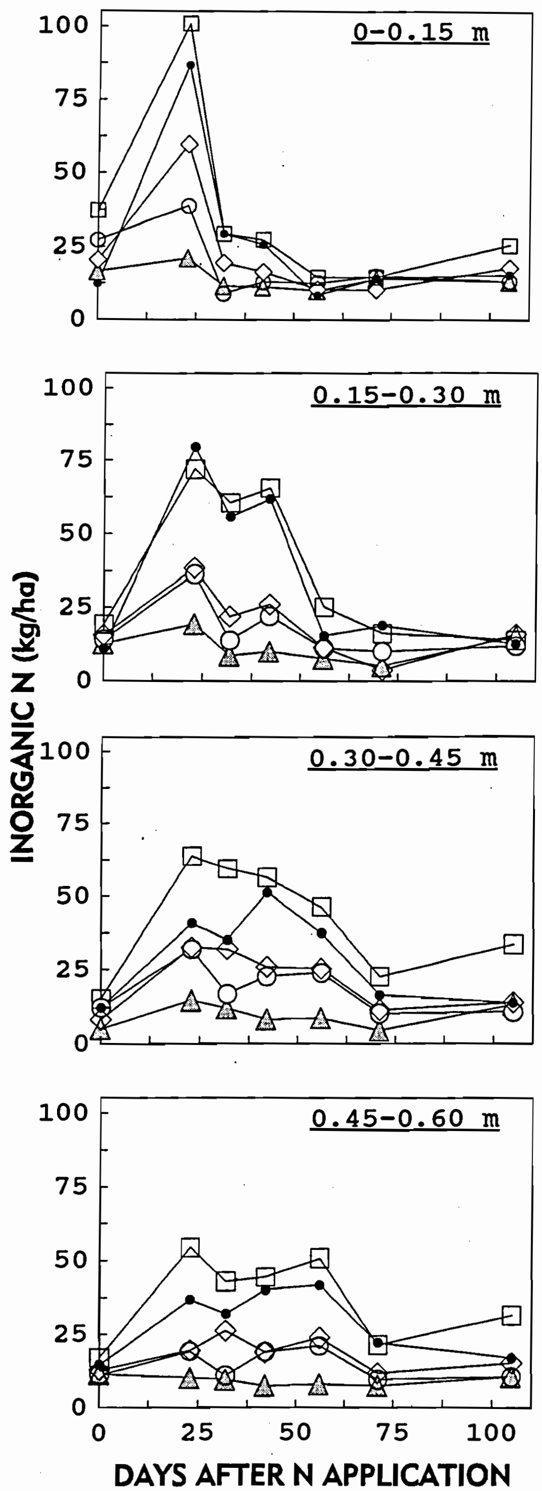

Fig. 2. Distribution of inorganic N at four sampling depths during the wet season crop in the Oxisol. Applied N(kg/ha) □ 160; ● 120; ◇ 80; ○ 40; ▲ 0.

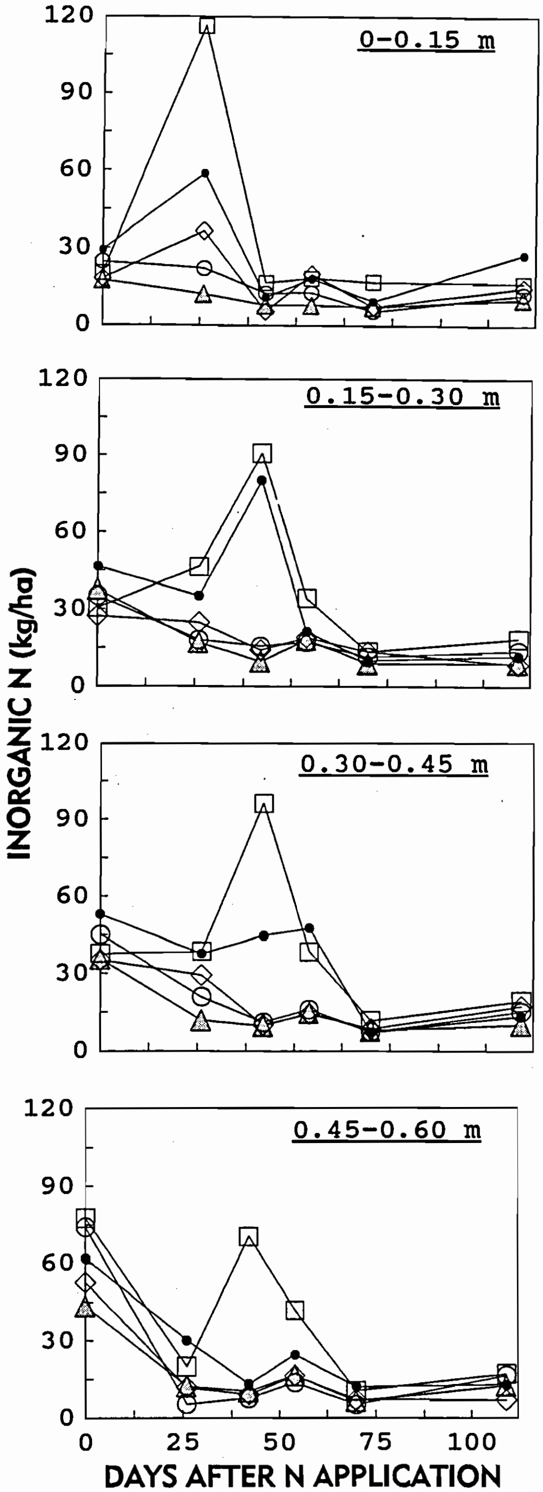

Fig. 3. Distribution of inorganic N at four sampling depths during the wet season crop in the Entisol. Applied N(kg/ha) □ 160; ● 120; ◇ 80; ○ 40; ▲ 0.

In surface layers of both soils maximum N_i levels were detected on the second sampling date and declined to a similar level among N treatments in subsequent sampling dates. Increases in N_i concentrations between samples at zero and 23 DAP for all depths in the Oxisol indicated that fertilizer N had moved to the 0.60 m depth by the second sampling date. For treatments with 120 and 160 kg N ha^{-1} increases in N_i across all sampling depths between zero and 23 DAP exceeded fertilizer N inputs by 58 and 66 kg N ha^{-1}, respectively. This may be attributed to a 'priming effect' of fertilizer N on native soil N mineralization [8]. Whereas N_i declined markedly for surface layer samples taken after 23 DAP in the Oxisol, there was a gradual reduction in N_i concentrations for subsurface layer samples taken between 23 and 42 DAP. These differences in N_i distribution with time between surface and subsoil layers were particularly evident in treatments with 120 and 160 kg N ha^{-1}. In the Entisol peak N_i concentrations for subsurface layers generally occurred in samples taken 16 days after maximum N_i levels were detected in the zero to 0.15 m layer. At subsequent sampling dates subsurface N_i levels decreased in a similar pattern to the surface soil layer.

Since there were marked differences in native soil N_i between soils, delta N_i was used to compare the rate of fertilizer N depletion from the zero to 0.60 m in the Oxisol and Entisol profiles. There were significant N treatment and time effects on delta N_i for both the Oxisol and Entisol profiles. Rate by time interactions, however, were not significant. When averaged across N treatments, reductions in delta N_i with time after N application followed an exponential pattern. Depletion of mean delta N_i with time in both soils was described by the following equation:

$$\text{Delta } N_i \text{ (kg ha}^{-1}) = 189.3e^{-0.025(\text{days})}$$
$$(r = 0.84;\ n = 11)\,.$$

Regression coefficients were significant at the 0.001 probability level. Although rates of fertilizer N disappearance from both soil profiles were described by a single function, data in Figures 2 and 3 would suggest that distribution of N among depth increments differed across time between soils.

Comparison of hydraulic conductivity and macroporosity data between soils (Table 1) would suggest a faster rate for downward flow of excess water in the Oxisol, thus allowing less time for equilibration with the soil solution in micropores. This flow process may have contributed to the presence of N_i in deep layers of the Oxisol at the first sampling date following N applications. Previous studies have indicated that recently applied fertilizer N moves through by-pass flow in macropores, whereas NO_3 retained in aggregate micropores, through either fertilizer N diffusion or soil N mineralization, moves downward at a slower rate [19] [24]. The longer fertilizer N residence time in subsurface layers of the Oxisol may be related to the greater anion exchange capacity of this soil (Table 2). Several investigators have attributed retarded leaching of NO_3 to the presence of colloids with net positive charge [1] [24] [25]. Measured anion exchange capacity in the zero to 0.60 m depth of the Oxisol would be equivalent to approximately 150 kg NO_3-N ha^{-1} as opposed to 34 kg NO_3-N ha^{-1} in the Entisol.

Dry season crop. Effects of N rates on soil N_i were limited primarily to the zero to 0.30 m sampling depths (Table 4). The lower mean soil N_i levels at all depths for the zero and 80 kg N ha^{-1} treatments planted to corn, relative to bare plots with similar N rates, was probably a reflection of N accumulation by the crop (Table 5). For each N rate and depth increment, variations in soil N_i as a function of time after planting are shown in Figure 4. Relative to the wet season experiment in this Oxisol (Fig. 2), both initial (before applying N) and final soil N levels were higher during the dry season. Soil N_i levels in the surface layer increased after each N application and decreased by the subsequent sampling date. In the subsurface layers, the pattern of variation in N_i concentration was similar to the surface layer but the magnitude of the difference between N rates decreased with increasing depth. Reduced rainfall (Fig. 1) and distribution of fertilizer N in three split applications, during the dry season experiment, contributed to less downward movement of N_i relative to the previous wet season crop.

Table 4. Analysis of variance summary of soil N_i at each sampling depth during the dry season crop in the Oxisol

Source of Variation	df	Profile depth, cm			
		0–15	15–30	30–45	45–60
		F value			
Replication	3	1.8	3.2	1.8	0.3
Treatments	5	13.8**	3.8*	1.9	6.1**
N Rate (0 vs. 80)	1	33.5**	7.1*	1.8	2.0
Cropping	1	16.6**	10.0**	4.8*	7.0*
(0 N vs. 80 N) × Cropping	1	5.0*	0.0	0.7	5.2*
40 N vs. 120 N	1	13.4**	0.8	2.2	10.2**
40 + 120 N vs. Others	1	0.2	1.0	0.0	5.8*
Time	6	14.3**	6.6**	7.3**	8.9**
Treatment × Time	30	3.4**	1.7*	1.7*	0.8

*, **: Significant at $p \leq 0.05$ and 0.01, respectively.

Table 5. Mean[a] soil N_i concentration in cropped and bare plot treatments at each sampling depth during the dry season crop in the Oxisol

Treatment	Depth increment, cm			
	0–15	15–30	30–45	45–60
	kg N ha^{-1}			
Cropped	44 ± 17[b]	35 ± 12	29 ± 10	26 ± 8
Bare	57 ± 24	41 ± 16	34 ± 10	30 ± 11
LSD 0.05	7	4	4	3

[a] Mean values for zero and 80 kg N ha^{-1}.
[b] Standard deviation based on 56 observations.

N uptake and recovery

Nitrogen fertilization increased total dry matter and N accumulation in all crops (Table 6). Apparent N recovery, however, decreased with increasing N applications. The Entisol wet season crop accumulated more dry matter and N than the two Oxisol crops. Since the quantity of crop N derived from native soil reserves was similar between wet season crops, apparent fertilizer N recovery was greater for the Entisol. Although contributions of native soil N to corn were higher during the dry season in the Oxisol, total dry matter accumulation was reduced by a limited water supply during the dry season. Consequently, N accumulation and apparent fertilizer N recovery in the Oxisol was lower for the dry season crop than for the wet season crop. Under similar rainfall conditions with a Typic Paleudult in Nigeria, van der Kruijs and co-workers [26]

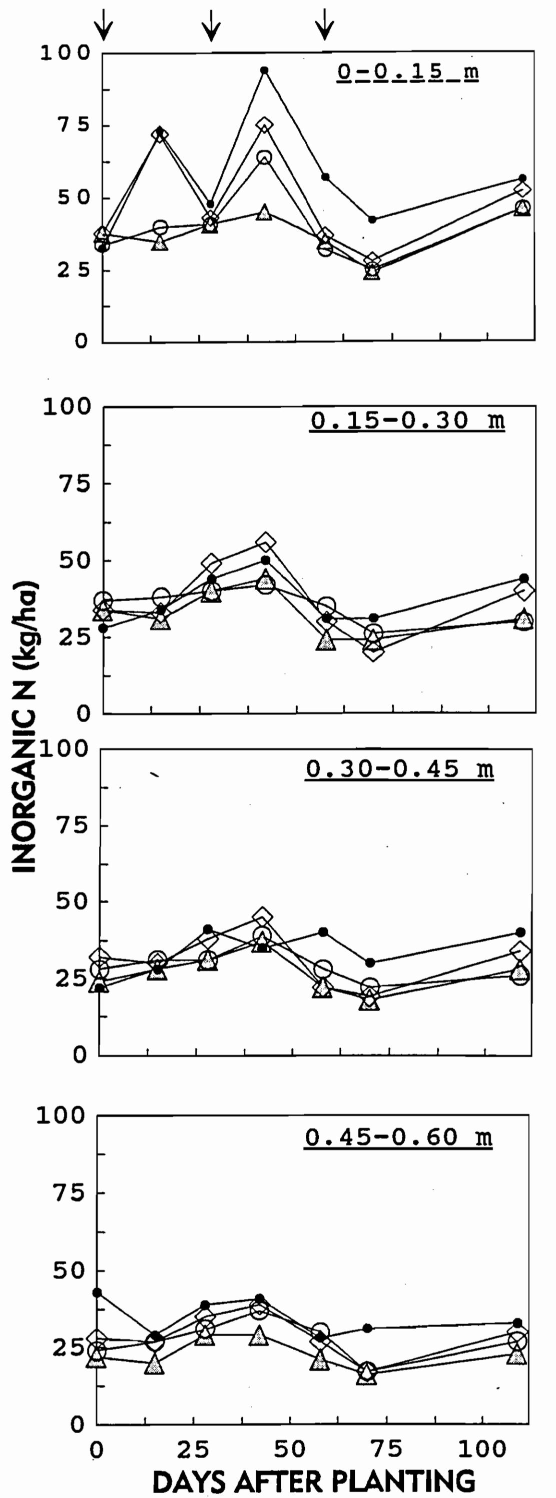

Fig. 4. Distribution of inorganic N at four sampling depths during the dry season crop in the Oxisol. Arrows indicate time when fertilizer N was applied. Applied N (kg/ha) ● 120; ◇ 80; ○ 40; ▲ 0.

reported 7.5 t ha^{-1} of corn dry matter and 31% recovery of fertilizer ^{15}N (138 kg urea-N ha^{-1}) distributed in two split applications. These values are similar to dry matter and apparent N recovery values obtained in the Oxisol wet season crop with 160 kg N ha^{-1}.

Estimates on the amount of fertilizer N, in each crop and N rate, which could be accounted for at harvest were determined by the summation of delta N_i with the quantity of crop accumulated N which exceeded the zero N treatment. At the 80 kg N ha^{-1} rate accountability for fertilizer N ranged from 60% in the Entisol to 66% in the Oxisol wet season crop. The range of fertilizer N accounted for at the 120 kg N ha^{-1} rate increased to a maximum of 69% in the Entisol and a minimum of 42% in the Oxisol wet season crop. Soil N_i data in the 0.45 to 0.60 m profile increment suggested that deeper N movement may have occurred with high N rates in both wet season crops. It is also possible that some of the unaccounted fertilizer N in both wet and dry season crops was retained in roots, lost by volatilization or immobilized. During the first year after fertilization, 22% of the ^{15}N labelled urea applied to corn in an Ultisol in Nigeria was recovered in the drainage water primarily in the NO_3 form [26].

Root distribution

Profile root distribution, during the wet season crops, was not affected by N fertilization at either location. Therefore, mean values across N rates were used to compare root distribution between the Entisol and Oxisol profiles (Fig. 5). Approximately 90% of the roots occurred in the surface 0.30 m of soil at both sites, and root numbers declined progressively with increasing depth. Marked differences were observed between sites when considering either the proportion of roots below the surface 0.10 m or the absolute number of roots at different depths. In the Entisol 67% of the roots were below the zero to 0.10 m layer while only 46% were below an identical depth in the Oxisol. Root number in the zero to 0.30 and 0.30 to 0.60 m depth increments for the Entisol were 1.5 and four times greater than those in the Oxisol. The observed differences in root number and distribution be-

Table 6. Total dry matter (TDM), crop N accumulation (CNA), delta soil N_i (DN_i), and apparent N recovery (ANR) at harvest of each crop in the Entisol and Oxisol

N Rate	Entisol				Oxisol							
					Wet season				Dry season			
	TDM	CNA	DN_i	ANR	TDM	CNA	DN_i	ANR	TDM	CNA	DN_i	ANR
kg ha^{-1}	t ha^{-1}	kg ha^{-1}		%	t ha^{-1}	kg ha^{-1}		%	t ha^{-1}	kg ha^{-1}		%
0	2.8	23	–	–	1.9	19	–	–	2.8	35	–	–
40	6.0	57	16	85	4.1	40	−6	53	4.1	51	1	40
80	6.4	65	6	53	5.8	61	11	53	4.9	58	28	29
120	7.4	82	24	49	5.5	62	7	36	4.6	52	45	14
160	7.4	89	29	41	7.0	77	53	36	–	–	–	–
LSD .05	1.9	28	NS	23	1.5	18	NS	12	1.4	13	40	20

NS: Not significant at $p \leq 0.05$.

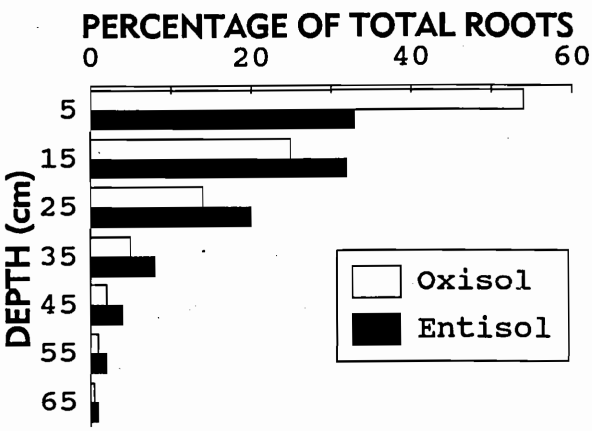

Fig. 5. Corn root distribution at silking stage in the wet season crops.

tween the Entisol and Oxisol are in agreement with the high subsoil acidity in the Oxisol (Table 2). The lower quantity of roots in subsurface layers of the Oxisol probably contributed to the lower apparent recovery of fertilizer N relative to the Entisol (Table 6).

Modeled nitrate movement

Simulations of NO_3 movement in both soils under weather conditions for the three corn crops provided a means for evaluating the extent to which soil N_i movement was influenced by climatic differences among the crop growth cycles. Results indicated that there was a linear relation in each soil between depth of movement

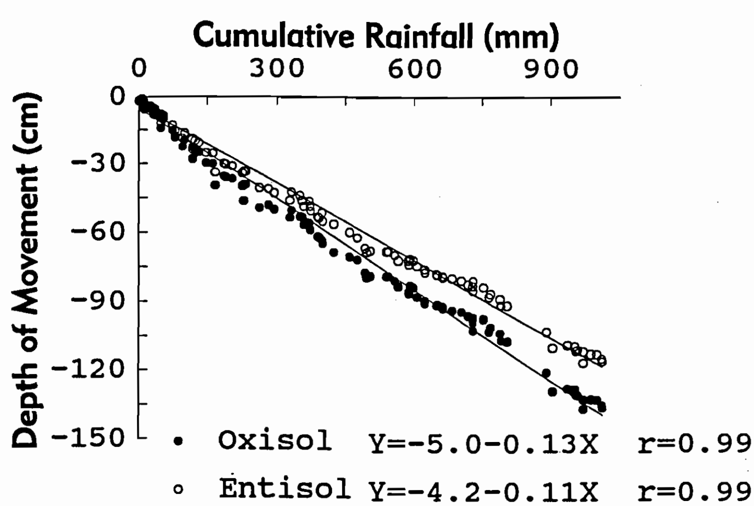

Fig. 6. Relationship between simulated depth of movement for the leading edge of a NO_3 front in the Oxisol and Entisol and cumulative rainfall during the three corn growth cycles in the wet and dry seasons.

of the leading edge of a NO_3 solution and cumulative rainfall (Fig. 6). Linear regression slopes indicated that movement of the NO_3 front in the Oxisol exceeded the Entisol by 2 cm for every 100 mm of rainfall. Based on these results, the 50 mm difference in cumulative rainfall between wet season crop cycles increased depth of solute movement in the Oxisol by 1.0 cm. With the actual rainfall records for each wet season crop and soil, predicted movement of the leading NO_3 solute edge to a 0.30 m depth occurred at 30 days after N fertilization in the Entisol as opposed to 18 days in the Oxisol. Maximum predicted depth of movement of the solute front for the dry season crop in the Oxisol was 0.42 m. Simulation results for wet season crops are in agreement with the detection of N_i peaks at an earlier date in subsoil layers in the Oxisol than in the Entisol (Figs. 2 and 3) and suggested that differences in physical properties between soils were of greater significance than differences in rainfall regimes in promoting a higher rate of solute movement in the Oxisol.

Conclusions

Results from these studies suggested that N leached from both soils during the wet season. The greater macroporosity and hydraulic conductivity in the Oxisol contributed to a faster rate of downward N_i movement in this soil than in the Entisol. These soil differences, along with a reduced proportion and total number of corn roots in subsurface layers of the Oxisol, were conducive to a lower crop yield and apparent N recovery than in the Entisol. The greater residence time for N_i in acid subsoil layers of the Oxisol, apparently by NO_3 adsorption on net positive charged colloids, suggested that management practices which diminish chemical constraints to root growth in acid subsoil conditions could also enhance plant recovery of fertilizer N.

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References

1. Arora Y and Juo ASR (1982) Leaching of fertilizer ions in a kaolinitic Ultisol in the high rainfall tropics: leaching of nitrate in field plots under cropping and bare fallow. Soil Sci Soc Am J 46: 1212–1218
2. Correa JC (1984) Caracteristicas físico-hidricas dos solos latossolo amarelo, podzolico vermelho amarelo e podzol hidromorfico do estado de Amazonas. Pesq Agropec Bras 19: 347–360
3. Craswell ET and Godwin DC (1984) The efficiency of nitrogen fertilizers applied to cereals in different climates. Adv Plant Nutr 1: 1–55
4. Cravo M and Smyth TJ (1987) Lime requirements and downward movement of Ca and Mg. In: Caudle N and McCant CB (eds.) TropSoils Technical Report 1985–1986, pp 102–106. Raleigh, NC: North Carolina State University
5. EMBRAPA (1979) Manual de Metodos de Analise do Solo. Rio de Janeiro, Brazil: Empresa Brasileira de Pesquisa Agropecuaria/Servico Nacional de Levantamento e Conservacao de Solos
6. EMBRAPA (1987) Boletim Agrometeorologico 1985. Boletim agrometeorologico, 6. Manaus, Brazil: Empresa Brasileira de Pesquisa Agropecuaria/UEPAE de Manaus
7. Grimme H and Juo ASR (1985) Inorganic nitrogen losses through leaching and denitrification in soils of the humid tropics. In: Kang BT and van der Heide J (eds.) Proc Symp Nitrogen Management in Farming Systems in Humid and Subhumid Tropics, pp 57–71. Ibadan, Nigeria: International Institute of Tropical Agriculture
8. Jansson SL and Persson J (1982) Mineralization and immobilization of soil nitrogen. In: Stevensen FJ et al. (eds.) Nitrogen in Agricultural Soils. Agronomy 22: 229–252
9. Jones CA and Kiniry JR (1986) CERES-Maize: A Simulation Model of Maize Growth and Development. College Station, TX: Texas A&M University Press
10. Keeney DR and Nelson DW (1986) Nitrogen-inorganic forms. In: AL Page et al. (eds.) Methods of Soil Analysis Part 2, 2nd edn. Agronomy 9: 643–698
11. Klute A and Dirksen C (1986) Hydraulic conductivity and diffusivity: laboratory methods. In: Klute A (ed.) Methods of Soil Analysis, Part 1, 2nd edn. Agronomy 9: 687–734
12. Kopke U (1980) Methods for studying root growth. In: Russell RC et al. (eds.) The Soil/Root System in Relation to Brazilian Agriculture, Proc of the Symposium on the Soil/Root System, pp 304–318. Parana, Brazil: IAPAR, Fundacao Instituto Agronomico do Parana
13. Melgar RJ (1989) Nitrogen utilization by annual crops in the Central Amazon. PhD Thesis, North Carolina State Univ, Raleigh, NC

14. Nielsen DR, Biggar JW and Wierenga PJ (1982) Nitrogen transport processes in soil. In: Stevensen FJ (ed.) Nitrogen in Agricultural Soils. Agronomy 22: 423–448
15. Nofziger DL and Hornsby AG (1985) Chemical movement in soil: IBM PC user's guide. Computer series, Software in Soil Science. Gainsville, FL: IFAS, University of Florida
16. Ritchie SW, Hanway JJ and Benson GO (1986) How a corn plant develops. Special report No. 48. Ames, IO: Iowa State Univ of Sci and Tech Cooperative Extension Service
17. Roose EJ (1974) Influence du type de plante et du niveau de fertilisation sur la composition des eaux de drainage en climat tropical humide. J. L'Hydraulique (France) 13: 1–7
18. SAS Institute (1985) SAS User's Guide: Statistics. Cary, NC: SAS Institute, Inc
19. Smettem KRJ, Trudgill ST and Pickles AM (1983) Nitrate loss in soil drainage waters in relation to bypassing flow and discharge on an arable site. J Soil Sci 34: 499–509
20. Schubart HOR and Salati E (1982) The natural systems. In: Hetch SB (ed) Amazonia: Agriculture and Land Use, pp 211–241. Cali, Colombia: Centro Internacional de Agricultura Tropical
21. Smyth TJ and Sanchez PA (1980) Effects of lime, silicate and phosphorus applications to an Oxisol on phosphorus sorption and ion retention. Soil Sci Soc Am J 44: 500–505
22. Smyth TJ, Cravo MS and Melgar RJ (1989) Nitrogen management. In: Caudle N (ed) TropSoils Technical Report 1986–87, pp 152–154. Raleigh, NC: North Carolina State University
23. White RE (1988) Leaching. In: Wilson JR (ed) Proc of Symp Advances in Nitrogen Cycling in Agricultural Ecosystems, Brisbane, Australia, May 11–15, 1987, pp 193–211. Walling, UK: CAB International
24. Wild A (1972) Nitrate leaching under bare fallow at a site in northern Nigeria. J Soil 23: 315–324
25. Wong MTF, Wild A and Juo ASR (1987) Retarded leaching of nitrate measured in monolith lysimeters in south-east Nigeria. J Soil Sci 38: 511–518
26. van Der Kruijs ACBM, Wong MTF, Juo ASR and Wild A (1988) Recovery of ^{15}N-labelled fertilizer in crops, drainage water and soil using monolith lysimeters in south-east Nigeria. J Soil Sci 39: 483–492