Soil Nitrate and Water Dynamics in Sesbania Fallows, Weed Fallows, and Maize

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ABSTRACT

We hypothesized that the integration of trees into agricultural land-use systems can reduce NO_3 leaching and increase subsoil N utilization. A field study was conducted on a Kandiudalfic Eutrudox (Ochinga site) and a Kandic Paleustalf (Muange site) in the subhumid highlands of Kenya to measure changes in soil NO_3 and water to 200-cm depth for one rainy season in four land-use systems (LUS): (i) planted tree fallow using *Sesbania sesban* (L.) Merr., (ii) unfertilized maize (*Zea mays* L.), (iii) weed fallow, and (iv) bare fallow. Subsoil (50-200 cm) NO_3-N at the start of the season ranged from 58 to 87 kg ha^{-1} for the four LUS and two sites. In maize, subsoil NO_3-N differed by <5 kg ha^{-1} between planting and harvest at both sites. In sesbania, subsoil NO_3-N decreased by 22 kg ha^{-1} at both sites, whereas in weed fallow subsoil NO_3-N decreased by 26 and 38 kg ha^{-1} at Ochinga and Muange, respectively. At both sites, subsoil water contents at the start of the season were similar in the four LUS; but at the end of the season, soil water at 100 to 200 cm was significantly lower for sesbania than for maize. Adsorption of NO_3 increased with soil depth. Sorbed NO_3 at 100 to 200 cm was about 60% in the Kandiudalfic Eutrudox and about 15% in the Kandic Paleustalf. Rotation of maize with either a sesbania fallow or a weed fallow can result in more effective subsoil NO_3 and water utilization than maize monoculture.

NITRATE FREQUENTLY ACCUMULATES in tropical soils during the onset of rains following a dry season (Birch, 1958; Semb and Robinson, 1969). As the rains continue, the accumulation of soil NO_3 is usually followed by a rapid decrease in topsoil NO_3 due to a combination of plant uptake, denitrification, immobilization, and leaching (Greenland, 1958). Leaching can result in appreciable loss of topsoil NO_3 (Poss and Saragoni, 1992) and accumulation of NO_3 in the subsoil (Leutenegger, 1956; Jones, 1976).

Nitrate leached down the profile of tropical soils can be adsorbed on positively charged surfaces (Wild, 1972; Cahn et al., 1992). Sorption of NO_3 typically increases with depth, decreased pH, decreased organic matter, increased kaolinite, and increased Fe and Al oxides (Black and Waring, 1979). Sorption of NO_3 can retard downward movement of NO_3 (Wong et al., 1987) and results in accumulation of NO_3 below the rooting depth of crops. Michori (1993) observed 2200 kg NO_3-N ha^{-1} at 1- to 5-m depth under fertilized coffee in Kenya. The peak in subsoil NO_3 corresponded to a soil layer with low pH, high positive surface charge, and 1:1 clay minerals.

Natural fallows have long been a way to overcome soil fertility depletion that results from continuous cropping with no nutrient inputs (Nye and Greenland, 1960). As land pressure increases due to increasing population and other competing land-use demands, long-duration natural fallows are no longer a viable option. As a result, a shift is required to more permanent food-production systems that optimize nutrient cycling, enhance soil biological activity, and maximize the use efficiency of minimal external nutrient inputs (Sanchez, 1994). One such possible system is a short-duration, planted tree fallow.

In planted tree fallows, a preferred tree is grown as the fallow species in rotation with cultivated crops. The ideal tree species is typically fast growing, N fixing, and efficient at nutrient capture and cycling. One promising tree species is *sesbania sesban*. Kwesiga and Coe (1994) showed that 1- to 3-yr planted sesbania fallows increased yield of subsequent maize crops on a N-responsive soil in Zambia, but little is known about the ability of sesbania fallows, compared with natural fallows and cereal crops, to reduce the loss of soil NO_3 and to utilize subsoil NO_3.

The objective of this study was to compare the effects of a sesbania planted fallow, a weed fallow, and maize on seasonal changes in soil water and NO_3 to the 200-cm depth. A bare fallow was included as a control in order to assess soil water and NO_3 status in the absence of plant growth.

MATERIALS AND METHODS

Site Description

A field experiment was conducted at two farms (Ochinga and Muange) in the highlands of Kenya during the short rains of 1993. Ochinga (0°06'N, 34°34'E) is at an altitude of 1420 m with a mean annual rainfall of 1800 mm. Muange (1°31'S, 37°19'E) is at an altitude of 1920 m with a mean annual rainfall of 900 mm. Both sites have bimodal distribution of rainfall and two growing seasons. The growing season during the short rains is from September to January at Ochinga and from October to March at Muange. The cumulative rainfall was 483 mm between 1 Sept. 1993 and 17 Jan. 1994 at Ochinga and 413 mm between 1 Nov. 1993 and 26 Mar. 1994 at Muange.

The soil at Ochinga is a very fine, isohyperthermic Kandiudalfic Eutrudox, and the soil at Muange is a fine, mixed, isothermic Kandic Paleustalf (Table 1). The methods of soil analysis were: pH(H_2O) in a 1:1 soil/water suspension; pH(KCl) in 1 *M* KCl suspension (1:1); organic C by wet oxidation with heated acidified dichromate followed by colorimetric determination of Cr^{3+} (Anderson and Ingram, 1993); extractable P and exchangeable K by extraction with 0.5 *M* $NaHCO_3$ +0.01 *M* ethylenediaminetetraacetic acid, pH 8.5; and exchangeable Ca, Mg, and acidity by 1 *M* KCl extraction. Minerals at Ochinga are predominantly kaolinite, with a small amount of hematite and very small amounts of mica and goethite. Predominant minerals at Muange are kaolinite and hematite, although in smaller quantity than at Ochinga. Miner-

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Published in Soil Sci. Soc. Am. J. 60:568-574 (1996).

Abbreviations: LUS, land-use system; DAS, days after sowing; SED, standard error of the mean difference.

Table 1. Chemical characteristics and particle size distribution of soils at Ochinga and Muange.

Site	Depth	pH(H_2O) (1:1)	pH(KCl) (1:1)	Exchangeable acidity	Organic C	Extractable P	Exchangeable cations			Sand	Clay	Bulk density
							Ca	Mg	K			
	cm			$cmol_c\ kg^{-1}$	$g\ kg^{-1}$	$mg\ kg^{-1}$	—— $cmol_c\ kg^{-1}$ ——			—— % ——		$Mg\ m^{-3}$
Ochinga	0-15	5.1	4.1	0.4	15.0	2	3.4	1.4	0.12	26	46	1.10
	15-30	5.3	4.2	0.5	13.4	1	3.6	1.3	0.07	24	51	1.22
	30-50	5.4	4.4	0.4	10.2	1	3.2	1.0	0.05	17	60	1.25
	50-100	5.5	4.6	0.3	5.9	1	3.2	0.8	0.05	16	65	1.32
	100-150	5.5	4.5	0.4	5.2	2	2.8	0.8	0.05	16	65	1.28
	150-200	5.5	4.5	0.5	5.7	2	2.0	0.7	0.05	18	66	1.29
Muange	0-15	5.7	4.7	0.2	8.0	5	3.4	1.1	0.47	56	29	1.49
	15-30	5.5	4.6	0.2	6.2	3	3.3	1.1	0.47	58	32	1.53
	30-50	5.4	4.5	0.3	5.3	2	3.1	1.2	0.42	58	36	1.55
	50-100	5.5	4.5	0.5	3.9	1	3.2	1.7	0.31	50	43	1.40
	100-150	5.5	4.6	0.4	3.2	1	2.8	1.8	0.25	48	44	1.31
	150-200	5.6	4.7	0.4	3.2	1	2.7	1.5	0.28	48	44	1.31

alogy was determined as described by Soil Survey Laboratory Staff (1992).

Experimental Layout

The experimental design at both farms was a randomized complete block with four replications and four LUS: sesbania fallow, unfertilized maize, weed fallow, and bare fallow. Plots were 10 by 10 m. Soil NO_3 and gravimetric water were measured six times between September 1993 and January 1994 at Ochinga and six times between November 1993 and March 1994 at Muange.

The sesbania was established in the season before the start of the experiment. At Ochinga, sesbania (Kisii provenance) was direct seeded in four rows (2.25 by 0.4 m spacing) on 4 Apr. 1993. Three rows of maize (0.75 by 0.25 m spacing) were grown between the sesbania rows, and the maize was harvested in August. Thereafter, the sesbania plots were not cropped with maize and were kept weed free by regular hand pulling. At Muange, 4-mo-old sesbania (Kisii provenance) seedlings were planted at 10 000 plants ha^{-1} (1 by 1 m spacing) on 11 May 1993. Maize was not planted with the sesbania, and plots were manually kept weed free.

Maize, weed fallow, and bare fallow plots were cropped with maize (0.75 by 0.25 m spacing) in the season before the start of the experiment. This maize was harvested 15 August at Ochinga and 17 September at Muange, and then all aboveground biomass was manually removed from these plots. In the maize LUS, maize (hybrid 512 at Ochinga and hybrid 511 at Muange) was sown at 53 330 plants ha^{-1} (0.75 by 0.25 m spacing) on 1 September at Ochinga and 2 November at Muange. It was harvested on 17 January (138 DAS) at Ochinga and 26 March (144 DAS) at Muange. The weed fallow contained natural regrowth following the August weeding at Ochinga, and the September weeding at Muange. The predominant weeds were *Guizotia scabra* (Vis) Chiov., *Hibiscus* sp., *Digitaria abyssinica* (A. Rich.) Stapf, and *Eleusine* sp. at Ochinga and *Bidens pilosa* L., *Tagetes minuta* L., *Nicandra physalodes* Scop., and *Oxygonum sinuatum* (Meisn.) Dammer at Muange. The bare fallow was maintained free of vegetation by regular hand pulling with removal of weeds from plots. Twice during the season, 1-m-deep trenches were dug around the sesbania plots and then back filled in order to limit root growth both outside the plots and into other plots.

Soil Sampling and Analysis

Soil samples were collected with an Edelman auger from six depths: 0 to 15, 15 to 30, 30 to 50, 50 to 100, 100 to 150, and 150 to 200 cm. In each maize, weed fallow, and bare fallow plot, soil was collected and bulked from eight locations for layers above 100 cm and from four locations for layers below 100-cm depth. In maize plots, half the sampling locations were between maize rows and half were within rows. In sesbania plots, the distance between two rows at Ochinga and the diagonal distance between two trees at Muange were divided into strata (Rao and Coe, 1991). At Ochinga, the distance between rows of sesbania (2.25 m) was divided into nine strata with a width of 25 cm. Soil samples were collected from all strata between the four sesbania rows (27 locations) and bulked. At Muange, the diagonal distance between two trees (1.4 m) was divided into three strata (0-25, 25-50, and 50-70 cm from the tree). Four to eight samples were collected from each stratum and then bulked into one sample per stratum. Nitrate and water for a plot were calculated as a weighted mean of values for the three strata, taking into account the surface area represented by each stratum.

One subsample of each soil sample was dried at 105°C for 48 h, immediately after collection, in order to determine gravimetric water content. Another subsample was placed, field moist, in a refrigerator at 5°C immediately after collection. About 10 g of field-moist soil were extracted with 100 mL of 2 *M* KCl with shaking for 1 h at 150 reciprocations per minute and subsequent gravity filtering using prewashed Whatman no. 42 paper. Soil water content was determined on the stored field-moist soil at the time of extraction in order to calculate the dry weight of extracted soil.

Nitrate plus nitrite was determined by Cd reduction (Dorich and Nelson, 1984), with subsequent colorimetric determination of NO_2 (Hilsheimer and Harwig, 1976). No effort was made to separate NO_3 and NO_2. Because NO_2 was probably small relative to NO_3, the values were reported as NO_3 for the sake of simplification. Soil bulk density was determined with cores (100 cm^3) collected for each depth from within a pit. The bulk density was used to convert NO_3 values from milligrams per kilogram to kilograms per hectare and to convert soil water to a volumetric basis.

Nitrate adsorption isotherms for soil from each sampled layer were determined as described by Cahn et al. (1992), except for slight modifications. Potassium nitrate was used instead of $Ca(NO_3)_2$ for the equilibrium solution because Cahn et al. (1992) found similar NO_3 sorption with both salts. After equilibration, samples received five drops of superfloc 127 solution (5 g L^{-1} water), which serves as a flocculating agent. They were then centrifuged at 3000 rpm for 15 min, decanted, and filtered through prewashed Whatman no. 5 paper. Reported values are the means of triplicate analyses.

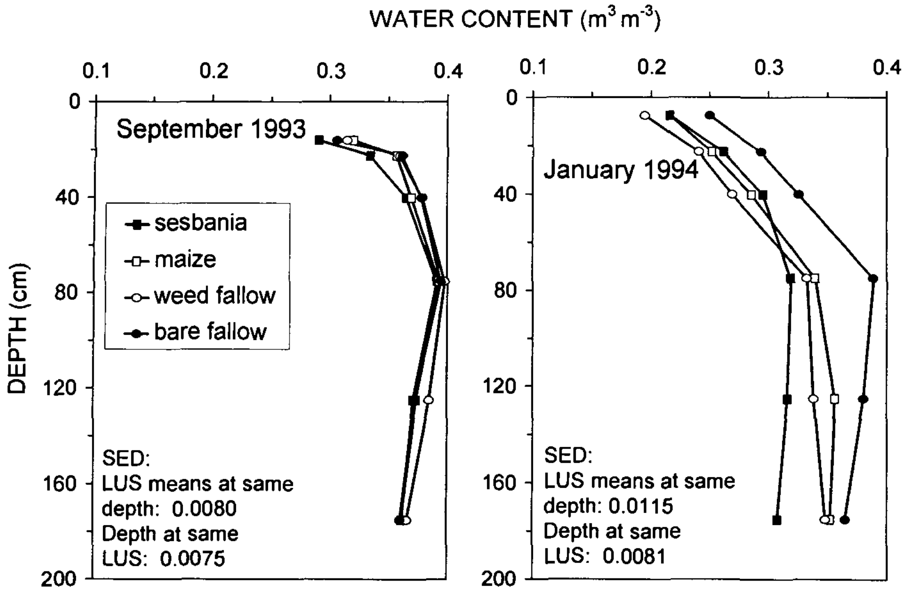

Fig. 1. Soil water in the land-use systems (LUS) at the start (September) and end (January) of the season at Ochinga.

Statistical Analysis

The NO_3 data were tested for normality using analysis of variance with untransformed data, whereafter the residuals were examined (Lane et al., 1987). The residuals were not normally distributed and showed a variance that increased with the mean. Logarithmic transformation of data was used to overcome the skewed distribution and nonconstant variance of data, and then the data were analyzed by GENSTAT version 5 (Genstat 5 Committee, 1988). Nitrate and water content data for a sampling time for each site were analyzed as a split plot with LUS as the main plot (error df = 9) and depth as the subplot (error df = 60). Nitrate data from one depth for the six sampling times were analyzed as a split plot with LUS as the main plot (error df = 9) and time as the subplot (error df = 60).

When an analysis of variance is conducted with log-transformed data, comparing means statistically can only be done on the log-transformed scale. Nitrate results are reported on the transformed scale for comparison of means, and on the untransformed scale for the presentation of values in kilograms per hectare or milligrams per kilogram.

RESULTS AND DISCUSSION

Soil Water Profiles

At the beginning of the season at Ochinga (September), soil water at 0 to 30 cm was significantly ($P \leq 0.05$) lower for sesbania than for maize and weed fallow (Fig. 1). Sesbania, which was sown 5 mo before the September sampling, was actively extracting topsoil water as compared with the maize and weeds, which were growing for only 2 wk before the sampling.

At Ochinga, soil water decreased between September and the end of the season (January) due to plant uptake and evaporation exceeding rainfall (Fig. 1). At the end

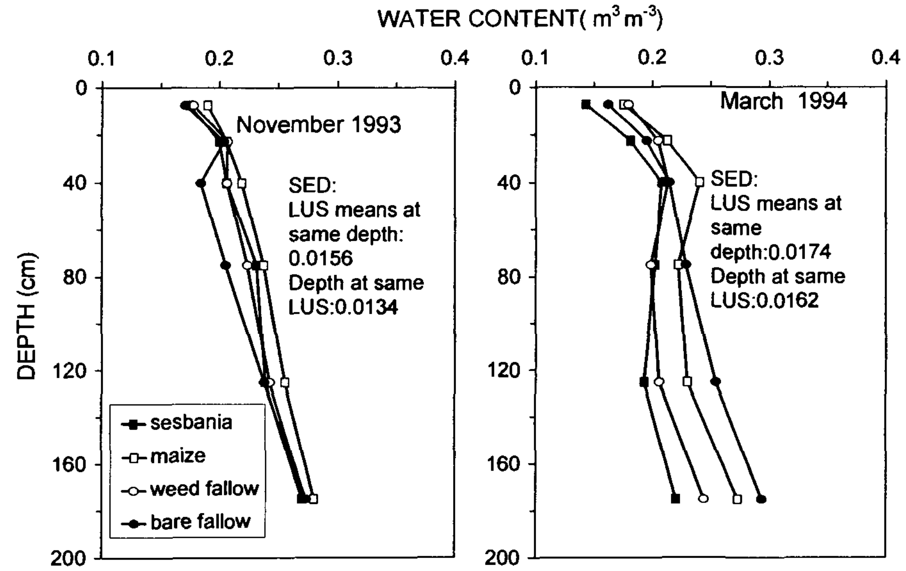

Fig. 2. Soil water in the land-use systems (LUS) at the start (November) and end (March) of the season at Muange.

Table 2. Nitrate-N (log transformed) for four land-use systems (LUS) at the start (September) and end (January) of the season at Ochinga.

	September 1993†				January 1994†			
Depth	Sesbania	Maize	Weed fallow	Bare fallow	Sesbania	Maize	Weed fallow	Bare fallow
cm	(log mg kg^{-1} + 1)10^3							
0–15	1133	1132	1112	1136	712	937	780	1485
15–30	914	899	993	992	647	695	895	1375
30–50	709	777	821	799	647	777	750	1187
50–100	723	788	823	750	532	820	715	992
100–150	584	549	607	527	462	597	537	870
150–200	411	468	585	389	317	415	327	520

† Standard errors of the mean difference (SED) for comparing LUS means at the same depth are 99 for September and 107 for January; SED for comparing depth means at the same LUS are 93 for September and 102 for January.

of the season (January), soil water differed markedly among the LUS, and the LUS × depth interaction was highly significant ($P \leq 0.001$). Soil water above 50 cm was lower for weed fallow than for sesbania, but below 50 cm it was higher for weed fallow than for sesbania (Fig. 1). Sesbania was more effective than maize or weeds in extracting water below 100 cm. Soil water below 100 cm was significantly ($P \leq 0.05$) lower for sesbania than for maize, and soil water below 150 cm was significantly lower for sesbania than for weed fallow.

At Muange, soil water at the beginning of the season (November) was similar for sesbania, maize, and weed fallow throughout the profile (Fig. 2), possibly due to heavy rain (43 mm) 4 d before the November sampling. Soil water at the end of the season (March) was lowest for sesbania and weed fallow (Fig. 2), but interaction between LUS and depth was slight ($P = 0.092$). As at Ochinga (Fig. 1), soil water below 100 cm was significantly ($P \leq 0.05$) lower for sesbania than for maize, and subsoil water for weed fallow was intermediate to sesbania and maize.

Nitrate Profiles

Soil NO_3-N at the beginning of the season at Ochinga (September) and Muange (November) was similar ($P \leq 0.05$) among LUS at each depth (Tables 2 and 3). Initial NO_3 concentrations at Ochinga (September) decreased with depth (Fig. 3, Table 2). At Muange, initial NO_3 concentrations (November) were greatest at 15 to 30 cm and relatively high below 150 cm (Fig. 4, Table 3). Initial mean NO_3-N at 150 to 200 cm was 5.5 mg kg^{-1} at Muange compared with 2.0 mg kg^{-1} at Ochinga.

At Ochinga, soil NO_3 in the bare fallow increased throughout the profile between September and January, due to mineralization of soil organic N exceeding losses (Fig. 3, Table 2). The presence of plants (sesbania, weeds, or maize) reduced topsoil NO_3 between September and January, and in January topsoil NO_3 was significantly lower in the planted plots than the bare fallow. Nitrate-N in January was consistently lowest for sesbania throughout the profile, but NO_3-N below 100 cm was not significantly different ($P \leq 0.05$) among sesbania, maize, and weed fallow. The greater uptake of water from below 100 cm by sesbania, compared with other LUS (Fig. 1), did not coincide with lower subsoil NO_3 for sesbania (Fig. 3, Table 2).

At Muange, the seasonal increase in soil NO_3 in the bare fallow was less (Fig. 4, Table 3) than at Ochinga. Lower soil organic C at Muange than at Ochinga (Table 1) and a 2-mo dry period (January and February) at Muange (Fig. 5) probably contributed to lower mineralization rates at Muange than at Ochinga.

At Muange, in contrast to Ochinga, NO_3-N at 15 to 50 cm was lower ($P \leq 0.05$) for weed fallow than for sesbania. Nitrate-N below 100 cm was similar for weed fallow and sesbania (Table 3). Subsoil NO_3, like subsoil water (Fig. 2), was lower for weed fallow and sesbania than for maize (Fig. 4).

Subsoil Nitrate Contents

Nitrate-N in the subsoil (50–200 cm) at the start of the season ranged from 58 to 76 kg ha^{-1} at Ochinga and 78 to 87 kg ha^{-1} at Muange (Fig. 5). Nitrate-N at 50–200 cm in the bare fallow increased during the season at both sites, suggesting that NO_3 movement into this subsoil layer plus nitrification in this layer were greater than NO_3 losses by leaching and denitrification. The increase in NO_3-N between the first and last sampling was 47 kg ha^{-1} at Ochinga and 34 kg ha^{-1} at Muange.

Maize had no net effect on NO_3 at 50 to 200 cm during

Table 3. Nitrate-N (log transformed) for four land-use systems (LUS) at the start (November) and end (March) of the season at Muange.

	November 1993†				March 1994†			
Depth	Sesbania	Maize	Weed fallow	Bare fallow	Sesbania	Maize	Weed fallow	Bare fallow
cm	(log mg kg^{-1} + 1)10^3							
0–15	837	875	910	1019	521	636	366	1048
15–30	1129	932	1047	1022	576	442	208	1088
30–50	678	566	660	663	635	484	170	1031
50–100	522	527	519	606	490	557	195	905
100–150	742	685	743	616	561	680	557	729
150–200	769	909	742	810	711	836	657	770

† Standard error of the mean difference (SED) for comparing LUS means at the same depth are 161 for November and 162 for March; SED for comparing depth means at the same LUS are 126 for November and 131 for March.

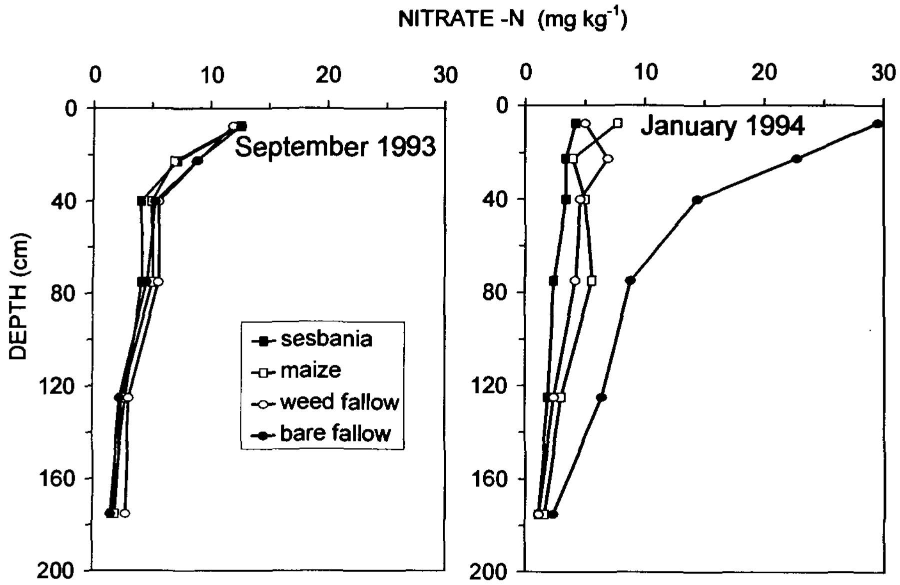

Fig. 3. Nitrate-N in the land-use systems at the start (September) and end (January) of the season at Ochinga.

the growing season; NO_3-N at the start and end of the growing season differed by <5 kg ha^{-1} at both sites. Sesbania and weed fallow, on the other hand, decreased NO_3 at 50 to 200 cm at both sites. At Ochinga, NO_3 was lower ($P \leq 0.05$) in the last than first sampling for both sesbania and weed fallow (Table 4). The decrease between the first and last sampling was 22 kg N ha^{-1} for sesbania and 26 kg N ha^{-1} for weed fallow. At Muange, the decrease was 22 kg N ha^{-1} for sesbania and 38 kg N ha^{-1} for weed fallow; the decrease for weed fallow was significant at $P \leq 0.05$.

Nitrate-N in the subsoil (50-200 cm) at the end of the season was lower for sesbania and weed fallow than for maize at both sites (Fig. 5, Table 4). At Ochinga, NO_3-N at the end of the season in both the subsoil (Fig. 5) and throughout the soil profile (Fig. 3) was lowest for sesbania. Subsoil water (Fig. 1) was also lowest for sesbania. At Muange, NO_3-N at the end of the season in the subsoil (Fig. 5) and throughout the profile (Fig. 4) was lowest for weed fallow, but NO_3 for weed fallow was not significantly different ($P \leq 0.05$) from that for sesbania. Subsoil water (Fig. 2) was also similar for weed fallow and sesbania.

The low subsoil NO_3 and water following growth of sesbania and weed fallow, as compared with maize, presumably resulted from deeper rooting and greater uptake of NO_3 by sesbania and weeds than by maize. Preliminary root observations at Ochinga revealed that the portion of the total length density below 60 cm was 26% for maize and 63% for sesbania (Mekonnen, 1996). Very few maize roots were observed below 120 cm, whereas sesbania and weed roots extended below 200 cm.

At Ochinga, the changes in subsoil NO_3 differed among LUS (LUS × time interaction: $P \leq 0.001$). The rapid initial decrease in subsoil NO_3 between the first (16

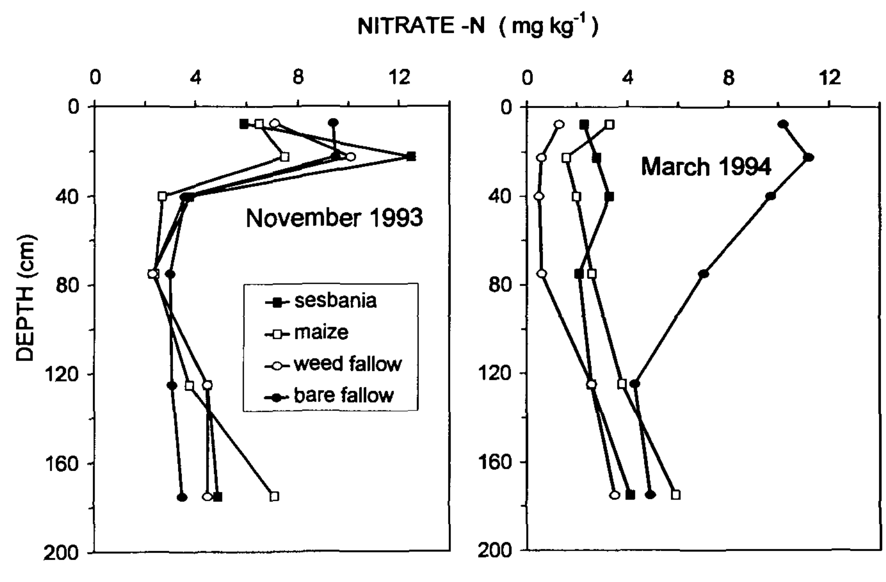

Fig. 4. Nitrate-N in the land-use systems at the start (November) and end (March) of the season at Muange.

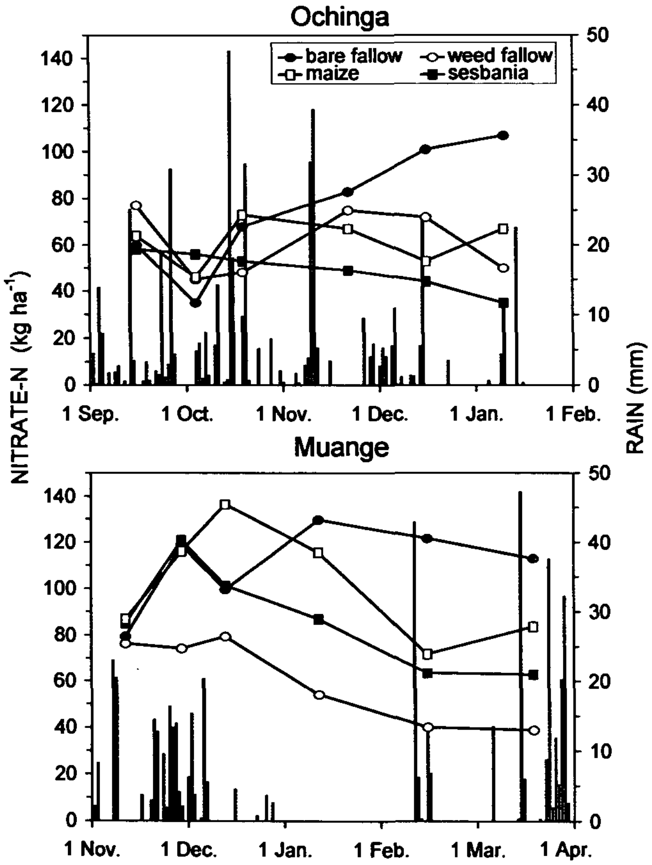

Fig. 5. Nitrate-N in the 50- to 200-cm soil layer and daily rainfall at Ochinga and Muange.

Sept.) and second sampling (4 Oct.) at Ochinga (Fig. 5) suggests that NO_3 might have been lost by leaching from weed fallow, bare fallow, and maize. This is consistent with the observation by others (Poss and Saragoni, 1992; Silvertooth et al., 1992) that leaching potential is high early in the rainy season when evapotranspiration is low. The absence of an initial decrease in subsoil NO_3 with sesbania at Ochinga (Fig. 5), on the other hand, suggests that leaching loss was either less or negligible with sesbania.

Sealing of the soil surface due to impact of raindrops occurred in the bare fallow after the heavy October rains at Ochinga. This enhances runoff and reduces infiltration (Le Bissonnais and Singer, 1993), and could have reduced N loss by leaching in the bare fallow. Leutenegger (1956) reported lower leaching in bare than mulched plots and attributed this to greater evaporation, sealing of the soil surface, and runoff in bare plots.

Nitrate Adsorption

Adsorption of NO_3 was considerable at Ochinga but not at Muange (Fig. 6). When relatively small amounts of NO_3 (5 and 15 mg N kg^{-1}) were added to Ochinga subsoil (100–200 cm), about 60% of the total NO_3 was sorbed. Sorption of NO_3 was relatively small above 50 cm at Ochinga and in all soil layers to 200 cm at Muange.

As reported by others (Kinjo and Pratt, 1971; Cahn et al., 1992), sorption of NO_3 was concentration-dependent and increased with soil depth (Fig. 6). The increase in sorption with depth might relate to decreased organic matter and increased amorphous minerals with depth, but it was not related to decreased soil pH with depth (Table 1). The soil pH was 0.9 to 1.1 units higher in 1:1 (w/v) water than 1 *M* KCl for all depths at both sites, indicating that the positive charge (anion-exchange capacity) is limited (Mekaru and Uehara, 1972).

Sorption values at high levels of NO_3 addition may be slight overestimations because the addition of KNO_3 solution reduced soil pH, and reduction in pH is known to increase NO_3 sorption (Kinjo and Pratt, 1971). The decrease in pH with the highest rate of NO_3 addition used in the isotherms ranged between 0.3 and 0.7 units for all depths and both soils. Anion adsorption is best determined under pH and ionic strength conditions similar to those in the soil solution (Wong et al., 1990).

The sorption of NO_3 in acid tropical soils can delay its downward movement (Wong et al., 1987; Bowen et al., 1993), which may result in the accumulation of NO_3 in lower horizons (Wild, 1972; Jones, 1976; Michori, 1993). Deep-rooted plants could be important in utilizing this sorbed NO_3, which is below the rooting depth of maize.

CONCLUSIONS

Weeds and sesbania, unlike maize, reduced soil NO_3 levels below 50 cm, suggesting that rotation of maize with either planted tree fallows or weed fallows may result in more effective utilization of subsoil NO_3 than for maize monoculture in tropical soils without chemical and physical barriers to deep rooting.

The integration of deep-rooting trees with cultivated

Table 4. Nitrate-N (log transformed) in the 50- to 200-cm soil layer for four land-use systems (LUS) at Ochinga and Muange.

	Ochinga†					Muange†			
Sampling date	Sesbania	Maize	Weed fallow	Bare fallow	Sampling date	Sesbania	Maize	Weed fallow	Bare fallow
	(log kg ha^{-1})10^2					(log kg ha^{-1})10^2			
16 Sept.	176	181	188	178	12 Nov.	194	194	189	191
4 Oct.	175	167	165	155	30 Nov.	209	207	188	208
19 Oct.	173	186	169	184	13 Dec.	201	214	191	200
22 Nov.	169	182	188	192	12 Jan.	194	207	174	212
16 Dec.	164	173	186	201	16 Feb.	181	186	161	209
10 Jan.	155	183	170	203	21 Mar.	181	192	160	206

† Standard error of the mean difference (SED) for comparing LUS means at the same sampling date are 10 for Ochinga and 25 for Muange. SED for comparing sampling date means at the same LUS are 8 for Ochinga and 10 for Muange.

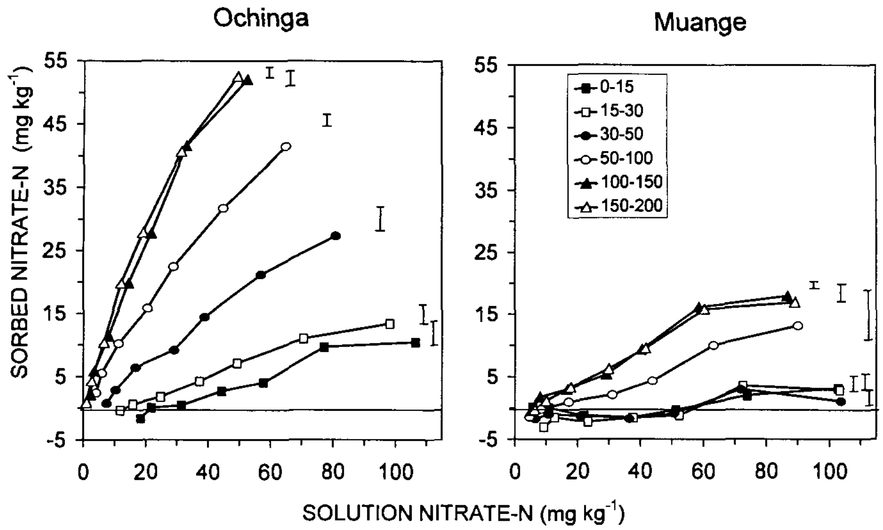

Fig. 6. Nitrate adsorption isotherms for six soil depths at Ochinga and Muange. Vertical bars represent the largest standard deviation for measurements at a soil depth.

crops might be especially effective at reducing losses of soil NO_3 and improving the cycling of subsoil N in soils with positively charged surfaces. Sorption of NO_3 on positive-charged surfaces delays downward movement of NO_3 and tends to retain NO_3 below the rooting zone of crops. This study suggests that fast-growing, deep-rooting trees, such as sesbania, grown in rotation with maize could utilize and recycle sorbed subsoil NO_3 that would otherwise be unavailable to maize.

ACKNOWLEDGMENTS

We thank Jeremiah Maroko for determination of the NO_3 adsorption isotherms and Obadiah Kyunguti for management of the experiment at Muange.

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