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Inorganic nitrogen dynamics in fallows and maize on an Oxisol and Alfisol in the highlands of Kenya

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Abstract

Fallows with naturally regenerated or planted vegetation are important in many subsistence agricultural systems of tropical regions, but the underlying soil processes in fallows are not properly understood. We investigated N dynamics under different fallow vegetation on a Kandiudalfic Eutrudox (2372-mm rain in 16 months) and a Kandic Paleustalf (1266-mm rain in 15 months) in the Kenyan highlands. The treatments, which extended for three cropping seasons (15–16 months), were *Zea mays* (maize), natural regrowth of vegetation (natural fallow), planted *Sesbania sesban* (sesbania fallow) and uncultivated soil without vegetation (bare fallow). Inorganic N (nitrate + ammonium-N) to 2-m depth under bare fallow increased by 242 kg N ha^{-1} $year^{-1}$ on the Oxisol and 54 kg N ha^{-1} $year^{-1}$ on the Alfisol, indicating that N mineralization exceeded N losses. Subsoil inorganic N (0.5–2.0 m) remained relatively unchanged after three crops of unfertilized maize, which produced limited total biomass because of P deficiency. Inorganic N decreased during natural and sesbania fallows, and both fallows similarly depleted subsoil inorganic N. The fallows depleted inorganic N at 0.5–2.0 m by 75–125 kg N ha^{-1} $year^{-1}$ down to a minimum N content between 40 and 80 kg N ha^{-1}. After slashing sesbania and incorporating the above-ground biomass with 154–164 kg N ha^{-1}, soil inorganic N increased within 2 months by 136 kg N ha^{-1} on the Oxisol and 148 kg N ha^{-1} on the Alfisol. Inorganic N decreased after cropping the bare fallow on the Oxisol with maize, indicating that inorganic N was

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prone to leaching during heavy rains when the maize was small. A considerable part of the N in biomass of the natural fallow was recycled. Much of the total N accumulated by the sesbania fallow was removed with the wood and the amount of N recycled was similar on the Oxisol and Alfisol. We conclude that sesbania fallows can retrieve considerable subsoil inorganic N on deep soils with high subsoil N and effectively cycle this N through its rapidly decomposable biomass to subsequent crops.

Keywords: agroforestry; improved fallow; subsoil N; nitrate; Kenya; maize; natural fallow; bare fallow; *Sesbania sesban*

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1. Introduction

Nitrogen is commonly deficient and limits crop production in cultivated soils of the tropics (Sanchez, 1976; Ahmad, 1996). The main sources of N for crops are the mineralization of soil organic matter, inorganic fertilizers and organic inputs, and biological N_2 fixation. In tropical regions, the supply of organic inputs is often insufficient to meet crop demand for N, and inorganic fertilizers are commonly expensive with low profitability (McIntire, 1986). For many farmers, the only viable option for increasing N supply in crops is through fallowing — the rotation of crops with either naturally regenerated or planted vegetation.

An ideal fallow species — from a soil N point of view — would grow fast, take up and recycle N within the soil–plant system and fix atmospheric N_2. The fallow species should also yield economic products like wood, fodder or fruits. Young (1997) listed several species that fit these criteria, including *Sesbania sesban* (L.) Merr., a N_2-fixing shrub with a high potential to maintain and improve soil fertility. Studies in Zambia indicated that planted sesbania fallows of 2–3 years can increase yields of subsequent maize (*Zea mays* L.) crops without the use of inorganic fertilizers (Kwesiga and Coe, 1994; Kwesiga et al., 1999). Maize grain yields were 2.3, 5.6 and 6.0 Mg ha^{-1} after 1, 2 and 3 years, respectively, of fallow with sesbania as compared with yields of 1.6, 1.2 and 1.8 Mg ha^{-1} after 1, 2 and 3 years, respectively, of continuous maize cropping.

The processes responsible for such yield increases following sesbania are yet to be quantified (Sanchez et al., 1997), but they could include changes in soil physical properties, input of N through biological N_2 fixation, and retrieval of N from subsoil layers that are inaccessible to maize roots (Buresh and Tian, 1997). Obviously, the processes differ under contrasting agro-ecological conditions with different fallow vegetation. In order to quantify the effects of sesbania fallows on nutrient dynamics and soil properties, we started experiments in 1993 in the highlands of Kenya. We compared planted sesbania fallows with continuous cropping of maize and with the farmers' existing fallowing practice, which involves natural regeneration of native vegetation without cultivation. The experiments were conducted on an Alfisol and an Oxisol, which are common soil types in Kenya (Sombroek et al., 1982) and they represent about 25% of the soils in Africa (Eswaran et al., 1997).

From these experiments, Hartemink et al. (1996) reported N dynamics during one crop growing season and provided evidence that sesbania fallows take up NO_3–N from oxic subsoils. Maroko et al. (1998) in these experiments, and Barrios et al. (1997) in other experiments in Zambia, measured N mineralization and soil inorganic N at the end of fallows and showed distinct differences between fallows. These studies did not report soil inorganic N dynamics during an entire fallow cycle, quantify changes in inorganic N immediately after slashing the fallow vegetation and planting maize, nor estimate the uptake of subsoil N by fallow vegetation.

In this paper, we report soil inorganic N during and immediately following 1.5-year long fallows (equivalent to three cropping seasons) with either planted sesbania, natural regrowth of native vegetation or uncultivated bare soil. The objectives are (i) to monitor inorganic N changes in fallows and a maize crop control on two different soil types, (ii) to estimate the retrieval of subsoil inorganic N by sesbania and natural fallows, (iii) to monitor changes in soil inorganic N after slashing the fallows and planting maize and (iv) to compare N accumulation and recycling by the fallows with changes in soil inorganic N.

2. Materials and methods

2.1. Site description

The research was done at two farms (Ochinga and Muange) in Kenya. Ochinga (0°06′N, 34°34′E) is located in the highlands of western Kenya (Vihiga District) at an altitude of 1420 m. Rainfall is distributed between two crop growing seasons with a yearly mean of about 1800 mm. The soil at Ochinga is classified as an Acric Ferralsol (World Reference Base) or as a very fine, kaolinitic, isohyperthermic Kandiudalfic Eutrudox (Oxisol) in USDA Soil Taxonomy. Air-dried and sieved (< 2 mm) soil had the following properties in the top 0.15 m: pH H_2O (1:2.5 w per v) = 5.1, organic C = 15 g kg^{-1}, bicarbonate–EDTA extractable P = 2 mg kg^{-1}, KCl extractable Ca = 34 $mmol_c$ kg^{-1}, KCl extractable Mg = 14 $mmol_c$ kg^{-1}, bicarbonate–EDTA extractable K = 1.2 $mmol_c$ kg^{-1}, exchangeable acidity = 4 $mmol_c$ kg^{-1}, clay = 460 g kg^{-1} and sand = 260 g kg^{-1}.

Muange (1°31′S, 37°19′E) is located in the highlands of eastern Kenya (Machakos District) at an altitude of 1920 m. Mean annual rainfall is about 900 mm, distributed between two crop growing seasons. The soil at Muange is classified as a Rhodic Luvisol in the World Reference Base and as a fine, mixed, isothermic Kandic Paleustalf (Alfisol) in USDA Soil Taxonomy. Air-dried and sieved (< 2 mm) soil had the following properties in the top 0.15 m: pH H_2O (1:2.5 w per v) = 5.7, organic C = 8 g kg^{-1}, bicarbonate–EDTA extractable P = 5 mg kg^{-1}, extractable Ca = 34 $mmol_c$ kg^{-1}, extractable Mg = 11 $mmol_c$ kg^{-1}, extractable K = 4.7 $mmol_c$ kg^{-1}, exchangeable acidity = 2 $mmol_c$ kg^{-1}, clay = 290 g kg^{-1} and sand = 560 g kg^{-1}. Additional soil analytical data are given in Hartemink et al. (1996).

2.2. Experimental set-up

The experiment was laid out at each site as a randomized complete block with four treatments (land-use systems): sesbania grown for three seasons (sesbania fallow), natural regrowth of vegetation without cultivation for three seasons (natural fallow), unfertilized maize grown for three seasons (maize) and bare uncultivated soil without vegetation for three seasons (bare fallow). All treatments were followed by unfertilized maize. Treatments were replicated four times at each site. Plot size was 10×10 m^2.

Sesbania was established one season before the start of the experiment. On the Oxisol, sesbania (Kisii provenance) was direct-seeded in four rows (2.25×0.4-m^2 spacing) on 4 April 1993. Three rows of maize at 0.75×0.25-m spacing were grown between two sesbania rows, and the maize was harvested in August. Thereafter, the sesbania plots were not cropped with maize. On the Alfisol, 4-month old sesbania (Kisii provenance) seedlings were planted without maize at 10,000 plants ha^{-1} at 1×1-m^2 spacing on 11 May 1993. Maize, natural fallow and bare fallow plots were cropped with maize in the season before the start of the experiment and harvested on 15 August 1993 on the Oxisol and on 17 September 1993 on the Alfisol. Weeds were manually removed from all plots at the start of the experiment (September 1993 on the Oxisol and November 1993 on the Alfisol).

In the maize land-use system, maize (Kenya seed, hybrid 511 or 512) was sown at 53,330 plants ha^{-1} at 0.75×0.25-m^2 spacing in each season. On the Oxisol, maize was sown on 1 September 1993 and harvested on 17 January 1994 (138 days after sowing, DAS) in season 1, sown on 14 March and harvested on 4 August 1994 (143 DAS) in season 2 and sown on 25 August 1994 and harvested on 27 January 1995 (155 DAS) in season 3. On the Alfisol, maize was sown on 2 November 1993 and harvested on 26 March 1994 (144 DAS) in season 1, sown on 27 March and harvested on 9 September 1994 (166 DAS) in season 2 and sown on 14 October 1994 and harvested on 13 March 1995 (150 DAS) in season 3. In all maize plots, weeds were manually removed at regular intervals, and all above-ground maize biomass was removed after each crop.

Natural fallow contained regrowth of weeds following manual removal of weeds at the start of the experiment. Predominant weed species are described in Hartemink et al. (1996) and Maroko et al. (1999). The bare fallow was maintained free of vegetation by frequent hand-pulling of weeds. Sesbania plots were manually maintained free of weeds for the duration of the experiment on the Alfisol, but only in the first season (September 1993 to February 1994) on the Oxisol. In order to limit root growth outside the sesbania plots, 1-m deep trenches were dug at least once in each cropping season around the sesbania plots and then back filled.

On 16–18 January 1995 on the Oxisol and 20–21 February 1995 on the Alfisol, all vegetation in the sesbania and natural fallows was cut at ground level and placed in the plots to dry. Woody materials were removed from the plots but leaves and litter were incorporated into the soil. The woody material removed from the sesbania fallow was 19.7 Mg ha^{-1} on the Oxisol and 24.6 Mg ha^{-1} on the Alfisol, whereas woody biomass removed from the natural fallow was 4.1 Mg ha^{-1} on the Oxisol and 0.4 Mg ha^{-1} on the Alfisol. All plots were manually tilled to 0.15-m depth and maize was sown at a spacing of 0.75×0.25 m^2 without the use of inorganic fertilizers, on 14 March 1995 on the Oxisol and 27 March 1995 on the Alfisol (Maroko et al., 1999).

2.3. Soil sampling and analysis

Soils were sampled six or seven times during each of the three growing seasons (September 1993 to January 1995 on the Oxisol and November 1993 to February 1995 on the Alfisol) and two times after slashing the fallows. Soil samples were collected with an Edelman auger from six depths: 0–0.15, 0.15–0.30, 0.30–0.50, 0.50–1.0, 1.0–1.5 and 1.5–2.0 m.

In each plot with maize, natural fallow and bare fallow, soil was collected and composited from eight locations for layers above 1.0 m and from four locations for layers below 1.0 m. In maize plots, half the sampling locations were between maize rows and half were within rows. In sesbania plots, the distance between two rows on the Oxisol and two diagonal trees on the Alfisol was divided into strata (Rao and Coe, 1991; Mekonnen et al., 1999). On the Oxisol, the distance between rows of sesbania (2.25 m) was divided into nine strata in the first season (stratum width = 0.25 m) and six strata in the second and third season (stratum width = 0.37 m). Soil samples were collected from all strata between the four sesbania rows (27 locations in the first season and 18 locations in the second and third season) and composited into one sample per stratum.

On the Alfisol, the diagonal distance between two trees (1.4 m) was divided into three strata (0–0.25, 0.25–0.50 and 0.50–0.70 m from the tree) in the first season and two strata (0–0.50 and 0.50–0.70 m from the tree) in the second and third season. Four to eight samples were collected from each stratum and then composited into one sample per stratum. Inorganic N for a plot at each site was calculated as a weighted mean of values for all strata, taking into account the surface area represented by each stratum. For more details on the soil sampling procedures, see Mekonnen et al. (1999).

Soil samples were stored, field moist, in a refrigerator at 5°C immediately after collection. In the first season, about 10 g field moist soil was extracted with 100 ml 2-M KCl, with shaking for 1 h at 150 reciprocations per min and subsequent gravity filtering using prewashed Whatman 42 paper. In the second season, about 20 g field moist soil was extracted with 100 ml 2-M KCl and filtered through prewashed Whatman 5 paper. Soil water content was determined simultaneously with extraction in order to calculate the dry weight of the extracted soil. No difference was found in the bulk density of the different treatments. Ammonium-N in the KCl extract was determined by the salicylate–hypochlorite method (Anderson and Ingram, 1993). Nitrate- plus nitrite-N was determined by cadmium reduction (Dorich and Nelson, 1984) with subsequent colorimetric determination of NO_2 (Hilsheimer and Harwig, 1976). Reported inorganic N values are the sum of NH_4-N, NO_3-N and NO_2-N. Soil bulk density, determined with cores collected in a pit before the first season (for details, see Hartemink et al., 1996), was used to convert inorganic N values into kilogram per hectare.

2.4. Plant sampling and analysis

Litterfall in the sesbania plots was collected at 3–4-week intervals with three litter traps per plot for 1 year before the harvest of the trees. The area of each litter trap was 1.7 m^2 at the Oxisol site and 1.0 m^2 at the Alfisol site. Total biomass of sesbania litter, leaves and pods on the trees at harvest and wood (> 2 cm diameter and ≤ 2 cm diameter) at harvest were determined on an oven dry weight (70°C) basis. In the natural fallow plots, total above-ground woody and non-woody biomass were determined at harvest on an oven dry weight (70°C) basis. In plots with maize, maize stover and grain and weeds from each of the three seasons were dried at 70°C and expressed on an oven dry weight basis. Subsamples of all collected plant parts in each plot were analyzed for total N by digestion with H_2SO_4 and H_2O_2 (Parkinson and Allen, 1975).

2.5. Statistical procedures

Inorganic N was summed for the six sampling depths to determine total inorganic N in the 2-m soil profile. Changes in inorganic N were calculated for periods roughly corresponding to each of the three cropping seasons and the interval between cropping seasons. An analysis of variance was conducted on these changes using GENSTAT version 5, and standard errors of the differences in treatment means (SED) are reported. The inorganic N data for individual sampling times were grouped into intervals that roughly corresponded to the period before treatment differences, the latter part of the first season, the second season and the third season. Orthogonal contrasts were conducted on means for these intervals, whereby the treatments were grouped as sesbania fallow vs. natural fallow, maize vs. sesbania and natural fallows and bare fallow vs. other treatments.

Inorganic N for each sampling depth was compared at three sampling times during the experiment to determine changes within the soil profile for each land-use system. The three sampling times were handled as treatments, and an individual analysis of variance was conducted for each sampling depth of the four land-use systems. SED are reported.

About 95% of all inorganic N data sets undergoing an analysis of variance were normally distributed. Log transformation of those data sets without normal distribution before analysis of variance had no effect on the separation of treatment means at $P < 0.05$. Therefore, all analysis of variance were conducted with untransformed data. Mention of statistical significance refers to $P < 0.05$ unless stated otherwise.

3. Results

3.1. Inorganic N during fallows

On the Oxisol, levels of soil inorganic N to 2-m depth varied between 131 and 246 kg N ha^{-1} under maize during the three growing seasons from September 1993 and January 1995 (Fig. 1). During the first and second growing season of maize, inorganic N decreased by 39 and 57 kg N ha^{-1}, respectively. In the third season, inorganic N increased by 21 kg N ha^{-1} (Table 1). After three growing seasons, inorganic N under maize increased slightly (25 kg N ha^{-1}).

Inorganic N increased under bare fallow by 323 kg N ha^{-1} between September 1993 and January 1995 (Fig. 1, Table 1). However, inorganic N decreased under the natural and sesbania fallows during this period. The decrease was 162 and 108 kg N ha^{-1} under natural and sesbania fallows, respectively (Table 1).

Ammonium-N to 2-m depth was not affected by land-use systems, and it remained relatively constant throughout the three seasons. Ammonium-N to 2-m depth during the three seasons ranged between 36 and 106 kg N ha^{-1} and averaged 62 kg N ha^{-1} in the Oxisol. As inorganic N decreased with duration of the natural and sesbania fallows (Fig. 1), the relative contribution of NO_3 to inorganic N decreased. At the completion of the fallows in January 1995, NO_3-N represented 25% of the inorganic N under the natural fallow, 38% of the inorganic N under the sesbania fallow, 76% of the inorganic N under continuous maize and 90% of the inorganic N under bare fallow.

Total rainfall during the three growing seasons on the Oxisol was 2372 mm. The first season was relatively dry with 404 mm of rain, whereas rain was 959 mm in the second season and 587 mm in the third season (Table 1). The highest daily rainfall was 85 mm on 20 April 1994. Little relation was evident between daily rainfall and total inorganic N under the different land-use systems,

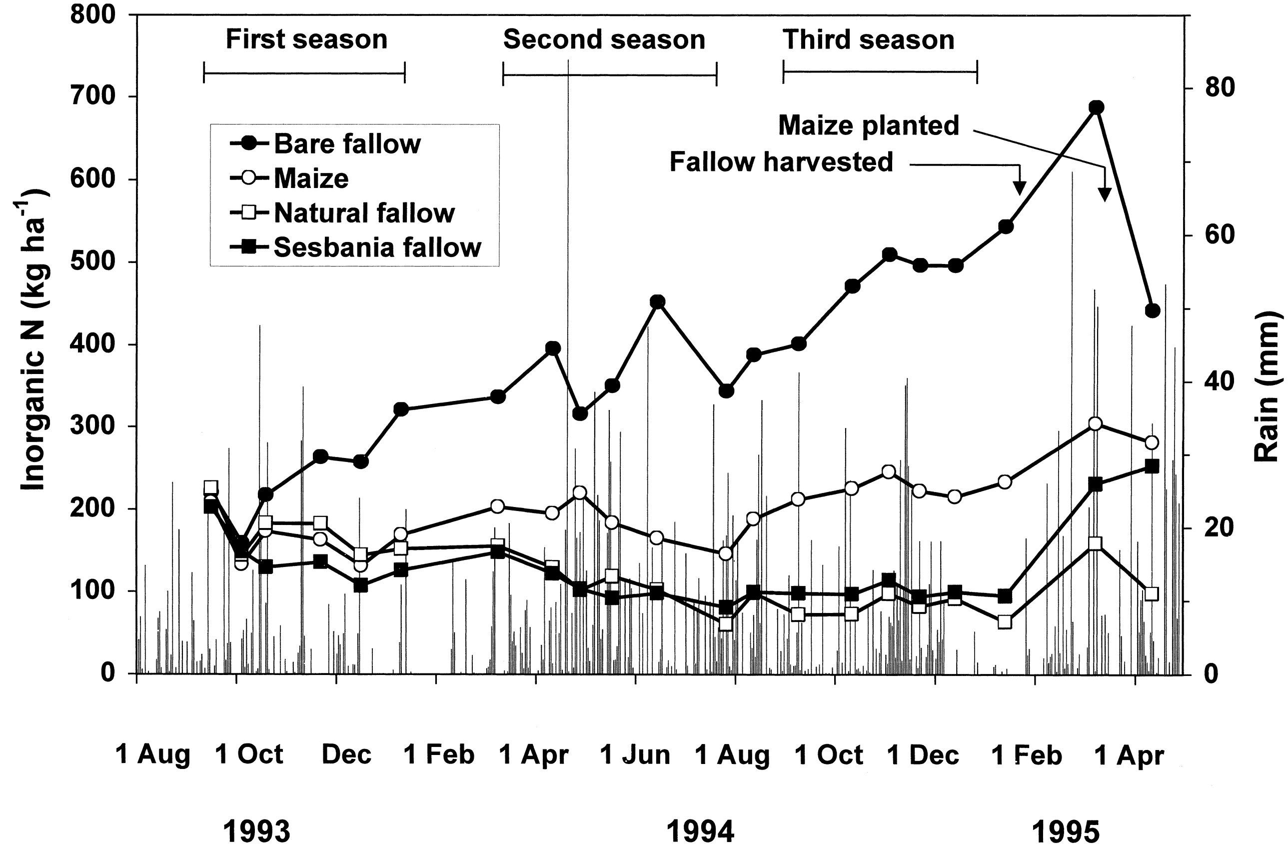

Fig. 1. Soil inorganic N to 2-m depth under different land-use systems and daily rainfall during three cropping seasons on an Oxisol in Kenya.

Table 1
Changes in soil inorganic N to 2-m depth under different land-use systems during three growing seasons on an Oxisol and Alfisol in Kenya

Soil	Growing season	Period	Changes in inorganic N (kg ha^{-1})					Rainfall (mm)
			Maize	Natural fallow	Sesbania fallow	Bare fallow	SED[a]	
Oxisol	First	September 1993–January 1994	−39	−73	−77	100	35	404
		January 1994–March 1994	34	3	22	16	23	120
	Second	March 1994–July 1994	−57	−95	−67	7	14	959
		July 1994–September 1994	66	12	17	57	24	302
	Third	Sep. 1994–January 1995	21	−9	−3	142	20	587
	All	September 1993–January 1995	25	−162	−108	323	24	2372
	Post fallow	January 1995–March 1995	71	95	136	144	14	291
Alfisol	First	November 1993–March 1994	−34	−93	−43	47	28	299
	Second	March 1994–September 1994	−29	−21	−65	5	23	306
		September 1994–October 1994	17	16	14	28	24	64
	Third	October 1994–February 1995	−26	−24	−20	−12	35	597
	All	November 1993–February 1995	−72	−122	−114	68	51	1266
	Post fallow	February 1995–April 1995	17	101	148	18	53	138

[a]Standard error of the difference in means. Error d.f. = 9.

although the decrease in N under bare fallow in April and June 1994 followed high rainfall (Fig. 1).

The increase in inorganic N to 2-m depth under bare fallow was less on the Alfisol than on the Oxisol. On the Alfisol, inorganic N increased under bare soil by 68 kg N ha^{-1} during the three seasons from November 1993 to February 1995 (Table 1), and it reached 277 kg N ha^{-1} after three growing seasons (Fig. 2). Inorganic N under maize decreased in all three growing seasons, and the overall decrease was 72 kg N ha^{-1} (Table 1). As on the Oxisol, inorganic N decreased under natural and sesbania fallows. During the three seasons, inorganic N decreased by 122 and 114 kg N ha^{-1} under natural and sesbania fallows, respectively. Soil inorganic N slightly increased in the dry period between the second and third season in all four land-use systems on the Alfisol (Table 1).

Most of the inorganic N for all four land use systems on the Alfisol was in the NO_3 form. Ammonium-N was not affected by the land-use systems. During the three seasons, NH_4 to 2-m depth ranged between 16 and 51 kg N ha^{-1}, and it averaged 30 kg N ha^{-1}. At the completion of the fallows in February 1995, NO_3-N represented 61% of the inorganic N under the natural fallow, 62% of the inorganic N under the sesbania fallow, 71% of the inorganic N under continuous maize and 93% of the inorganic N under bare fallow. These trends among land-use systems were similar to those found on the Oxisol, although percentages differed.

Rainfall was much lower at the Alfisol than at the Oxisol site. As on the Oxisol, soil inorganic N was not strongly related to rainfall, although inorganic N decreased in all land-use systems after relatively heavy rain (329 mm) in November 1994.

During the first 2 months of the experiment, total inorganic N to 2-m depth was comparable among the land-use systems on both soils (Figs. 1 and 2). Inorganic N remained comparable under sesbania and natural fallow throughout the fallow period on both soils. Inorganic N became progressively greater under maize than sesbania and natural fallows, and the difference was significant ($P < 0.001$) in the second and third growing seasons in the Oxisol (statistical analysis not shown). On the Alfisol, mean inorganic N was only slightly higher under maize than natural and sesbania fallows between April and September 1994 (76 kg N ha^{-1}, $P < 0.10$) and between October 1994 and February 1995 (63 kg N ha^{-1}, $P < 0.07$). Inorganic N was significantly greater ($P < 0.001$) under the bare fallow than under other land-use systems after November 1993 on the Oxisol and after April 1994 on the Alfisol.

3.2. Changes in subsoil inorganic N

Concentrations of subsoil inorganic N (0.5–2.0 m) did not significantly ($P = 0.05$) change under maize during the three growing seasons between the

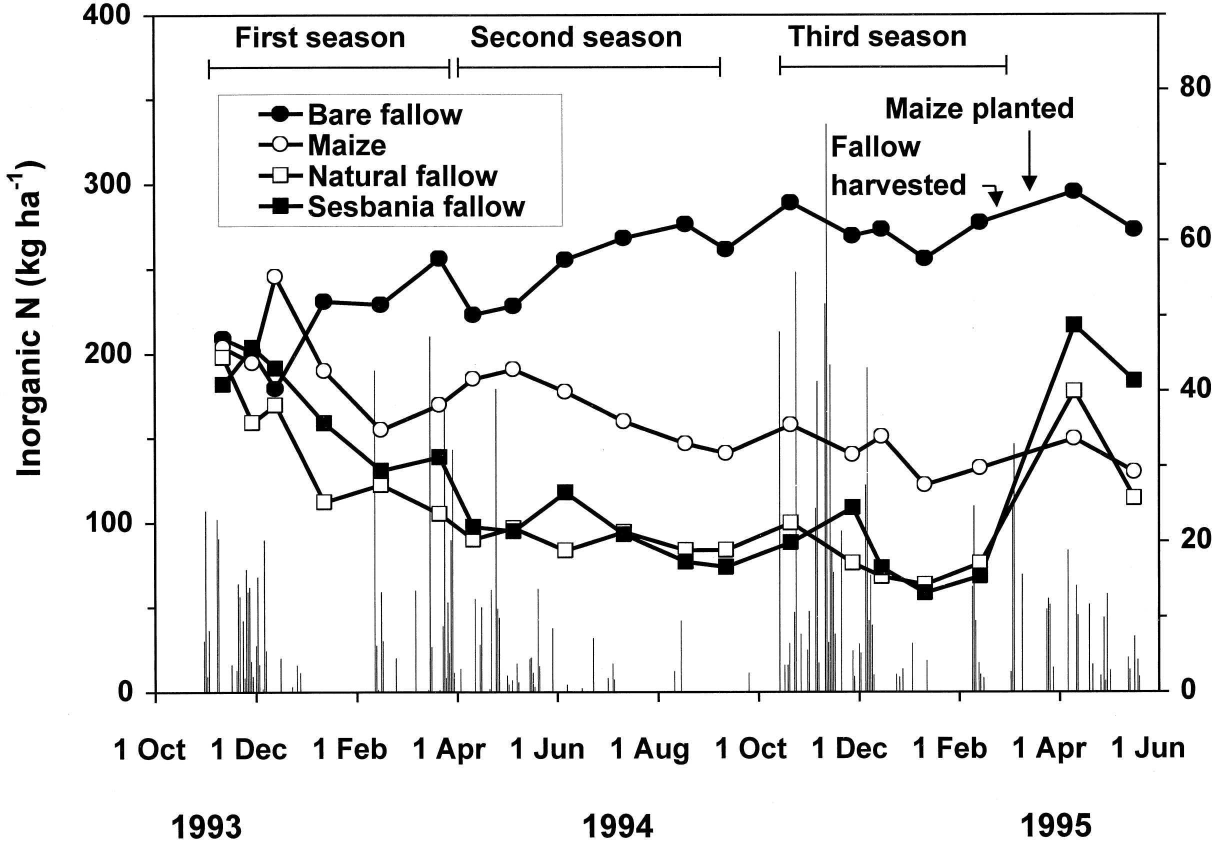

Fig. 2. Soil inorganic N to 2-m depth under different land-use systems and daily rainfall during three cropping seasons on an Alfisol in Kenya.

onset of the experiment and the end of the fallows (16 months on the Oxisol and 15 months on the Alfisol) (Fig. 3). However, inorganic N significantly increased at 0.5–1.0-m depth under the bare fallow on both soils during this time. Inorganic N decreased in each of the three subsoil layers under natural and sesbania fallows on both soils.

Inorganic N in the subsoil (0.5–2.0 m) under sesbania was 136 kg N ha^{-1} at the beginning of the fallow on the Oxisol (Table 2). When the sesbania was slashed 16 months later, the inorganic N had decreased by 71 kg N ha^{-1} (Table 2). The decrease in subsoil N under sesbania on the Alfisol was comparable (69 kg N ha^{-1}). More than half of the decreases in subsoil inorganic N under sesbania occurred in the 1.0–2.0-m soil horizon (Table 3). Subsoil inorganic N similarly decreased under natural fallow, and the decrease in the 0.5–2.0-m soil horizon during the entire fallow was 105 kg N ha^{-1} on the Oxisol and 80 kg N ha^{-1} on the Alfisol (Table 2). As with the sesbania fallow, most of the decrease in subsoil inorganic N under natural fallow occurred in the 1.0–2.0-m soil horizon (Table 3).

Under bare fallow, subsoil inorganic N (0.5–2.0 m) considerably increased during the fallow period (44 kg N ha^{-1} on the Oxisol and 86 kg N ha^{-1} on the Alfisol). This increase occurred mainly at 0.5–1.0-m depth (Fig. 3). The change in subsoil inorganic N under three continuous maize crops was small and not consistent between the two soils. Subsoil inorganic N slightly increased under maize on the Oxisol, but it decreased under maize on the Alfisol (Tables 2 and 3).

The decrease in subsoil inorganic N under natural and sesbania fallows essentially occurred within the first 10 months of the fallows. After 10 months, the subsoil inorganic N remained relatively constant under these fallows (Tables 2 and 3). During the first 10 months, the inorganic N at 0.5–2.0-m depth under sesbania decreased by 77 kg N ha^{-1} on the Oxisol and 63 kg N ha^{-1} on the Alfisol. The corresponding decreases at 1.0–2.0-m depth were 45 kg N ha^{-1} on the Oxisol and 52 kg N ha^{-1} on the Alfisol. The decreases under the natural fallow were similar to those under sesbania fallow.

During the last 6 months of the natural and sesbania fallows on the Oxisol, inorganic N at 0.5–2.0 m stabilized between 45 and 80 kg N ha^{-1} (average = 61 kg N ha^{-1} under natural fallow and 71 kg N ha^{-1} under sesbania). Inorganic N at 1.0–2.0 m stabilized between 30 and 50 kg N ha^{-1} (average = 44 kg N ha^{-1}). During this period, most of the inorganic N was NH_4. Nitrate averaged about 25–30% of the subsoil inorganic N under the natural and sesbania fallows. Subsoil NO_3 concentration remained ≤ 2 mg N kg^{-1} and averaged 0.7 mg N kg^{-1} under natural fallow and 1.1 mg N kg^{-1} under sesbania.

On the Alfisol, inorganic N at 0.5–2.0 m stabilized between 40 and 65 kg N ha^{-1} under the natural and sesbania fallows (average = 57 kg N ha^{-1}). Inorganic N at 1.0–2.0 m stabilized between 25 and 45 kg N ha^{-1}. Unlike on the Oxisol, most subsoil inorganic N was NO_3. Nitrate represented 60% of the

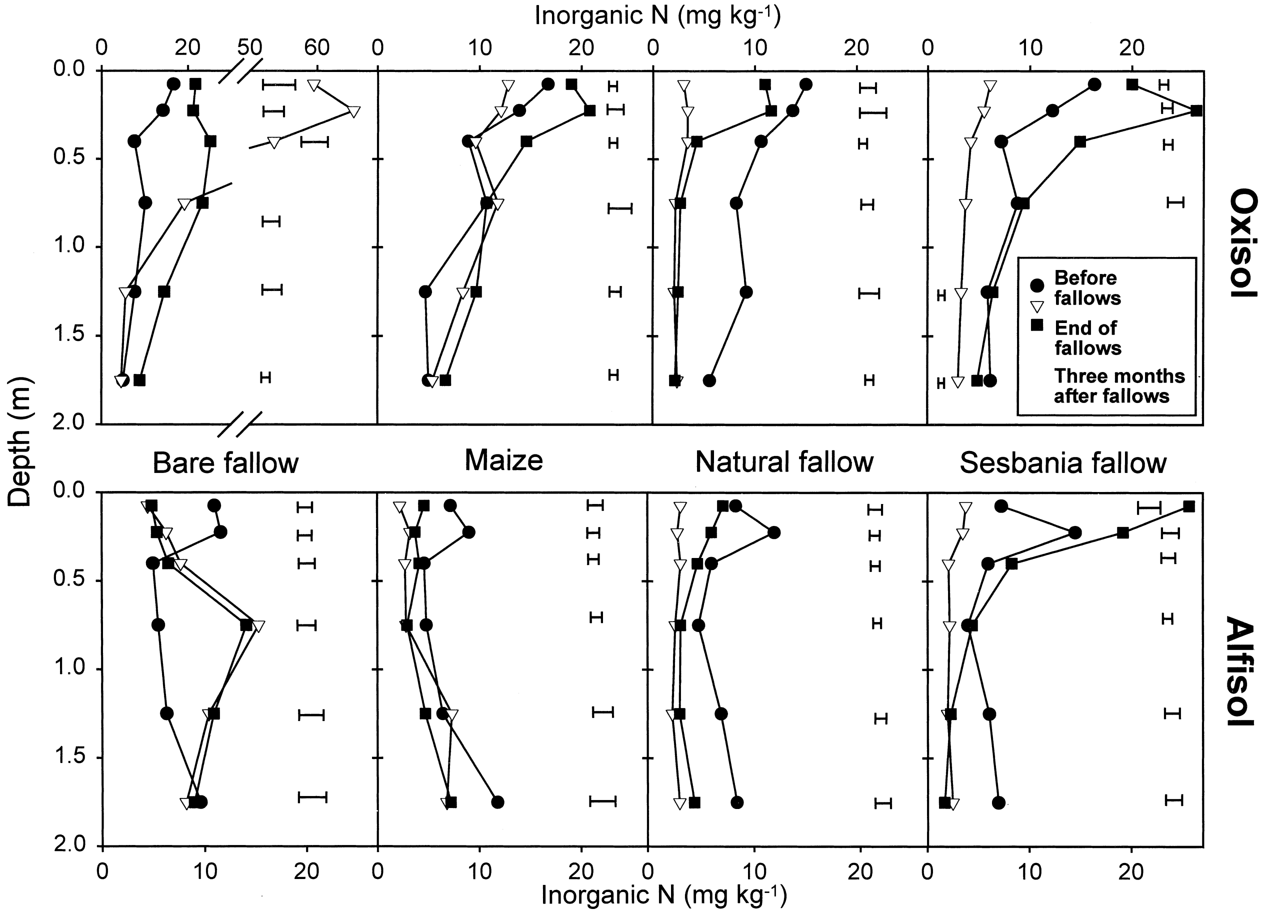

Fig. 3. Soil inorganic N profiles of an Oxisol and Alfisol at the start of the fallows, at the end of the fallows (13 January for the Oxisol and 14 February on the Alfisol) and 3 months later, which corresponds to 1 month after maize planting on the Oxisol and 2 months after maize planting on the Alfisol. Horizontal bars indicate standard error of the difference in means (6 d.f.).

Table 2
Inorganic N at 0.5–2.0-m depth under four land-use systems during three growing seasons on an Oxisol and an Alfisol in Kenya

Soil	Sampling	Period	Inorganic N (kg ha^{-1})				
			Maize	Natural fallow	Sesbania fallow	Bare fallow	SED[a]
Oxisol	Initial (before fallows)	September 1993	133	149	136	148	23
	After 10 months	July 1994	105	47	58	158	17
	After 16 months (end of fallows)	January 1995	166	44	64	192	19
	Change during 10 months	September 1993–July 1994	−28	−102	−77	10	29
	Change during 16 months	September 1993–January 1995	33	−105	−71	44	32
Alfisol	Initial (before fallows)	November 1993	153	133	114	142	57
	After 10 months	September 1994	122	64	51	161	42
	After 15 months (end of fallows)	February 1995	112	53	45	229	33
	Change during 10 months	November 1993–September 1994	−30	−69	−63	18	32
	Change during 15 months	November 1993–February 1995	−41	−80	−69	86	56

[a] Standard error of the difference in means. Error d.f. = 9.

Table 3
Inorganic N at 1.0–2.0-m depth under four land-use systems during three growing seasons on an Oxisol and an Alfisol in Kenya

Soil	Sampling	Period	Inorganic N (kg ha^{-1})				
			Maize	Natural fallow	Sesbania fallow	Bare fallow	SED[a]
Oxisol	Initial (before fallows)	September 1993	62	95	78	81	16
	After 10 months	July 1994	52	32	33	62	8
	After 16 months (end of fallows)	January 1995	88	29	40	66	11
	Change during 10 months	September 1993–July 1994	−10	−62	−45	−19	19
	Change during 16 months	September 1993–January 1995	26	−65	−38	−16	21
Alfisol	Initial (before fallows)	November 1993	119	100	86	104	45
	After 10 months	September 1994	98	54	34	92	36
	After 15 months (end of fallows)	February 1995	92	35	30	122	29
	Change during 10 months	November 1993–September 1994	−21	−46	−52	−11	26
	Change during 15 months	November 1993–February 1995	−27	−65	−56	18	53

[a]Standard error of the difference in means. Error d.f. = 9.

subsoil inorganic N at the end of natural and sesbania fallows. Subsoil NO_3 concentration was <2 mg N kg^{-1} at the end of the fallows.

3.3. N uptake and changes in the soil

Total biomass accumulation in maize plots during the three growing seasons was higher on the Alfisol than on the Oxisol (Table 4), but maize accumulated less N on the Alfisol because of lower grain production as compared to the Oxisol. Total above-ground biomass and N accumulation by the sesbania was greater than the above-ground biomass and plant N in the natural fallow at harvest. A considerable part of the N in the final standing biomass in the natural fallow was recycled, i.e. returned to the soil when the fallow was slashed. Much of the total N accumulated by the sesbania fallow (54% on the Oxisol and 36% on the Alfisol) was removed with the wood. Overall, the amount of N recycled by the sesbania fallow was similar on the Oxisol and Alfisol.

The last column in Table 4 shows the net changes in soil inorganic N over the three seasons (data from Table 1), and these represent the net effects of gains by N addition and mineralization and N removal by leaching, gaseous loss and plant uptake. The change in soil inorganic N was comparable to the total N accumulation by the maize on the Alfisol but not the Oxisol. The inorganic N values for maize plots have a high standard deviation, reflecting the high plot to plot variability in subsoil inorganic N.

The net decrease in soil inorganic N was greater than the N in the standing biomass at the end of the natural fallow, possibly because values for N accumulation do not consider (a) N in below-ground plant parts and (b) the tie up and cycling of soil inorganic N through the turnover of plant biomass within the natural fallow. The N accumulation in sesbania biomass was greater than the net decrease in inorganic soil N. This could be related to inputs of N via biological N_2 fixation. The estimation of N_2 fixation by difference requires assumptions on the magnitude of N losses and net N mineralization. Given the uncertainty with these values and likely differences in N mineralization among land-use systems as indicated by Maroko et al. (1998), reliable estimates cannot be made on the magnitude of biological N_2 fixation.

3.4. Inorganic N after fallows

Soil inorganic N on both soils increased considerably after slashing the natural and sesbania fallows and incorporating the leaf and litter material into the soil (Figs. 1 and 2). During the 2 months after slashing the fallows, total inorganic N to 2-m depth increased in the previous sesbania plots by 136 kg N ha^{-1} on the Oxisol and by 148 kg N ha^{-1} on the Alfisol (Table 1). The increase in the previous natural fallow plots was 95 kg N ha^{-1} on the Oxisol and 101 kg N ha^{-1} on the Alfisol. On the Oxisol, inorganic N also increased in the previous

Table 4
Biomass and N accumulation and changes in soil inorganic N to 2-m depth of different land-use systems during three seasons on an Oxisol and Alfisol in Kenya (values ± 1 SD)

Land-use system	Biomass accumulation (Mg ha^{-1})[a]		N accumulation in biomass (kg ha^{-1})[a]		N recycled in biomass (kg ha^{-1})[b]		Change in soil inorganic N (kg ha^{-1})[c]	
	Oxisol	Alfisol	Oxisol	Alfisol	Oxisol	Alfisol	Oxisol	Alfisol
Maize	10.5 ± 2.6	12.2 ± 1.8	125 ± 33	88 ± 18	0	0	25 ± 50	− 72 ± 120
Natural fallow	10.9 ± 3.3	9.3 ± 3.5	90 ± 46	107 ± 44	56 ± 43	105 ± 44	− 162 ± 38	− 122 ± 47
Sesbania fallow	28.6 ± 7.5	31.1 ± 4.1	353 ± 62	241 ± 51	164 ± 23	154 ± 47	− 108 ± 4	− 114 ± 20

[a] Biomass and N values for maize include grain, straw and weeds for three growing seasons. Biomass and N values for natural fallow represents the final standing biomass. Biomass and N values for sesbania fallow include final standing biomass of sesbania and weeds and litterfall from sesbania.

[b] Recycled N in the natural fallow includes N in non-woody biomass incorporated at the end of the fallow. Recycled N in the sesbania fallow includes N in sesbania litterfall and in non-woody sesbania and weed biomass incorporated at the end of the fallow. (Data from Maroko et al., 1998).

[c] Data from Table 1.

bare fallow (144 kg N ha^{-1}) and continuous maize plots (71 kg N ha^{-1}), but on the Alfisol total inorganic N remained relatively constant in the 2 months following the bare fallow and continuous maize. After planting maize in the previous bare fallow plots, total inorganic N to 2-m depth decreased on the Oxisol (Fig. 1) but not on the Alfisol (Fig. 2). Total inorganic N also decreased after planting maize in the previous natural and sesbania fallow plots on the Alfisol (Fig. 2).

Fig. 3 presents inorganic N profiles for the Oxisol when all fallow vegetation was slashed (13 January 1995) and 3 months later (11 April 1995), which corresponds to 1 month after maize was planted in all plots. Inorganic N increased throughout the soil profile during the 3 months following clearance of the sesbania fallow, although the increase was greatest in the top 0.5 m. Inorganic N increased above 0.3 m after the natural fallow, but the increase was less than after the sesbania fallow. Inorganic N also increased above 0.5-m depth following continuous maize. Inorganic N in the 3 months after the bare fallow considerably decreased in the top 0.5 m.

On the Alfisol, soil was sampled on 14 February, when all fallow vegetation was slashed, and 3 months later (16 May), which corresponds to 2 months after maize was planted in all the previous land-use systems. Inorganic N increased in the top 1.0 m after clearing the sesbania fallow, but in contrast to the Oxisol, inorganic N did not increase below 1.0-m depth after the sesbania fallow (Fig. 3). Inorganic N increased in the top 0.3 m after natural fallow. Unlike on the Oxisol, inorganic N did not change at any depth during the 3 months following continuous maize and bare fallow.

4. Discussion

There was large variation in the soil inorganic N data, particularly on the Alfisol as evidenced by the relatively high SED values (Tables 1, 2 and 3). Spatio-temporal variation is common in soil measurements (Hoosbeek, 1998), and has also been reported for inorganic N measurements in both temperate regions (Selles et al., 1986) and the tropics (Wong and Nortcliff, 1995). Despite the relative high variation in our data and quantitative differences in inorganic N between the Oxisol and Alfisol, similar trends appeared in both soil types. In this discussion, we focus on the consistent trends in inorganic N for the two soils during and after the fallow period.

4.1. N changes during fallows

The net increase in inorganic N under bare fallow was 68 kg N ha^{-1} on the Alfisol as compared to 323 kg N ha^{-1} on the Oxisol (Table 1). These values correspond to average increases of 54 kg N ha^{-1} year^{-1} on the Alfisol and 242 kg N ha^{-1} $year^{-1}$ on the Oxisol, and they clearly indicate that N mineralization exceeded N losses in the absence of N uptake by plants. Leaching was likely less in the bare fallow than the other treatments because of reduced infiltration arising from the sealing of the bare soil surface due to impact of raindrops (Hartemink et al., 1996).

Inorganic N in the bare fallows on both soils was mostly in the NO_3 form. Accumulation of NO_3 in a bare fallow is common, and it has been attributed to capillary rise and topsoil drying, which physically protects NO_3 from microbial reduction (Simpson, 1960). Greater accumulations of inorganic N in the Oxisol was likely due to an almost two times greater organic C content in the Oxisol, higher rainfall without prolonged dry periods and higher temperatures at the Oxisol site. All these factors are known to favor mineralization of soil organic matter (Jenny et al., 1949). The accumulation of inorganic N under bare fallows on the Oxisol could also be related to its oxic subsoil, which can retard NO_3 leaching (Wild, 1972; Wong et al., 1990). Hartemink et al. (1996) showed that up to 60% of the NO_3 in the 1.0–2.0-m soil horizon was sorbed on the Oxisol used in this experiment. The corresponding value on the Alfisol was only 15%, and therefore NO_3 at comparable rates of downward water movement would be more prone to leaching on the Alfisol than the Oxisol.

Inorganic N in the soil profile remained relatively constant during three unfertilized maize crops on the Oxisol (Fig. 1). The failure of the maize to deplete inorganic soil N even in the topsoil (Fig. 3) can be attributed to poor maize growth caused by severe P deficiency (Jama et al., 1998).

Soil inorganic N consistently decreased under sesbania and natural fallows, presumably because of plant uptake. The total N in above-ground standing biomass at the end of the sesbania fallow plus litterfall during the fallow was 353 kg N ha^{-1} on the Oxisol and 241 kg N ha^{-1} on the Alfisol (Table 4). The total N in above-ground standing biomass at the end of the natural fallow was 90 kg N ha^{-1} on the Oxisol and 107 kg N ha^{-1} on the Alfisol. Plant N in the sesbania fallow overestimated uptake of soil N because some plant N originated from biological N_2 fixation. Plant N in the natural fallow underestimated total uptake of soil N because it failed to consider N uptake by roots and decomposing plant material.

4.2. Retrieval of subsoil N

The consistent decline in subsoil N under the sesbania and natural fallows, but not under maize, can be attributed to greater rooting depth and greater N demand in the fallows. Sesbania and vegetation in the natural fallow rooted below 2-m depth on the Oxisol, whereas unfertilized maize only rooted to only 1.2-m depth (Mekonnen et al., 1997). Maize growth was limited by P deficiency on the Oxisol and water deficit on the Alfisol (Jama et al., 1998), which explains the lack of soil N depletion by maize.

The slight tendency for greater N depletion of subsoil N under natural than sesbania fallows is likely an artifact arising from slightly lower initial subsoil N under sesbania than natural fallow because some subsoil N was depleted by sesbania before the start of the inorganic N measurements (Tables 2 and 3). Overall, the decreases in subsoil N were statistically comparable for the sesbania and natural fallows. The fallows depleted inorganic N at 0.5–2.0-m depth by 75–125 kg N ha^{-1} $year^{-1}$ down to a relatively stable N content between 40 and 80 kg N ha^{-1} (Table 2). They depleted inorganic N at 1.0–2.0-m depth by 50–75 kg N ha^{-1} $year^{-1}$ down to a minimum N content between 25 to 50 kg N ha^{-1} (Table 3).

Estimations of nutrient dynamics and changes in nutrient stocks within agroforestry systems have been hampered by little data on nutrient retrieval by trees from below the root zone of crops (Szott et al., 1999). We present one of the few reported approximations of a rate in subsoil inorganic N change under natural and planted tree fallows. The total uptake of subsoil N by fallow vegetation would be even greater than the measured change in subsoil inorganic N if N inputs to the subsoil exceeded the outputs of N by processes other than N uptake. It is highly probable that N inputs to the subsoil by N mineralization and movement from other soil layers exceeded N outputs by immobilization, leaching and denitrification. Nonetheless, our study demonstrated that N retrieval from below the rooting depth of crops could be appreciable by fallow vegetation.

Subsoil inorganic N levels stabilized before the end of the natural and sesbania fallows, indicating that subsoil NO_3 and NH_4 were depleted and equilibrium concentrations were reached. Subsoil NO_3 concentrations decreased to ≤ 2 mg N kg^{-1} on both soils. Nitrate concentrations exceeded NH_4 concentrations in the subsoil on the Alfisol, whereas NH_4 concentrations exceeded NO_3 concentrations on the Oxisol. This suggests that the stabilized concentrations of subsoil NO_3 and NH_4 under fallow vegetation with high N demand differ among soils.

4.3. N changes after fallows

Trends in soil inorganic N were distinctly different among the land-use systems after the fallows were slashed and maize was planted (Figs. 1 and 2). A large increase in soil inorganic N after cutting the sesbania and incorporating above-ground biomass was due to the mineralization of incorporated biomass and sesbania roots. Soil inorganic N increased less after the natural fallow than after the sesbania fallow. Although laboratory-determined aerobic N mineralization was comparable after the natural and sesbania fallows, potential N mineralization as determined in the laboratory by anaerobic N mineralization and N in incorporated plant biomass were less after the natural than after sesbania fallow (Maroko et al., 1998).

Barrios et al. (1997) similarly reported greater topsoil inorganic N and laboratory-determined N mineralization after sesbania than natural grass fallows. They attributed the high N mineralization following sesbania to the high quality of its leaf biomass, as indicated by its relatively high N content and low lignin and polyphenol contents. Lower inorganic N and N mineralization after natural than sesbania fallows can also be attributed to the higher C-to-N ratio of organic residues from natural than sesbania fallows (Maroko et al., 1998).

The substantial decrease in inorganic N after planting maize in the former bare fallow on the Oxisol coincided with a period of intense rain (Fig. 1), suggesting that NO_3 leaching caused the loss of inorganic N. Most of the inorganic N under the bare fallows was in the NO_3 form. Rainfall was much less during the same period on the Alfisol, and inorganic N did not appreciably decrease after planting maize on the bare fallow (Fig. 2). The rapid loss of inorganic N after the bare fallow on the Oxisol occurred early in the maize growing season, when leaching potential is great due to relatively low soil water depletion and root development by the crop (Silvertooth et al., 1992). Hagedorn et al. (1997) similarly found that large decreases in topsoil inorganic N on an Oxisol in Rwanda coincided with heavy rains at the onset of the rainy season. High N losses have also been reported by others on Oxisols (Duwig et al., 1998).

5. Conclusions

The retrieval of subsoil inorganic N by fallow vegetation and the subsequent rapid in situ mineralization of plant biomass after slashing the fallow can partly explain the reported residual benefits of fallows to crops. The retrieval of subsoil inorganic N can be appreciable with both sesbania and natural fallows on deep soils with accumulations of inorganic N in the subsoil. Sesbania fallows, however, produce higher N content organic residues, which more readily release inorganic N to subsequent crops. Sesbania fallows also produce wood that can be useful in areas where firewood is scarce, and they fix atmospheric N_2.

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