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SOIL NITRATE VARIATIONS UNDER GRASS, SORGHUM AND BARE FALLOW IN SEMI-ARID KENYA

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SUMMARY

Topsoil nitrate was measured every few days under grass, sorghum and bare fallow at two sites in lower Embu District, Kenya. Concentrations were highest soon after the start of rain and within a week most nitrate had been lost. Under bare fallow and sorghum, nitrate concentration increased during dry weather and losses occurred when soil water content exceeded 10%. Modelling of soil water movement indicated that there was no leaching below the rooting zone, so denitrification may be the main route for loss of soil nitrogen. Application of nitrogen fertilizer early in the season is not recommended as it would be lost with the native soil nitrate. The use of phosphorus fertilizer at the phosphorus-deficient site reduced soil nitrate concentration throughout the season and increased nitrogen uptake by sorghum. At the phosphorus-rich site, vigorous sorghum growth kept the soil nitrate concentration low, even though much nitrate was produced and lost in bare fallow. Adequate soil phosphorus is considered essential if the natural nitrogen resources of the soil are to be managed efficiently.

INTRODUCTION

The need for more productive and sustainable farming systems for the semi-arid tropics is universally accepted. To achieve this, effective use of plant nutrients in the soil is essential. Nitrogen (N) is taken up by plants as mineral-N (nitrate-N plus ammonium-N) and nitrate is normally the dominant form. Since the earliest measurements of soil nitrate, it has been known that wide fluctuations in its concentration occur during the growing season (Lawes, 1883; Russell and Appleyard, 1917). Nitrate concentration changes quickly because it reflects the net effect of (i) inputs from organic matter mineralization, fertilizers and the atmosphere and (ii) removal by plant uptake, microbial immobilization, leaching and gaseous loss. A review of the present knowledge of nitrate in tropical soils (Wong and Nortcliff, 1995) found that the highest concentrations normally occur during the transition from dry to wet seasons. This is because the decomposition of soil organic matter (SOM) is enhanced by drying followed by wetting, and the longer the dry period, the more N is mineralized (Birch, 1960). The natural flush of mineral-N was observed in bare fallowed soil at thirteen East African sites

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(Semb and Robinson, 1969), and its magnitude varied from 13 to 183 kg N ha^{-1}. Typically, total N uptake by sorghum in this climate ranged from 17.2 to 68.9 kg N ha^{-1} at Kampi ya Mawe, Kenya (Okalebo *et al*., 1989), so the mineral-N flush could represent a major contribution to the crop's N supply.

Previous studies of mineral-N in fields in the semi-arid tropics have been made with intervals of a week or more between sampling (Greenland, 1958; Semb and Robinson, 1969). We consider this to be a long time in relation to the potential speed of N loss in warm, moist soils often subjected to intense rainfall events. Semb and Robinson (1969) included two semi-arid sites (Katumani, Kenya and Ukiriguru, Tanzania) in their study and after the flush at the start of the rains found that mineral-N fluctuated around 10–25 mg kg^{-1}. Nitrogen levels were probably adequate for supplying arable crops, although the N demand was not assessed. More recently, Pilbeam and Warren (1995) estimated that the rate of gross N mineralization was sufficient to meet the N demand by maize or beans at Kiboko, Kenya. They assumed that all the N mineralized was taken up by the crop, maintaining a low mineral-N concentration in the soil. In the work reported here, the major objective was to measure soil mineral N concentration often enough to identify both the flush and subsequent maxima and minima, and then relate the changes to soil moisture, crops and soil N transformations in semi-arid farming conditions.

MATERIALS AND METHODS

Field experiment

The field sites were located in a semi-arid zone of Eastern Province, Kenya, near lat 0°45′S, long 37°45′E at an altitude of 1000 m. Rainfall was bimodally distributed (Table 1) and the October to January cropping season was wetter than the March to June season. Rainfall exceeded evaporation only in November and December. Mutuobare was a little lower, warmer and wetter than Machang'a (Table 2). The climax vegetation was *Acacia*- and *Commiphora*-dominated bush; neither site had been cultivated in living memory, but grazing had become a major land use in the last 30 years. The soils at the experimental sites were provisionally classed as chromic Cambisols, overlying granitoid gneiss basement complex (van de Weg and Mbuvi, 1975). At Machang'a, the soil profile depth was about 70 cm and the topsoil had a loam texture; at Mutuobare profile depth was about 35 cm and the surface texture was clay loam. The main difference between the sites was in soil fertility. Mutuobare soil was particularly fertile, with a high natural extractable phosphorus (P) concentration whereas the soil at Machang'a was very deficient in P.

In February 1994 the sites were cleared from bush and the three treatments were bare fallow, sorghum (*Sorghum bicolor*) and grass pasture. The bare fallow plots were tilled by hand once a month, removing all plant matter. The sorghum cultivar KARI Mtama-1 was dry-planted in the second week of March and October, and all seeds and crop residues were removed after harvest. The work

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Table 1. *Monthly distribution of rainfall and class 'A' pan evaporation at Machang'a, in lower Embu District, Kenya*

	J†	F	M	A	M	J	J	A	S	O	N	D	Total
Rainfall (mm)	55	33	79	149	45	2	5	3	2	82	165	121	740
Evaporation (mm)	159	177	204	156	147	139	146	183	229	223	133	121	2015

†First letters of months, January to December, 1989–1995.

reported refers to the October planting of 1994. The grass pasture was intended to simulate grazed land and, to create it, the bush was cut by hand to ground level and natural regrowth allowed without disturbing the soil. The grass cover was maintained by cutting two or three times during the rainy season. At Machang'a, the sward was dominated by the grasses *Aristida kenyensis*, *Brachiaria leersoides* and *Eragrostis caespitosa*. At Mutuobare, *Enteropogon macrostachys*, *Brachiaria leersoides* and *Aristida kenyensis* were the commonest grasses, although herbaceous species comprised a higher proportion of the sward than at Machang'a and the most frequent herb was *Blepharis interifolia* (J. I. Kinyamario, Department of Botany, University of Nairobi, personal communication). At Machang'a, the three treatments were unfertilized or were given one basal application of 250 kg P ha^{-1} as triple superphosphate applied in March 1994. In the fertilized treatments this raised Olsen-P from 0.87 to 27.4 mg kg^{-1}, close to Olsen-P in Mutuobare soil. No other fertilizers were used and all treatments were replicated three times.

Soil sampling and analysis

The soil monitoring was undertaken during the second season. The first sampling was on 30 May, at the end of the previous rainy season, the second on 8

Table 2. *Characteristics of the two sites and the soils at Machang'a and Mutuobare in lower Embu District, Kenya*

	Machang'a	Mutuobare
Altitude (m)	1050	900
Rainfall (mm)		
Mean annual†	740	809
Mean October to January season†	423	497
October 1994 to January 1995	439	616
Mean annual temperature (°C)†	23	25
pH (water)	6.47	6.54
pH ($CaCl_2$)	5.60	5.84
Total C [combustion] (%)	0.921	1.18
Total N [Kjeldahl] (%)	0.078	0.098
Olsen-P‡ (mg P kg^{-1})	0.87	30.0
Sand (%)	46	59
Silt (%)	30	21
Clay (%)	24	18
Bulk density (<2 mm soil)	1.28	1.30

†1989–1995; ‡Extracted by 0.5 M $NaHCO_3$ at pH 8.5.

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October before the onset of rain. After the first rain (12 October) sampling was at variable intervals, usually every 2–5 days at Machang'a. The aim was to sample frequently enough to record all the maximum and minimum values of soil nitrate, but with economy of effort when changes were expected to be slow. After the first two weeks the grass plots were sampled less frequently than the other plots in order to save work and reduce damage to the grass sward. Priority was given to the Machang'a site for practical reasons, and a lower sampling frequency was accepted for Mutuobare. For ease of presentation, the days of the season are numbered sequentially from 1 October 1994.

For each plot, five soil cores 5 cm in diameter were taken to a depth of 15 cm. This soil was mixed by hand in a bucket and a sample of about 1 kg placed in a polyethylene bag. Fresh soil (45 g) was weighed into a polypropylene bottle (250 ml), 1M KCl (200 ml) added and shaken end-over-end (10 revolutions min^{-1}) for one hour. The suspension was allowed to settle for a few minutes then filtered (Whatman GF/A filter). To minimize unintended incubation and mineralization of N, these operations were carried out on site, so that the maximum time between sampling and extraction was about three hours.

The soil extracts were taken to the KARI Regional Centre in Embu and analysed immediately, or stored under refrigeration and analysed within one week. Nitrate-N was measured with a 'Heliflow' portable flow injection analyser (WPA Ltd, Ware, UK), using the Griess–Ilosvay procedure (Keeney and Nelson, 1982). In this method, nitrate is reduced to nitrite by copperized Cd metal, reacted with NEDD (N-(1-naphthyl)ethylene diamine dihydrochloride) and measured colorimetrically (at 540 nm). For selected samples from Machang'a, ammonium-N was also measured on three occasions: 30 May, the end of the previous season, 19 December, about half way through the season investigated and 1 February 1995. This was done with a Perstorp flow injection analysis system at Reading University, where ammonium-N was measured as ammonia by gas diffusion (Perstorp Analytical Ltd, Maidenhead, UK, application note AN50/84).

To obtain the water content the rest of the soil sample was air-dried (25–30°C) for two to five days in a freely ventilated shed at Machang'a. Soils from Machang'a and Mutuobare dried in this way contained approximately 2% water on an oven-dry basis. Results here are presented on the basis of air-dry soil.

RESULTS

Ammonium, nitrate and mineral-N

Concentrations of ammonium-N were almost constant for the three treatments and the three sampling dates when it was measured in dry and wet seasons (Fig. 1). Only on 30 May was ammonium-N higher under bare fallow than under plots with sorghum. With this exception, there were no significant differences in ammonium-N between sorghum and fallow, between fertilized and unfertilized plots or between sampling dates. Therefore, almost all of the variation in mineral

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N was in the nitrate component (Fig. 1). For most sampling dates, only nitrate was measured. Since there was little variation in ammonium this was considered acceptable for tracing the short term temporal variations in mineral-N.

Soil water

Throughout the study period, soil water content was recorded on a gravimetric, air-dry soil basis. Although there were occasions when the bare fallow soil seemed wetter than the soil under grass, no significant differences in soil water were found between the treatments. The soil water data are therefore the means over all treatments. The maximum gravimetric water content at Machang'a, 18.6% on day 46, corresponded to a volumetric water content (θ) of 24%.

Nitrate in bare fallow soil at Machang'a

The concentration of nitrate in bare fallow soil was closely associated with the incidence of rainfall and changes in soil water. The first rain of the season fell on days 12 to 15 and, after wetting, soil nitrate increased to the highest values recorded in the season. The increase from day 8 to day 18 was significant at the 5% level and was a clear demonstration of the flush of mineral N on rewetting soil after the dry season.

After the initial flush, rainy spells and increases in soil water were accompanied by decreases in nitrate concentration, while dry periods were accompanied by increases in nitrate. There were four occasions when soil water rose above 10% (Fig. 2) and on all occasions except the initial wetting, these increases were accompanied by a substantial decline in nitrate concentration. The mechanisms of nitrate loss are discussed below.

Comparison between unfertilized fallow, grass and sorghum at Machang'a

During the dry season (30 May to 8 October), the total rainfall was 23.4 mm, and the change in the mean value of soil nitrate-N from 4.27 to 5.22 mg kg^{-1} was

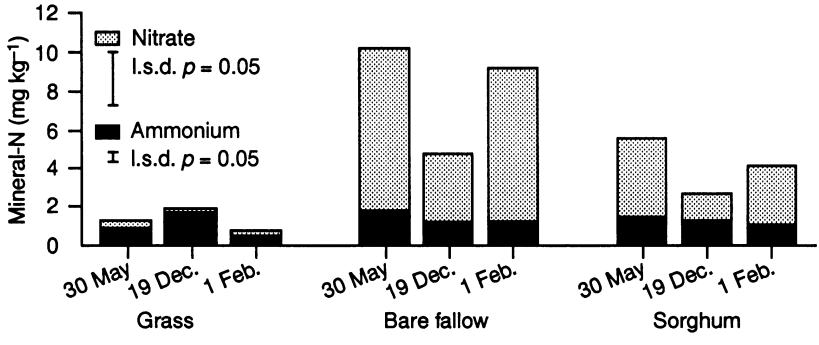


Fig. 1. Concentrations of ammonium-N (■) and nitrate-N (□) (mg N kg^{-1} soil) under unfertilized grass, bare fallow and sorghum at Machang'a on three occasions during 1994–5. l.s.d. = least significant difference.

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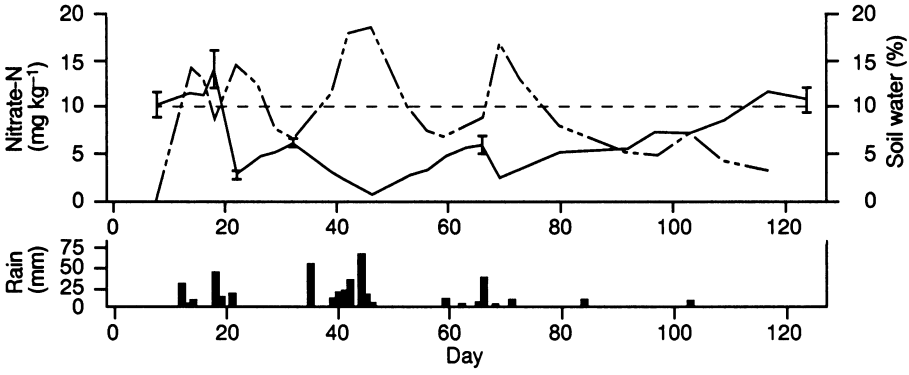


Fig. 2. Soil water content (–···–, gravimetric, % air-dry soil) and soil nitrate-N concentration (—, mg N kg^{-1} soil) under bare fallow at Machang'a, and daily rainfall (■) from October 1994, (day 1) to January 1995 (day 120). For nitrate, standard error bars are shown at days 8, 18, 22, 32, 66 and 124.

not significant. The relationships between the different treatments were maintained during the dry season, as indicated by the initially parallel trends (Fig. 3a). Thus the initial nitrate was largely nitrate left over from the preceding season.

Nitrate was highest in the bare fallow plots, where mineralization of organic matter occurred after site clearance in February 1994, but there were no plants to utilize it. Under grass there was a small and non-significant flush of nitrate which then returned to a constant low concentration (Fig. 3a). It was assumed that the dense grass rooting system absorbed most N upon mineralization. In sorghum plots, crop uptake removed some N, so nitrate was present at concentrations which paralleled the changes under bare fallow but at a lower level (Fig. 3a). After the rainiest period, around day 46, most mineral N had been lost and there were no significant differences between the three cropping treatments. In January, from around day 100, nitrate started to rise again in the bare fallow soils and, by the end of the season, the concentration of soil nitrate in each treatment was approaching the value at the start of the season.

Effects of phosphorus fertilizer at Machang'a

The temporal changes in soil nitrate and the effects of cropping system followed the same general pattern without fertilizer and with applied P (Fig. 3a and b). Fertilizer P significantly reduced the amount of soil nitrate in sorghum and fallow treatments at the start of the season. This was expected for sorghum, where improved crop growth in the preceding season would have taken more N from the soil.

The decrease in soil nitrate concentration in bare fallow plots with fertilizer P was surprising. It was speculated that additional P promoted microbial activity enough to cause rapid immobilization of freshly mineralized ammonium in preference to accumulation as nitrate. It was also possible that the effect was an artefact of heterogeneity of the field. One area (unfertilized treatments in Block 3)

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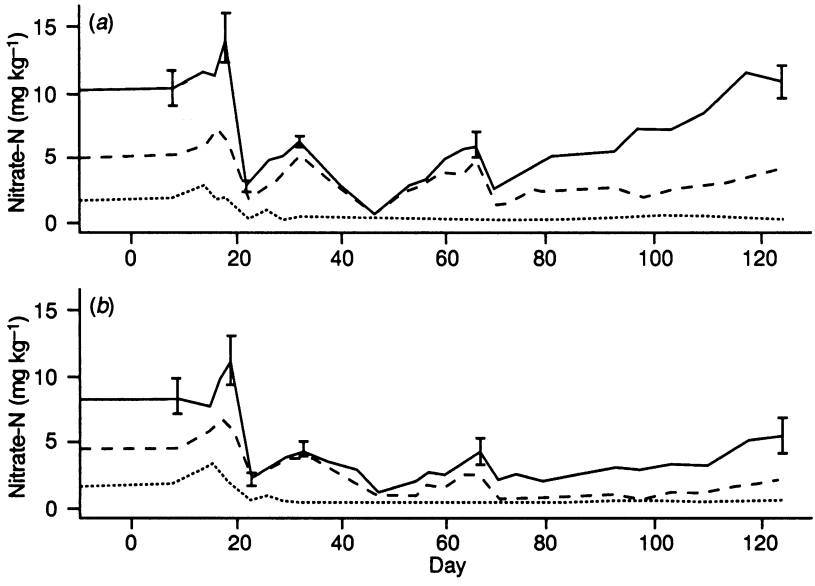


Fig. 3. Soil nitrate-N concentrations (mg N kg^{-1} soil) under grass (. . . . .), sorghum (- - - -) and bare fallow (———) at Machang'a, either (*a*) without or (*b*) with fertilizer phosphorus, from October 1994 (day 1) to January 1995 (day 120). At days 8, 18, 22, 32, 66 and 124 standard error bars are shown on the line for bare fallow.

gave consistently high soil nitrate values but when excluded from the statistical analyses did not affect the significance of the treatment effects. This high result remained unexplained.

Heavy rain eliminated significant differences between the treatments by mid-November (day 46). Thereafter the depression of nitrate after P application reappeared and was significant at most sampling dates. In the period from day 70 to day 100, sorghum given fertilizer P took up N so efficiently that soil nitrate was the same as under grass (Fig. 3b).

Mutuobare site

Practical considerations made it impossible to measure soil nitrate as frequently at Mutuobare as at Machang'a. Consequently, some details of the fluctuations and the possibility of recording an opening flush of nitrate at the initial rainfall (50 mm during day 12 to day 14) were missed. However, from day 59 to day 76, measurements were made every 3 to 5 days and this period included one heavy rainfall event. The soil at Mutuobare showed the same generally inverse relationship between soil water and soil nitrate under bare fallow (Fig. 4) as at Machang'a. Although large losses occurred when the soil was wetted, nitrate build-up occurred with a soil water content above 10%, if the soil was drying not wetting. This was seen between day 60 and day 66 and also between day 69 and day 80.

Sorghum growth was vigorous and the demand for N so high that from day 48

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soil nitrate under sorghum was not significantly different from soil nitrate under grass (Fig. 5).

Nitrogen mineralization rates

After the initial nitrate flush in unfertilized bare fallow soil at Machang'a, three distinct periods of net N mineralization could be identified: days 22 to 32, 46 to 66, and 69 to 117 during the period October 1994 to January 1995 (Fig. 2). The net production of nitrate-N was estimated from the rise in nitrate during these periods (Table 3), assuming that there were no losses from the topsoil which was sampled. Nitrate was highest soon after the start of the season, (day 18) with 26.2 kg N ha^{-1} in the topsoil. Net mineralization of nitrate from day 22 to day 32 released another 6.3 kg N ha^{-1} before much crop growth had occurred in the sorghum plots.

The rates of net mineralization were also compared between soils, where comparable sampling dates were available. From day 73 to day 109 the concentration of nitrate-N in fallow soil rose by 15.3 mg kg^{-1} at Mutuobare, by 5.0 mg kg^{-1} at Machang'a where the soil was unfertilized, and by 0.6 mg kg^{-1} at Machang'a where the soil was fertilized.

Final crop yields

Rainfall in this October 1994 to January 1995 season was close to the recent average (Table 2) so the grain yield for sorghum was typical for the region (Table 4) and somewhat lower than the range (950–4200 kg ha^{-1}) found by Okalebo *et al.* (1989) at three other semi-arid Kenyan sites. Yield and nutrient uptakes were significantly higher at Mutuobare (Table 4), with more fertile soil (Table 1) than at Machang'a with or without fertilizer P. A large response to P was found at Machang'a, where soil extractable P had been increased from 0.87 to 27.4 mg kg^{-1} by fertilizer P application (Table 2).

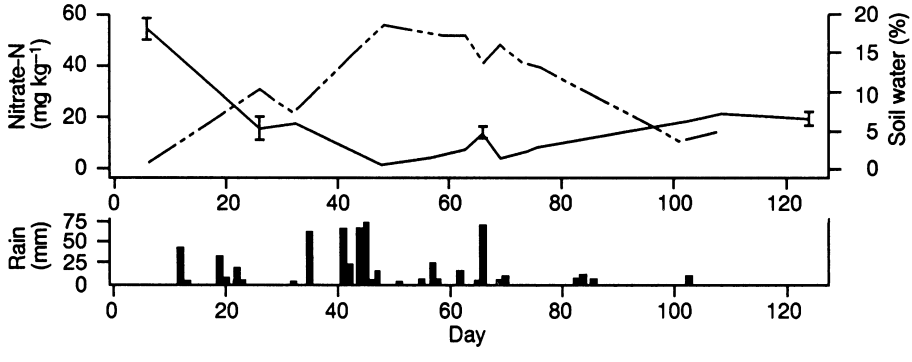


Fig. 4. Soil water content (– · · –, gravimetric % air-dry soil) and soil nitrate-N concentration (——, mg N kg^{-1} soil) under bare fallow at Mutuobare with daily rainfall (■) from October 1994 (day 1) to January 1995 (day 120). For nitrate, standard error bars are shown at days 6, 26, 66 and 124.

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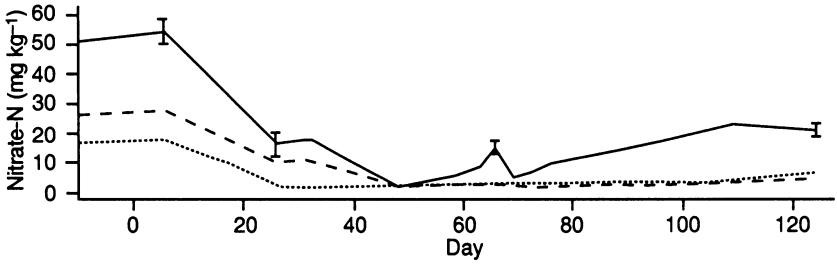


Fig. 5. Soil nitrate-N concentrations (mg N kg^{-1} soil) under grass (. . . .), sorghum (- - - -) and bare fallow (——) at Mutuobare from October 1994 (day 1) to January 1995 (day 120). At days 6, 26, 66 and 124, standard error bars are shown on the line for bare fallow.

DISCUSSION

Effects of phosphorus availability on soil nitrate

Fertilizer P increased the grain yield of sorghum and the uptake of N and P very significantly at Machang'a (Table 4) where the soil was deficient in available P. Extractable P was similar in soil at Mutuobare and in fertilized soil at Machang'a (Table 2), suggesting that the more favourable N supply at Mutuobare resulted in significantly higher sorghum grain yield and N and P uptakes. This was supported by the soil nitrate data. Bare fallow at Mutuobare usually contained 10–50 mg nitrate-N kg^{-1} except after heavy rain (Fig. 4), but at Machang'a bare fallow almost always contained less than 10 mg nitrate-N kg^{-1} (Fig. 2). The rate of net mineralization between day 73 and day 109 was also greater at Mutuobare as noted above and this showed that the N supply was greater at Mutuobare. Despite this the soil nitrate concentration in December and January under sorghum was usually lower at Mutuobare, ranging between 0.8 and 2.8 mg N kg^{-1}, compared with 1.4 to 4.8 mg N kg^{-1} for unfertilized soil at Machang'a, a consequence of the low P status leading to poor uptake of nitrate by the crop.

These results support the conclusion of Okalebo *et al.* (1989) that crop responses to N and P fertilizers need to be considered in relation to the soil mineral N supply.

Table 3. *Accumulation of nitrate-N in the 0–15 cm horizon of unfertilized bare fallow soil at Machang'a in the lower Embu District, Kenya at the end of each period of net mineralization during the October 1994 to January 1995 season*

Mineralization period	Increase in nitrate-N concentration (mg N kg^{-1})	Mineralized nitrate-N in topsoil on last day of each mineralization period (kg N ha^{-1})
Before day 18	14.08	26.2
Day 22 to day 32	3.41	6.3
Day 46 to day 66	5.25	9.8
Day 69 to day 117	8.22	15.3
Total	—	57.6

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Table 4. *Grain and total dry matter yields (kg ha^{-1}) and nitrogen and phosphorus uptakes (kg ha^{-1}) by sorghum grown at Machang'a and Mutuobare in the lower Embu District, Kenya during the October 1994 to January 1995 season*

	Machang'a (unfertilized)	Machang'a (+ P fertilizer)	Mutuobare (unfertilized)
Dry matter yield			
Grain	735 (288)†	2115 (288)	2459 (125)
Total	3055 (662)	6136 (662)	7431 (212)
Nitrogen uptake			
Grain	12.3 (4.1)	32.5 (4.1)	40.1 (0.38)
Total	28.6 (5.5)	51.9 (5.5)	70.1 (2.98)
Phosphorus uptake			
Grain	1.12 (0.78)	5.61 (0.78)	8.77 (0.22)
Total	2.08 (0.81)	7.71 (0.81)	16.58 (1.19)

†Standard error of the mean in parentheses.

Where the soil is deficient in P, as at Machang'a, P fertilizer improves the uptake of the soil N supply significantly.

Timing of mineralization

In arable cropping, the supply of available N appeared to be poorly synchronized with crop demand. Most of the 32.5 kg nitrate-N ha^{-1} produced in unfertilized bare fallow soil at Machang'a before 2 November (Table 3) was lost from the topsoil in the following rainy period. In total, some 57.6 kg nitrate-N ha^{-1} was made available by net mineralization during the season, much more than the N uptake by unfertilized sorghum (28.6 kg N ha^{-1}), and still exceeding the N uptake by sorghum given P fertilizer (51.9 kg N ha^{-1}). Additional nitrate was also mineralized in the subsoil and this assessment reflects only net mineralization. Much more N would be mineralized and then re-immobilized by the natural turnover of soil organic matter. Some of this freshly mineralized N could be utilized by crops if required, instead of being re-immobilized. These data suggest that in the infertile Machang'a soil the total supply of mineralized soil N was more than sufficient for the crop. However, much of it was available early in the season and then lost from the soil.

These results show that N fertilizer is likely to be ineffective if applied to arable crops early in the season because fertilizer nitrate will be lost with the rest of the soil nitrate. However, N may be topdressed at a later stage, when a fuller crop root system is present. In contrast, the nitrate concentration of the soil remained low under grass, where the continuous presence of roots ensured that mineralized N was utilized as already shown for both temperate and tropical grasslands (Greenland, 1958).

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Mechanism of nitrate loss

It appeared that about 32 kg nitrate-N ha^{-1} was lost early in the season at Machang'a. At Mutuobare, the initial loss of nitrate-N was 91 kg ha^{-1} between day 6 and day 48. The loss after heavy rain was obvious, but the pathway was not identified. Leaching was proposed as the loss mechanism by Semb and Robinson (1969) for their Katumani experiment. Data collated by Pieri (1995) for cereals at three West African sites (annual rainfall 507–705 mm) showed only small annual leaching losses of 0.3–7.1 kg N ha^{-1} for cereals in this climate, although 25 kg N ha^{-1} was leached under groundnuts. In East Africa, substantial amounts of nitrate can be leached to depths which are out of reach of roots (Michori, 1993), although this was demonstrated in a zone with higher rainfall. At Machang'a, 115.1 mm rain had fallen by day 22 and the topsoil contained 27 mm water, suggesting that leaching was possible. Direct measurements were not made, and so the possibility of leaching was assessed by modelling the soil water balance at Machang'a using the PARCH model version 3.01 (Bradley, 1995). The model was run using the measured soil texture, daily meteorological data, and an initially dry soil. It was assumed that runoff was negligible and that macropore flow dominated in the top 10 cm. The model indicated that, with or without sorghum, about 29 mm water moved below 15 cm by day 22 (Fig. 6), by which time much nitrate could have leached out of the topsoil. When the model was run to crop maturity (day 126), no drainage below 75 cm was predicted. Thus, nitrate leached early in the season should have been recovered by sorghum roots later on or would have remained in the profile. Auger-coring in selected plots to a depth of 1 m later in 1995 revealed no sign of nitrate accumulation. The following factors point to important losses of N by denitrification: low N uptake compared with net mineralization; no drainage predicted; and no accumulation of nitrate in the soil.

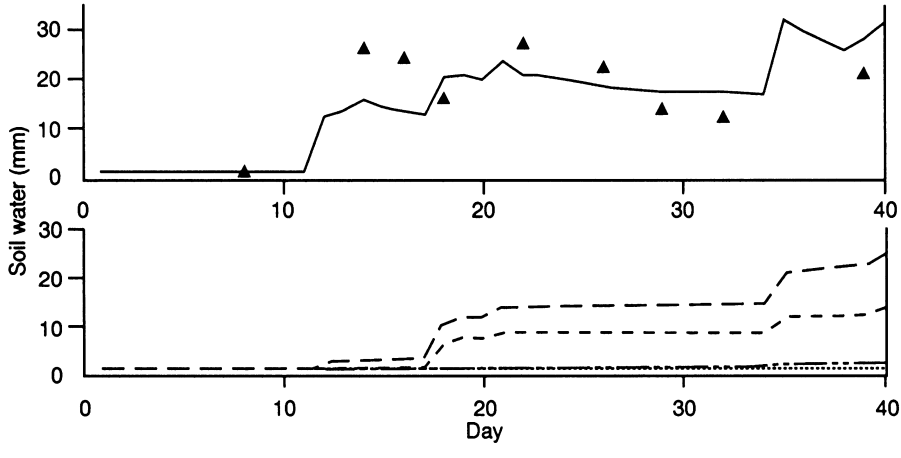


Fig. 6. Amounts of soil water (mm) in five horizons (——, 0–15 cm; – – –, 15–30 cm; - - - -, 30–45 cm; —- - —, 45–60 cm; ·····, 60–75 cm) of bare fallow soil at Machang'a during the first 40 days of the cropping season starting in October 1994 (day 1). For the 0–15 cm horizon (——) predictions were made by the PARCH model from actual measurements depicted by triangles (▲).

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Although the Machang'a soil is considered well-drained and not liable to waterlogging, warm soil conditions (25–30°C) at the start of the season together with high nitrate concentration and soil moistening to produce anaerobic microsites (Fillery, 1983) are conducive to denitrification and the formation of N_2 gas. At the start of the season, the initial burst of microbial activity on rewetting would produce the flush of mineral N observed, and would also create a high oxygen demand within soil aggregates. Therefore, the generation of anaerobic microsites could have taken place before the saturation of the soil. Direct estimates of denitrification present technical difficulties, especially in developing countries, and at present there is little such data for tropical agricultural systems other than rice (Groffman, 1995). However, the possibility of substantial denitrification is supported by the high rates of N_2O production in rewetted soils from the dry climates of California and Mexico (Davidson, 1992; Davidson *et al*., 1993). In those soils, denitrification was thought to be the dominant source of N_2O in fully wetted soil. Further examination of the routes of N loss in semi-arid conditions is desirable.

CONCLUSIONS

During the rainy season, wide fluctuations in topsoil nitrate were observed between soil samplings taken only a few days apart. These fluctuations mean that if mineral N is measured infrequently or on a single occasion the results are of limited help in assessing the N status of soil.

Substantial losses of nitrate occurred early in the rainy season although it is not known whether the N was leached or denitrified. For semi-arid conditions, the natural pattern of mineral N production is not conducive for the efficient production of single-season arable crops. Farming systems development should take this into account if the aim is to conserve natural N resources for sustainable production. In particular, basal applications of N fertilizer are likely to be inefficient. Efficient uptake of nitrate occurs under permanent grass and also, if soil P is high, by sorghum with a well developed rooting system. In semi-arid systems, soil fertility can be conserved by maximizing the areas under pasture and perennial crops, so that the roots can use the flush of N. Food crops which grow for more than one season, such as pigeonpeas (*Cajanus cajan*) and two-season sorghum varieties, can conserve mineralized N because the existing roots should be able to capture some of the initial nitrate by the second season.

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