

Leaching of nitrate, calcium and magnesium under maize cultivation on an oxisol in Togo

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Abstract

In tropical regions, crop yields generally decrease with time, partly due to a decline in the levels of exchangeable bases linked to acidification of the upper layers of the soil. Nitrogen, calcium and magnesium balances were studied on an oxisol in southern Togo under continuous maize cropping with mineral fertilization and crop residue return, by measuring inputs and outputs.

The balance was near equilibrium for nitrogen (urea dressing, 120 kg N ha⁻¹ y⁻¹) and negative for calcium and magnesium. Leaching represented between 29% and 85% of the total output for nitrogen and accounted for practically all the calcium and magnesium outputs.

In the upper horizons, nitrate, calcium and magnesium contents in the soil solution were correlated. This was interpreted as an exchange between the calcium and magnesium ions adsorbed on the soil and the protons released by the transformation of ammonium into nitrate. The nutrient content of the soil solution increased in the case of no potassium fertilization, probably because of a lower nitrogen immobilization by microorganisms, the crop residue yield being reduced by the induced deficiency. An insufficient potassium fertilization increases leaching losses of calcium, magnesium and nitrogen.

In the deeper horizons, the nitrate content of the soil solution was not correlated with the calcium and magnesium contents. Nitrogen was probably taken up by roots and some calcium and magnesium ions exchanged during their transport through the soil.

Résumé

En régions tropicales, les rendements déclinent généralement au cours du temps, en partie à cause d'une diminution des teneurs en bases échangeables du sol couplée à une acidification des horizons superficiels. Les bilans de l'azote, du calcium et du magnésium ont été étudiés dans un oxisol du Togo méridional, pour une culture continue de maïs avec fertilisation minérale et restitution des résidus de récolte, en mesurant les entrées et les sorties du système.

Le bilan est proche de l'équilibre pour l'azote (apport d'urée de 120 kg N ha⁻¹ an⁻¹), négatif pour le calcium et pour le magnésium. La lixiviation représente 29% à 85% des sorties du système pour l'azote, la quasi totalité pour le calcium et le magnésium.

Dans les horizons superficiels, les teneurs en nitrate, en calcium et en magnésium de la solution du sol sont liées. Cette liaison semble résulter de l'échange d'ions calcium et magnésium fixés sur le complexe d'échange contre des protons libérés lors de la transformation de l'azote de la forme ammoniacale à la forme nitrique. Les teneurs sont accrues par l'absence de fertilisation potassique.

probablement en raison d'une moindre immobilisation de l'azote dans les micro-organismes, la masse de résidus de récolte produite étant plus faible pour une culture carencée. Une fertilisation potassique insuffisante augmente les entraînements de calcium, de magnésium et d'azote par lixiviation.

Dans les horizons profonds, les teneurs en nitrate ne sont pas liées à celles du calcium et du magnésium. L'azote est probablement prélevé par les racines, des ions calcium et magnésium échangés au cours du transfert à travers le sol.

Introduction

In West Africa, the challenge of a population growth rate in excess of 3% per annum with an increasing food deficit cannot be met without the efficient use of chemical fertilizers [16, 28, 29]. The quantities of nutrients to be applied are usually calculated from an agronomic and economic analysis of crop response to NPKS fertilizers [1, 5]. However, the yield of crops usually declines with time for a given level of fertilization. This evolution results partly from acidification of the upper layers of the soil associated with a decrease in exchangeable cations (mainly calcium and magnesium) and an increase in exchangeable aluminium for low pH soils [22, 16].

Lysimeter and ceramic cup studies have shown that in West African tropical environments leaching of nitrate, calcium and magnesium ions always represents a large part of agrosystem outputs, as soon as drainage occurs [11, 10, 14, 4, 27]. Although the dynamics of soil nutrients is only partially understood, some research on the relationships between ions in the soil solution, both in the field [15, 24] and in soil columns [17], have shown that nitrate ions move in the soil solution in association with other cations. Under temperate climates, losses of calcium and magnesium from the agrosystem alter the chemical properties of the soil only in the long term and they are compensated by liming. Under tropical climates, where cation exchange capacity (CEC) of the soil is generally low, these losses produce a rapid change in the level of exchangeable cations seldom corrected by the application of fertilizers or amendments.

In a previous paper [24] changes with time of the nutrient contents of the soil solution were studied in a continuous maize cropping system in Togo, and losses by leaching were estimated. This paper reports on the nutrient balances of

nitrogen, calcium and magnesium and on the relationships between nutrients in the soil solution, in connection with K fertilisation.

Materials and methods

Experimental site

The experiments were carried out at the IRAT (Institut de Recherches Agronomiques Tropicales) experimental station of Davié (6° 22'N, 1° 13'E), 35 km north of Lomé. The annual weather pattern in this part of Togo (Altitude, 50 m) is tropical with two wet seasons (mean annual rainfall, 1040 mm; mean annual temperature, 27°C). The soil is a Ferralsol (Soil Taxonomy, Typic Eustrustox) representative of those of southern Togo locally called 'Terres de Barre'. The main chemical and physical properties of the soil are in Table 1.

Treatments

Two plots of a long-term NPK factorial experiment were used to estimate nutrient balances in 1985 and 1986. Both plots had been cropped twice a year with maize since 1976 (variety NH1, 110 days duration, 42,000 plants per hectare). One of the plot (K2), had received a NPK fertilization since 1976, the other (K0) had received N and P but no K. In 1985, the fertilization level was 20 kg P ha⁻¹ and 75 kg K ha⁻¹ for the first cropping seasons, 13 kg P ha⁻¹ and 50 kg K ha⁻¹ for the second, the nitrogen fertilization being 60 kg N ha⁻¹ in both seasons. In 1986, the same level (60 kg N ha⁻¹, 20 kg P ha⁻¹ and 75 kg K ha⁻¹) was applied in each season. The fertilizers, urea (46% N), triple superphosphate (21% P, 14% Ca) and KCl (52% water soluble K, 47% chloride), were incorporated with a hoe to a depth of 5 cm of soil.

Table 1. Physical and chemical properties of the 0–20 cm soil layer at the Davié experimental station (mean values of 6 samples)

	Fallow (after 13 years)	Treatment K1 (after 11 years of cultivation)	Treatment K2
Clay (<2 µm)	41	13	17
Silt (2–50 µm)	9	—	6
Sand (50–2000 µm)	80	80	77
pH (water)	5.4	5.2	5.6
Organic carbon (%)	0.99	0.50	0.62
C/N	12	15	13
Exchangeable cations (meq 100 g ⁻¹)			
Ca	2.1	1.0	1.4
Mg	1.5	0.5	0.6
K	0.20	0.08	0.35
Na	0.04	0.04	0.04
Al	0.00	0.03	0.01
Cation exchange capacity	3.9	2.0	2.7
P Olsen-Dabin* (ppm)	40	46	25

*Extraction by NaHCO₃ 0.5 M and FNH₄ 0.5 M at pH 8.5

Phosphorus and potassium were applied at sowing, nitrogen was applied half at thinning and half at tasselling. Crop residues remained on the plots and were incorporated once a year before the first cropping season.

Experimental design and measurements

The mineral content of the rains was determined on 8 samples collected from 1984 to 1986 (Table 2). The annual amount of nutrients brought by the rains was estimated by multiplying the average content by the year's total rainfall. Both plots (8.0 × 4.5 m) were equipped with 4 neutron access tubes and 14 tensiometers to monitor soil water content and movement. Measurements were made every day during the period of cultivation and twice a week for the rest of the year. Drainage below the root zone (1.5 m) was estimated using Darcy's law and suction-conductivity relationships [19]. Statistical calculations were made to estimate the standard error on drainage [18].

A battery of 4 ceramic cups (Soil Moisture

4.5 cm in diameter) was placed at 30 and 180 cm depths to collect soil solutions. Samples were taken twice a month through the year by applying a 600 hPa suction for 24 hours. Nitrate content was measured by the phenoldisulfonic method, calcium and magnesium by atomic absorption spectrophotometry and potassium by flame spectrophotometry. As the roots never reached below 150 cm and as the clay content of the soil did not change with depth at this level, the nutrient content of the soil solution was assumed to be the same at 180 cm and at 150 cm. Leaching of each element between two sampling dates was calculated by multiplying its content in the soil solution by the amount of drainage during the period.

Dry matter yields and crop removals were determined by collecting 10 plants from each of the plots for 3 years prior to the experiment [23]. The dry matter weight of each organ (root, stem, leaves, leaf sheaths and grain) was determined after drying at 80°C, and nutrient content measured on 2 sub-samples. A relationship was established between the grain yield and the

Table 2. Mean rainfall content and corresponding amounts supplied in precipitation (8 samples collected from 1984 to 1986, average rainfall 1934–1986: 1043 mm)

Nutrient	NO ₃	Ca	Mg	NH ₄	K	PO ₄	Cl
Content (mg l ⁻¹)	0.05	0.5	0.02	0.3	0.01	0.008	0.08
Input (kg ha ⁻¹ y ⁻¹)	4.4	40	2.5	7.2	1.1	1.1	29.5

weight of crop residues to estimate the crop removals for each plot and each cropping season from the grain yield of the plot.

Results

Nutrient balances

The nutrient balance sheet of each element was calculated taking into account the amounts supplied in precipitation and fertilizer dressings as inputs, leaching below the root zone (150 cm) and crop removals as outputs. Losses by runoff were disregarded, as the site was flat (slope less than 1%). Ammonium content in the soil solution, between 0.06 and 0.11 meq l⁻¹, was neglected. Losses of nitrogen in the gaseous phases were not measured. Ammonia volatilization was probably low, being negligible in tropical regions as soon as the fertilizer is incorporated [8]. Losses by denitrification were generally low, although a value of 30% for applied nitrogen has

the crop residues returned to the soil was 2000 kg ha⁻¹ y⁻¹ in treatment K0 and 4600 kg ha⁻¹ y⁻¹ in K2. Despite this large difference in growth, annual evapotranspiration from both plots differed by less than 10%, as evaporation from the soil remained high throughout the year (maximum LAI, 2.5). Consequently, the difference in drainage between both plots was less than 20%. This result is consistent with experiments carried out in the Niger [29] where NPK fertilization increased grain yields of pearl millet, but had little effect on water use. In 1986, drainage was higher than 1985 due to both the distribution and quantity of rainfall (Fig. 1). The precision of the drainage value was poor (CV 31%), as direct measurement was impossible in the field [18]. For nitrogen, the balance was near equilibrium in both treatment plots (Table 4), except in treatment K0 in 1986 where the confidence interval was high because of heavy drainage. If denitrification occurred, the balance was slightly negative. For calcium and magnesium, the balance was negative in all cases despite intensive

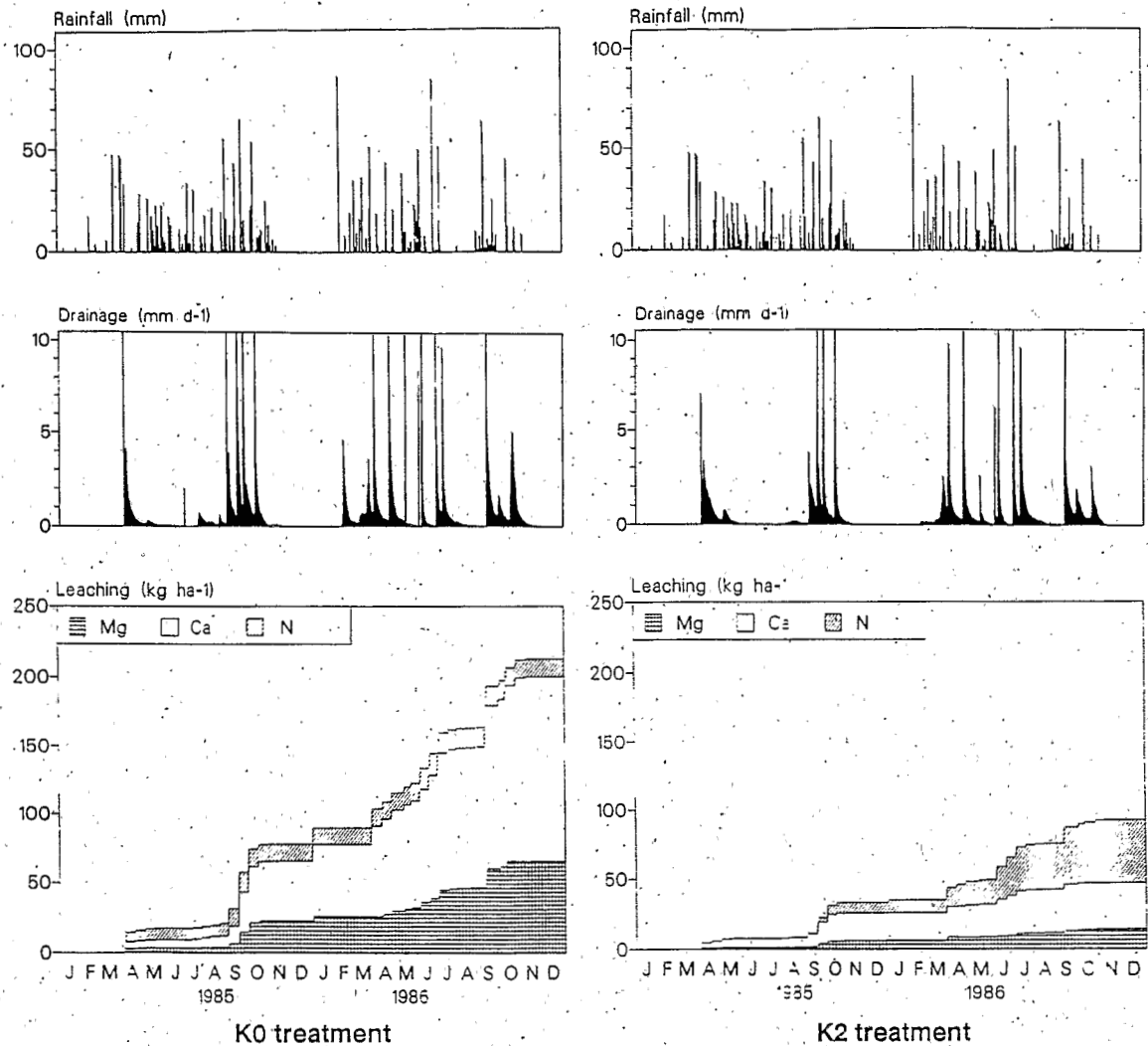


Fig. 1. Rainfall, drainage and leaching of nitrogen, calcium and magnesium at 150 cm soil depth in 1985 and 1986.

treatment K2, 76% (1985) and 128% (1986) in K0.

Nitrate leaching depends on the distribution of rainfall. In 1985, leaching in the K0 plot was 21 kg N ha⁻¹ during the first growing seasons (April to July) with 377 mm of rainfall. It was 95 kg N ha⁻¹ in 1986 during the same period with only 308 mm (Fig. 1). There were many light rains in 1985 and few by heavier rains in 1986.

In both years, nitrate leaching was higher at the start of the rainy season than during the rest of the rainy period. This phenomenon was partly due to the decrease in drainage during the rainy

seasons because of plant transpiration. However plant transpiration did not increase the evapotranspiration much during the cropping season. On the contrary, the nitrate content in the soil solution varied with time between 0.04 and 2.4 meq l⁻¹ in treatment K0 at a depth of 30 cm (Fig. 2).

The highest nitrate contents in the soil solution was recorded at the very beginning of the rainy seasons, and this increase preceded the application of nitrogen fertilizers. The lowest nitrate content in the soil solution was recorded in June and November for both years. The quantities of nitrate leached were about three times higher in

Table 4. Nutrient balances in 1985 and 1986

Nitrogen balance

1985

1986

1985

1986

The table content is completely obscured by heavy horizontal black bars, rendering the data unreadable.

treatment K0 than in K2 during a given year (Table 4). By increasing dry matter production, potassium fertilization decreased drainage. But, as noted previously, the differences in drainage remained less than 20% between the two plots. The higher leaching in treatment K0 was therefore mainly due to a higher nitrate content of the soil solution (average nitrate content at 180 cm: 2.4 meq l⁻¹ for K0 treatment and 1.3 meq l⁻¹ for K2).

Calcium and magnesium leaching

After 11 years of cultivation, exchangeable calcium and magnesium in the upper layers of the soil had sharply decreased (Table 1) and almost all outputs of calcium and magnesium from the agrosystem came from leaching (Table 4). Calcium and magnesium concentrations in the soil solution were correlated:

Plot K0 (30 cm)

$$[\text{Mg}] = 0.58 (\pm 0.08) [\text{Ca}] - 0.08 (\pm 0.20)$$

$$(r^2 = 0.65, n = 31)$$

(1)

Plot K2 (30 cm)

$$[\text{Mg}] = 0.70 (\pm 0.04) [\text{Ca}] - 0.01 (\pm 0.08)$$

$$(r^2 = 0.90, n = 34)$$

(2)

(Ca and Mg contents expressed in meq l⁻¹)

These relationships are close to those already observed in the same climatic area [15]. At 30 cm depth, the Mg/Ca ratio in the soil solution of treatment K0 was about 0.59 and 0.71 in K2, whereas it was respectively 0.50 and 0.44 in exchangeable forms in the 0–20 cm soil layer (Table 1). The Mg/Ca ratio of the exchangeable ions of the soil increased with depth between 20 and about 70 cm (Figs 3 and 4). Exchangeable magnesium was therefore preferentially leached from the upper layers of the soil, compared with exchangeable calcium. It can be concluded that exchangeable magnesium was adsorbed by the

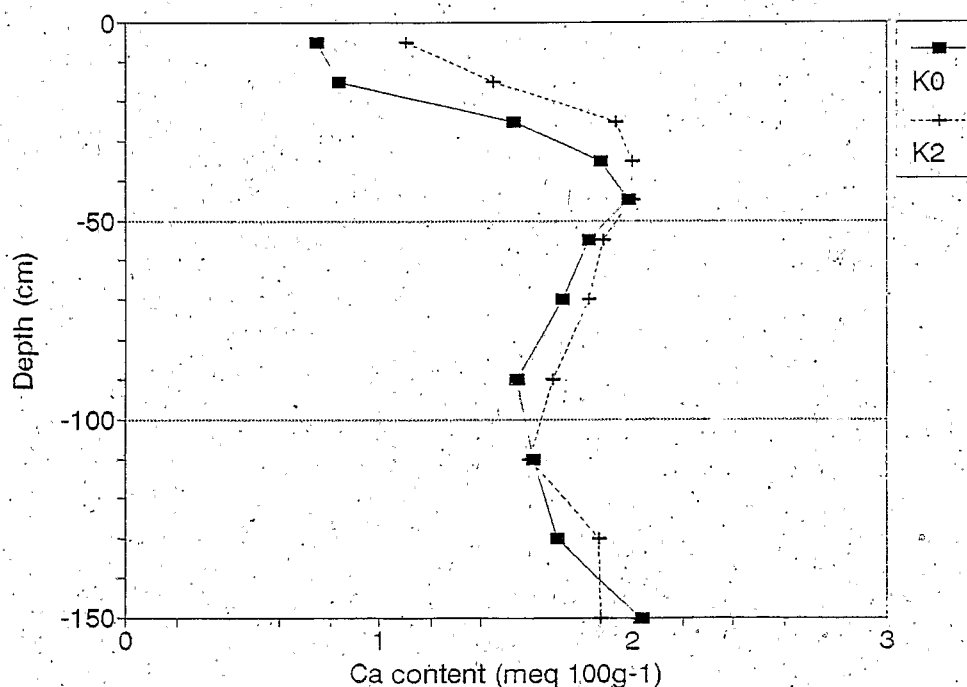


Fig. 3. Exchangeable calcium profile distribution for treatment K0 and K2 (mean values of 6 samples).

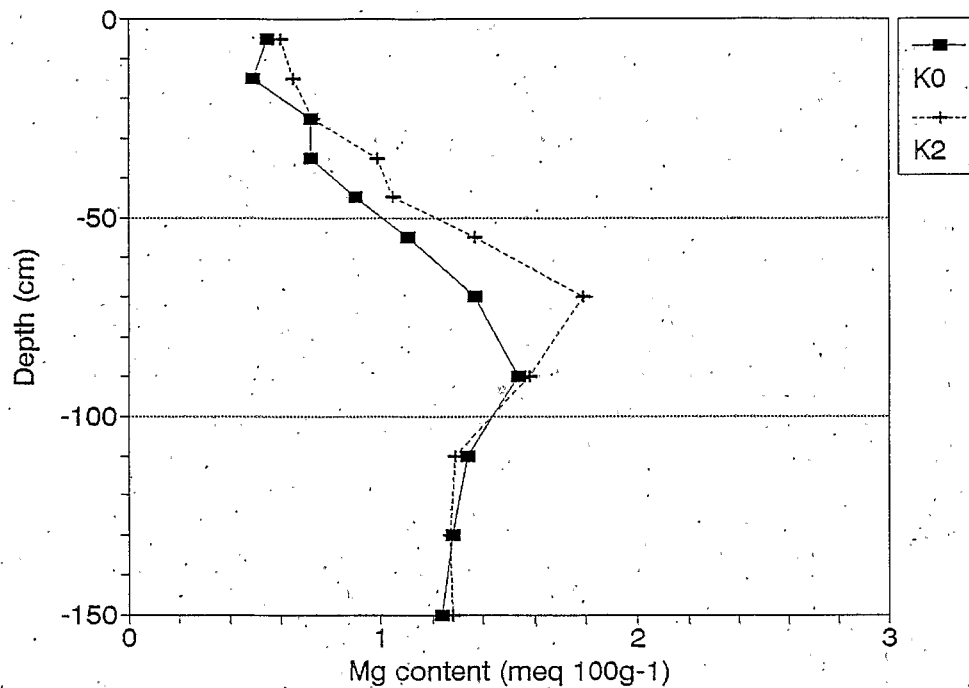


Fig. 4. Exchangeable magnesium profile distribution for treatment K0 and K2 (mean values of 6 samples).

solid phase of the soil less than exchangeable calcium. Changes with time of calcium and magnesium contents in the soil solution followed the same pattern as the nitrate content (Fig. 2). For the K0 treatment, calcium and magnesium contents were correlated with the nitrate content but there was no significant correlation with potassium (Table 5):

Plot K0 (30 cm).

$$[\text{Ca} + \text{Mg}] = 1.03 (\pm 0.08) [\text{NO}_3] + 0.42 (\pm 0.30) \quad (3)$$

($r^2 = 0.85$, $n = 31$)

(NO_3 , Ca and Mg contents expressed in meq l^{-1})

For the K2 treatment, calcium and magnesium concentrations in the soil solution were correlated with both nitrate and potassium contents

Table 5. Correlation matrix between the concentration of ions in the soil solution as affected by fertilizer treatment and depth of sampling

	NO_3	Ca	Mg	K	NO_3	Ca	Mg	K	NO_3	Ca	Mg	K
NO_3	1.00				1.00				1.00			
Ca	0.92***	1.00			0.81***	1.00			-0.08*	1.00		
Mg	0.82***	0.81***	1.00		0.82***	0.95**	1.00		-0.03*	0.70***	1.00	
K	0.33*	0.24*	0.27*	1.00	0.76***	0.67***	0.63***	1.00	0.02*	0.40**	0.45**	1.00

Treatment K0 at 30 cm ($n = 31$)

Treatment K2 at 30 cm ($n = 34$)

Treatment K2 at 180 cm ($n = 35$)

*** $P \leq 0.01$

** $0.01 < P \leq 0.05$

* $0.05 < P$

(Table 5). The potassium content of the soil solution was always between 0.04 and 0.08 meq

either organic matter or urea, one proton is released in the soil solution. As the pH in the

than in K0. As a great part of the leaching occurred at the beginning of the cropping season it seems that the decrease in nitrate

was lower. Magnesium leaching went deeper than calcium leaching. This is in agreement with results obtained from magnesium-calcium

- maize (*Zea mays* L.) in southern Guinea Savanna, agroecology of Nigeria. *Fert Res* 29: 139-144
2. Arora Y and Juo ASR (1982) Leaching of fertilizer ions in a kaolinitic ultisol in the high rainfall tropics: leaching of nitrate in field plots under cropping and bare fallow. *Soil Sci Soc Am J* 46: 1212-1218
 3. Blondel D (1971) Contribution à l'étude du lessivage de l'azote en sol sableux (Dior) du Sénégal. *Agron Trop* 26: 687-696
 4. Chabalièr PF (1984) Comparaison de deux méthodes de mesure de la lixiviation en sol ferrallitique. *Agron Trop* 39: 22-30
 5. Christianson CB and Vlek PLG (1991) Alleviating soil fertility constraints to food production in West Africa: efficiency of nitrogen fertilizers applied to food crops. *Fert Res* 29: 21-33
 6. Dabin B (1956) Contribution à l'étude de la fertilité des terres de Barre. *Agron Trop* 11: 490-506
 7. Faurie G (1977) Etude in vitro du rôle de la nitrification sur la lixiviation du calcium dans les sols calcaires. *Science du Sol* 4: 207-218
 8. Ganry F (1990) Application de la méthode isotopique à l'étude de bilans azotés en zone tropicale sèche. Th Univ Nancy I. Nancy, France, 355 pp.
 9. Gigou J and Chabalièr PF (1987) L'utilisation de l'engrais azoté par les cultures annuelles en Côte d'Ivoire. *Agron Trop* 43: 171-179
 10. Godefroy J, Muller M and Roose E (1970) Estimation des pertes par lixiviation des éléments fertilisants dans un sol de bananeraie de basse Côte d'Ivoire. *Fruits* 25: 403-423
 11. Greenland DJ (1959) A lysimeter for nitrogen balance studies in tropical soils. *J West Afr Sci Assoc* 5: 79-89
 12. Larsen S and Widdowson AE (1968) Chemical composition of soil solution. *J Sci Fd Agric* 19: 693-695
 13. Martinez J and Guiraud G (1990) A lysimeter study of the effects of a rye-grass catch crop, during a winter wheat/maize rotation, on nitrate leaching and on the following crop. *J Soil Sci* 41: 5-16
 14. Omoti U, Ataga DO and Isenmila AE (1983) Leaching losses of nutrients in oil palm plantations determined by tension lysimeters. *Plant and Soil* 73: 365-376
 15. Pieri C (1979) Etude de la composition de la solution d'un sol sableux cultivé du Sénégal à l'aide de capteurs en céramique poreuse. *Agron Trop* 34: 9-22
 16. Pieri C (1989) Fertilité des terres de savanes. Bilan de trente ans de recherche et de développement agricoles au sud du Sahara. Ministère de la coopération-IRAT/CIRAD, Paris, France 444 pp.
 17. Pleyrier JL and Juo ASR (1981) Leaching of fertilizer ions in a ultisol from the high rainfall tropics: leaching through undisturbed soil columns. *Soil Sci Soc Am J* 45: 754-760
 18. Poss R (1991) Transferts de l'eau et des éléments minéraux dans les terres de Barre du Togo. Conséquences agronomiques. Th Univ Paris 6, Paris, France 335 pp.
 19. Poss R and Saragoni H (1987) Quelques problèmes posés par l'estimation du bilan hydrique en plein champ. Milieux poreux et transferts hydriques 22: 32-46
 20. Poss R, Fardeau JC, Saragoni H and Quantin P (1991) Potassium release and fixation in Ferralsols (Oxisols) from Southern Togo. *J Soil Sci* 42: 649-660
 21. Powlson DS (1988) Measuring and minimising losses of fertilizer nitrogen in arable agriculture. In: Jenkinson DS and Smith KA (eds) *Nitrogen efficiency in agricultural soils*. pp 231-245. Elsevier, Amsterdam, the Netherlands
 22. Roose E (1981) Dynamique actuelle de sols ferrallitiques et ferrugineux tropicaux d'Afrique occidentale. *Travaux Documents n° 150*. 569 p. ORSTOM, Paris, France
 23. Saragoni H and Poss R (1992) Production de matière végétale et prélèvements minéraux du maïs au sud-Togo. *Agron Trop* 46: 185-201
 24. Saragoni H, Poss R and Oliver R (1990) Dynamique et lixiviation des éléments minéraux dans les terres de Barre du sud-Togo. *Agron Trop* 45: 259-273
 25. Saragoni H, Poss R, Marquette J and Latrille E (1992) Fertilisation et succession des cultures vivrières au sud-Togo. Synthèse d'une expérimentation de longue durée (1976-1989) sur terres de Barre. *Agron Trop* 46: 107-120
 26. Udo EJ (1978) Thermodynamics of potassium-calcium and magnesium-calcium exchange reactions on a kaolinitic soil clay. *Soil Sci Soc Am J* 42: 556-560
 27. Van Der Kruijs ACB, Wong MTF, Juo ASR and Wild A (1988) Recovery of ¹⁵N-labelled fertilizer in crops, drainage water and soil using monolith lysimeters in south-east Nigeria. *J Soil Sci* 39: 483-492
 28. Vlek PLG (1990) The role of fertilizers in sustaining agriculture in sub-Saharan Africa. *Fert Res* 26: 327-339
 29. Wong MTF, Wild A and Mkwunye AU (1991) Overcoming soil nutrient constraints to crop production in West Africa: Importance of fertilizers and priorities in soil fertility research. *Fert Res* 29: 45-54