

## Leaching of plant nutrients from an acid forest soil after nitrogen fertilizer application

B. O. MOCHOGE\* and F. BEESE\*\*

\* *Department of Soil Science, University of Nairobi, Kenya* and \*\* *Inst. of Soil Science and Forest Nutrition, University of Goettingen, F.R.G.*

Received 14 January 1985. Revised May 1985

**Key words** Acid soil Breakthrough curve Column study Fertilizer Leaching Plant nutrient

**Summary** In a laboratory experiment, the effect of nitrogen fertilizers on the leaching patterns and input-output budgets of plant nutrients in an acid soil (dystric cambisols) was studied. An amount of N corresponding to 80 kg/ha was applied to the top surface of undisturbed soil columns of 30 cm layers with a diameter of 14.4 cm as  $\text{Ca}(\text{NO}_3)_2$  or  $(\text{NH}_4)_2\text{SO}_4$ . After establishing steady state flow condition, a flux of 0.5 cm solution/column was applied daily for 60 days. The leachates were collected and analysed every four days. It was found that not only the amount and quality of the applied cation influences the leaching pattern of plant nutrients in an acid soil but also the accompanying anion. To interpret leaching data properly, it was necessary to know the magnitude of N transformed in the different processes. Although the two applied salts influenced plant nutrient transport in different ways, total outputs of cations and anions were somewhat similar though outputs after  $(\text{NH}_4)_2\text{SO}_4$  were slightly higher than after  $\text{Ca}(\text{NO}_3)_2$  addition.

### Introduction

Studies on the leaching of plant nutrients from soils after nitrogen fertilizer application are scarce. Previous studies on nitrogen behaviour in soils<sup>1,4,19</sup>, have been limited to N transport and transformations without considering the effect it has on the other elements in the soil. An application of a salt to the soil followed by a percolating solution may lead to a different chemical behaviour in soil and may even change the chemistry of the soil solution<sup>4,9,13,29</sup>. Studies to show the effects of an acid rain on the leaching of plant nutrients especially in acid soils have recently received much attention<sup>1,4,23,27,29</sup>. One potential long-term effect of continuous leaching of nutrients from the soil is a decrease in soil fertility. This may lead even to a reduction of plant productivity especially in soils of low buffering capacity.

Applying  $\text{NO}_3^-$  to an acid soil, the accompanying cation can induce ion exchange which may result to high  $\text{H}^+$  ion-concentrations in soil solution. Uptake of  $\text{NO}_3^-$  by plants and micro-organisms, and its reduction to gaseous compounds will consume one proton per  $\text{NO}_3^-$  removed from the soil solution, causing soil alkalinization. An addition of  $\text{NH}_4^+$  into a soil may be involved in oxidation to nitrates, in cation exchange and in assimilation by micro-organisms. During its oxidation,

two moles of  $H^+$  ions are produced per mole of  $NH_4^+$  whereas its uptake creates one of  $H^+$ . The degree of  $NH_4^+$  oxidation and its uptake will therefore affect the  $H^+$  dynamics and other related soil processes<sup>26</sup>.

This study was carried out to observe and to quantify some of the effects of nitrogen fertilizers on the leaching patterns and input-output budgets of plant nutrients in an acid soil.

### Materials and methods

Undisturbed soil columns from an upper 30 cm layer with a diameter of 14.4 cm of an acid soil (dystric cambisols) were used for this study. The soil was sampled from a forested area of mountainous region of Solling district in W. Germany, occupied by 120 year old beech trees. The soil is derived from loess (0–60 cm) and lies over solifluction masses which consist of weathered triassic sandstone. The rooting zone of this soil is strongly acidic. The soil has low bulk density, well aggregated and has a high physical stability. Table 1 shows some of the physical and chemical properties of the soil.

In order to collect the leachates completely, the experiment was set in a column study<sup>18</sup>. Unsaturated steady state flow of soil solution in the columns was established. This condition was maintained for 60 days by a flux of 0.5 cm solution/column/day. This solution was prepared and had a concentration composition of ions similar to a concentration from a saturated extract of a 30 cm layer of this acid soil (Table 2). Each column was treated with 130.3 mg N (an amount corresponding to 80 kg/ha) as  $Ca(NO_3)_2$  or  $(NH_4)_2SO_4$  in dissolved form. This amount was applied in one lot and to the top surface of the columns. The study took place at 23°C.

Under a tension of 100 ml  $H_2O$  column, the effluents were collected from the bottom of every column once every four days and analysed for pH, main cations and anions. The analysis was done according to Ulrich<sup>25</sup>. Na, K, Ca, Mg and Mn were determined by atomic absorption, Fe by Calorimetric as phenanthroline complex<sup>5</sup>, Al by calorimetric with aluminon<sup>11</sup>, S by potentiometric titration with EDTA after  $BaSO_4$  precipitation<sup>8</sup>, Cl by titrating against  $AgNO_3$ ,  $NH_4$ -N and  $NO_3$ -N by distillation-titration method according to Fleige<sup>6</sup>, and C according to Wösthoff<sup>30</sup>.

The concentrations of cations and anions analysed from 5 replicates for the 60 days (2.3 pore volumes), plotted against the corresponding volumes of effluents collected led to the construction of breakthrough curves (BTCs). A breakthrough curve is a standard form of presenting concentration changes of solutes in the effluent with time from a soil column. Such curves can give information about the behaviour of solutes in porous media because their shapes are influenced by physical, chemical and bio-chemical reactions during their passage in soil.

### Results

Fig. 1 (a–k) shows the BTCs after  $Ca(NO_3)_2$  and  $(NH_4)_2SO_4$  application. The curves obtained after  $Ca(NO_3)_2$ , particularly those for  $K^+$ ,  $Ca^{2+}$ ,  $Al^{3+}$ ,  $Mn^{3+}$  and  $NO_3^-$  show distinct peaks. The concentrations of these ions in the soil solution at the beginning were low but as leaching continued, their concentrations steadily increased and reached the maximum after 28 days. Except for  $K^+$ , the peaks of other ions almost coincided with the exchange of the first pore volume, *i.e.* after 26 days.

After  $(NH_4)_2SO_4$  application, a different behaviour was expected

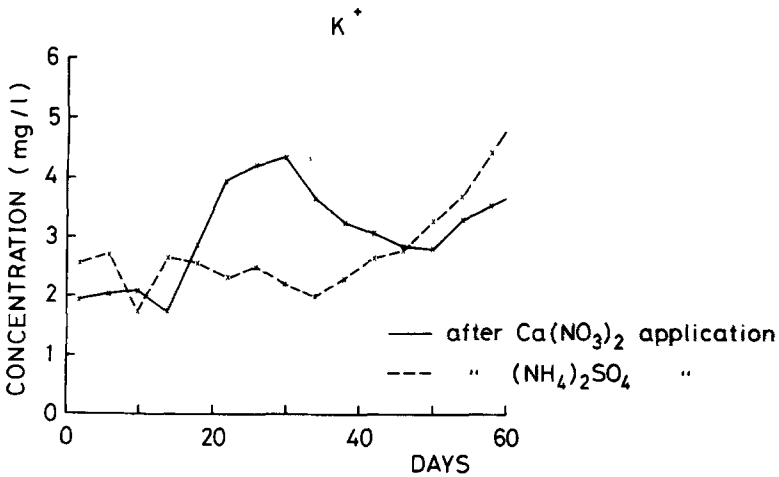
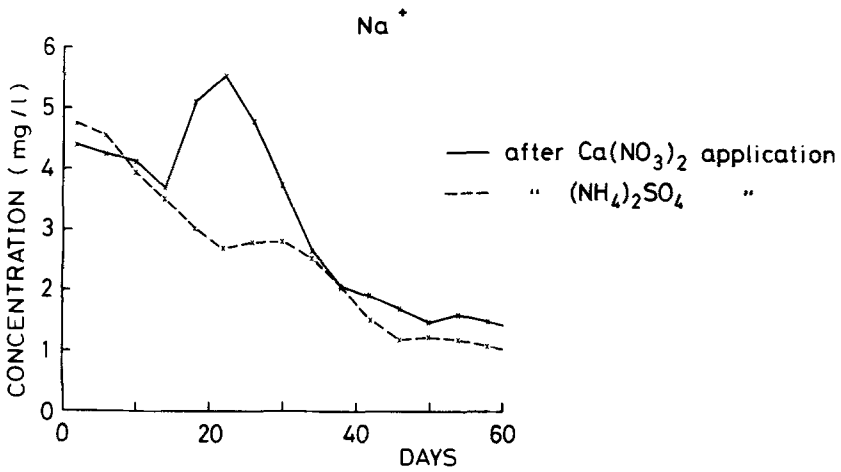
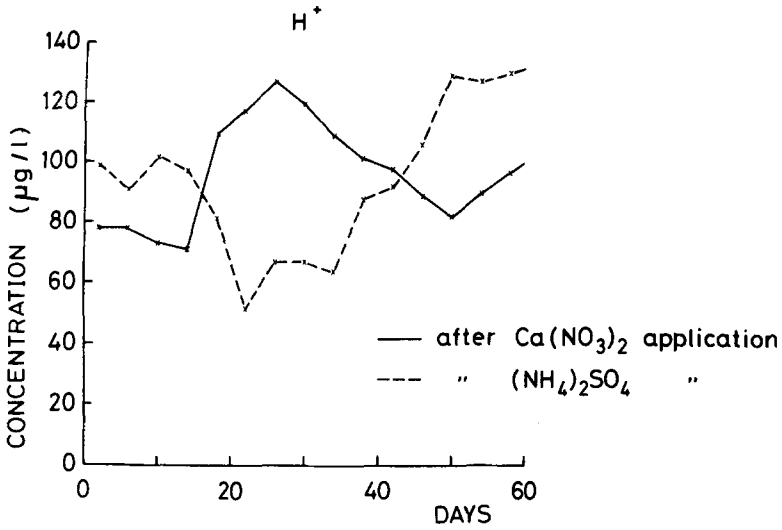
Table 1. Mean values of chemical and physical data of the soil studied (n = 5)

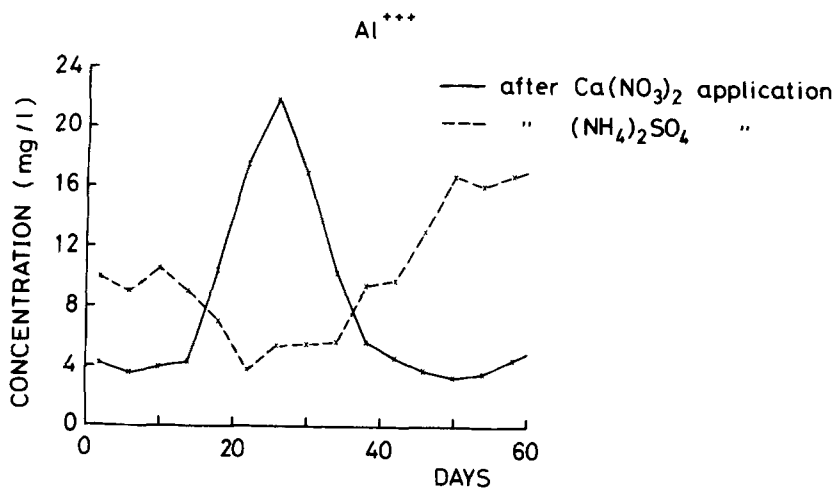
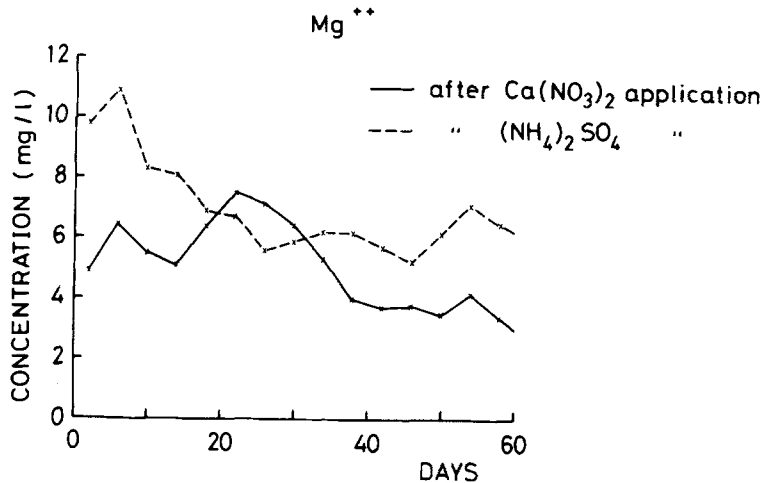
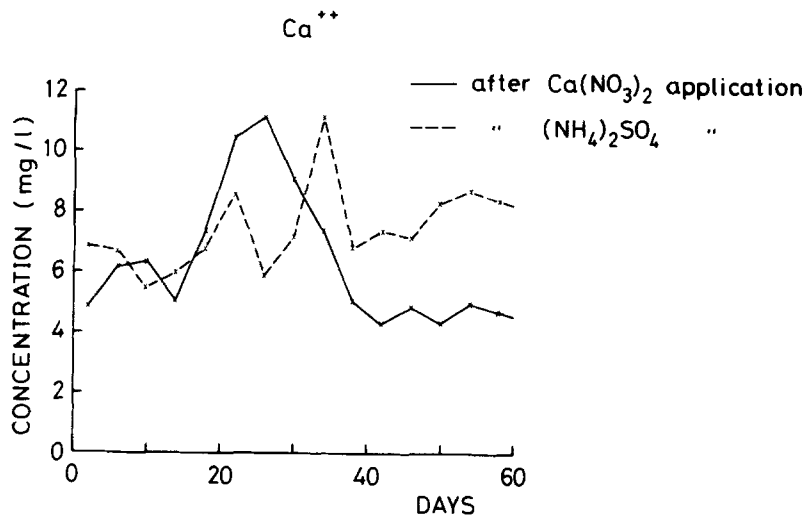
Depth (cm)	pH	H	Na	K	Mg	Ca	Al	Fe	Mn	C.E.C.	C	N	C/N	BD
	CaCl <sub>2</sub>	(meq. kg <sup>-1</sup> )	(g/cm <sup>3</sup> )											
0-3	3.07 (0.06)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	45.1 (5.25)	1.63 (0.05)	27.67 (3.22)	0.18 (0.08)
6-6	2.89 (0.07)	55.2 (20.8)	1.40 (0.29)	6.37 (3.19)	0.40 (0.22)	15.2 (8.40)	80.7 (8.03)	5.45 (2.05)	1.65 (0.53)	166.4 (41.9)	11.1 (5.22)	0.69 (0.35)	16.09 (3.27)	0.73 (0.31)
6-9	3.03 (0.09)	29.7 (10.2)	1.00 (0.13)	2.45 (0.51)	0.14 (0.05)	4.0 (1.13)	74.1 (8.91)	3.23 (1.31)	1.11 (0.44)	115.7 (13.6)	4.5 (1.35)	0.26 (0.08)	17.31 (3.59)	1.13 (0.15)
9-12	3.18 (0.08)	17.9 (6.3)	0.9 (*0.15)	2.04 (0.22)	0.08 (0.02)	2.42 (0.43)	76.7 (11.68)	1.78 (0.91)	2.34 (0.69)	104.2 (9.1)	3.1 (0.63)	0.17 (0.03)	18.23 (2.68)	1.29 (0.07)
12-15	3.34 (0.69)	10.3 (3.3)	0.9 (0.11)	1.70 (0.12)	0.05 (0.005)	1.55 (0.20)	77.4 (9.13)	0.79 (0.46)	2.74 (0.73)	95.6 (6.5)	2.31 (0.24)	0.14 (0.01)	16.5 (1.51)	1.33 (0.08)
15-20	3.49 (0.09)	5.9 (1.5)	1.00 (0.9)	1.56 (0.18)	0.05 (0.01)	1.44 (0.05)	80.6 (8.00)	0.36 (0.11)	2.71 (0.73)	93.6 (6.7)	2.25 (0.38)	0.13 (0.01)	17.31 (2.16)	1.23 (0.01)
20-25	3.62 (0.1)	3.9 (1.0)	0.9 (0.12)	1.34 (0.21)	0.04 (0.004)	1.15 (0.31)	76.0 (0.25)	0.20 (0.05)	1.99 (0.4)	85.6 (2.3)	1.73 (0.39)	0.12 (0.007)	14.42 (3.6)	1.18 (0.12)
25-30	3.71 (0.11)	3.0 (1.0)	1.0 (0.07)	1.42 (0.42)	0.03 (0.006)	1.52 (0.35)	72.3 (4.08)	0.14 (0.05)	1.59 (0.44)	81.0 (5.3)	1.89 (0.50)	0.11 (0.008)	17.18 (3.76)	1.14 (0.10)

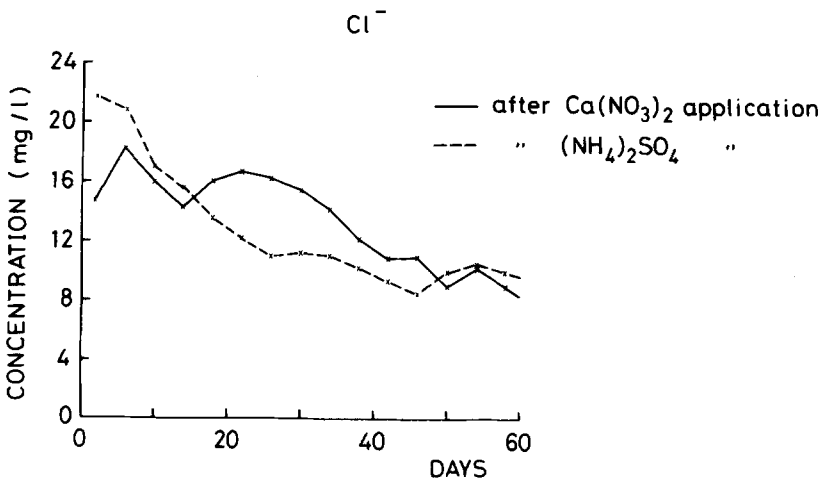
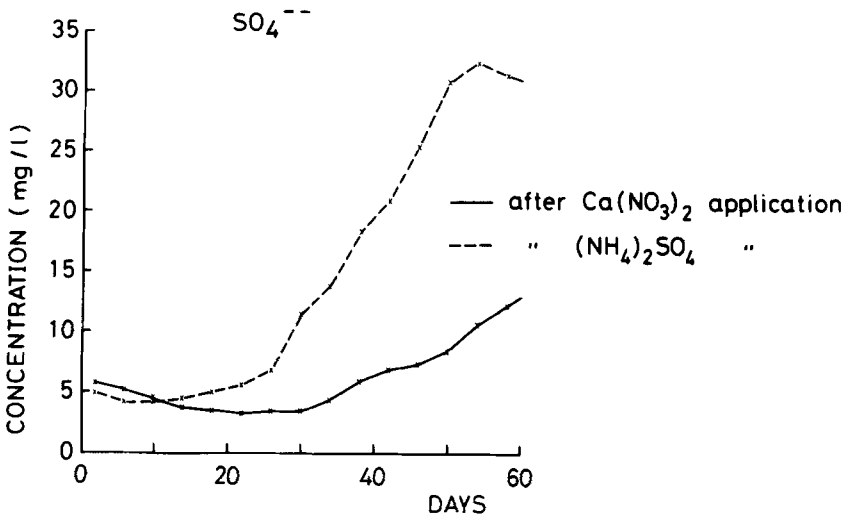
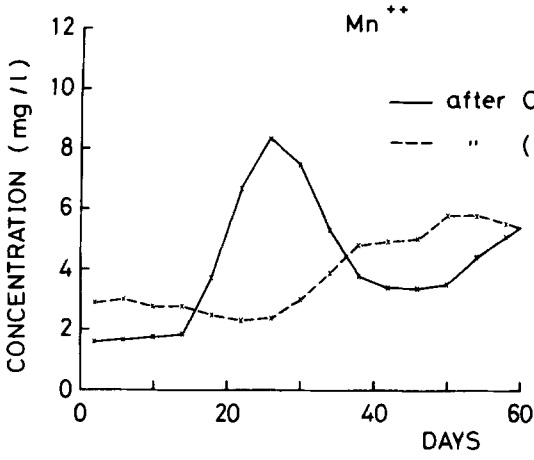
( ) = standard deviations

n.d. = not determined

+ BD = Bulk density







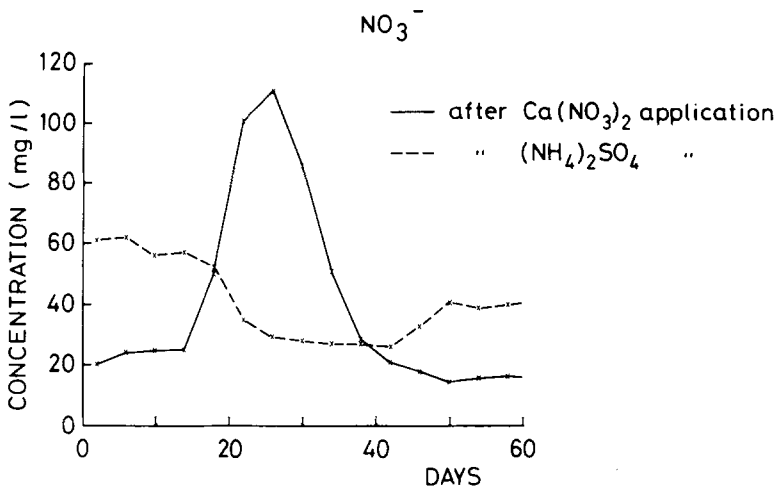


Fig. 1. 1–k. Breakthrough curves (BTCs) of cations and anions following  $\text{Ca}(\text{NO}_3)_2$  and  $(\text{NH}_4)_2\text{SO}_4$  application. (mean values,  $n = 5$ ). pages 20–23

- a)  $\text{H}^+$                       b)  $\text{Na}^+$ ;                      c)  $\text{K}^+$                       d)  $\text{Ca}^{2+}$ ;  
 e)  $\text{Mg}^{2+}$                     f)  $\text{Al}^{3+}$ ;                    g)  $\text{Mn}^{2+}$ ;                    h)  $\text{SO}_4^{2-}$ ;  
 i)  $\text{Cl}^-$ ;                      k)  $\text{NO}_3^- \text{N}^-$ .

Table 2. The composition of the input solution (mg/l)

pH	Na	K	Ca	Mg	Al	Fe	Mn	$\text{SO}_4\text{-S}$	Cl
3.65	0.50	0.38	1.40	0.22	0.33	0.26	0.09	3.88	4.89

due to the possible transformation of  $\text{NH}_4^+$  in soil. This indeed was the case as the curves show. In general, there were no clear peaks except for  $\text{Ca}^{2+}$ . Instead there was distinct retardation of ions such as  $\text{H}^+$ ,  $\text{Al}^{3+}$ ,  $\text{Mn}^{2+}$  and  $\text{SO}_4^{2-}$  in the soil solution. The low concentrations were especially pronounced immediately before and after the first pore volume. In both treatments, the concentrations of  $\text{Mg}^{2+}$ , Na and  $\text{Cl}^-$  tended to decrease with time while that of  $\text{K}^+$  tended to increase.

The input-output balances of the analysed cations and anions are shown in Table 3. After  $\text{Ca}^{2+}$  application, the leaching of cations was highest with  $\text{Al}^{3+}$  followed by  $\text{Mg}^{2+}$ ,  $\text{Mn}^{2+}$ ,  $\text{Na}^+$ ,  $\text{K}^+$   $\text{NH}_4^+$  in that decreasing order.  $\text{Ca}^{2+}$ ,  $\text{Fe}^{2+}$  and  $\text{H}^+$  were retained in the soil. Consequently, the output of both cations and anions was slightly less by about 7 and 2% for cations and anions, respectively, than the input. After  $\text{NH}_4^+$  application, a similar behaviour was found with the following leaching order of decreasing:  $\text{Al}^{3+} > \text{Mg}^{2+} > \text{Ca}^{2+} > \text{Na}^+ > \text{K}^+$ . In this case  $\text{Ca}^{2+}$  was released while  $\text{NH}_4^+$  and  $\text{Fe}^{3+}$  were retained in the soil. The input-output balance shows that about 39% of the anions,

Table 3. Input-output balances of cations and anions (Keq. ha<sup>-1</sup>; mean values (n = 5))

	H	Na	K	NH <sub>4</sub> -N	Ca	Mg	Al	Fe	Mn	SO <sub>4</sub> -S	Cl	NO <sub>3</sub> -N	+	-
<i>Ca(NO<sub>3</sub>)<sub>2</sub> application</i>														
Input	0.67	0.1	0.03	-	5.55	0.06	0.11	0.4	0.01	0.66	0.41	5.72	6.93	6.79
Output	0.31	0.43	0.23	0.19	0.97	1.29	2.61	0.02	0.4	1.11	1.12	4.43	6.45	6.66
	(0.11)	(0.05)	(0.1)	-	(0.32)	(0.19)	(1.2)	(0.009)	(0.14)	(0.31)	(0.12)	(1.40)		
Input														
-Output	+0.36	-0.33	-0.20	-0.19	+4.58	-1.23	-2.50	+0.38	-0.39	-0.45	-0.71	+1.29	+0.48	+0.13
<i>(NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> application</i>														
Input	0.67	0.1	0.03	5.72	0.21	0.06	0.11	0.4	0.01	12.08	0.41	-	7.31	12.49
Output	0.27	0.32	0.19	0.22	1.05	1.64	3.3	0.02	0.34	2.69	1.02	3.93	7.35	7.64
	(0.12)	(0.04)	(0.13)	-	(0.25)	(0.29)	(1.46)	(0.005)	(0.08)	(0.67)	(0.18)	-		
Input														
-Output	+0.40	-0.22	-0.16	+5.50	-0.84	-1.58	-3.19	+0.38	-0.33	+9.39	-0.61	-3.93	-0.04	+4.85

( ) = Standard deviations, + = Sink in soil, - = Source from soil, + = Sum of cations, - = Sum of anions.



mainly sulphates were retained in soil whereas for cations it was almost zero. In the side of anions, the soil released  $\text{Cl}^-$  and  $\text{SO}_4^{2-}$  and retained  $\text{NO}_3^-$  after  $\text{NO}_3^-$  application whereas  $\text{NO}_3^-$  and  $\text{Cl}^-$  were released and  $\text{SO}_4^{2-}$  retained after  $\text{SO}_4^{2-}$  application. The phosphates were negligible in the leachates.

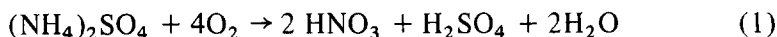
## Discussion and conclusions

During percolation, cations accompanying anions undergo cation exchange, precipitation and dissolution reactions. This applies also to some anions except for  $\text{Cl}^-$  and  $\text{NO}_3^-$  which are seldom involved in chemical reactions and rarely interact with the solid part of the soil.

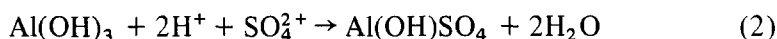
The formation of peaks by  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Al}^{3+}$  and  $\text{Mn}^{2+}$  after  $\text{Ca}^{2+}$  application demonstrates the quick participation and ability of  $\text{Ca}^{2+}$  in exchanging other cations from the soil complex. While the leachability of  $\text{Ca}^{2+}$ ,  $\text{Al}^{3+}$  and  $\text{Mn}^{2+}$  was faster, thus their maximum concentrations coincided with the first pore volume *i.e.* when the water in the soil was replaced one time, that of  $\text{K}^+$  showed some resistance. This behaviour of  $\text{K}^+$  to leaching has also been observed by others<sup>4,9,22</sup>. Hartikainen<sup>9</sup> from a leaching experiment with an acid soil, reported that  $\text{K}^+$  showed highest resistance to leaching while  $\text{Na}^+$  showed the least. Nevertheless, in acid soils where exchange sites depend on pH,  $\text{K}^+$  leachability may be enhanced<sup>15,28</sup>. This shows therefore that leaching of nutrients from soils does not depend only on the availability of the nutrient but also on other factors such as the nature of the element itself, environmental variables and the history of the soil. For anions,  $\text{NO}_3^-$  exhibited the expected pattern of transport *i.e.* with minimum interaction in the soil. Its maximum concentration in the output almost coincided with the replacement of one pore water volume, *i.e.* after 26 days. This is comparable to the maximum outputs of  $\text{Ca}^{2+}$ ,  $\text{Al}^{3+}$  and  $\text{Mn}^{2+}$ . This could therefore suggest that cations do follow the same pattern as the sum of the anions. The BTCs shown in Fig. 2 could therefore support the assumption of electroneutrality because peaks of  $\text{NO}_3^-$  and those of  $\text{Ca}^{2+}$ ,  $\text{Al}^{3+}$  and  $\text{Mn}^{2+}$  are exhibited after 28 days of leaching. With respect to other anions ( $\text{Cl}^-$  and  $\text{SO}_4^{2-}$ ), the situation is different. The chloride showed a slight increase in concentration when  $\text{NO}_3^-$  had passed its maximum, whereas  $\text{SO}_4^{2-}$  concentration was slightly depressed.

The absence of distinct peaks after  $(\text{NH}_4)_2\text{SO}_4$  application demonstrates the slow participation of  $\text{NH}_4^+$  in exchanging other cations from the soil complex. This is because  $\text{NH}_4^+$  is submitted to various reactions in soil such as oxidation, fixation in clay mineral lattices and immobilization by microbes. In this case however, not only  $\text{NH}_4^+$

is affected but also  $\text{SO}_4^{2+}$ . The change involves two different processes.  $\text{NH}_4^+$  is oxidized to nitrates. During this reaction, two strong acids are formed, *i.e.*



The sulphuric acid that is formed can react with aluminium hydroxide in soil solution to form insoluble  $\text{Al}(\text{OH})\text{SO}_4$ .



The possibility of  $\text{Al}(\text{OH})\text{SO}_4$  formation in acid soils was reported by van Breemen<sup>3</sup>. He observed that there were changes of aluminium ion activity in solutions of different pH values. His findings have been confirmed by others<sup>2,24</sup>. The formation of this compound is pronounced when there is abundant  $\text{SO}_4^{2+}$  ions. The reverse situation occurs when the  $\text{SO}_4^{2+}$  concentration decreases in soil solution or when the compound goes into solution through hydrolysis. The formation and dissolution of the compound therefore govern the behavioural pattern of  $\text{H}^+$ ,  $\text{Al}^{3+}$  and  $\text{SO}_4^{2+}$  movement in soil. This therefore supports the described retention and release mechanism of sulphates in acid soils<sup>20</sup>. Prenzel<sup>20</sup> came up with a mechanism which demonstrates the temporary  $\text{SO}_4^{2+}$  retention in acid soil.

Besides  $\text{Al}(\text{OH})\text{SO}_4$  formation,  $\text{SO}_4^{2+}$  in the soil can be adsorbed. This can be either through the neutralization of positive charges, usually referred as non-specific<sup>21</sup> or through the ligand exchange reaction (specific type) whereby the adsorbed ion must be able to donate or accept protons depending on the soil reaction<sup>7,10</sup>. Other findings<sup>12,16</sup> show that  $\text{SO}_4^{2+}$  adsorption is higher at lower soil layers than at the top (0–10 cm), a layer rich in humus.

Due to the retardation of the anion applied, the movement of the accompanying cations are also retarded to fulfill the electroneutrality. As a consequence, the BTCs of cations and anions differ considerably after the application of the two salts.

The salt balances (on charge basis) exhibit differences which can be explained by the internal transformations of matter in the soil. The input of the salts was dominated by the fertilizers which was in one case  $\text{Ca}^{2+}$  and  $\text{NO}_3^-$  and in the other case  $\text{NH}_4^+$  and  $\text{SO}_4^{2+}$  with percentages of total salt input ranging between 81 and 96.

After 60 days, the outputs following the  $\text{Ca}(\text{NO}_3)_2$  application was slightly lower than the input (0.43–0.13  $\text{Keq. ha}^{-1}$ ). This on a first view indicates that the soil behaved like an ion exchanger modifying the concentrations of the ions in the output according to their fractions in and at the binding strength to the soil. However from

Table 4. Internal nitrogen transformations, proton production and – consumption (kmol<sub>c</sub>/ha)

	Ca(NO <sub>3</sub> ) <sub>2</sub> application		(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> application	
	N	H <sup>+</sup>	N	H <sup>+</sup>
Input	5.72		5.72	–
Fixation	–	–	1.5	–
Incorporation	0.86	– 0.86	2.0	+ 2.0
Denitrification	2.14	– 2.14	1.79	+ 1.79
Percolation	2.71	–	0.36	1.72
Mineralization, nitrification and percolation	1.70	+ 1.70	3.5	+ 3.5

the findings<sup>17</sup> (see Table 4), we know that other processes occurred in the soil during the study. Only 2.7 Kmol<sub>c</sub>/ha of the applied N was leached through the soil. 1.70 Kmol<sub>c</sub>/ha of the nitrate came from the soil organic matter after mineralization and nitrification, forming an equivalent amount of protons. In the same time, 0.86 and 2.14 Kmol<sub>c</sub>/ha H<sup>+</sup> were consumed by organic regime and gaseous N respectively. This therefore leads to a net proton consumption or OH<sup>–</sup> production of 1.30 Kmol<sub>c</sub>/ha. In the output, these OH<sup>–</sup> ions are completely displaced by SO<sub>4</sub><sup>2+</sup> and Cl<sup>–</sup> ions.

After application of (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>, the situation was however different. Table 4 shows that most of the applied NH<sub>4</sub>-N was transformed to other compounds. The processes involved combined with proton formation, induce cation exchange and other chemical reactions. Due to the formation of HNO<sub>3</sub>, there was an excess H<sup>+</sup> production of 0.36 Kmol<sub>c</sub>/ha. This, however, was only a small fraction of the possible maximum proton production of 5.72 Kmol<sub>c</sub>/ha, which could have been produced had all the NH<sub>4</sub>-N applied been transformed to NO<sub>3</sub>-N. Besides the protons which came from the fertilizer, there was a production of 3.5 Kmol<sub>c</sub>/ha of HNO<sub>3</sub> from organic matter through mineralization and nitrification. This led to a total internal production of protons of 3.86 Kmol<sub>c</sub>/ha which in turn led to an increase of cation outputs of only 0.04 Kmol<sub>c</sub>/ha which means 3.82 Kmol of the total protons produced was consumed internally.

From this study, however, one is not able to give an accurate answer as to what type of processes took place in soil. Nevertheless, the results obtained showed that the processes and reactions induced by the fertilizer application are much more complex as the charge balances indicate.

In conclusion, the results of this experiment show that

1. not only the amount and quality of the applied cation influences

the leaching pattern of actions in an acid soil but also the accompanying anion.

2. nitrogen compounds both from fertilizer and soil are submitted to different processes in soil. Without the knowledge of the quantities of N transformed in different processes, it is practically impossible to interpret leaching data properly.

3. the approach used, *i.e.* the measurement of change through breakthrough curves and the formation of a charge balance combined with tracer studies, gives a better insight of the multiple processes involved in N-fertilizer transformations and transport in soils.

#### References

- 1 Abrahamen G, Bjor K, Horntretd R and Treite B 1976 Effects of acid precipitation on coniferous forest. *In* Impact of Acid Precipitation on Forest and Fresh Water Ecosystems in Norway. Ed. F H Braekke 36–63 SNSF Project. Aas-NLH Norway.
- 2 Adams F and Rawajfih Z 1977 Basaluminite and alunite. A possible cause of sulphate retention by acid soils. *Soil Sci. Soc. Am. Proc.* 41, 686–692.
- 3 van Breemen N 1973a Dissolved aluminium in acid sulphate soils and acid mine waters. *Soil Sci. Soc. Am. Proc.* 37, 694–697.
- 4 Cronan C S 1980 Controls on leaching from coniferous forest floor microcosms. *Plant and Soil* 59, 301–322.
- 5 Eichelsdorfer D and Rosopuco A 1957 Methoden der Eisenbestimmung in Trink – und Betriebswasser. *Jahrbuch 'com Wasser'* 26, 82–96.
- 6 Fleige H B, Meyer B and Scholz H 1971 Franktionierung des Boden-Stickstoffs fuer N-Haushalts-Bilanzen. *Goettinger Bodenkundl. Ber.* 18, 1–37.
- 7 Gebhardt H and Coleman W Z 1974 Anion adsorption by allophanic tropical soils. II. Sulphate adsorption. *Soil Sci. Soc. Am. Proc.* 38, 728–734.
- 8 Grether C 1965 Die Bestimmung von Sulfat mit Potentiometrischer Titration. *Application Bulletin Nr. A 38 d, Methrom Herisau, Schweiz.*
- 9 Hartikainen H 1978 Leaching of plant nutrients from cultivated soils. I. Leaching of cations. *Journ. of the Scientific Agr. Soc. of Finland* vol. 50, 263–269.
- 10 Hingston F J, Atkinson R J, Posner A M and Quirk J P 1967 Specific adsorption of anions. *Nature* 215, 1459–1461.
- 11 Hsu P H 1963 Effect of initial pH, phosphate and silicate on the determination of aluminium hydroxides. *Mineral. Mag.* 33, 749–768.
- 12 Khanna P K and Beese F 1978 The behaviour of sulphate on salt input in pozolic brown earth. *Soil Sci.* 125, 16–22.
- 13 Khanna P K and Ulrich B 1973 Ion exchange equilibria in acid soil. *Goettinger Bodenkundl. Ber.* 29, 211–230.
- 14 Kowalenko C G 1980 Transport and transformations of fertilizer nitrogen in a sandy field plot using tracer techniques. *Soil Sci.* 129, 218–221.
- 15 Krause H H 1965 Effect of pH on leaching losses of potassium applied to forest nursery soils. *Soil Sci. Soc. Am. Proc.* 29, 613–615.
- 16 Meiwes K J, Khanna P K and Ulrich B 1980 Retention of sulphate by an acid brown earth and its relationship with the atmospheric input of sulphur to forest vegetation. *Z. Pflanzenernaehrung Bodenk.* 143, 402–411.
- 17 Mochoge B O 1981 The behaviour of nitrogen fertilisers in neutral and acid loess soils. *Goettinger Bodenkundl. Ber.* 69, 1–173.
- 18 Mochoge B O and Beese F 1983 The behaviour of nitrogen fertilizers in neutral and acid loess soils. I. Transport and transformations of nitrogen. *Z. Pflanzenernaehrung Bodenk.* 146, 89–100.

- 19 Overrein L N 1969 Lysimeter studies on tracer nitrogen in forest soil. 2. Comparative losses of nitrogen through leaching and volatilization after the addition of urea, ammonium – and nitrate  $N^{15}$ . *Soil Sci.* 107, 149–159.
- 20 Prenzel J 1983 A mechanism for storage and retrieval of sulphate in acid soils. Eds. B Ulrich and J Pankrath. *Effects of accumulation of air pollutants in forest ecosystems* 78, 157–170. D. Reidel Publ. Co.
- 21 Russel E W 1973 *Soil Conditions and Plant Growth* 10th edition Longman, 327–387 pp.
- 22 Seibt G, Knigge W, Reemtsma J B and Ulrich B 1968 *Allgem. Forst-und Jagdzng.* 139, 25–37, 57–72.
- 23 Swarup A, Beese F and Ulrich B 1983 The effect of potassium chloride on ion dynamics and – budget in a slightly acidic forest soil. *Z. Pflanzenernaehrung Bodenkd.* 146, 772–782.
- 24 Ulrich R 1978 *Tonabbau und Aluminium lagerung in Sauren Waldboden.* Diplomarbeit. Inst. fuer Bodenkunde und Waldernaehrung, Goettingen.
- 25 Ulrich B 1966 Kationenaustausch-Gleichgewichte in Boden. *Z. Pflanzenernaehrung Bodenkd.* 113, 141–159.
- 26 Ulrich B 1980 Production and consumption of hydrogen ions in the ecosphere. *In Effects of Acid Precipitation on Terrestrial Ecosystems* pp 255–282. Eds. T C Hutchinson and M Haras. Plenum Press New York, London.
- 27 Ulrich B, Mayer R and Khanna P K 1980 Chemical changes due to acid precipitation in a loess-derived soil in Central Europe. *Soil Sci.* 130, 193–199.
- 28 Wiklander L 1960 Influence of liming on adsorption and desorption of cations in soil. *Int. Congr. Soil Science, Trans.* 7th (Madison, Wisc.) 283–291.
- 29 Wiklander L 1975 The role of neutral salts in the ion exchange between acid precipitation and soil. *Geoderma* 14, 93–105.
- 30 Wösthoff O H G, *Apparatebau* 1959 *Gasanalysen-Messanlage.*