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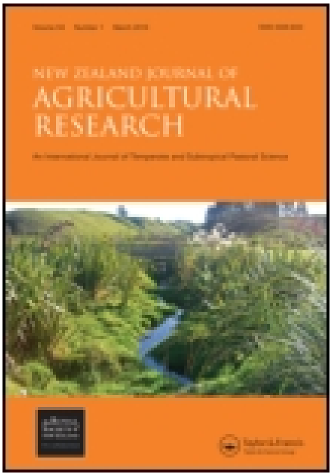

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Leaching losses of major nutrients from a mole-drained soil under pasture

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Leaching losses of major nutrients from a mole-drained soil under pasture

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Abstract The concentrations of chloride (Cl^-), sulphate (SO_4^{2-}), nitrate (NO_3^-), potassium (K^+), magnesium (Mg^{2+}), calcium (Ca^{2+}), and sodium (Na^+) in mole-tile drainage and the quantity of drainage from two 0.125 ha paddocks were measured over 2 years. The soil, a Typic Fragiaqualf, was under pasture periodically grazed by sheep. In the autumn of both years, potassium chloride (KCl) was applied to both paddocks and sulphur (S) as either superphosphate or elemental S, supplying equal amounts of S, was also applied. Cl^- was the dominant anion in the drainage, with losses totalling c. 100 kg/ha per yr. The leaching loss of SO_4^{2-} was c. 13 kg S/ha per yr from the paddock fertilised with superphosphate compared with 3 kg/ha per yr from the elemental S-fertilised paddock. Less than 20 kg N/ha per yr was leached which is less than other workers have found under cattle-grazed pasture. Losses of K^+ were less than 11 kg/ha per yr but losses of Na^+ of up to 65 kg/ha per yr were found. Losses of Ca^{2+} and Mg^{2+} were of the order of 40 and 10 kg/ha per yr, respectively. There was a close agreement between the moles of charge of inorganic anions and cations in the drainage water.

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Keywords calcium; leaching; magnesium; mole-drains; nitrate; potassium; sheep-grazed pasture; sodium; sulphate; nutrients; soil

INTRODUCTION

The study of leaching is becoming increasingly important because the movement of nutrients out of the root-zone represents an immediate loss to the plant, and an economic loss to the farmer. When these solutes reach surface or ground water they may also create environmental and health problems.

Many studies of nitrate (NO_3^-) leaching have been made in New Zealand. Losses from grazed pasture have been shown to be caused mainly by grazing animals, particularly cattle (Sharpley & Syers 1979; Ryden et al. 1984; Steele et al. 1984). Intensifying agriculture increases pasture production and livestock numbers, increasing leaching losses of nitrogen (N) as a result of greater urine deposition. As McLaren & Cameron (1990) note, there have been relatively few field studies of SO_4^{2-} leaching in New Zealand. Both Gregg & Goh (1978) and Smith et al. (1983) showed that significant leaching of SO_4^{2-} can occur when superphosphate is applied just before winter.

Most leaching studies tend to focus on one or two anions in isolation, without considering the associated cations. In a laboratory study, Hogg & Cooper (1964) reported that the addition of superphosphate to potassium chloride (KCl) markedly increased the amount of potassium (K^+) leached. Using suction samplers, Steele et al. (1984) studied the leaching of NO_3^- and other ions from pasture grazed intensively by cattle in North Auckland, and found increased losses of NO_3^- occurred as a result of N application, and that these were accompanied by increased losses of calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and potassium (K^+). Hogg (1981) reported similar findings from a laboratory lysimeter study. However, both lysimeters and suction samplers have limitations for measuring leaching losses (Wild & Cameron 1980; Litaor 1988), because of the variations in soil solution concentrations and water flow through the soil which can occur over relatively short distances. This can be seen from the relatively large standard deviation in the lysimeter leaching results within a site and between different sites presented by Close & Woods (1986) on irrigated pasture soil in northern Canterbury, New Zealand. When drains intercept most of the percolating water, they integrate the flow from a large area, providing a more accurate estimate of leaching losses. A comprehensive study of the major cations and anions leached from a mole-tile drained soil has not been carried out. We present the results of such a study for a mole-drained soil under pasture grazed by sheep. The leaching losses of SO_4^{2-} from single superphosphate (SSP) and elemental S (S°) applications were compared. A claimed advantage of S° over SSP as a source of S is that it maintains yields while reducing leaching losses. Studies carried out to date have concentrated on the oxidation rate of S° in different climatic zones (Sinclair et al. 1985; Boswell & Swanney 1986; Smith & McDougall 1988), but the suggested reduction in leaching has not been investigated.

MATERIALS AND METHODS

Field experiment

An experiment was carried out during the winters of 1988 and 1989 on three adjacent mole-tile drained paddocks under permanent pasture on Massey University's No. 4 dairy farm. The soil is Tokomaru silt loam, classified as a Central Yellow Grey Earth in the New Zealand system, or as a Typic Fragiaqualf (Anon. 1974). It is characterised by its low SO_4^{2-} retention capacity (Metson 1968; Bolan et al. 1986) and poor internal drainage (Pollock 1975). Moles were pulled in 1975, and again in 1986, at a depth of 0.45 m and at 2 m spacing. Drainage from the moles was intercepted by tile drains laid at c. 0.75 m depth. Drainage from two of the paddocks (each with a drained area of 0.125 ha) was directed to individual V-notch weirs, allowing flow rates to be continuously monitored using flow meters (ISCO Model 2310). Drainage samples were collected at a frequency proportional to flow rate using automatic water samplers (ISCO Model 2900). The third paddock was not instrumented for drain flow measurements, but had suction cup samplers installed. This was used as a control. The suction cups were pre-soaked with deionised water before insertion at 200–250 mm and c. 500 mm (below mole-drain) depths. Ten suction cups were installed at the shallower depth and five at the deeper depth in each paddock. The cups were put under vacuum with a hand-operated pump the day after all major rainfall events, and solution samples were collected the following day using a neoprene tubing attached to a syringe.

On 16 June 1988, S was applied at a rate of 50 kg S/ha to one treatment paddock as SSP and to the other as S°. Triple superphosphate, at an amount of phosphorus (P) equivalent to that supplied to the SSP paddock, was also applied to the S° paddock. KCl was applied at 200 kg/ha to both paddocks. The fertilisers were re-applied on 31 May 1989 using the same rate of KCl but with only 30 kg S/ha. Urea at 50 kg N/ha was applied to both paddocks on 7 September 1989. Particle size measurements on S° indicated that the sample used for the 1988 season was slightly coarser (26% < 0.5 mm) than that used for the 1989 season (50% < 0.5 mm). No fertiliser was applied to the control.

The paddocks were not grazed between June and October 1988, but were grazed intermittently by sheep during the following summer and winter periods of 1989. A mob of 40–50 sheep grazed each paddock for c. 1 week at each grazing. Rainfall was measured at the site using a recording rain gauge.

Chemical analyses

The drainage samples collected from the two paddocks were analysed for Cl^-, SO_4^{2-}, NO_3^-, Ca^{2+}, K^+, Mg^{2+}, Na^+, and pH. The solution samples from the suction cups were also analysed for SO_4^{2-}. Cl^- was analysed colorimetrically with a Flow Injection Analyzer (Tecator Model 5020) using an automated version of the mercuric thiocyanate-ferric nitrate procedure (Florence & Farrar 1971). Sulphate was analysed using a modification of the method of Johnson & Nishita (1952) (CSIRO Division of Forest Research, Method No. PS 17) on an autoanalyser (Technicon Series II). Nitrate was analysed by reducing it to nitrite (NO_2^-) using hydrazine sulphate and measurement on an autoanalyser (Technicon Series II) following the method of Kamphake et al. (1967). Ca^{2+} and Mg^{2+} were analysed using atomic absorption spectroscopy, and K^+ and Na^+ by emission spectroscopy. pH was measured using a glass electrode.

RESULTS AND DISCUSSION

Drainage

The cumulative drainage from the SSP and S° paddocks from the time of fertiliser application in 1988 was 304 and 257 mm respectively (Fig. 1A). Drainage for the two paddocks agreed well throughout

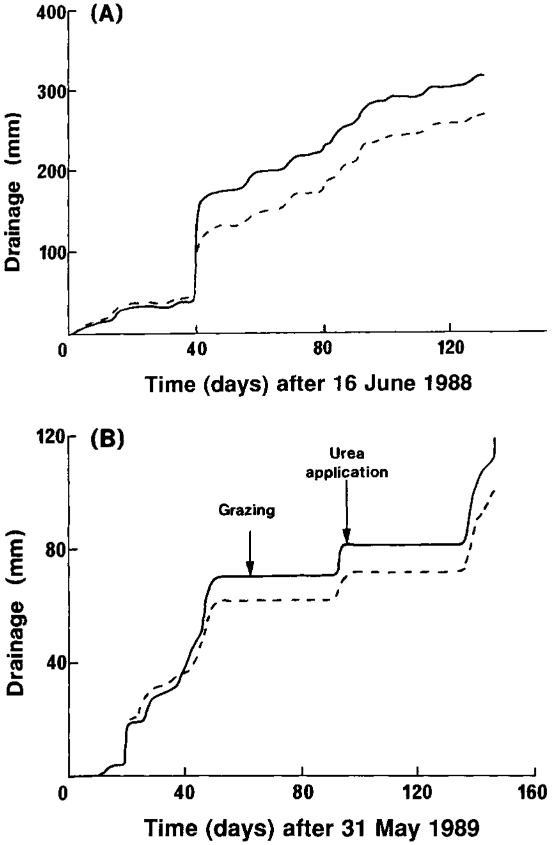

Fig. 1 Cumulative drainage from the SSP paddock (______) and S^0 paddock (_ _ _ _) for (A) 1988 and (B) 1989. Times of grazing and urea application are indicated by arrows.

the season, except on Day 40 after fertiliser application, when a 90 mm rainstorm occurred which gave 46 mm more drainage from the SSP paddock than the S^0 paddock. This was probably caused by water running off less intensively drained adjacent land onto the SSP paddock. The cumulative drainage from the two paddocks from the time of fertiliser application in 1989 (Fig. 1B) agreed well in the early part of the period, but deviated somewhat later, with 118 mm being collected from the SSP paddock and 100 mm from the S^0 paddock. Points of note are the large difference between the 2 years in the total amount of drainage collected, the very rapid drainage from the intense storm event in 1988, and the two long dry spells during the winter of 1989. These features have important consequences for the leaching patterns of both cations and anions, as discussed below.

The total rainfall for the two drainage periods (i.e., from the time of fertiliser application until the last drain flow event) was 509 and 343 mm in 1988 and 1989 respectively. Evaporation calculated using the Priestley & Taylor (1972) approach was 151 and 237 mm respectively for the two periods, and taking into consideration the soil water deficit before fertiliser application, drainage for 1988 and 1989 was predicted to be 338 and 104 mm respectively. The similarity between these figures and the measured drain flows in the two years indicates percolation below mole drain depth was small, and nearly all excess water was accounted for in the drain flow. The impermeable fragipan between 800 and 1100 mm in the soil profile (Pollock 1975) makes this a not unexpected result.

Leaching of anions

The concentrations of Cl^-, SO_4^{2-}, and NO_3^- in the drainage are shown in Fig. 2. In 1988 (Fig. 2A and B) the initial concentrations of Cl^- were similar for both paddocks at around 2 mol/m^3 (70 g/m^3), and fluctuated between 1.5 and 2.5 mol/m^3 in the first 50 mm of drainage, possibly because of preferential movement of applied Cl^- to the drains. The concentration decreased to 1 mol/m^3 in the next 50 mm of drainage, which resulted from the intense storm event mentioned above. The high flow rates apparently led to pronounced preferential flow and dilution of the drainage water by rainwater, the mechanism for which is described by Thomas & Phillips (1979) and White (1985). Some data are missing between 75 and 100 mm cumulative drainage, but following the high flows associated with the storm event, the concentrations rose sharply and then declined with further drainage.

Cl^- concentrations between 2 and 3 mol/m^3 (70–107 g/m^3) were observed throughout the early part of the 1989 drainage period in both paddocks (Fig. 2C and D). The increase probably resulted from the extra KCl added and the lower rainfall intensities during that period. The Cl^- concentration dropped to about 1 mol/m^3 (35 g/m^3) after 70–80 mm of drainage, which corresponded with the end of a dry and relatively mild period in mid winter. Measurements of dry matter yield (Heng 1991) showed that plant growth, probably stimulated by urea application and mineralisation, was associated with substantial Cl^- uptake during this period, resulting in lower Cl^- concentrations in the soil when drainage resumed. The cumulative amount of Cl^- leached, averaged over both treatment paddocks, were 105 kg/ha during 1988, and 74 kg/ha in 1989 (Table 1). Steele et al. (1984) measured similar leaching losses in their study. It is interesting that although the quantity of drainage in 1989 was less than half of that in 1988, the amount

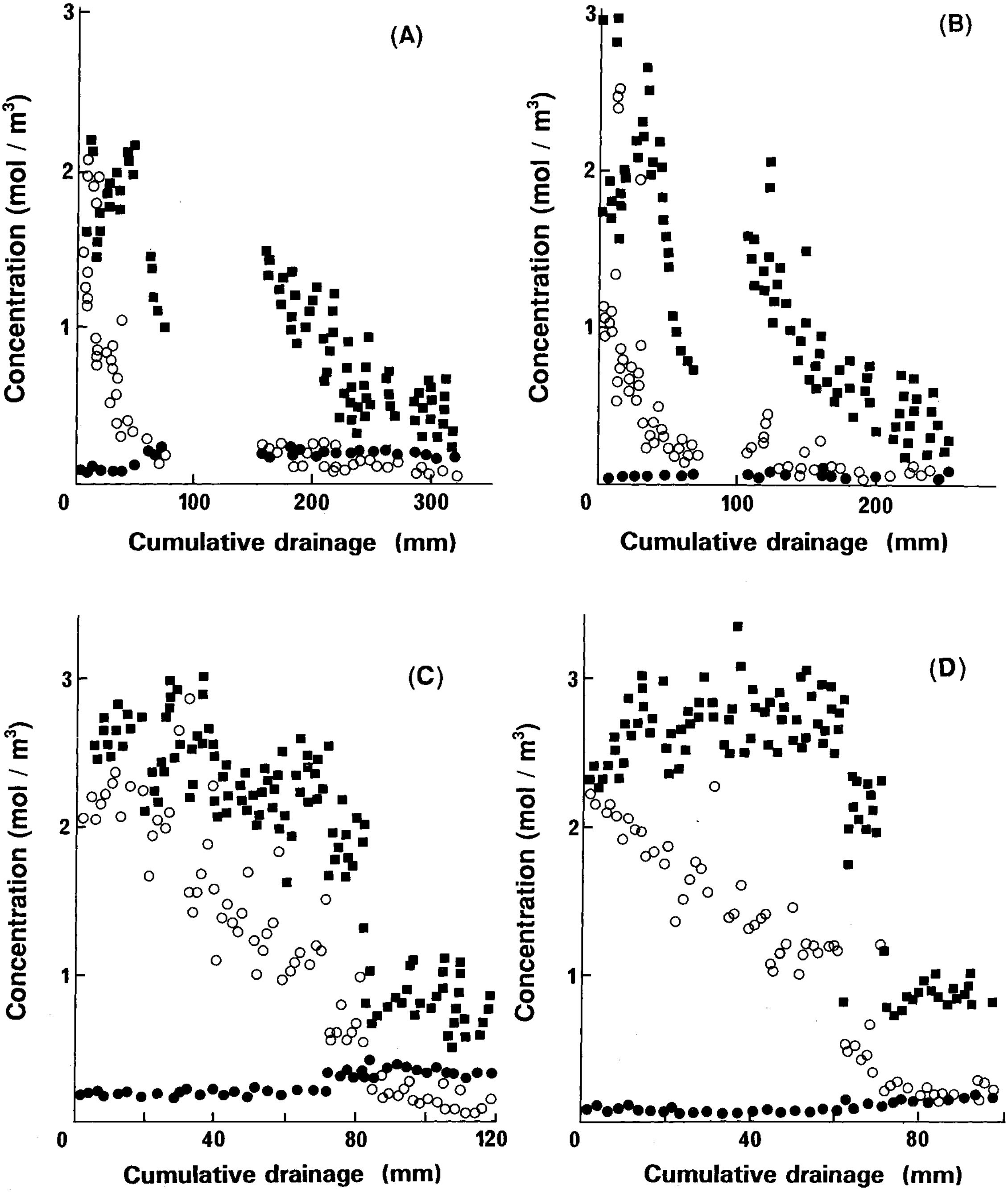

Fig. 2 Concentration of Cl$^-$ (■), SO$_4^{2-}$ (●), and NO$_3^-$ (○) in the drainage for (A) SSP paddock 1988, (B) S° paddock 1988, (C) SSP paddock 1989, and (D) S° paddock 1989.

of Cl^- leached was only 30% less. The reason for this was that the bulk of the Cl^- was leached early in the drainage period during which time 50% or more of the total drainage occurred.

Figure 2 shows that Cl^- was the dominant anion in the drainage. This in part was because of the addition of KCl fertiliser, but soil sampling over the summer period, when evaporation exceeded rainfall, indicated a substantial input of Cl^- from the atmosphere. As the site was only 30 km from the sea in the direction of the prevailing westerlies, such an input would be expected. At Taita near Wellington (12 km from the sea), Blakemore (1973) found an average annual Cl^- input in rainfall of 113 kg/ha.

The SO_4^{2-} concentrations in the drainage from both the SSP and S° fertilised paddocks were less than 0.1 mol S/m^3 at the beginning of the drainage period in 1988 (Fig. 2A and B). However, SO_4^{2-} concentrations in drainage from the SSP paddock showed a 3-fold increase to 0.2 mol S/m^3 (6 g/m^3) after 50 mm of drainage, and remained at that level until the end of the drainage period. In contrast, the SO_4^{2-} concentration from the S° paddock remained low. The increase in SO_4^{2-} concentration from the SSP paddock after 50 mm drainage showed that some SO_4^{2-} from the SSP was readily leached. This agrees with the field observations made by Gregg & Goh (1978) and Smith et al. (1983). The relative stability of the SO_4^{2-} concentrations throughout the season, compared to the Cl^- concentrations, can be attributed to SO_4^{2-} buffering in the soil solution, adsorption and desorption, and transformations to and from organic forms. Heng (1991) showed that the Tokomaru silt loam adsorbs SO_4^{2-} to some extent and that adsorption increases with soil depth. Similarly Bolan et al. (1986) have shown that the leaching of SO_4^{2-} in soil is influenced by the capacity of the soil to adsorb SO_4^{2-}. Rapid transformation of a fraction of the SO_4^{2-} in SSP into organic forms probably occurred also, as observed by Goh & Gregg (1982) and Ghani et al. (1988) in their respective field and laboratory incubation studies.

The low SO_4^{2-} concentration in both the S° and control paddocks suction cup samples (0.05 ± 0.02 mol S/m^3 compared to 0.04 ± 0.02 mol S/m^3) in 1988 indicates that application of S° with the particle size range used in that year had little effect on the amount of SO_4^{2-} leached. This size range was much bigger than that recommended by the Ministry of Agriculture and Fisheries (MAF) in New Zealand (Sinclair et al. 1985; Edmeades et al. 1990) for annual application around Palmerston North.

The amounts of SO_4^{2-} leached during 1988 were 17 and 3.4 kg S/ha for the SSP and S° paddocks respectively (Table 1). Thus the application of 50 kg/ha of SO_4-S in SSP in early winter caused a 5-fold increase in leaching. Smith et al. (1983) also observed increased leaching when SSP was applied.

The SO_4^{2-} concentration in the drainage from the SSP paddock in 1989 was constant at 0.2 mol/m^3 for the first 70 mm of cumulative drainage, then increased to 0.4 mol S/m^3 (13 g/m^3) after the prolonged dry period in mid winter in 1989. This increase can probably be attributed to higher than normal daytime temperatures together with wetting and drying cycles that increased net mineralisation relative to plant uptake. In the same year, the SO_4^{2-} concentration in the drainage from the S° paddock was constant at 0.1 mol S/m^3 for most of the season, but increased to around 0.2 mol/m^3 after the dry period. These differences in SO_4^{2-} concentration between the SSP and S° paddocks were reflected in the amounts of SO_4-S leached in both years, 17 and 3.4 kg S/ha for the SSP and S° paddocks respectively in 1988, and 9.4 and 3.5 kg S/ha respectively in 1989 (Table 1).

The NO_3^- concentration tended to be highest in the first drainage event of each year and declined steadily with further drainage (Fig. 2). This pattern of change in concentration with continuing drainage was also observed by Turner et al. (1976) and Haigh & White (1986). High NO_3^- concentrations at the beginning of a winter drainage season have been attributed to an excess of mineralisation of organic N over plant uptake as the soil wets up during autumn and early winter (White et al. 1983; Haigh & White 1986). Interestingly the NO_3^- concentration exceeded the World Health Organization guideline for potable water of 10 g N/m^3, or 0.7 mol/m^3 (WHO 1978) only in the first 80 mm of drainage. This suggests that a substantial improvement in water quality can be achieved by temporary storage or treatment of the early drainage water only.

Table 1 Losses of nutrients (kg/ha) in drainage.

	1988		1989	
Element	Paddock A	Paddock B	Paddock A	Paddock B
Chlorine	117.8	92.8	76.3	71.9
Sulphur	17.0	3.4	9.4	3.5
Nitrogen	12.6	8.6	19.1	14.9
Calcium	52.5	35.2	40.8	30.7
Potassium	10.8	5.7	7.1	3.3
Magnesium	15.0	10.8	11.3	9.1
Sodium	64.5	50.8	31.9	31.1

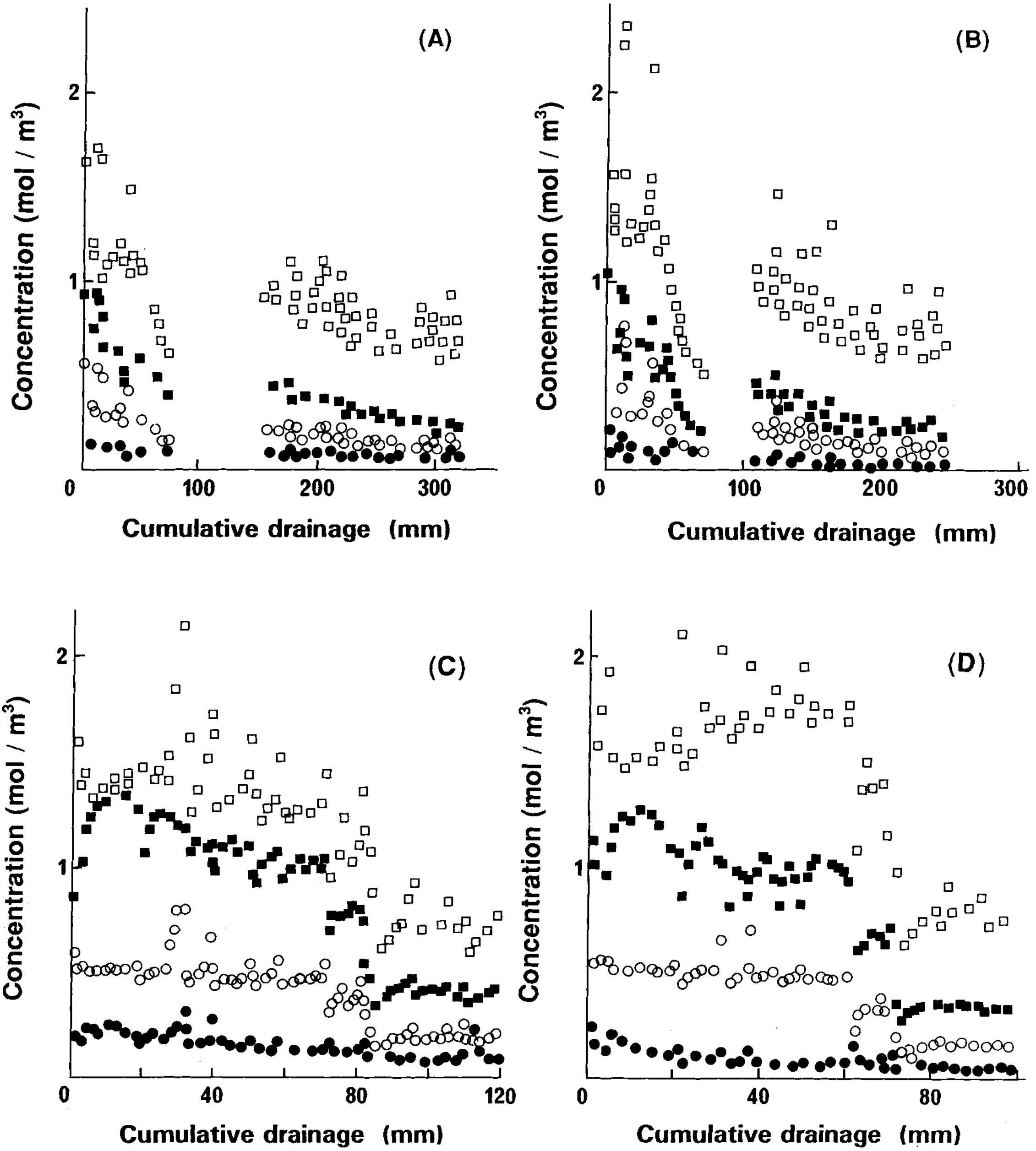

Fig. 3 Concentration of Ca^{2+} (■), Mg^{2+} (○), K^+ (●), and Na^+ (□) in the drainage for (A) SSP paddock 1988, (B) S° paddock 1988, (C) SSP paddock 1989, and (D) S° paddock 1989.

The NO_3^- level in 1989 was generally higher than that in 1988, especially in the first 70 mm of drainage. Since no N was added to the paddocks until late 1989, the higher concentration in early 1989 could have resulted from more efficient leaching (i.e., less preferential flow) under the drier soil conditions prevailing during 1989 compared to 1988. During the dry period between August and September in

1989, urea was applied at 50 kg N/ha to all three Paddocks A, B, and C as part of another experiment, and grazing also took place. However, the addition of N from these two sources did not result in a measurable increase in concentration either in the first drainage event following the dry mid-winter period, or in the subsequent events. This was different from the increased NO_3^- concentration in tile drainage reported by Sharpley & Syers (1979) after the application of urea (60 kg N/ha) to dairy-cattle-grazed paddocks in July. The extra N added may have been taken up by the pasture, as indicated from the large increase in the pasture growth rate following urea application (Heng 1991). Other possible processes which could account for N losses are NH_3 volatilisation, denitrification, and immobilisation. Some volatilisation could have taken place, because the process tends to increase with temperature and in soils of high moisture that are allowed to dry. Such conditions prevailed after urea application. Little denitrification would be expected to occur as the soil was not saturated or waterlogged. These processes were not measured in this experiment. Losses in drainage as NH_4^+ were also not measured, because studies by Turner et al. (1979) and Sharpley & Syers (1981) showed little NH_4^+ was lost in drainage water. Measurement of NH_4^+ in the tile drainage made by G. N. Magesan (pers. comm.) after urea application in September 1989 confirmed this.

The amount of N leached during the two winter periods was between 9 and 19 kg N/ha (Table 1). More N was leached in 1989 than in 1988, although there was less drainage in that year. Because most of the N was lost in the first 70–80 mm of drainage, the total drainage was of little relevance to the amount of N leached.

The amounts of nitrate leached were much lower than those found by Steele et al. (1984) for intensive dairy cattle-grazed pasture and Haigh & White (1986) for both cattle and sheep-grazed pasture. Differences in the grazing animal could be one of the reasons for the large difference between the amount leached in the Steele et al. (1984) study and the present study, because of the larger volume of urine excreted per urination by cattle (1600 ml), compared to sheep (150 ml) (Doak 1952). Ryden et al. (1984) argued that "hot spots" resulting from urination by grazing animals were the major cause of high NO_3^- leaching losses from grazed pastures. Although enhanced leaching following grazing by sheep has also been observed (Turner et al. 1979; Field et al. 1985), it is likely to be less pronounced than that following grazing by cattle.

Leaching of cations

The concentrations of cations in the drainage water are shown in Fig. 3. The concentration of K^+ was low in both years (between 0.1 and 0.3 mol/m^3), despite a high rate of K fertiliser being applied. In general, the amount leached is small compared to the amount taken up by plants (During 1984). Although Hogg (1981) and Williams et al. (1990) observed that preferential K leaching can occur from cattle urine patches, only small amounts of K loss through leaching were observed here. The low and stable K^+ concentration can be attributed to the presence of mixed layer clay minerals in this soil, which help to hold it on the exchange sites and hence retard movement down the profile. The total K^+ lost through leaching was between 3 and 11 kg K/ha (Table 1). This is similar to that found by Smith et al. (1984), Steele et al. (1984), and Close & Woods (1986) for New Zealand pasture soils, and by Bolton et al. (1970) and Burke et al. (1974) in overseas studies.

The concentrations of Ca^{2+} in the drainage are also given in Fig. 3. The Ca^{2+} concentration was high at the start of both years (around 1 mol Ca/m^3 or 40 g/m^3) but dropped off with increasing drainage to less than 0.5 mol/m^3 (20 g/m^3) by the end of the drainage period. The total leaching loss ranged from 31 to 52 kg/ha per yr (Table 1), with a larger amount leached from the SSP paddock than the S° paddock in both years. The large losses of Ca^{2+} may result from the fact that it is the dominant cation present in the Tokomaru silt loam (Pollock 1975; During 1984). Note that Ca^{2+} was applied in either SSP or TSP to both paddocks, so the difference in leaching losses may be associated with the differences in NO_3^-, Cl^-, and SO_4^{2-} leaching between the two paddocks.

The Mg^{2+} concentrations in drainage water are also presented in Fig. 3. Although Mg^{2+} was not applied, significant amounts were detected in both years' drainage. In general, the concentrations followed the same trends as those of Ca^{2+}, but were somewhat lower. The losses were between 9 and 15 kg/ha per yr. Because Mg^{2+} is needed for preventing hypomagnesaemia in stock, fertiliser consultants and farmers should take account of the significant quantity of this element lost through leaching.

The high Na^+ concentration in the drainage relative to the other cations is worth noting (Fig. 3). The concentrations were much higher than those reported by Steele et al. (1984). The amount lost averaged 58 kg/ha in 1988 and 32 kg/ha in 1989 (Table 1). The high Na^+ concentrations were probably caused by a high input of salt through rainfall, as discussed above for Cl^-. It is likely that a quasi steady state exists for

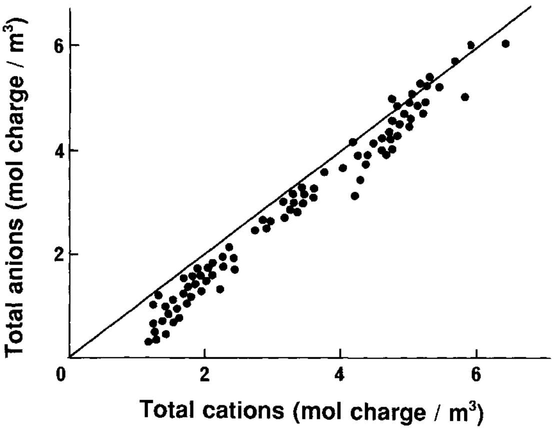

Fig. 4 Relationship between anion and cation moles of charge in drainage samples for 1988 and 1989 (●). The 1:1 line is shown for comparison.

Na^+ (and Cl^-), with leaching losses in approximate balance with the atmospheric input from rainfall and dry deposition. It can therefore be inferred that the higher Cl^- concentration over Na^+ in the drainage resulted from the KCl application. When that was assumed, about 45 and 57% of the Cl leached in 1988 and 1989 respectively was calculated to come from fertiliser KCl. The low amounts of Na^+ adsorbed on the exchange sites of unimproved Tokomaru silt loam (Pollock 1975) would reflect the relatively weak adsorption of this cation, in accordance with the lyotropic series (Bohn et al. 1979).

The moles of charge from the three major anions in each drainage sample from both years are plotted against the total moles of cation charge in Fig. 4. Phosphate (PO_4^{3-})was not measured, but other studies have shown that its concentration in drainage water is negligible relative to other anions (Turner et al. 1976; Sharpley et al. 1977; Steele et al. 1984). The data show that there was a near balance of total cation and anion moles of charge, with only a slight surplus of cation over anion moles of charge at most concentrations (Fig. 4). The contribution from bicarbonate (HCO_3^-)may be a possible reason for the discrepancy, as the pH in the drainage was found to be high (between 6 and 8) throughout both years.

The above results illustrate how the addition of fertiliser and atmospheric salt, and net mineralisation of organic N and S, can increase the soil solution concentration and lead to increased losses of both anions and cations. Conversely, net immobilisation and plant uptake will tend to decrease leaching losses of both anions and cations. Often leaching studies have concentrated on only one anion or cation in isolation, without considering the associated ions.

CONCLUSIONS

Implicit in the results are the interactions between the physical, chemical, and biological processes which determine the leaching losses of individual ions (White 1988). The large losses of Cl^- through leaching were caused by KCl fertiliser application, and the high Cl^- input from wet and dry deposition from the atmosphere. The rate of leaching depended on the intensity of rainfall, as with high drain flows the Cl^- concentration decreased. However, for a biologically and chemically active ion such as SO_4^{2-}, the leaching pattern is also affected by the instantaneous, reversible nature of the adsorption capacity of the soil, the rate of mineralisation of organic S, and the form of S applied. Application of coarse S^o instead of SSP on average reduced leaching losses from c. 13 to 3 kg S/ha per yr. Application of SSP in late autumn to soils of low PO_4^{3-} retention capacity, and so low sulphate retention, such as the Tokomaru silt loam, resulted in a large proportion of the sulphate being leached, hence such practice is not recommended. In situations where S is needed, pure elemental S or a mixture of S^o with reactive phosphate rock or partially acidulated phosphate rocks (Boswell 1987; Swanney et al. 1988) should be considered as alternatives. Relatively little NO_3^- leaching was observed, which could be because of the relatively small inputs to the system from fertiliser and grazing animals.

Leaching of K^+ was minimal, even when it was applied in relatively large quantities just before the drainage season. Relatively large amounts of Na^+ were leached. This probably reflects the amount added in salt from the atmosphere. Substantial amounts of Ca^{2+} and Mg^{2+} were also leached, and this should be taken into account when fertiliser recommendations are being made.

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