

Nitrate retention under sugarcane in wet tropical Queensland deep soil profiles

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Abstract

Nitrate leaching below the crop root-zone in variable charge soils may be adsorbed at anion exchange sites, thereby temporarily reducing the risk of contamination of water bodies. The objectives of this study were (i) to investigate whether nitrate adsorption, accumulation, and retention in the Johnstone River Catchment of Far North Queensland wet tropics is widespread; (ii) to assess the capacity of soil in the Johnstone River Catchment to retain nitrate; and (iii) to deduce the consequences of nitrate adsorption/desorption on contamination of water bodies. Soil cores ranging from 8 to 12.5 m depth were taken from 28 sites across the catchment, representing 9 Ferrosol soil types under sugarcane (*Saccharum officinarum*-S) cultivation for at least 50 years and from rainforest. The cores were segmented at 0.5-m depth increments and subsamples were analysed for nitrate-N, cation and anion exchange capacities, pH, exchangeable cations (Ca, Mg, K, Na), soil organic C, electrical conductivity, sulfate-S, and chloride. Nitrate-N concentration under sugarcane ranged from 0 to 72.5 mg/kg, compared with 0 to 0.31 mg/kg under rainforest, both Pin Gin soils. The average N load in 1–12 m depth across 19 highly oxidic profiles of the Pin Gin soil series was 1550 kg/ha, compared with 185 kg/ha under 8 non-Pin Gin soils and 11 kg/ha in rainforest on a Pin Gin soil. Most of the nitrate retention was observed at depth of 2–12 m, particularly at 4–10 m, indicating that the accumulation was well below the crop root-zone. The average maximum potential nitrate retention capacity was 10.8 t/ha for the Pin Gin and 4.7 t/ha for the non-Pin Gin soil. Compared with the current N load, the soils still possess a large capacity to adsorb and retain nitrate in profiles. Retention of large quantities of the leached nitrate deep in most of the profiles has reduced the risk of contamination of water bodies. However, computations show that substantial quantities of the nitrate leached below the root-zone were not adsorbed and remain unaccounted for. This unaccounted nitrate might have entered both on- and off-site water bodies and/or have been denitrified.

Additional keywords: nitrate adsorption and retention, leached nitrate, nitrate retention capacity, soil types, environmental concern.

Introduction

The environmental health concerns of the Great Barrier Reef have been associated with nutrients (especially N and P) and sediment loading from cropping and other land uses (Yellowlees 1991). The Great Barrier Reef is a United Nations listed World Heritage site; therefore, its preservation and maintenance is of national and global interest. The two major river systems in the Johnstone River Catchment (JRC) of Far North Queensland, which discharges into the Great Barrier Reef lagoon, carry runoff and drainage from both cropland and pristine tropical rainforest, another World Heritage site. The mineral nutrient that is most often linked to the GBR health concerns is N, particularly nitrate-N. Nitrogen mass-balance studies for the major cropping systems (sugarcane, bananas [*Musa* spp.], and pasture) on Ferrosols in the JRC have shown that 30–50 kg N/ha.year of the fertiliser-N

applied to crops on Ferrosol soils leached below the crop root-zone (<0.75 m) as nitrate-N, compared with <10 kg/ha.year transported in surface runoff (Moody *et al.* 1996; Prove and Moody 1997).

The cropping systems in the JRC use relatively large quantities of N fertiliser. The annual application of fertiliser-N ranges from 100 to 200 kg/ha for sugarcane (Rasiah *et al.* 1999), 100 to 900 kg/ha (mean 520 kg/ha.year) for bananas (Daniells 1995), and 20 to 500 kg/ha for grazed pasture (G. Sipson, pers. comm.). In the JRC, \approx 45 000 ha of pasture, 16 000 ha of sugarcane, 7 000 ha of banana, and another 2 000 ha of other fruit crops receive N fertilisers at the aforementioned rates. Thus, the loss of 30–50 kg N/ha.year of the applied fertiliser-N as nitrate leached below the root-zone is not only a potential environmental issue, it is an economic input loss to producers.

Because large quantities of N were leaching below the crop root-zone, research has focused on its fate. The leached nitrate could be adsorbed at anion exchange sites (Rasiah and Armour 2001), denitrified, or enter streams/rivers through lateral-flow and/or aquifers by deep drainage. Several workers (Black and Waring 1976, 1979; Gillman and Abel 1987; Rasiah and Armour 2001) have shown that the anion exchange capacity (AEC) and the other chemical attributes of Ferrosols provide conditions favourable for adsorption of the leached nitrate in soil matrix. In this way the AEC acts as a nitrate filter, although nitrate adsorption may ultimately be limited by the maximum potential nitrate retention capacity (MPNRC) of the soils. Despite the potential for retention of nitrate, the Ferrosols' deep profiles (1 to >10 m, Cotching 1995) and high hydraulic conductivity and percolation rate (Bonell *et al.* 1983), and the relatively long saturated profile condition (December–May), high rainfall (\approx 3500 mm/year, 60-year average), and undulating topography/landscape (Hair 1990; Cotching 1995) in the JRC may be providing conditions favourable for the transportation of nitrate in lateral-flow and/or into deeper aquifer.

Limited information exists on catchment-scale nitrate retention in the JRC, particularly across the soil types and management practices adopted in the JRC. Further quantitative information on nitrate accumulation at a catchment scale may encourage producer groups to undertake improved N fertiliser management practices. The objectives of this study were (i) to investigate whether nitrate adsorption, accumulation and retention in the JRC is widespread; (ii) to assess the capacity of the soils in the JRC to retain nitrate; and (iii) to deduce the consequences of nitrate adsorption on the contamination of water bodies.

Materials and methods

Site description

The JRC is \approx 1634 km² in area and located approximately at 17°30'S, 145°50'E. The major river systems in the JRC are the Johnstone and South Johnstone, both of which rise in the south-eastern section of the Atherton Tableland (Malanda elevation 740 m), pass through large areas of native rainforest in the midsections of the catchment and then drain undulating lowlands and flood plains (Fig. 1). The rivers converge at Innisfail, where the Johnstone River estuary discharges into the GBR lagoon. Pristine rainforest covers \approx 52% of the catchment, pasture 28% (both dairy and beef), sugarcane 12%, and banana 6% (Prove and Moody 1997). Rainfall is typically summer-dominant, with mean annual values of 1680 mm at Malanda in the upper catchment and 3500 mm at Innisfail on the coast.

Twenty-eight soil cores to a depth of 8–12.5 m were taken across the JRC between 1998 and 2000, \approx 8–9 cores/year; 27 cores were from under long-term sugarcane and the other was from an undisturbed rainforest site, which in this study is considered as the background against which the cultivated sites are compared. The cores were taken from major representative soil types in the catchment, but the majority of them belong to the Pin Gin series (Murtha 1986), which is the predominant soil type in JRC (Table 1). The cores also represented different trash and fertiliser management systems, from different slope aspects on the landscape and proximity to drainage systems.

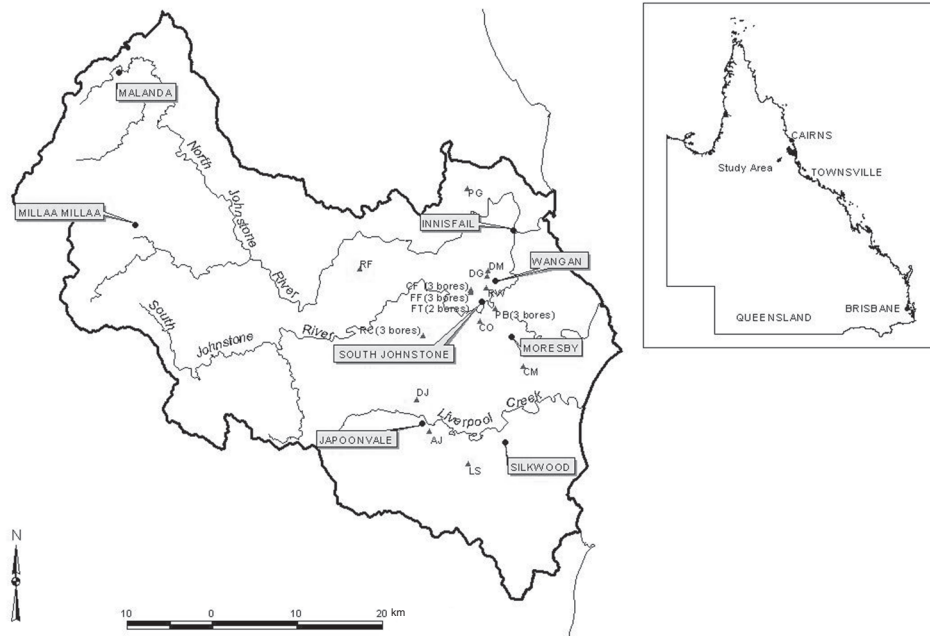


Fig. 1. Coring locations (sites) in the catchment.

Soil cores (0.05 m diam.) were taken from each site at 1.5-m depth increments, using a hydraulic rig, placed in split PVC tubes, and segmented at 0.5-m depth increments to 12.5 m. Subsamples were taken from each segment immediately after coring and stored at $<4^{\circ}\text{C}$ for nitrate-N and ammonium-N determination in the laboratory. The 0.5-m segmented cores were air-dried at 40°C and sieved to <2 mm. These samples were analysed for cation exchange capacity (CEC), AEC, pH, electrical conductivity (EC), exchangeable cations (Ca, Mg, K, Na), soil organic C (SOC), sulfate-S, and chloride. The pH and EC were measured in 1:5 soil:water suspension. The SOC was determined using the Walkley (1947) procedure with a colorimetric finish. Nitrate was extracted with 1 M KCl and determined using a Griess-Ilosvay colorimetric procedure (Best 1976). Sulfate-S was determined using inductively coupled plasma-atomic emission spectroscopy after extraction in calcium phosphate (Rayment and Higginson 1992). Chloride was determined using the mercuric thiocyanate colorimetric procedure (APHA 1995), and AEC was measured using the compulsive exchange method of Gillman and Sumpter (1986). The exchangeable cations were determined by flame AAS after extraction in 1 M NH_4Cl (Rayment and Higginson 1992, method 15A1). The CEC was calculated as the sum of exchangeable bases plus acidity (Rayment and Higginson 1992, method 15J1), and sum of Ca, Mg, K, and Na was defined as total cations.

Although the KCl-extractable nitrate (KCl-NO_3), obtained from field-moist soil, is considered to be that adsorbed at anion exchange sites (AD-NO_3), at least a proportion of it will be present in soil solution and hence may be water-extractable. Because our major emphasis is on adsorption, the extracted nitrate value was corrected for water-extractable nitrate. The adjustment was made using the regression equation developed using data on water-extractable nitrate ($\text{H}_2\text{O-NO}_3$) of selected air-dried soil samples, KCl-NO_3 of field-moist soil and the corresponding soil moisture content (θ):

$$\text{AD-NO}_3 = 0.69 \text{KCl-NO}_3 - 0.0051\theta \quad (R^2 = 0.99, P < 0.001) \quad (1)$$

where AD-NO_3 is the difference between the KCl-NO_3 and $\text{H}_2\text{O-NO}_3$, and the variables are in mg/kg. Eqn 1 indicates that $\approx 30\%$ of nitrate was water-extractable, with an additional impact of θ on adsorbed nitrate becoming significant when was $\theta > 300$ mg/kg soil. Further, the poor correlation between KCl-NO_3 and θ :

$$\text{KCl-NO}_3 = 1.74 + 2.04 \times 10^{-5}\theta \quad (r = 0.16, P < 0.001) \quad (2)$$

Table 1. Site name and N-fertiliser and other management practices followed at each site

Site no.	Site abbreviation	Soil type	Type and rate (kg N/ha.year) of N-fertiliser used ^A	Trash retained or burned	Slope aspect
1	AJ134	Thorpe	Urea, 120	Retained since 1990	<1% on shoulder
2	CO139	Innisfail	Urea/AmSul, 120	Retained since 1990	<1% toeslope
3	DG132	Eubenangee	Urea, 150	Retained since 1986	1–2% on shoulder
4	DJ133	Galmara	DAP, 140	Burned and no-till since 1984	<1% toeslope
5	DM138	Garradunga	Urea, 150	Retained since 1986	1–2% on shoulder
6	FF136	Pin Gin	Nitram/urea, 140	Retained since 1988	5–10% steep toeslope
7	GN137	Pin Gin	Urea/AmSul, 100	Retained since 1989	≈5% on shoulder
8	PB140	Mundoo	Urea, 140	Burned and no-till since 1987	1–2% on shoulder
9	RC135	Pin Gin	Urea, 145	Retained since 1992	5–8% on shoulder
10	RW150	Pin Gin	Urea, 135	Retained since 1991	< 1% midslope
11	RCR151 (repeat of RC153)	Pin Gin	Urea, 145	Retained since 1992	5–8% on shoulder
12	FFR152 (repeat of FF136)	Pin Gin	Nitram/urea, 140	Retained since 1988	5–10% toeslope
13	CM149	Kurrimine	Urea, 140	Retained since 1990	1–2% toeslope
14	FTR154 (repeat of Cane 118)	Pin Gin	Nitram/urea, 140	Retained since 1990	5–10% toeslope
15	CF147	Pin Gin	AmSul, 160	Retained since 1986	≈5% toeslope
16	LS148	Tully	Urea, 150	Burned/retained 50:50 since 1992	<1% toeslope
17	PBR153 (repeat of PB140)	Mundoo	Urea, 140	Burned and no-till since 1987	<1% on shoulder
18	FTRR154 (re-repeat of Cane 118)	Pin Gin	Nitram/urea, 140	Retained since 1990	5–10% toeslope
19	FFRR155 (re-repeat of FF136)	Pin Gin	Nitram/urea, 140	Retained since 1988	5–10% toeslope
20	CF156	Pin Gin	AmSul, 160	Retained since 1986	5–10% midslope
21	CF157	Pin Gin	AmSul, 160	Retained since 1986	5–10% midslope
22	PBRR158 (re-repeat of PB140)	Mundoo	Urea, 140	Burned and no-till since 1987	<1% on shoulder
23	RCRR159 (re-repeat of RC135)	Pin Gin	Urea, 145	Retained since 1992	5% on shoulder
24	RCRR160 (re-repeat of RC135)	Pin Gin	Urea, 145	Retained since 1992	5% on shoulder
25	PGO20	Pin Gin	AmSul/urea, 145	Retained since 1993	7–10% midslope
26	CANE-118	Pin Gin	Urea, 140	Retained since 1985	7–7% on shoulder
27	CANE-130	Pin Gin	Urea, 140	Retained since 1985	<3% mildslope
28	RAINFOREST	Pin Gin	Nil	Natural Heritage	<2% toeslope

^AAmSul, ammonium sulfate; DAP, diammonium phosphate.

suggests the influence of H_2O-NO_3 , through θ , on $KCl-NO_3$ is small. Only the AD- NO_3 nitrate data is reported and discussed in the text.

Soil characteristics

The soils in the JRC predominantly belong to the Ferrosol soil order (Isbell 1994); they are red to brown, acidic, well-structured clay soils formed on basalt, with deep profiles ranging from 1 m to >10 m. This group includes soil series formed *in situ* (Pin Gin, Eubenangee), and those formed on alluvium derived from basalt (Mundoo, Garradunga) (23 soil profiles, Table 1). The remaining soils are a Yellow Kandsol formed on alluvium from granite (Thorpe), Brown Dermosol soils developed on mixed alluvium (Innisfail, Tully), and Podisol (Kurrimine) (Table 1).

Fertiliser management history at the sites

Urea was usually applied at 50 kg N/ha at planting (July–September), with superphosphate (60 kg P/ha) and muriate of potash (150 kg K/ha). Urea was side-dressed at a rate of 100–120 kg N/ha in October–November. After harvesting in June–September, the ratoon crop received 165 kg N/ha as urea and 180 kg K/ha as muriate of potash. This fertiliser management was repeated for subsequent ratoons, usually 3 or 4. On average, the sugarcane paddocks received 130 kg N/ha.year, mostly as urea during the last 50 years. The information on fertiliser management history was gathered by us through personal interview with the producers involved in the project. The current producers in general are descendants of the producers in past 50–60 years; thus, the information provided is reliable, but may be guestimates by the producers in some instances.

Statistical analysis

Soil data from the rainforest are considered to represent the undisturbed natural system and were used as the background against which the cultivated sites were compared. The data were subjected to different statistical tests as reported by Rasiah and Armour (2001). Briefly, the depth-incremented nitrate distribution data for rainforest were compared with the corresponding data from a given cultivated site using the paired *t*-test. The analysis indicated significant difference between rainforest and each one of the 28 cultivated profiles. The pair-wise comparison was repeated on the data paired at 2-m depth increment, to determine whether any correlation existed between depth incremented data within a profile. The analysis produced results similar to the 1-m increment analysis, providing evidence that there was no association between depth-incremented data at a given site. The cumulative effect of the soil variables (CEC, AEC, pH, chloride, sulfate-S, SOC, EC, total cations, and total N) on nitrate-N retention was explored using a stepwise multi-variable selection procedure with the data pooled from all the sites, exclusive of rainforest. The SAS (1991) software package was used for the above purpose.

Results and discussion*Nitrate-N*

Nitrate-N concentration in individual depth increments of cropped profiles throughout the 1–12 m depth ranged from 0 to 73 mg/kg, compared with 0 to 0.3 mg/kg under rainforest (Table 2). The profile average nitrate-N concentration across cropped profiles was 9.1 mg/kg, compared with 0.1 mg/kg under rainforest. Because the Pin Gin soil series is the predominant soil type in the JRC, we focused our attention on this soil and compared it with other soil types and rainforest. For simplicity, the other 8 soil types are grouped as non-Pin Gin in this study. The typical nitrate distributions in 2 Pin Gin soils, with high (RC135) and low (CF156) nitrate, are compared with rainforest in Fig. 2*a*. A similar comparison is shown for 2 non-Pin Gin soils, AJ134 and CO139, high and low nitrate, respectively, in Fig. 2*b*. The distributions shown in Fig. 2*a* and *b* generally indicate that nitrate under cropping was higher than rainforest and much higher in the Pin Gin soil series than the non-Pin Gin soils. High nitrate concentrations (nitrate bulges) were observed at depths >4 m in RC135 and AJ134, and these bulges extended down to the maximum coring depth, 12.5 m. The bulges were not apparent in the Pin Gin CF156 or the non-Pin Gin CO139 (Fig. 2*a*, *b*). However, when the graphs were redrawn by scaling down the *X*-axis by an order of magnitude, bulging became apparent both in CF156 and CO139 at depths >2 m and extending down to 12 m (Fig. 2*c*, *d*). Compared to the rainforest, larger nitrate bulges under cropping indicate nitrate accumulation and retention after land clearing for cropping. Because coring was limited to 12 m depth, we cannot state whether nitrate accumulation and retention has occurred at depth >12 m under cropping. The sources of N for high nitrate under cropping include N-fertiliser, soil N, crop residue, and rain. However, the most obvious difference from the rainforest is the long-term application of high rates of N-fertiliser.

Table 2. Nitrate-N distribution (mg/kg) in soil profiles
 Nitrate-N concentrations in DJ133 and CF147 were <0.1 mg/kg throughout the profile, except that at 0.5 m depth (4.4 mg/kg) in CF147. For Cane-118 and Cane-130, see Rasiah and Armour (2001). Zero values in the table refer to <0.1 mg/kg, which is the lower detection limit of the instrument

Depth (m)	AJ 134	CO 139	CG 132	DM 138	FF 136	GN 137	PB 140	RC 135	RW 150	RC R151	FFR 152	CM 149	FTR 154	LS 148	PBR 153	FTRR 154	FFRR 155	CF 156	CF 157	PBRR 158	RCRR 159	RCRR 160	PG 02	Forest
0.5	0.1	0.1	0.1	8.6	10.0	0.1	0.1	0.1	3.5	0.9	1.2	0.0	1.2	0.0	0.0	0.7	0.1	0.4	0.9	0.8	2.1	0.8	1.0	0.0
1.0	0.1	0.1	2.3	3.2	55.7	0.1	0.1	0.1	13.4	2.9	22.4	0.0	0.0	0.0	0.0	0.3	15.8	5.2	2.5	1.0	1.0	1.1	0.8	0.2
1.5	0.1	0.1	0.1	4.2	50.8	0.1	0.1	0.1	2.3	9.9	17.2	0.0	0.0	0.0	0.0	0.3	61.7	1.0	1.7	1.2	4.8	0.5	11.7	0.0
2.0	0.1	0.1	1.2	1.8	46.1	0.1	0.1	0.7	1.9	3.3	23.3	0.0	0.0	0.0	0.0	0.5	62.9	1.6	4.3	1.1	4.8	4.0	12.1	0.2
2.5	0.1	0.1	1.4	0.7	23.9	0.1	2.0	0.1	1.0	1.5	37.0	0.0	0.0	0.0	0.0	0.4	57.1	2.0	3.6	1.2	2.4	1.3	9.6	0.0
3.0	0.1	0.1	0.9	1.4	26.1	0.1	6.7	0.1	1.2	1.3	24.1	0.0	0.0	0.0	3.9	0.6	20.4	0.8	2.6	2.0	1.8	0.9	4.5	0.1
3.5	0.1	1.0	3.1	0.8	13.0	0.1	10.4	0.1	1.4	0.8	17.2	0.0	1.2	0.0	3.1	0.6	19.5	1.2	2.5	2.4	2.3	1.4	4.6	0.0
4.0	0.1	1.0	1.9	1.1	16.2	0.1	7.7	0.1	1.2	0.0	14.5	2.6	3.1	0.0	3.1	5.9	18.0	1.0	2.6	3.1	2.2	1.9	7.1	0.1
4.5	1.1	1.2	1.9	0.8	17.9	0.7	3.9	0.1	1.2	0.8	13.3	1.6	5.8	0.0	3.8	12.3	16.4	1.0	2.8	5.0	1.8	2.1	6.3	0.0
5.0	1.0	1.1	4.1	1.2	23.3	0.8	5.9	0.7	2.0	1.6	16.4	1.4	9.0	0.0	4.1	16.3	25.9	1.7	1.6	5.2	1.5	1.2	6.6	0.1
5.5	1.9	1.1	4.3	1.5	26.0	0.8	9.4	2.4	2.0	3.1	15.9	1.2	12.2	0.0	6.0	21.9	49.3	2.0	1.7	5.0	1.4	1.1	1.0	0.0
6.0	1.5	0.9	3.3	2.5	17.1	1.4	9.9	21.5	3.5	9.9	15.2	0.0	30.9	0.0	11.2	24.5	19.9	1.0	1.0	15.1	2.8	1.6	0.6	0.1
6.5	1.2	0.8	6.1	1.5	15.0	1.9	12.1	72.5	4.8	28.1	15.8	0.0	46.6	0.0	17.3	15.8	13.2	1.7	1.0	18.2	3.7	10.7	0.8	0.0
7.0	1.6	0.7	7.1	1.9	10.4	2.9	23.4	33.2	3.7	64.9	9.9	0.0	38.4	1.3	18.3	6.8	11.9	1.7	1.6	18.3	21.9	15.0	0.6	0.0
7.5	3.0	0.8	6.5	2.1	9.6	4.3	19.7	44.8	2.1	42.8	7.9	0.0	15.7	1.4	15.6	7.0	8.6	1.5	2.5	15.3	47.5	29.7	0.6	0.0
8.0	2.6	0.7	6.3	2.0	7.2	10.6	19.8	53.4	1.2	38.3	7.7	0.0	10.7	1.0	16.8	8.1	6.6	2.3	2.6	14.6	29.1	39.7	0.6	0.1
8.5	3.1	1.0	4.6	2.6	5.8	11.2	22.9	37.5	1.9	55.1	5.3	0.0	7.9	1.0	18.2	5.3	7.5	2.0	1.9	12.8	27.1	20.0	0.7	0.0
9.0	3.2	1.0	3.8	0.0	4.3	5.2	24.2	25.5	1.6	34.2	5.7	0.0	8.5	0.8	15.7	6.3	7.0	1.4	0.8	13.3	26.4	21.9	1.0	0.1
9.5	3.2	1.0	3.0	0.0	3.9	6.1	22.2	12.9	1.5	31.8	5.9	0.0	6.7	0.7	16.4	5.2	5.7	1.2	0.7	8.3	31.3	23.3	0.7	0.0
10.0	3.2	0.8	1.7	0.0	3.2	6.3	17.7	21.3	1.6	31.9	4.2	0.0	6.5	1.0	15.4	4.8	4.7	1.1	0.5	12.8	32.2	19.3	1.4	0.1
10.5	3.0	1.0	2.6	0.0	2.8	3.4	18.4	12.7	1.5	37.3	3.6	0.0	4.1	1.8	13.7	2.9	3.6	1.2	0.3	14.6	27.8	11.7	1.1	0.0
11.0	2.8	0.8	2.9	0.0	1.7	3.2	14.7	10.1	1.4	25.8	2.1	0.0	3.7	1.7	10.8	0.1	1.7	0.9	0.3	11.2	16.6	9.0	1.0	0.2
11.5	2.9	0.1	1.4	0.0	0.1	1.2	12.9	10.8	1.4	21.3	0.6	0.0	3.9	1.5	9.5	0.1	1.9	0.8	0.3	9.4	12.8	11.8	1.0	0.0
12.0	0.0	0.0	1.7	0.0	0.0	0.0	0.0	0.0	3.4	15.7	0.8	0.0	1.8	1.4	0.0	0.1	1.7	0.8	0.6	4.6	10.8	9.5	0.4	0.3
Mean	1.5	0.6	3.0	1.6	16.2	2.5	11.0	15.0	2.5	19.3	12.0	0.3	9.1	0.6	8.5	6.1	18.4	1.5	1.7	8.2	13.2	10.0	3.2	0.1
Total (t/ha)	0.27	0.12	0.55	0.28	2.93	0.46	1.98	2.70	0.46	3.48	2.15	0.05	1.64	0.10	1.52	1.10	3.31	0.27	0.31	1.47	2.37	1.80	0.57	0.01

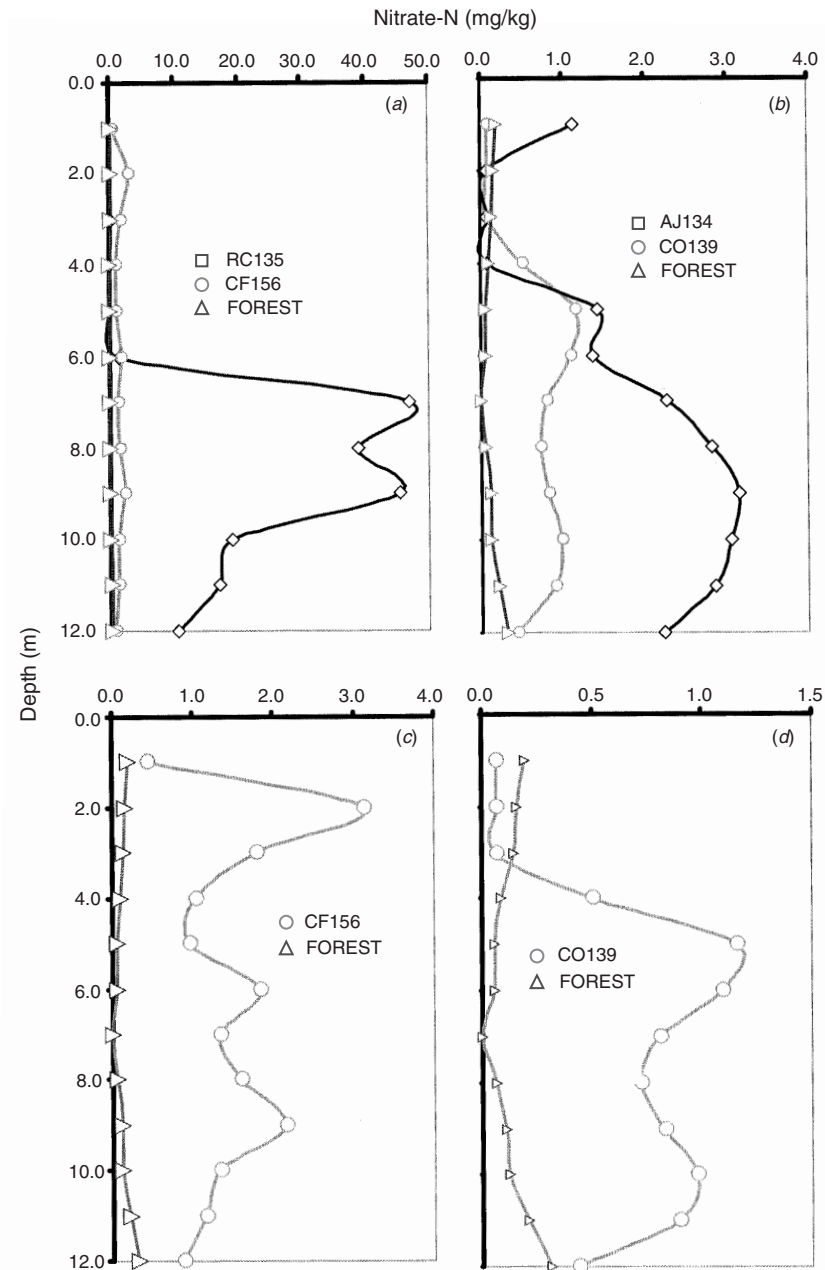


Fig. 2. Nitrate-N concentration in selected sugarcane profiles compared with rainforest.

For a better appreciation of nitrate retention in soil profiles in relation to the quantities of fertiliser-N applied, the concentration data (mg/kg) were transformed to N-load (kg/ha). The N-load at 1–12 m depth under cropping ranged from 10 to 3475 kg/ha, compared with 11 kg/ha for the rainforest (Table 2).

Table 3. The distribution of selected soil properties, averaged across profiles, under sugarcane and the minimum, maximum, and mean values of the properties across and within profiles

Depth (m)	Soil organic carbon (g/kg)	Total nitrogen	CEC	AEC	Total cations	Sulfate-S (mg/kg)	Chloride (mg/kg)	EC (dS/m)	pH
			(cmol _c /kg)						
0.15	16.8	0.91	1.22	0.76	2.44	216	11.3	0.08	4.96
1.15	3.77	0.19	0.59	2.34	1.17	541	17.5	0.08	4.88
2.15	3.02	0.11	0.63	2.66	1.26	537	26.0	0.04	4.91
3.15	2.21	0.06	0.82	2.56	1.65	514	29.5	0.04	4.96
4.15	1.77	0.06	1.09	2.26	2.19	431	31.9	0.04	5.34
5.15	1.78	0.06	1.53	2.07	3.05	363	33.7	0.04	5.00
6.15	1.63	0.05	2.05	1.88	4.10	224	43.2	0.03	5.17
7.15	1.40	0.04	1.98	1.67	3.96	114	52.6	0.03	5.20
8.15	1.27	0.04	1.97	1.36	3.95	83	43.2	0.03	5.23
9.15	1.42	0.05	2.75	1.36	5.51	69	40.1	0.03	5.47
10.15	1.42	0.04	3.30	1.05	6.61	56	35.0	0.03	5.50
11.15	1.39	0.04	3.74	0.86	7.47	40	24.0	0.02	5.42
Min.	0.10	0.01	0.05	0.05	0.20	2.3	1.0	0.01	4.21
Max.	23.3	1.60	43.1	4.06	53.9	1270	156	0.60	6.20
Mean	3.00	0.20	5.1	1.73	3.6	278	34	0.04	5.22

N-load and soil types

The maximum, minimum, and mean values for the measured soil properties (CEC, AEC, pH, EC, Ca, Mg, K, Na, SOC, sulfate, and chloride) are provided in Table 3. In general, the average nitrate, sulfate, chloride, AEC, or CEC across the Pin Gin soils was higher than the corresponding non-Pin Gin value, and the non-Pin Gin soils were slightly less acidic than the Pin Gin soils (Table 4). Across the 19 Pin Gin profiles, the N-load ranged from 30 to 3475 kg/ha. In 13 out of the 19 Pin Gin profiles the N-load was >1000 kg/ha, and 30–1000 kg/ha in the other 6 profiles. Across the non-Pin Gin soils, excluding the Mundoo, the N-load ranged from 12 to 545 kg/ha. In only 1 non-Pin Gin (DJ133) was the N-load (10 kg/ha) less than in the rainforest. Exclusive of this location, the N-load at each one of the 27 cultivated sites was higher than the rainforest site.

The average N-load across the 19 Pin Gin profiles was 1580 kg/ha, compared with 590 kg/ha across the non-Pin Gin soils. Although Mundoo is a non-Pin Gin, the N-load is comparable to the average N-load in the Pin Gin. The high N-load in Mundoo could be attributed to basalt origin (Murtha 1986) and similar surface charge characteristics

Table 4. Mean values for soil properties of the Pin Gin soils compared with non-Pin Gin

pH	EC (dS/m)	Total N (g/kg)	Soil organic C (g/kg)	Total cations (cmol _c /kg)	AEC	CEC	Chloride	Sulfate-S (mg/kg)	Nitrate-N
<i>Pin Gin soils</i>									
5.17	0.04	0.20	3.2	0.98	2.09	4.50	42.7	357	9.12
<i>Non-Pin Gin soils</i>									
5.38	0.05	0.20	3.10	1.29	0.92	3.16	11.8	153	1.52
<i>Rainforest</i>									
5.30	n.d.	15.0	n.d.	0.29	2.83	1.18	15.0	n.d.	0.12

n.d., Not determined.

(Gillman and Abel 1987) to the Pin Gin. The average N-load across the other 7 non-Pin Gin soils was 185 kg/ha. At catchment scale, the average N-load under sugarcane was ≈ 635 kg/ha. Obviously, with fertiliser-N annual application rates ranging from 100 to 200 kg/ha, N-loads >200 kg/ha in profiles cannot be attributed to adsorption and retention of the whole fertiliser applied in a single year. N-load as high as 3475 kg/ha indicates that nitrate accumulation was probably an ongoing process over several years. The results generally show nitrate adsorption, accumulation, and retention in the JRC is widespread and the quantities retained seem to depend on soil type.

It should be noted here that the aforementioned N-load is only that assumed to be adsorbed at anion exchange sites (Eqn 1). In addition, there was ≈ 720 kg/ha in soil-water, which we consider not being adsorbed at exchange sites, in Pin Gin soils compared with ≈ 85 kg/ha in non-Pin Gin. Thus, the average N-load across Pin Gin profiles was ≈ 2290 kg/ha compared with ≈ 270 kg/ha in non-Pin Gin. The water-extractable nitrate in the Pin Gin is relatively high, and we suspect that at least some of it was desorbed during water extraction and was counted as that in soil-water. We cite Eqn 2 as evidence for our claim. Further, recently Rasiah *et al.* (2003) showed that the nitrate-N load in groundwater from some of these bore sites that are now serving as piezometers ranged from 40 to 110 kg/ha. Thus, it seems that some discrepancy exists with regard to the adsorbed *v.* soil-water nitrate. There is only one method available to resolve this issue—suction cup sampling for soil-water nitrate-N determination, which is difficult, if not impossible to determine up to 12 m depth. Therefore, for the purpose of this study we consider the adsorbed nitrate-N as the conservative estimate computed using Eqn 1.

N-load and trash retention

Although green-trash blanketing for sugarcane was introduced ≈ 15 years ago, the impact of this practice on nitrate retention seems unclear. However, a comparison of N-load in the trash-burned Pin Gin site DJ133 (≈ 11 kg/ha) with that of the trash-retained Pin Gin site CF147 (22 kg/ha) suggests that there was a response to trash retention. Nevertheless, it could also be argued that the response to trash retention was small, because the N-loads at both sites are relatively low compared to the average N-load of 1580 kg/ha for the Pin Gin soils. Therefore, in the absence of data on trash burned *v.* retained systems at a given site, it is unwise to conclude the difference observed in this study represents a response to differences in management. It has been suggested the trash-N turnover requires several years for significant nitrate release to occur, thereby contributing towards nitrate accumulation and retention.

At site PB140 a trash-burn system was in place under no-till sugarcane until 1987; since then, this site has been under grass fallow. The high N-load in this profile in 1998, 1999, or 2000 cannot be attributed to recent fertiliser-N input or that derived from trash. Repeated coring at this site in 1999 and 2002 produced data that showed little or no changes in nitrate distribution between years, suggesting the adsorbed nitrate was not being lost through other processes, such as denitrification and/or leaching further down the profile, and/or nitrate additions through native soil organic sources (Table 2).

Nitrate retention and soil properties

Because nitrate adsorption is primarily a chemical process, the following issues need clarification: whether the (i) nitrate bulges corresponded with AEC; (ii) Pin Gin with high N-load possesses the capacity to retain more nitrate than the current load; and (iii) low N-load in non-Pin Gin soils is associated with insufficient nitrate retention capacity.

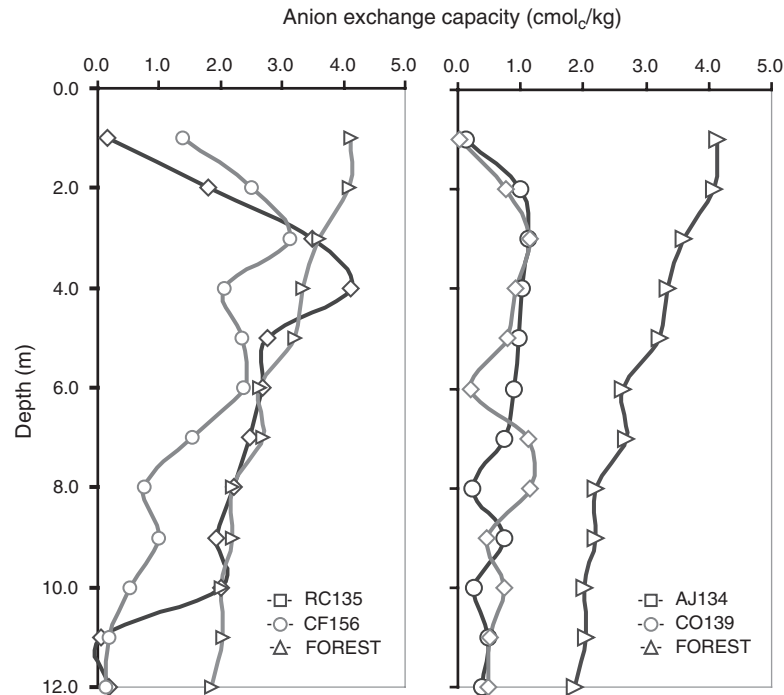


Fig. 3. Anion exchange capacities in selected sugarcane profiles compared with rainforest.

Because nitrate adsorption occurs at anion exchange sites, a brief description of it is relevant at this point. The AEC distributions shown in Fig. 3 for typical profiles indicate that it varied within and across profiles and showed a trend to decrease with depth. The AEC across and within profiles ranged from 0.05 to 4.06 cmol_c/kg compared with 2.01 to 4.12 cmol_c/kg under rainforest (Table 3 and Fig. 3). In general, the AEC of the Pin Gin soils was higher than the non-Pin Gin soils (Table 4) and the AEC of the rainforest was comparable to the Pin Gin soils (Fig. 3).

The AEC and nitrate distributions shown in Fig. 4 indicate little or no relationship between AEC and nitrate distributions, particularly where the nitrate bulges were observed. Given that nitrate bulges were generally observed at depths of 2–12 m, AEC bulges would be expected at these depths. For example, in the soil with high N-load (RC135, Fig. 4), AEC at 6 and 7 m was 2.48 and 2.21 cmol_c/kg , respectively, whereas the corresponding N-load was 150 and 232 kg/ha , respectively. This suggests the high N-load was not necessarily associated with higher AEC or *vice versa*. The bulges deep down in the profiles may be reflecting bypass flow, whereby the AEC adsorption sites at shallower depths were bypassed by the rapid percolation transporting the nitrate from shallower depths under high intensity and rainfall conditions, which is not unusual in this catchment. However, nitrate adsorption and accumulation does occur at anion exchange sites and this chemical phenomenon is supported by the positive correlation that exists between nitrate and AEC (Table 5).

The distributions of selected soil properties, averaged across the cropped profiles (Table 3), indicate that, in general, at depths >1 m the SOC, total N, sulfate, and EC decreased with depth, whereas there was an opposite trend for chloride, CEC, and pH. The sulfate-S across and within profiles ranged from 2 to 1266 mg/kg compared with 1 to

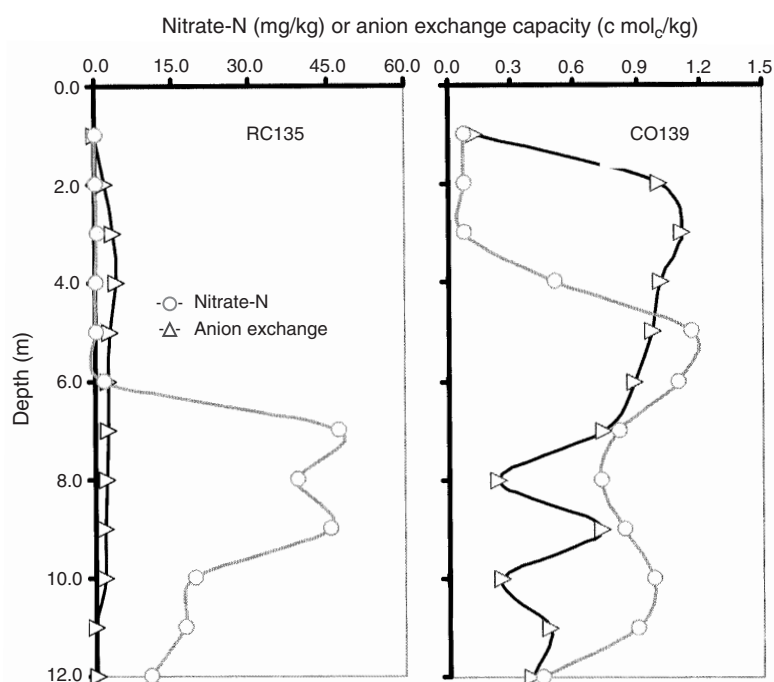


Fig. 4. Nitrate-N distribution in selected soil profiles compared with anion exchange capacity.

156 mg/kg for chloride and 4.21 to 6.20 for pH. Under the rainforest the sulfate ranged from 220 to 1100 mg/kg compared with 0 to 18 mg/kg for chloride, and pH from 5.2 to 5.7. In general, there was a significant difference between rainforest and cropped profiles for chloride distribution and load (data not shown). This is anticipated because of high muriate of potash (KCl) input, an average of 150 kg K/ha.year, for sugarcane in this catchment during the last 50 years. The simple correlations between nitrate and other soil properties, provided in Table 5, are consistent with our previous findings (Rasiah and Armour 2001).

Table 5. A summary of the results of the simple linear correlation analysis of nitrate-N v. the other soil properties

Soil property	Correlation coefficient, r , and the significance level (P)		
	Pooled data	Pin Gin	Non-Pin Gin
Anion exchange capacity	+0.29*	+0.22*	+0.44**
Cation exchange capacity	-0.19*	-0.25*	n.s.
Soil organic carbon	-0.13*	-0.15*	n.s.
pH	-0.37**	-0.48**	n.s.
Total nitrogen	n.s.	n.s.	n.s.
Total cations	-0.19*	-0.20*	-0.22*
Chloride	+0.70***	+0.67***	+0.84***
Sulfate	n.s.	n.s.	n.s.
Electrical conductivity	n.s.	+0.33**	n.s.
No. of observations.	287	180	112

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; n.s., not significant.

In general, positive correlations existed between nitrate and chloride or EC and negative associations between nitrate and CEC, SOC, pH, or TC.

According to Katou *et al.* (1996), competitive anion adsorption at exchange sites was in the order sulfate > chloride > nitrate. In the Pin Gin profiles the sulfate concentrations were ≈ 30 –40 times higher than nitrate, whereas chloride concentrations were 5 to 8 times higher than nitrate (Table 4). Sulfate in the profiles is mostly native (Table 3), i.e. derived from atmospheric deposition, whereas chloride and nitrate are derived from fertiliser and their adsorption and accumulation depend on competition with sulfate and/or each other, and the hydraulic characteristics of profiles. It seems the positive association between nitrate and chloride (Table 5) is not chemically feasible, and we reported a similar trend in our previous paper (Rasiah and Armour 2001). In order to explore this inconsistency, and the sulfate > chloride > nitrate competitive adsorption phenomenon, we transformed the extractable anion concentration data into equivalent fractions (EF) of sulfate, chloride, and nitrate (Fig. 5). In general, the distributions show that when the EF of sulfate in the profiles decreased there was a corresponding increase in nitrate and chloride. For example, the intersection points of the curves indicate that when the EF of sulfate decreased to 0.4 (at ≈ 6 m) in RC153, a rapid increase in the EF of nitrate and chloride occurred. It was below the sulfate, nitrate, chloride EF intersection point that large quantities of nitrate accumulation occurred or the nitrate bulges were observed, i.e. at depths >6 m depth (Fig. 2a). Although intersection points were not observed in AJ134 and CO139, rapid decreases in EF of sulfate from ≈ 1 to 0.6 in AJ134 at 8 m depth, and from ≈ 1 to 0.8 in CO139 at 6 m depth, corresponded with increases in EF of nitrate and chloride in these profiles (Fig. 5). In general, it seems that nitrate accumulation and bulges in profiles were observed at depth where rapid reductions in EF of sulfate occurred (Fig. 2b, d, and Fig. 5). Further, the smaller the value of EF of sulfate the larger was the N-load in profiles. Thus, we suggest that the magnitude of N-load and the depth at which nitrate accumulation and retention occur depended on the competition offered by native sulfate anion in the form of EF of sulfate and its distribution in profiles.

The functional relation between nitrate-N concentration (mg/kg) and the soil properties (listed in Table 3) as independent variables was explored using the stepwise multiple regression procedure. This approach produced the following equation:

$$\text{NO}_3 = 167.5 + 8.7\text{AEC} + 217.4 \text{ EC} - 10.6 \text{ pH} - 139.4 \text{ EF-SO}_4 - 162.5\text{EF-Cl}$$

$$(R^2 = 0.77, P < 0.001) \quad (3)$$

where EF-SO₄ and EF-Cl are equivalent fractions of sulfate and chloride, respectively. Eqn 3 indicates the primary soil variables that controlled nitrate adsorption were AEC (adsorption capacity), pH, and EC (through ionic strength) and the competing anions sulfate and chloride. These variables accounted for 77% of the variability in nitrate retention in soil profiles.

Nitrate accumulation and retention deep in soil profiles could also be attributed to the rainfall pattern and hydraulic properties of the soils in the catchment (see *Introduction*). The wet season rainfall (2500–3000 mm from December to April with frequent high intensity storms), following high N-fertiliser applications, and high hydraulic conductivity of soil profiles probably provided conditions favourable for the rapid transport, possibly in bypass flow, of nitrate and chloride deep down into profiles, rather than their retention at shallower depths.

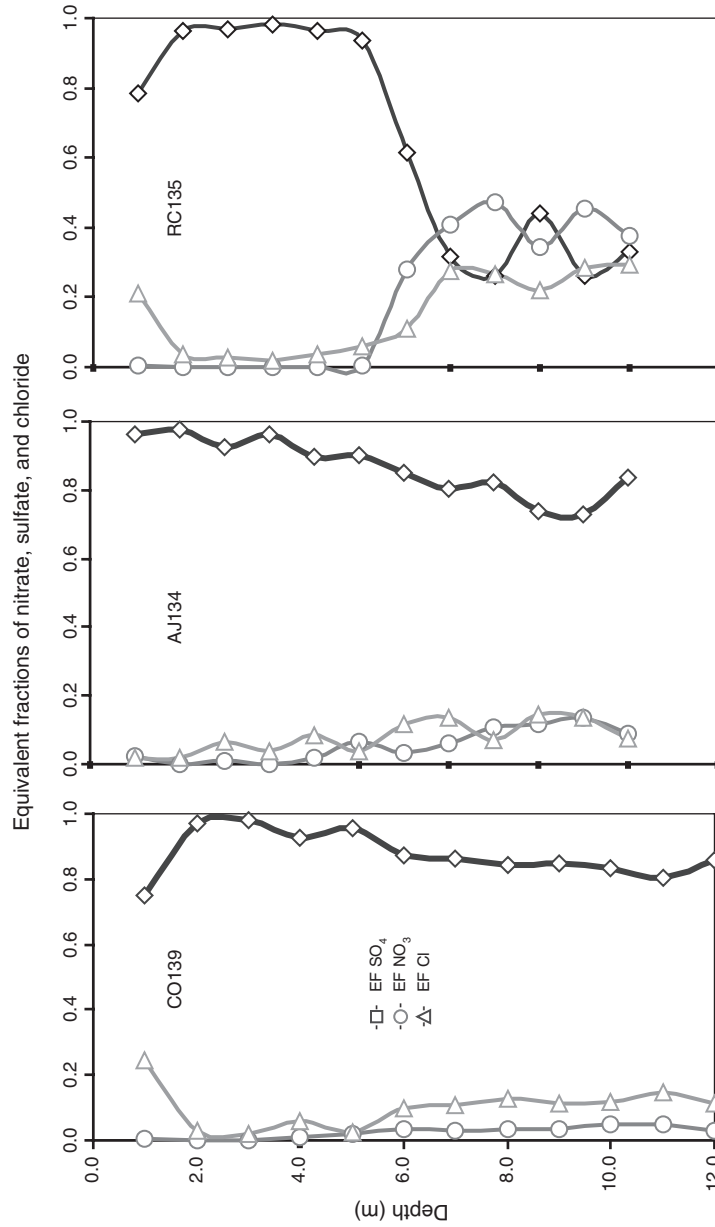


Fig. 5. The distribution of equivalent fractions of sulfate (EF SO₄), nitrate (NO₃), and chloride (Cl) in selected soil profiles.

Maximum potential nitrate retention capacity (MPNRC)

Wong *et al.* (1990) proposed a procedure to compute MPNRC, which the authors suggested as an index that can be used for assessing soils' anion retention capacity. We have adopted the MPNRC approach in this study. We assumed that 75% of the AEC was reserved for other anions such as sulfate and chloride, i.e. the MPNRC reflects only 25% of the total AEC. In our previous paper (Rasiah and Armour 2001), the MPNRC values were computed invoking 50% reservation for sulfate and chloride. We modified this assumption because of the very high native sulfate content in profiles, the data for which were not available during the preparation of our previous paper. The MPNRC is used to assess whether the Pin Gin soils with a high N-load still possess the capacity to retain more nitrate, and whether the low N-load in non-Pin Gin soils is the result of insufficient retention capacity. Our computation showed that in AJ134, the MPNRC to a depth of 12 m was 4.8 t N/ha, whereas the N-load was only 0.27 t N/ha, or 5.6% of the MPNRC. On the other hand, in RC135, the MPNRC was 11.7 t N/ha and the current N-load was only 2.7 t N/ha, or 23% of the MPNRC. In general, the MPNRC in JRC ranged from 3.1 to 16 t N/ha, suggesting that the major soils in JRC possess a large capacity for the accumulation and retention of nitrate. A comparison of N-loads, including the non-Pin Gin soils, with the corresponding MPNRC suggests that these soils still possess substantial capacity to serve as a natural filter, thereby reducing the N-load that leaves profiles through lateral flow, hence reducing the contamination of on- and off-site water bodies (Rasiah *et al.* 2003).

A comparison of N-load and MPNRC indicates sufficient capacity to retain the nitrate that leached below the root-zone generally, and in particular in the non-Pin Gin soils. Thus, the low N-load in profiles, particularly in the non-Pin Gin soils, is attributed, at least partially, to the high wet season rainfall and high hydraulic conductivity as indicated previously.

Multiple regression analysis produced the following equation for MPNRC:

$$\text{MPNRC (t/ha)} = 16.3 - 6.2 \text{ SOC} - 0.34 \text{ CEC} - 20.8 \text{ 7EQ-Cl} \quad (R^2 = 0.72, P < 0.001) \quad (4)$$

where SOC is soil organic carbon (%) and EQ-Cl is the equivalent fraction of the exchange sites occupied by chloride. Although SOC appears as a term in Eqn 4, the effect of this term is very small (Table 3 and 4) compared with the effect of the chloride term; the effect of the SOC term also decreased rapidly with increasing depth. Because sulfate in these soils is mostly native, rather than fertilizer-derived, it seems that the primary input variable that controlled MPNRC is chloride-based fertilisers. Thus, it seems reduction in chloride based fertiliser use may increase MPNRC, which in turn may be useful in decreasing the amounts of nitrate entering the deep groundwater or lateral-flow. Further, chloride is highly mobile, like nitrate, and high concentrations of it in soil and water may be environmentally unacceptable.

N-load predictions

The N-load (NL) as a function of soil properties was explored using stepwise multiple regression analysis and the procedure produced the following equation:

$$\text{NL} = 1256.4 - 1045.5 \text{ EFSO}_4 - 1218.7 \text{ EFCl} + 16300 \text{ EC} - 79.2 \text{ pH} + 65.3 \text{ AEC} \quad (5)$$

$$(R^2 = 0.54, P < 0.001)$$

where NL in kg/ha and other terms have already been defined previously in Eqn 3 and Table 3. Eqn 5 indicates that N-load is controlled by the availability of anion adsorption sites (the primary variable), pH, which controls the dynamics of AEC, the inherent variable sulfate, and the input variable chloride. It is evident from Eqn 5 that the only management variable that controlled N-load in soil profiles is chloride based fertilisers.

Nitrate retention and environmental concerns

Using the data on profile N-load, the average fertiliser-N input history, and the N-load in groundwater (Rasiah *et al.* 2003), we propose to deduce the environmental benefits of nitrate filtering and the magnitude of leaching that might have occurred to account for the accumulation of large quantities of nitrate in soil profiles and/or that in groundwater. Although this exercise is empirical and provides a crude mass-balance, the implications are shown to be significant in relation to the potential for N-load discharge to off-site water bodies.

We mentioned elsewhere in the text that the nitrate leached below the root-zone ranged from 30–50 kg/ha.year of the 170 kg/ha of the fertiliser-N applied annually (Prove and Moody 1997). However, the fertiliser-N input in the catchment ranged from 100 to 200 kg N/ha.year (Rasiah and Armour 2001) and ≈ 140 kg N/ha.year across the 28 core sites according to the producers. It seems that under the minimum leaching (30 kg N/ha.year) scenario, it would have taken at least 6 years for 185 kg N/ha accumulation to occur in non-Pin Gin soil types or ≈ 50 years for the 1550 kg N/ha (average) to accumulate in the Pin Gin soils, provided all the nitrate that leached below the root-zone was adsorbed at the anion exchange sites. It should be noted here that there was another ≈ 720 kg N/ha in soil water in the Pin Gin soils and this would require an additional ≈ 25 years, at least, for the accumulation to occur. At site RCR151 it would have taken at least 120 years for 3475 kg N/ha accumulation to occur. However, sugarcane cultivation under N-fertiliser input has been in place in this catchment for a maximum of 65–70 years. Further, preliminary results indicate the N-load in the shallow fluctuating groundwater that developed during the wet season (January–May) in the JRC ranged from 40 to 110 kg nitrate-N/ha and the potential existed for a major proportion of this nitrate to be discharged into drains/creeks and/or through lateral-flow (Rasiah *et al.* 2003). Thus, it seems the leaching losses were much higher than the 30–50 kg/ha.year, particularly in the Pin Gin soils to account for the high N-load in soil profiles and that in groundwater.

The potential for adsorption and accumulation to occur is high when the profile is relatively dry, i.e. from June to November. During this period, however, most of the nitrate that leached below the root-zone might have been leached out from the profile by lateral-flow and/or entered deep groundwater (Rasiah *et al.* 2003). Further, adsorption and retention of 100% of the nitrate leaching below the root-zone is very unlikely in this catchment, because the high rainfall, hydraulic conductivity, and lateral-flow favour the transport and discharge of nitrate into creeks/streams, etc., rather than being adsorbed at anion exchange sites (Rasiah *et al.* 2003), even though the potential nitrate retention capacity is not a limiting factor.

Small N-loads (185 kg N/ha) in the non-Pin Gin soils imply that ≈ 1315 kg/ha of the nitrate-N that leached below the root-zone during the last 50 years, under the minimum leaching scenario, either denitrified or entered lateral-flow and/or deep groundwater. However, the high N-load in groundwater, mentioned previously, indicates a major proportion of the leached nitrate was in groundwater. The larger N-load in groundwater of non-Pin Gin soils than the Pin Gin soils (Rasiah *et al.* 2003) supports the hypothesis that

the lateral-flow from the former was higher than the latter and that this led to small N-load in the non-Pin Gin soils. Thus, we suggest the low nitrate filtering by non-Pin Gin soils could contribute to high N-loading in drains/creeks from agricultural land to off-site water bodies. In this context, we suggest more stringent fertiliser-N input management practices to be considered for non-Pin Gin soils.

In general, the high N-load in soil profiles, particularly in Pin Gin soils, suggests this soil served as a nitrate filter, thereby reducing the risk, at least partially, of discharge of the nitrate leaching below the root-zone to off-site water bodies, including GBR lagoon. On the other-hand, the small N-load in non-Pin Gin soils suggests they were not as efficient as the Pin Gin soils in nitrate filtering; therefore, the nitrate leaching below the root-zone from these coarser profiles was probably discharged into drains/creeks etc.

Conclusions

Nitrate-N adsorption/accumulation/retention under sugarcane occurred well below the root-zone, at depths between 2 and 12 m, and is widespread across the JRC. The magnitude of the N-load in deep profiles depended on soil type and was higher in Pin Gin soils than the other 8 non-Pin Gin soils, exclusive of Mundoo. The role of sugarcane green trash retention practice on nitrate retention is unclear. Retention of large quantities of N, particularly in Pin Gin profiles, suggests that these soils served as nitrate filter, thereby reducing the risk, at least partially, of discharging of the nitrate leached below the root-zone into off-site water bodies, including GBR lagoon. Low retention in non-Pin Gin soils indicates that most of the nitrate that leached below the root-zone probably entered water bodies and/or denitrified. The current N-load in profiles in conjunction with high MPNRC suggests that nitrate accumulation and retention is not yet limited, either in Pin Gin or non-Pin Gin soils, by the available potential capacity of soils. The magnitude of the MPNRC values also suggests that these soils still possess a large capacity to adsorb and retain nitrate in addition to what is already held in profiles. Although nitrate is adsorbed and retained deep in the profiles, the amounts retained accounted for only a fraction, particularly in non-Pin Gin sites, of that leached below the root-zone over several years. The fate of the un-adsorbed nitrate in soil profiles needs urgent attention in relation to on- and off-site ecosystem environmental health issues, because this nitrate is available for transport in lateral-flow and/or to deep groundwater. The widespread nature of nitrate retention in the JRC suggests that N fertiliser management practices need to be refined to minimise nitrate leaching below the root-zone (e.g. through slow release N use, fly-ash, legume green manure N). The economics of the nitrate leached below the root-zone should be addressed with producer groups, to encourage them to switch over to cost-effective N-input practices that will reduce nitrate leaching. Nitrate derived from ammonia-based fertilisers and leached below the root-zone also poses subsoil acidification risk.

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