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Nitrogen leaching losses from different forms and rates of farm effluent applied to a Templeton soil in Canterbury, New Zealand

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Abstract The leaching losses of nitrogen from a range of farm effluents and wastes, including pig slurry, dairy pond sludge, farm-dairy effluent, and cow urine are compared on a Templeton fine sandy loam. At similar rates of application, leaching losses decreased in the following order: cow urine>pig slurry>farm-dairy effluent>dairy pond sludge. The susceptibility to leaching is determined by the forms of the N in the waste, and a high N:C ratio alone is not an adequate predictor of leaching intensity. Nitrate is most susceptible to leaching, followed by ammonium and organic forms of N. Splitting the applications of effluent into two or four portions applied at different times reduced the overall quantity of nitrate leached by c. 30%, depending on the waste. Similarly, reducing the overall rate from 400 to 200 kg N/ha also reduced the N leaching loss by c. 30%, depending on the particular waste. It is recommended that the land application of farm waste be based on a knowledge of the propensity of different kinds of wastes to contaminate groundwater, especially with nitrate-N. An effective mitigation technology to reduce nitrate leaching from grazed pasture soils is to treat the soil, including cow urine areas, with a nitrification inhibitor, e.g., dicyandiamide (DCD), which has been found to reduce nitrate leaching losses by 60%, decrease nitrous oxide emissions by over 75%, and increase pasture yield by over 10%.

Keywords farm; effluent; nitrate; leaching; urine; waste; nitrification inhibitor; pasture; water quality

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INTRODUCTION

Land application of wastes is becoming more widespread as regulatory authorities move to protect water quality by restricting waste disposal into rivers, lakes, and the marine environment (Cameron et al. 1997). The pressure to dispose of wastes onto land rather than into water often results in engineers being forced to design land treatment systems with little rigorous scientific information to guide them.

Wastes may contain valuable nutrients as well as toxic elements depending on their source (Cameron et al. 1997). Nitrogen in waste can be a valuable resource for crops and pasture plants, but there is a downside to its use depending on its chemical form. Nitrate leaching losses following land application of different farm effluents and wastes may pose an environmental risk that needs to be evaluated in a manner that compares the impact of one waste type relative to another. However, this is usually difficult to achieve from a comparison of published research because of differences in experimental conditions such as soil type, method of measurement, and climatic condition, as well as management practice.

In an attempt to address this difficulty, a series of lysimeter experiments was conducted at Lincoln University using a range of farm effluents and wastes applied to a single soil type under reasonably similar climatic conditions and pasture management methods. The results of these experiments have been published in a series of separate papers (Fraser et al. 1994; Cameron et al. 1996; Carey et al. 1997; Di et al. 1998a,b, 1999, 2002; Silva et al. 1999). Key results from these experiments are compared in this paper enabling an evaluation of their relative impacts.

The objective of this paper is to compare the leaching losses of nitrogen, in particular nitrate, from a range of farm effluents and wastes, including pig slurry, dairy pond sludge, and farm-dairy effluent. The leaching losses from these wastes will be examined in “cut and carry” and “grazed” pasture management systems that are distinctly different in relation to their nitrate leaching characteristics. The effects of rate of application on the amounts of nitrate lost from the systems will also be examined.

MATERIALS AND METHODS

Soil and pasture

The soil used was a Templeton fine sandy loam (Immature Pallic Soil, Hewitt 1998; Haplustepts, Soil Survey Staff 1998) from a Lincoln University farm located about 20 km south of Christchurch on the Canterbury plains. Key properties of this soil are given in Table 1. The soil texture changes from fine sandy loam in the surface layer to sandy loam or loamy sand down to between 65 and 120 cm depth, below which lie gravels. The pasture at the site is a mixture of perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*).

Lysimeters

A detailed description of lysimeter collection and installation has been given previously by Cameron et al. (1992). In brief, cylindrical lysimeters of 80 cm diameter and 120 cm depth (or 50 cm diameter × 70 cm depth) were collected by digging around the lysimeter casing and gradually pushing it down over the exposed soil monolith by small increments. A cutting plate was pushed under the lysimeters and the monolith was secured before being lifted out of the collection site. The bottom 5 cm soil in the lysimeter was replaced with gravels to create a free-draining condition similar to that in the field. The gap between the soil core and the metal casing was sealed using petrolatum and this ensured there were no edge-flow effects (Cameron et al. 1992). The lysimeters were installed in an underground lysimeter laboratory, or a field trench facility, with the surface of the lysimeters at the same level as that of the surrounding paddock, thus ensuring that plant growth occurred under normal field conditions. Pasture was cut periodically to simulate typical grazing practice.

Leachates were collected from the lysimeters daily or weekly depending on drainage rates and were analysed for nitrate, nitrite, and ammonium concentrations by flow injection analysis (FIA) (Tecator Inc., Sweden) or ion exchange chromatography (IEC) (Waters Inc., USA).

Farm-dairy effluent (FDE)

The FDE treatments were applied at rates of 200 and 400 kg N/ha per yr, split into either two or four equal applications of 50, 100, or 200 kg N/ha (Di et al. 1998a,b, 1999; Silva et al. 1999). For each application, fresh FDE was collected early in the morning, immediately after milking, and was analysed for

Table 1 Properties of the Templeton soil used in the lysimeter experiments.

Depth (cm)	pH	Organic C (g/kg)	Total N (g/kg)	Bulk density (t/m^3)	Total porosity (v/v%)
0–20	5.3	24.6	2.0	1.32	49
20–40	5.4	8.0	0.7	1.49	44
40–60	5.8	2.3	0.3	1.52	43
60–80	6.3	2.0	0.3	1.44	46

Table 2 Typical average chemical characteristics of farm effluents and wastes used in lysimeter experiments.

Waste	Total N (mg/litre)	NH_4-N (mg/litre)	NO_3^--N (mg/litre)	Total C (mg/litre)	C:N ratio	Reference
Farm-dairy effluent	238	55	0	1868	7.8	Di et al. (2002)
Farm-dairy effluent	350	95	0	3880	10.8	Di et al. (1998a)
Dairy pond sludge	1597	153	9	17 364	10.8	Cameron et al. (1996)
Pig slurry	1628	1026	0	1987	1.2	Carey et al. (1997)

total N concentration (Cameron et al. 1996). The required volume of FDE was then calculated on the basis of the total N concentration, and applied by pouring it onto the surface of the lysimeters. Typical average effluent characteristics are presented in Table 2.

Dairy pond sludge

Dairy pond sludge was collected on the “old” Lincoln University Dairy Farm by pumping bottom sediment from an anaerobic treatment pond. Dairy pond sludge was applied to the soil surface in a single application of 300 kg N/ha per yr or injected into the soil at 25 cm depth using a modified subsoiler (Cameron et al. 1996). Typical properties of the dairy pond sludge are given in Table 2.

Pig slurry

Unscreened pig slurry was collected from a local piggery and the chemical composition determined for each batch used. Typical chemical characteristics are given in Table 2.

Urine

In the experiments by Silva et al. (1999) and Di et al. (2002), urine was collected from Holstein Friesian milking cows that had been fed on ryegrass-white clover pasture. In the experiments by Di et al. (2002) the urine was labelled with ^{15}N in order to determine the fate of urine N and calculate a mass balance of N applied. The ^{15}N label consisted of highly enriched (>99% atom% ^{15}N) urea-N and glycine-N in a 9:1 ratio to give a final enrichment of 5% (atom%) ^{15}N after mixing with the urine. In the experiments by Fraser et al. (1994), synthetic urine was made up from urea, glycine, potassium chloride, bicarbonate, and sulphate.

Fertiliser

In the experiments where urea fertiliser was used it was applied at rates of 200 and 400 kg N/ha per yr, split into either two or four equal applications of 50, 100, or 200 kg N/ha (Di et al. 1998a,b; Silva et al. 1999; Di et al. 2002). The fertiliser was dissolved in water beforehand and was applied in the same volume of solution as that of the FDE. The same volume of water without N was applied to the controls.

Irrigation

From November to April (summer), either spray irrigation was applied once per month through a sprinkler to half of the lysimeters at a rate of 50 mm per month (i.e., 300 mm total), or flood irrigation was applied at 100 mm per month (i.e., 600 mm total). Both irrigation regimes are typical of district practices.

Rainfall

All lysimeters were leached under semi-controlled conditions to simulate a realistic “wet” year or “worst-case” leaching scenario. From May to October (winter), simulated rainfall was applied at the end of each month (if necessary), to supplement the natural rainfall received in order to reach the 75th percentile of local rainfall records for the same period of the year (c. 850 mm versus annual mean of 660 mm). Rainfall was recorded automatically on site using a tipping-bucket measurement system connected to a data logger (Campbell Scientific, USA).

RESULTS AND DISCUSSION

Forms and rates of application under “cut and carry” systems

Comparisons of the nitrate breakthrough curves show that pig slurry applied in a single application at 400 kg N/ha per yr in autumn (April) produced the highest peak nitrate concentration of all the effluent treatments (65 mg N/litre) (Fig. 1 and 2). The same rate of farm-dairy effluent (FDE) applied in two split applications (2 × 200 kg N/ha per yr in May and December) resulted in a lower peak concentration of 10 or 18 mg N/litre, depending on irrigation conditions. When FDE was applied in four split applications (4 × 100 kg N/ha per yr in May, August, November, and February) the peak concentration was reduced even further to 4 mg N/litre. These results emphasise that split applications of effluent and wastes produce less environmental impact than large single applications.

The annual rate of waste or effluent application clearly influences the amount of N leached. The amount of N leached from a single application of pig slurry at 400 kg N/ha per yr was 105 kg N/ha per yr, whilst pig slurry applied at half this rate (200 kg N/ha per yr) resulted in a smaller loss of 30 kg N/ha per yr (Table 3). The amount of N leached per year is also further reduced when the waste or effluent is applied in a series of split applications rather than in a single large application (Table 3). When FDE was applied in four split applications of 100 kg N/ha this resulted in a loss of only 10 kg N/ha per yr, compared with a leaching loss of 13 kg N/ha per yr when applied at 400 kg N/ha per yr but split into only two applications (Table 3).

The amount of N leached (1 kg N/ha per yr) from a single application of dairy pond sludge at 300 kg N/ha per yr was substantially less than that from pig slurry (30 kg N/ha per yr) applied at a lower rate (200 kg N/ha per yr) (Table 3). Both wastes had similar total-N contents but consisted of substantially different forms of N, with ammonium-N being the dominant form in the pig slurry, whilst organic-N forms predominated in the dairy pond sludge (Table 2). The N in the pig slurry was thus in a form that leached more readily compared with the less available organic-N forms present in the dairy pond sludge.

The C:N ratio does not necessarily provide a good index of the availability of N in organic wastes. The amount of N leached from farm-dairy effluent was

Table 3 Summary data on nitrate leaching losses from farm effluent and waste experiments conducted on Templeton soil lysimeters. FDE, farm-dairy effluent.

Form of N	Rate (kg N/ha per yr)	Split per year	Other conditions	Max. peak concentration (mg N/litre)	Loss (kg N/ha per yr)	Reference
(a) Lysimeter results						
Pig slurry	200	1		20	30	Carey et al. (1997)
Pig slurry	400	1		65	105	Carey et al. (1997)
Dairy-pond sludge	300	1	Surface applied	1	<1	Cameron et al. (1996)
Dairy-pond sludge	300	1	Injected @ 25 cm	7	5	Cameron et al. (1996)
Farm-dairy effluent	200	4 × 50	Flood irrigation 6 × 100 mm	4	6	Silva et al. (1999)
Farm-dairy effluent	400	4 × 100	Flood irrigation 6 × 100 mm	4	10	Silva et al. (1999)
Farm-dairy effluent	400	2 × 200	Spray irrigation 6 × 50 mm	18	25	Di et al. (1998a)
Farm-dairy effluent	400	2 × 200	Flood irrigation 6 × 100 mm	10	13	Di et al. (1998a)
Urine patch	500	1		42	40	Fraser et al. (1994)
Urine patch	1000	1	Flood irrigation 6 × 100 mm	120	124	Silva et al. (1999)
Urine patch	1000	1	Flood irrigation 6 × 100 mm	70	77	Di et al. (2002)
Urine plus farm-dairy effluent	1000 urine plus 400 FDE		Flood irrigation 6 × 100 mm	140	90	Di et al. (2002)
Control	0		Spray irrigation 6 × 50 mm	1	2.8	Di et al. (1998a)
Control	0		Flood irrigation 6 × 100 mm	1	2.6	Di et al. (1998a)
Control	0		Flood irrigation 6 × 100 mm	1	1.5	Di et al. (2002)
(b) Paddock scale losses*						
Calculated paddock loss for grazing only without effluent	1000 urine	1	Flood irrigation 6 × 100 mm	10	33	Silva et al. (1999)
Calculated paddock loss for farm-dairy effluent plus urine	1000 urine plus 400 FDE (4 × 100)		Flood irrigation 6 × 100 mm	10	36	Silva et al. (1999)

*Paddock losses calculated using Equation 1.

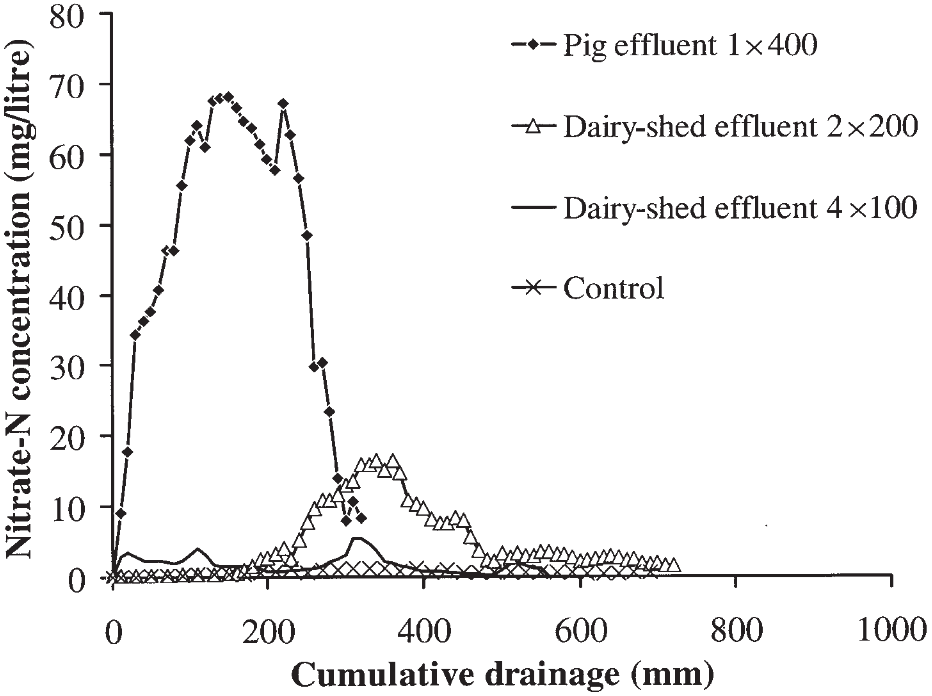

Fig. 1 Concentration of nitrate-N leached from different forms and rates of wastes and fertiliser applied to pasture soil. Types of effluent, frequency, and amount of N applied (kg N/ha per yr) per application are given in the figure. Data from Carey et al. 1997 and Di et al. 1998a.

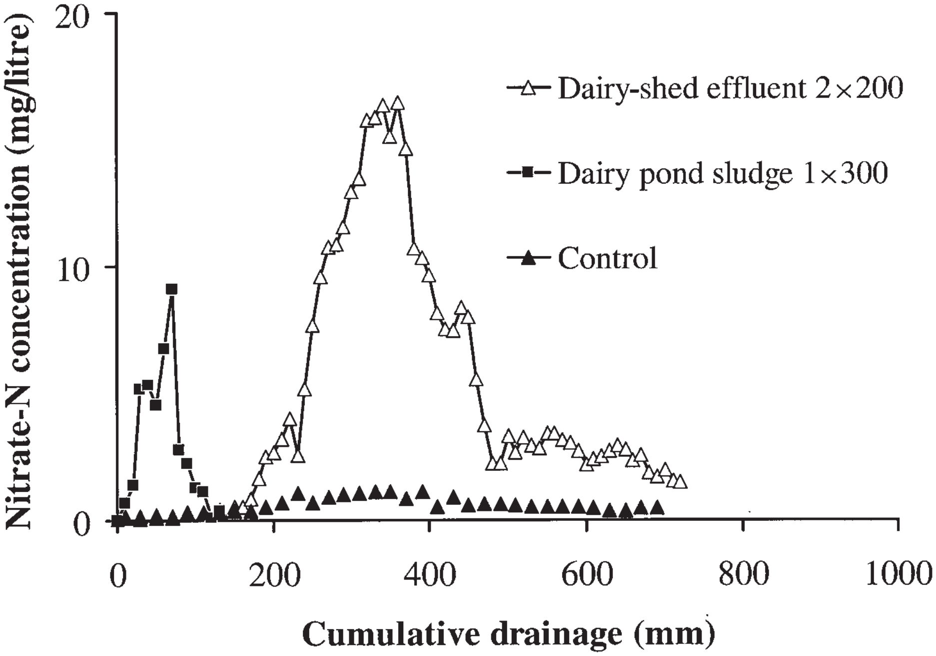

Fig. 2 Concentration of nitrate-N leached from different forms of farm effluents applied to a pasture soil. Types of effluent, frequency, and amount of N applied (kg N/ha per yr) per application are given in the figure. Data from Cameron et al. 1996 and Silva et al. 1999.

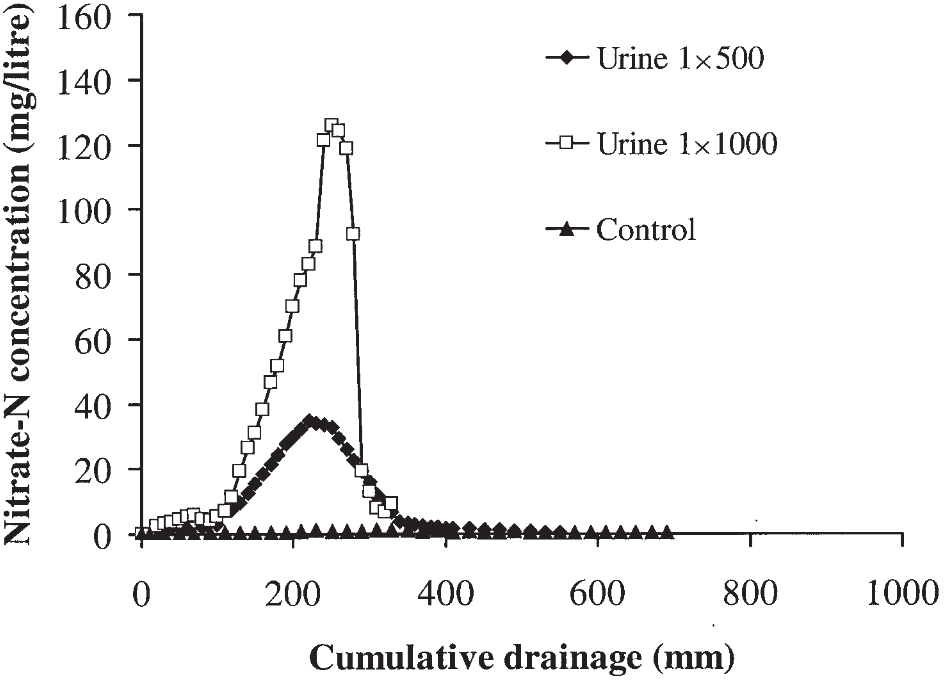

Fig. 3 Concentration of nitrate-N leached from different rates of animal urine applied to a pasture soil. Urine 500 is 500 kg N/ha per yr and Urine 1000 is 1000 kg N/ha per yr. Data from Fraser et al. 1994 and Silva et al. 1999.

higher than that from dairy pond sludge or sewage sludge, despite similar C:N ratios. The form of N (and C) therefore needs to be taken into account when assessing the availability of N in organic wastes. In particular, the potential mineralisation rate of organic-N forms in the wastes needs to be considered when decisions are being made on the appropriate rate of application of waste onto land.

Grazed pasture systems

In grazed pasture systems the leaching loss from animal urine patches usually dominates the loss of nitrogen from the pasture soil (Di & Cameron 2000). The rate of N return in a sheep urine patch is generally less than 500 kg N/ha whilst in a cattle urine patch it is about 1000 kg N/ha (Haynes & Williams 1993). The results in Fig. 3 show that the peak concentration leached from directly below a typical sheep urine patch (42 mg N/litre) is substantially less than that below a typical cattle urine patch (120 mg N/litre).

It is critically important to recognise that in leaching studies conducted in grazed pasture systems there are two distinct statistical populations: (1) urine patch areas with high nitrate concentrations in the drainage water and (2) non-urine patch areas with low nitrate concentrations in the drainage water. Since on grazed dairy farms about 25% of the paddock area receives animal urine per year (Haynes & Williams 1993; Ruz-Jerez et al. 1995), the annual average amount of nitrate-N leached can be calculated using the following formula (Di & Cameron 2000):

$$N_p = N_1 \times P_1 + N_2 \times P_2 \quad (1)$$

where N_p is the calculated annual N leaching loss (kg N/ha) under the paddock, N_1 is the annual average amount of nitrate leached from the urine, or urine plus FDE treatments, which were measured from the lysimeters, N_2 is the annual average amount of nitrate-N leached from the control and/or FDE treatment alone, measured from the lysimeters and P_1 and P_2 represent the proportion of urine patch and non-urine patch areas, respectively.

The calculated annual paddock average concentration (Silva et al. 1999 in Table 3b) was 12-fold lower than the annual average concentration of nitrate measured directly below the cow urine patch lysimeters (Silva et al. 1999 in Table 3a). The

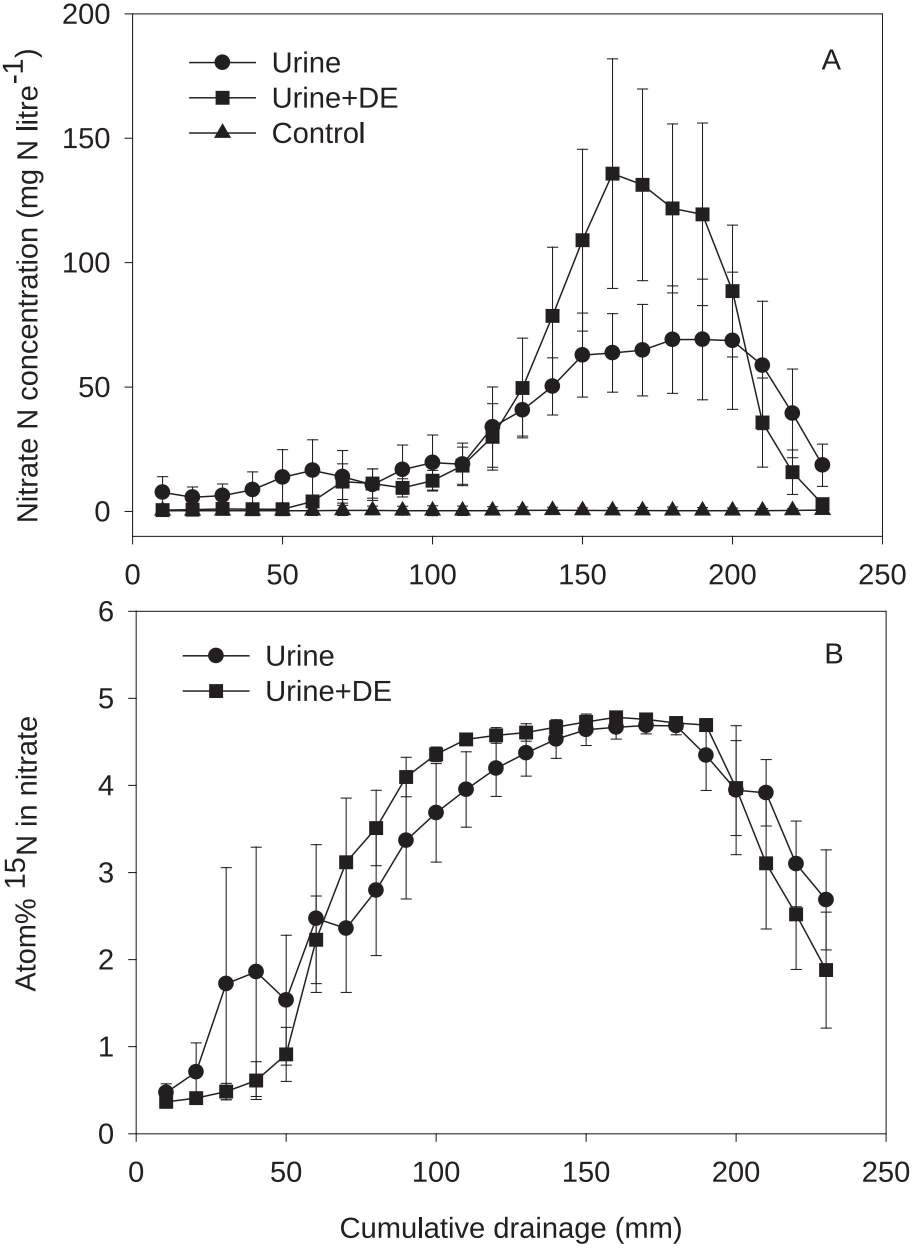

Fig. 4 **A**, Nitrate-N concentrations in the leachate (±SE); **B**, ^{15}N enrichment in the leachate NO_3^--N (±SE).

calculated amount of N lost from the paddock (33 kg N/ha per yr) was also lower than that measured from directly below the urine patch (124 kg N/ha per yr). Calculation of the N leaching loss from a grazed pasture must therefore account for both the urine and non-urine patch areas.

In the work of Di et al. (2002) there was a trend of greater peak NO_3^--N concentration in the Urine + FDE treatment than in the Urine alone treatment (Fig. 4A), although this was not always significant. The concentration in the Control was low. The ^{15}N enrichment in the NO_3^--N in the leachate increased with increasing drainage volume, peaking near 5% (atom%), which was the ^{15}N enrichment of the labelled urine N (Fig. 4B). The amount of NO_3^--N leached over the year was 1.5 kg N/ha in the Control, but this increased to 77 kg/ha in the Urine treatment and 90 kg/ha in the Urine + FDE treatment (Di et al. 2002 in Table 3a). However, the difference between the Urine and Urine + FDE treatments was not statistically significant.

Of the ^{15}N applied in the urine, 6.4–9.1% was recovered in the leachate, 29.3–38.8% was recovered in the pasture tops, 25.4–28.3% remained in the soil, and 19.2–20.3% was retained in the plant roots (Table 4). The recovery of ^{15}N in the harvested pasture was significantly higher ($P < 0.01$) in the Urine treatment than in the Urine + FDE treatment. The amount of ^{15}N unaccounted for was higher in the Urine + FDE treatment (13.9%) than in the Urine treatment (5.3%), although this was not statistically significant.

In this experiment by Di et al. (2002), the application of FDE at 400 kg N/ha per yr did not result in a significant increase in NO_3^--N leaching loss. This was probably due to a large proportion of the N in the FDE applied being in organic forms, from the cow dung, and therefore it would take time for this N to be released by mineralisation, resulting in a relatively lower risk of nitrate leaching compared with the N applied in the urine.

Because a large proportion of the NO_3^--N leached in a grazed pasture system is from urine patch areas, mitigation measures should focus on reducing NO_3^--N leaching from these urine spots. Di & Cameron (2002, 2003, 2004a,b) have shown that by treating grazed pasture soil, including urine patch areas, with a nitrification inhibitor, dicyandiamide (DCD), nitrate leaching can be reduced by about 60%. This could reduce NO_3^--N concentration in the drainage water from the most free-draining soils (e.g., shallow stony Lismore soil) under dairy farming to below the drinking water guideline (11.3 mg NO_3^--N/litre). In addition, the use of the nitrification inhibitor has been found to reduce nitrous oxide (N_2O) emissions by between 75–80% (Di & Cameron 2003). Because of increased N use efficiency, pasture yield is also increased by more than 15% following the treatment with DCD. Therefore, the treatment of grazed pasture soil with a nitrification inhibitor not only provides environmental benefits by reducing nitrate leaching and nitrous oxide emissions, but also provides agronomic benefits by increasing pasture production.

CONCLUSIONS

The main conclusions are:

1. At similar application rates leaching losses decrease in the following order: cow urine>pig slurry>farm-dairy effluent>dairy pond sludge.
2. Split applications of farm effluents reduce the risk of N leaching and are preferable to a single annual application.
3. The form of N (and C) in the waste should be taken into account when setting regional rules for land application rates of farm effluents.
4. Calculation of the N leaching loss from farm effluent applied to grazed pasture must take into

Table 4 Recoveries of ^{15}N in the leachate, pasture tops, soil-and roots following land application of farm-dairy effluent (FDE) with and without animal urine (Di et al. 2002). NS, not significant.

	% ^{15}N recovery		
Components	Urine (±SE)	Urine + FDE (±SE)	
Volatilisation	2.0 (0.2)[a]	2.0 (0.2)[a]	NS
Leachate	6.4 (1.7)	9.1 (2.5)	NS
Pasture top	38.8 (1.8)	29.3 (0.4)	**
Pasture roots	19.2 (1.5)	20.3 (2.0)	NS
Soil	28.3 (0.9)	25.4 (1.0)	NS
Total	94.7 (2.5)	86.1 (3.5)	NS
Unaccounted for	5.3 (2.5)	13.9 (3.5)	NS

[a]Estimates based on volatilisation measurements (^{15}N was not measured in the volatilisation experiment); **$P < 0.01$.

account the loss from both the urine and non-urine patch areas.

5. An effective mitigation strategy to reduce nitrate leaching from grazed pasture soils, including those receiving farm effluent, is to treat the soil with a nitrification inhibitor (e.g., DCD).

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