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Winter nitrate leaching losses from three land uses in the Pukekohe area of New Zealand

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Abstract The effects of three different land uses (dairy grazing, winter potatoes, and winter greens [spinach, cauliflower or cabbage] production) on soil mineral N contents and nitrate leaching losses from late June to early October 2000 were investigated on 18 commercial paddocks. All paddocks were in the Pukekohe area (approximately 50 km south of Auckland) on Patumahoe clay loam soils and received typical management practices for the district. On average, dairy paddocks received the least amount of N fertiliser during the study period (84 kg N ha^{-1}), had the lowest soil mineral N content in June (32 kg N ha^{-1}) and had the lowest leaching loss (15 kg N ha^{-1}). On average, potato paddocks received the greatest amount of N fertiliser (481 kg N ha^{-1}), had the greatest soil mineral N content in June (184 kg N ha^{-1}) and had the greatest leaching loss (114 kg N ha^{-1}). The winter greens paddocks were intermediate between the other land uses. Leaching losses from the potato and greens paddocks were the result of large applications of fertiliser N before winter and the rapid mineralisation of residues from the previous greens crops.

Keywords nitrate leaching; dairying; potato; green vegetables; groundwater; fertiliser

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INTRODUCTION

Elevated nitrate concentrations have been measured in shallow groundwater and surface water in many areas of New Zealand (Bright et al. 1998; Francis et al. 1999). In most cases, non-point sources in intensive agricultural production systems are regarded as the main contributor to this contamination (Selvarajah et al. 1994; Cathcart 1996). However, the land use that contributes most to this contamination may vary between regions. For example, contamination of groundwater and surface water in New Zealand is perceived to be a serious consequence of dairy farming in some regions (de Klein & Ledgard 2001) and of winter vegetable production in other regions (Anon. 1997; Crush et al. 1997). Similar concerns have been reported overseas for both dairy production (e.g., Jarvis 2000) and vegetable crops (e.g., MacDonald et al. 1997; Waddell et al. 2000).

Leaching losses under dairying arise from high rates of N cycling in grazed pastures, with the size of the potential leaching loss increasing with the stocking rate (Jarvis 2000). Most of the nitrate that is leached from dairy pastures comes from urine patch areas, which have very high concentrations of N that are greatly in excess of immediate plant requirements (Haynes & Williams 1993; Ledgard et al. 1999). In contrast, nitrate that is leached from winter vegetable crops largely originates from either applied N fertiliser or from the breakdown of postharvest crop residues. High rates of N fertiliser are often applied to these crops in an attempt to overcome their slow growth rates and their sparse root systems (Goulding 2000). Yields are often increased by these high fertiliser rates, although fertiliser recovery rates are often low, leaving large amounts of N in the soil that are susceptible to leaching (Greenwood et al. 1989; Rahn et al. 1992). The return of large amounts of postharvest plant residues also contributes to the high leaching loss potential under vegetable cropping. The returned residues usually have low C:N ratios and mineralise rapidly when incorporated, resulting in the accumulation of large amounts of nitrate in the soil (De Neve & Hofman 1998; Rahn et al. 1998; Mitchell et al. 2001).

Measurements of nitrate leaching losses have previously been reported for a number of different land uses in New Zealand (Painter et al. 1997). Research has also investigated ways of reducing nitrate leaching losses from particular land uses (e.g., Francis 1995; Williams et al. 2000a). However, as leaching losses can vary greatly from year to year, mostly in relation to rainfall amount and distribution, it can be difficult to make comparisons between studies that are conducted in different locations or in different years. Indeed, few, if any, studies in New Zealand have measured nitrate leaching losses from commercial paddocks under different land uses in the same locality and season. The aim of this study was to compare nitrate leaching losses from commercial paddocks under three different land uses (receiving typical management practices) in the same year in the same district to assess the relative impacts of these land uses on potential groundwater nitrate contamination.

MATERIALS AND METHODS

Site and soil

The study was conducted from late June to early October 2000 on 18 commercial paddocks in the

Table 1 Nitrogen fertiliser applied before and during winter leaching, soil profile mineral contents before and after winter leaching, and cumulative leached N for the different land uses (all units are kg N ha^{-1}).

Land use	Paddock	Fertiliser applied before winter leaching	Soil mineral N before winter leaching[1]	Fertiliser applied during winter leaching	Soil mineral N after winter leaching[2]	Cumulative leached N[3]	Paddock leached N[4]
Dairy	D1	10	38	55	26	14	14
	D2	10	22	55	63	14	14
	D3	10	38	85	32	29	29
	D4	10	30	85	42	14	14
	D5	45	26	50	38	11	11
	D6	10	42	85	35	10	10
	Mean[5]	16	32	68	38	15	15
Potatoes	Unfert. area (P1)	0	65	0	25	40	40
	P1	0	39	472	216	122	89
	P2	472	470	0	75	295	193
	P3	472	622	0	247	204	138
	P4	414	158	77	48	134	96
	P5	414	145	77	52	152	107
	P6	414	148	77	106	79	63
	Mean[5]	364	184	117	101	164	114
Greens	Unfert. area (G6)	0	82	0	25	73	73
	G1	64	215	60	110	240	173
	G2	124	152	0	146	142	114
	G3	124	151	0	203	175	134
	G4	124	193	0	172	73	73
	G5	150	117	100	22	85	80
	G6	0	93	250	41	91	84
	Mean[5]	98	148	68	90	134	110
	LSR (d.f. = 30)[6]		2.0		2.0		
	LSD (d.f. = 15)[1]					60	

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[1] For comparisons between land use means.

[2] Back-transformed from the log-transformed data (i.e., equivalent to geometric means).

[3] Calculated from soil solution nitrate concentrations and drainage beneath the fertilised area.

[4] Adjusted for fertilised and unfertilised areas (see text for details).

[5] For fertilised areas.

[6] Least significant ratio, for comparisons between land use means.

Pukekohe area (approximately 50 km south of Auckland), supporting either dairy farming, winter greens [spinach, cauliflower or cabbage] or winter potato production. All paddocks had well-drained Patumahoe clay loam soil (Orbell 1974), an allophanic oxidic granular soil in the New Zealand soil classification (Hewitt 1998). Sixteen of the paddocks were located within a 2-km radius, centred on the Crop and Food Research Farm in Pukekohe (NZMS 260 R12 756423). The other two paddocks (both growing greens) were located 15 km away. Six paddocks of each land use were selected, and all were managed by growers according to their standard practices. Each paddock had a long, documented history of its respective land use. For this region, mean annual rainfall is 1321 mm and mean annual drainage is 632 mm. On average, more than 60% of this drainage occurs between June and October (Anon. 1986). Daily meteorological data during the study was measured on the Crop and Food Research Farm in Pukekohe.

Paddock management

The six dairy paddocks (D1–D6) were on the same farm, under similar management practices. All dairy paddocks grew ryegrass (*Lolium perenne*)/white clover (*Trifolium repens* L.) pastures and had an average stocking rate for the whole year of 2.5 cows ha^{-1}. Each paddock was block grazed at approximately 250 cows ha^{-1} day^{-1} three times during the study. Cows were removed from these paddocks at night. Dairy shed effluent was not applied to these paddocks either before or during the study. Fertiliser N (10 kg N ha^{-1}) was applied to all paddocks in autumn (April/May), with additional fertiliser (25–35 kg N ha^{-1}) applied shortly after each grazing event. All fertiliser was surface broadcast, with a total of 65 – 95 kg N ha^{-1} applied to the dairy pastures between late April and October (Table 1).

The winter potato paddocks were located on two separate properties (P1–P3 and P4–P6), but all paddocks had very similar management practices. After each potato crop (harvested in October), paddocks were surface worked and sown with a cover crop of oats (*Avena sativa* L.). The oat crops were mulched before paddocks were ripped, mouldboard ploughed, and surface worked. Beds (1.6–1.7 m wide, with wheeltracks 60–70 cm between the beds) were then formed before potatoes were planted (between early May to mid June) and beds ridged. A total of 472–491 kg N ha^{-1} fertiliser was applied to the potato crop beds (which covered approximately 60% of each paddock's area). The majority (76% averaged over all the paddocks) of the fertiliser was applied at planting, at a depth 20 cm below the soil surface. The remainder of the fertiliser was applied as two small side dressings (each about 40 kg N ha^{-1}) during the growing season, which were surface banded over the beds. A fertiliser trial with four replicates was present in part of paddock P1, the unfertilised treatment of which was also sampled as part of this study.

The greens paddocks were also located on two separate properties (G1–G4 and G5–G6). Four of the paddocks (G1–G4) were growing spinach continuously, with the other paddocks growing either cabbage (G5) or cauliflower (G6) in a cabbage-cauliflower rotation. Cover crops were not grown in these greens paddocks. Between crops, paddocks were ripped, mouldboard ploughed, and surface worked. Beds (1.6–1.7 m wide, with wheeltracks 60–70 cm between the beds) were then formed before the greens crops were planted in mid to late June. A total of 124–250 kg N ha^{-1} was applied to the greens crop beds (which covered approximately 60% of each paddock's area). The majority (60% averaged over all the paddocks) of the fertiliser was applied at planting at a depth 10 cm below the soil surface. The remainder of the fertiliser was applied as one or two side dressings (total of 60–100 kg N ha^{-1}) during the growing season, which were surface banded over the beds. A fertiliser trial with five replicates was present in part of paddock G6, the unfertilised treatment of which was also sampled as part of this study.

For the potato and dairy paddocks, most of the N fertiliser was applied as urea, whereas the winter greens paddocks received a mixture of urea and calcium ammonium nitrate. Due to the rapid conversion of urea to ammonium and nitrate, the form of N in the applied fertilisers was not expected to have a major impact on the extent of N leaching during the experiment.

Postharvest residues from the previous crops were returned to the soil for both the winter greens and potato crops. The amount of N contained in these residues varied between crops (spinach = 13 kg N ha^{-1}; cabbage = 85 kg N ha^{-1}; cauliflower = 206 kg N ha^{-1}; potatoes = 5 kg N ha^{-1}) (C. S. Tregurtha unpubl. data).

Sampling and analysis

Soil samples were taken from all paddocks at the start and end of winter leaching, in late June and early October, respectively. The exception was paddock P1, from which the pre-leaching samples were taken in May. For each of the dairy paddocks, three sampling positions were randomly selected. For each of the potato and greens paddocks, three sampling positions were randomly selected within the fertilised areas. Additional samples were taken from the non-fertilised treatments of the fertiliser trials in paddocks P1 and G6. In all paddocks, two samples at each position were taken from 0–15, 15–30, and 30–60 cm depths. Each sample was thoroughly mixed, subsampled, and the field moist soil analysed for ammonium- and nitrate-N.

After planting, five porous ceramic samplers 25 mm wide and 55 mm long were installed to 60 cm depth in random locations within the fertilised areas in each of the potato and greens paddocks. Additional samplers (five per replicate) were installed in the non-fertilised treatments of the fertiliser trials in paddocks P1 and G6. Ten porous ceramic samplers were installed in random locations in each of the dairy paddocks. Soil solution samples were extracted within 24 h of each significant (>20 mm) rainfall event. Nitrate leaching losses were determined from mean soil solution nitrate concentrations at successive samplings and the calculated drainage between these samplings (Francis et al. 1992). The amount of drainage was calculated from a simple water balance based on measured initial soil moisture, daily rainfall, and evapotranspiration (Jamieson et al. 1995). Estimates of the crop ground cover were used to partition water use between transpiration and bare soil evaporation. Ammonium-N and nitrate-N in soil solution samples and soil extracts were determined as described in Francis et al. (1992).

Soil solution nitrate concentrations and cumulative nitrate leaching losses were analysed with analysis of variance (ANOVA). Soil mineral N data were analysed with ANOVA after first log-transforming the data (to make the variability more homogeneous across the treatments). In Table 1, the presented paddock and land use means for soil profile mineral N data are back-transformed from means of the log-transformed data. For each land use, therefore, the average of individual paddock back-transformed means is not the same as the presented land use mean. Similarly, for each land use the sum of the individual depth data in Table 2 is not the same as the presented land use profile mean in Table 1. Comparisons between land use means or depth means are made using the least significant ratio (LSR). The LSR is the smallest ratio between two back-transformed means (largest mean/smallest mean) such that the larger mean is significantly greater than the smaller mean. Between and within paddock variability were separately estimated within the analysis of variance, and differences between land uses were compared with the between paddock variability. Sample dates were included as a split-plot treatment in the analysis, and depths as split-split plot treatments. In the tables and graphs, only a selection of possible LSDs/LSRs are presented for simplicity.

RESULTS AND DISCUSSION

Rainfall and drainage

Total rainfall from late June to early October 2000 (512.8 mm) was fairly evenly distributed (Fig. 1) and was similar to the long-term average (524 mm) (Anon. 1986). Consequently, nitrate leaching losses from the trial paddocks are likely to be representative of long-term mean losses for the district. Calculated drainage amounts were also relatively evenly distributed throughout the trial period (Fig. 1). Drainage was similar for all land uses, as frequent

Table 2 Mean soil mineral N contents before and after winter leaching under fertilised dairy, potato, and greens paddocks. The presented means are back-transformed from the log-transformed data (i.e., equivalent to geometric means).

	Soil mineral N content (kg N ha^{-1})					
	Before winter leaching (cm)			After winter leaching (cm)		
Land use	0–15	15–30	30–60	0–15	15–30	30–60
Dairy	25.9	6.2	7.3	29.5	7.4	9.1
Potatoes	13.0	198.7	88.9	19.7	27.6	70.1
Greens	80.8	35.1	42.2	22.1	18.1	66.4
LSR (d.f. = 30)[1]		2.3			2.3	

[1] Least significant ratio.

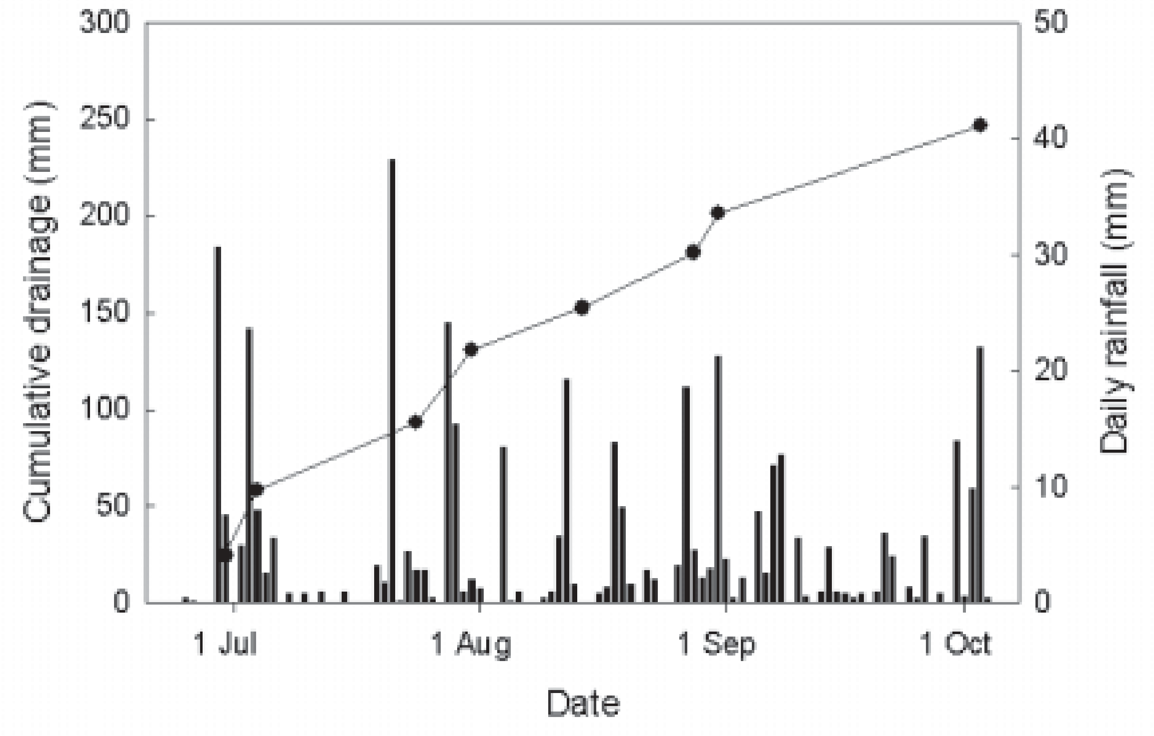

Fig. 1 Daily Pukekohe rainfall and cumulative winter drainage averaged for the three land uses in winter (late June–early October) 2000.

rainfall events and low evapotranspirative demand resulted in similar amounts of water being lost through transpiration and bare soil evaporation (Francis et al. 1998).

Soil mineral N contents

Mean soil profile mineral N contents before the start of winter leaching varied significantly between land uses. Dairy paddocks had the lowest contents, while fertilised potato paddocks had the highest contents (Table 1). These differences were largely the result of different N fertiliser application rates for the three land uses. The average N fertiliser rates applied to the different land uses in this study are typical of the Pukekohe district (Crush et al. 1997; Ledgard et al. 1999; de Klein & Ledgard 2001). In contrast, mineral N contents were low in the greens and potato paddocks to which no fertiliser had been applied before sampling. The range in mean soil mineral N content between paddocks under the same land use was relatively small (up to 20 kg N ha^{-1}) for the dairy paddocks, but very large (up to 477 kg N ha^{-1}) for the potato paddocks that had been fertilised before sampling (i.e., excluding paddock P1). The range in mean soil mineral N content between the greens paddocks that had been fertilised before sampling (i.e., excluding paddock G6) was intermediate (up to 122 kg N ha^{-1}). The small range in the dairy paddocks was due to the even, surface broadcasting of low rates of N fertiliser and uniform uptake of N by pasture. In contrast, the greater range for both the fertilised potato and greens paddocks probably resulted from variation in the application rate of the large amounts of fertiliser N that was applied before sampling. The uneven distribution across the paddock of postharvest residues from the previous crop may also have contributed to the range in measured soil mineral N content, especially for the cabbage and cauliflower paddocks.

The form and depth distribution of the soil mineral N before winter leaching varied between land uses. On average, most of the mineral N in the soil profile was present in the surface (0–15 cm) layer of dairy soil (Table 2), as N inputs from urine and fertiliser (mainly as ammonium) were applied to the soil surface. The rate of urea hydrolysis and

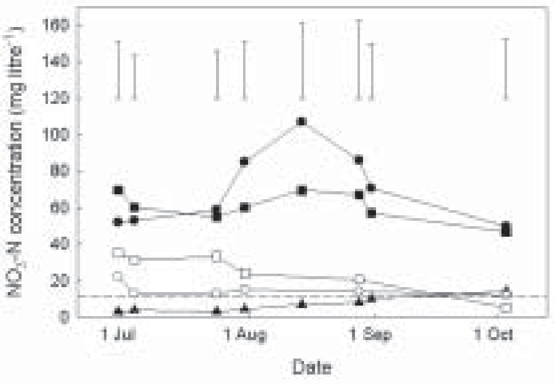

Fig. 2 Mean soil solution nitrate concentrations under fertilised dairy (▲), potato (●) and greens paddocks (■) and under unfertilised potato (○) and greens paddocks (□). Vertical bars represent LSDs (d.f. = 15) for comparisons between the different fertilised land uses at each sampling date. The dashed line is the New Zealand drinking water standard.

nitrification of ammonium was rapid at this depth, with almost all the mineral N present as nitrate (data not shown). In the potato paddocks, most of the mineral N was present at 15–30 cm depth. Fertiliser had been banded 3–6 weeks before sampling at 20 cm depth in these paddocks as either urea or ammonium. The applied fertiliser was still undergoing nitrification at the time of sampling as a large proportion of the soil mineral N was present as ammonium (data not shown). In the greens paddocks, some fertiliser (as urea, ammonium, and nitrate) had been banded at 10 cm depth and some fertiliser had been applied to the soil surface 1–3 weeks before sampling. As a result, most of the mineral N in the soil profile was present at 0–15 cm depth, with about 30% of it present as ammonium at this depth (data not shown). In the unfertilised areas of paddocks P1 and G6, soil mineral N contents increased with depth. The proportion of the mineral N at 30–60 cm depth was about 50% in the greens paddock and about 75% in the potato paddock (data not shown). All the vegetable paddocks used in this trial had a history of long-term cropping and would have had low organic matter and mineralisable N contents (Haynes & Francis 1990; Haynes & Tregurtha 1999). Recovery of applied N fertiliser by vegetable crops is often low (MacDonald et al. 1997), so it is likely that the mineral N in the unfertilised soil was partly unrecovered fertiliser N that had been applied to the previous crop and had subsequently been leached to this depth. In the cabbage and cauliflower paddocks, some of the mineral N may have originated from the large amount of crop residues that was returned to the soil when the previous crop was harvested. The residues of these vegetable crops have low C:N ratios, so rapidly mineralise when incorporated into the soil (De Neve & Hofman 1998; Rahn et al. 1998; Goulding 2000; Mitchell et al. 2000).

After winter leaching, mean soil profile mineral N contents were still significantly greater in the potato and greens paddocks than in the dairy paddocks (Table 1). Most of the soil mineral N was present as nitrate at all depths for all land uses due to nitrification of the applied fertiliser N between sampling events (data not shown). Between the sampling times, mean soil mineral N contents had stayed almost constant under dairy, but had decreased under both greens and potatoes. The soil mineral N contents in the unfertilised areas of paddocks P1 and G6 also decreased between the sampling events. The changes in soil mineral N content between sampling times were due to different amounts of leaching loss and crop uptake for the three land uses (see later). For dairy, the average distribution of mineral N was similar at both sampling times. For both the fertilised greens and potato paddocks there was an increase in the proportion of mineral N at 30–60 cm depth after winter leaching, due to the movement of nitrate down the soil during winter leaching. All land uses had similar soil mineral N contents at 0–15 cm depth, but there was significantly more mineral N at 15–60 cm depth under the fertilised greens and potatoes than under dairy land use (Table 2).

Soil solution nitrate concentrations and nitrate leaching losses

Mean soil solution NO_3-N concentrations at 60 cm depth were significantly greater throughout the trial under the fertilised potato and greens paddocks than under the dairy paddocks (Fig. 2). This was due to the greater soil nitrate contents in the fertilised potato and greens paddocks than in the dairy paddocks, especially deeper in the profile. Concentrations under the dairy and fertilised greens paddocks were relatively constant, whereas concentrations under the fertilised potato paddocks increased markedly during August. The increase in mean concentration in the potato paddocks would have been caused by the leaching to 60 cm depth of some of the very large amount of mineral N that was at 15–30 cm depth at the start of winter. Mean NO_3-N concentrations under the fertilised potato and greens paddocks exceeded the New Zealand Drinking Water Standard

(NZDWS) of 11.3 mg litre^{-1} (Anon. 2000) at all sampling events. High nitrate concentrations have previously been measured under crops of winter potatoes (Prunty & Greenland 1997; Waddell et al. 2000) and winter green vegetables (P. H. Williams unpubl. data). Such high concentrations are due to the very high rates of N fertiliser that are commonly applied to winter vegetable crops to maximise their marketable yield and value (Rahn et al. 1992). These crops have shallow (less than 60 cm deep) and sparse root systems and are very inefficient at recovering applied fertiliser N (Greenwood et al. 1989; Goulding 2000). Concentrations under the unfertilised areas of the greens and potato paddocks were lower than under the respective fertilised areas throughout the trial. Nevertheless, concentrations under the unfertilised paddocks also exceeded the NZDWS throughout most of the trial, probably due to unrecovered fertiliser N that had been applied to the previous crop and mineralisation of residues, especially from previous cabbage and cauliflower crops. In contrast, mean concentrations under the dairy paddocks were below 11.3 mg litre^{-1} throughout most of the trial.

Mean cumulative nitrate leaching losses were significantly greater throughout the trial from the fertilised areas of the greens and potato paddocks than from the dairy paddocks (Fig. 3), mainly due to the differing solution sampler nitrate concentrations under the three land uses (Fig. 2). Losses from the unfertilised areas in paddocks P1 and G6 were lower than from the fertilised potato and greens paddocks, but were higher than from the dairy paddocks. The mean cumulative loss over the winter (late June to early October) from the dairy paddocks in this study (15 kg N ha^{-1}) was lower than the estimated annual loss of 30–45 kg N ha^{-1} (Francis et al. 1999; de Klein & Ledgard 2001) from typical dairy farms (stocking rate 2.5–2.8 cows ha^{-1}; annual N fertiliser input 50–60 kg N ha^{-1}) or the measured annual loss of 20–74 kg N ha^{-1} (Ledgard et al. 1999) from Waikato dairy farmlets (stocking rate 3.3 cows ha^{-1}; no N fertiliser applied). In Pukekohe, however, only about 60% of the annual drainage and leaching occurs on average from late June to early October (Anon. 1986). Consequently, losses during winter only are expected to be lower than annual losses.

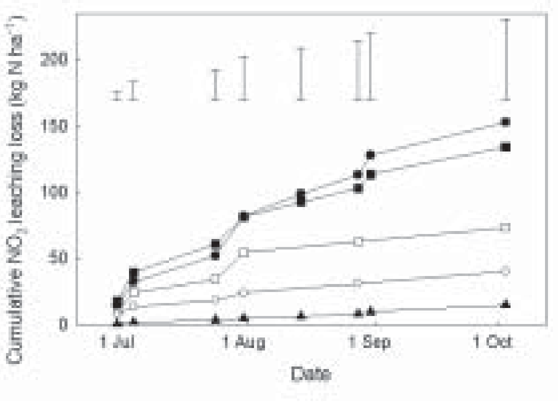

Fig. 3 Mean cumulative nitrate leaching losses from fertilised dairy (▲), potato (●) and greens paddocks (■) and under unfertilised potato (○) and greens paddocks (□). Vertical bars represent LSDs (d.f. = 15) for comparisons between the different fertilised land uses at each sampling date.

Losses from the fertilised land uses in Fig. 3 were calculated by assuming that 100% of the paddock area was covered by fertiliser. This was a reasonable assumption for the dairy paddocks in which fertiliser was surface broadcast. However, in the greens and potato paddocks, fertiliser was only applied to about 60% of each paddock's area. Consequently, for potato and greens land use cumulative losses averaged for the paddock were calculated as:

$$\text{Paddock average loss} = (FA \times FL)/100 + (UA \times UL)/100$$

Where FA and UA are the amounts of the paddock (in %) covered by the fertilised and unfertilised areas respectively, and FL and UL are the cumulative losses from the fertilised and unfertilised areas, respectively. Using this approach, mean cumulative losses were calculated to be 114 kg N ha^{-1} for the potato paddocks and 110 kg N ha^{-1} for the greens paddocks.

Cumulative losses from the potato paddocks in this study were similar to other measured losses of 80–115 kg N ha^{-1} from winter potato paddocks fertilised at rates of 308–520 kg N ha^{-1} and receiving average amounts of winter rainfall (P. H. Williams unpubl. data). Similarly, losses from spinach paddocks (G1–G4) in this study were similar to the reported loss of 140 kg N ha^{-1} from winter spinach in 1998 fertilised at a rate of 250 kg N ha^{-1} (Williams et al. 2000b). Losses from the cabbage and cauliflower paddocks (G5 and G6) were less than the reported loss of 178 kg N ha^{-1} for cabbage paddocks in 1999 that were fertilised at 150 kg N ha^{-1} (Williams et al. 2000b). This difference is not surprising, as leaching losses can vary substantially from year to year in relation to winter rainfall amount and distribution (Francis 1995). Winter rainfall in 2000 was similar to the long-term mean, whereas winter rainfall in 1999 was greater than the long-term mean. In addition, in 1999 more of the winter drainage occurred soon after planting than in 2000. Consequently, in 1999 the cabbage plants would have taken up very little N before drainage started, leaving more mineral N in the soil at risk of leaching.

The amount of N removed in animal products from the dairy paddocks was calculated at about 23 kg N ha^{-1} over the 4-month study. This figure is based on a 2-month dry period and a 2-month lactating period, during which periods mean pasture consumption was assumed to be 5.5 and 13.65 kg DM cow^{-1} ha^{-1} respectively (MAFTech 1987). The N content of the pasture was assumed to be 4% (de Klein & Ledgard 2001), with 80% of the consumed N returned to the soil as urine and dung (Haynes & Williams 1993). This calculation suggests that during the study period the N inputs were about 60 kg N ha^{-1} greater than the N removed in animal products, when averaged across the paddock. This is a relatively small difference and is consistent with the low mean N leaching losses from the dairy paddocks over the winter. However, most leaching losses from dairy paddocks occur from urine patches (Ledgard et al. 1999; de Klein & Ledgard 2001), as these localised areas have very high mineral N contents of up to 1000 kg N ha^{-1} (Francis et al. 1999)—well above the amount that can be rapidly taken up by the pasture. Nonetheless, as urine patches occupy only a fraction of the paddock's area (Haynes & Williams 1993), mean losses from dairy paddocks are usually relatively low, compared with cropping.

The ratio of crop N uptake to the amount of applied N fertiliser varied considerably between crops. The amount of N taken up by potatoes in the foliage, tubers, and roots was measured in paddock P1 at 114 kg N ha^{-1}, with over 95% of this N in the tubers (C. S. Tregurtha unpubl. data). As this was very similar to the mean N output in tubers of 115 kg N ha^{-1} from winter potatoes in the Pukekohe district (Crush et al. 1997), we expect that N uptake would have been comparable in all the potato paddocks in this study. Consequently, large N leaching losses were associated with this land use as the amount of N applied as fertiliser greatly exceeded the plant N uptake and removal in harvested product. The amount of N taken up in the tops and roots of the cauliflower crop (paddock G6) was 330 kg N ha^{-1} (C. S. Tregurtha unpubl. data). The total amount of crop N uptake was not measured in the other greens paddocks, but reported values for the Pukekohe district are 17–91 kg N ha^{-1} for winter spinach (Williams et al. 2002) and 190 kg N ha^{-1} for winter cabbage (P. H. Williams unpubl. data). Using these values for all the greens paddocks in this study, the N fertiliser inputs were similar to the expected crop N uptake amounts. These estimated N uptakes suggest that the risk of N leaching should be much lower from the greens than from the potato paddocks. However, measured leaching losses were comparable from the greens and potato paddocks, possibly because the amount of N returned to the soil in crop residues is greater for the greens (spinach = 13 kg N ha^{-1}; cabbage = 85 kg N ha^{-1}; cauliflower = 206 kg N ha^{-1}) than for the potato crops (5 kg N ha^{-1}) (C. S. Tregurtha unpubl. data). Consequently, the rapid mineralisation of residues from the previous greens crops may have contributed to the larger than expected nitrate leaching losses from the greens paddocks (De Neve & Hofman 1998; Rahn et al. 1998; Goulding 2000; Mitchell et al. 2001).

In the Pukekohe district, it appears that winter potato and winter greens production poses a greater threat to groundwater N contamination than does dairy farming. The actual contribution of these different land uses towards aquifer pollution will, however, depend on the proportion of the catchment area they each occupy. For the Pukekohe aquifer, similar areas are occupied by dairy farming (22%) and vegetable production (16%; Francis et al. 1999). For the winter potato paddocks, it is likely that a change in N fertiliser management is required to reduce the risk to N leaching. High rates of N fertiliser are commonly applied to winter potatoes as maximum yields and economic returns are shown to result at these high rates (Greenwood et al. 1989; Goulding 2000). Nevertheless, yields can be maintained at lower N fertiliser rates if N is applied strategically to match crop requirements rather than applied in one or two large applications (P. H. Williams unpubl. data). The estimated plant uptake for the greens paddocks suggests that the N fertiliser applications are reasonable. However, N derived from the rapid mineralisation of residues from the preceding greens crop is likely to contribute to the high soil mineral N contents and should be included in determining appropriate N fertiliser application rates to these crops.

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