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Control of nitrate leaching from a Nitrate Vulnerable Zone using paper mill waste

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Abstract.The effects on nitrate leaching of incorporation of paper mill waste at three cultivation depths in fields previously cropped to iceberg lettuce and calabrese are reported. In the lettuce experiment, incorporation of 40 t DM paper mill waste/ha resulted in a decrease in N leaching (measured with suction cups) from 177 to 94 kg/ha ($S.E._d = 23$). Deep ploughing with and without paper waste increased N leaching from 105 kg/ha (normal ploughing or surface incorporation) to 172 kg/ha ($S.E._d = 27$). Measurements of nitrate leaching using deep soil cores showed a less clear cut effect. Nitrous oxide (N_2O) emissions were very high immediately after paper waste was ploughed in to a depth of 35 cm. Non-significant increases in biomass N content were measured in the spring following paper waste application. There was no significant reduction in plant N uptake in subsequent crops. Removal of above-ground crop residues did not have a significant effect on nitrate leaching or N_2O losses. In the calabrese experiment, application of 40 t DM paper mill waste/ha followed by summer cropping with iceberg lettuce caused a decrease in N leaching (measured using deep soil cores) from 227 to 152 kg/ha ($S.E._d = 22$, mean of all cultivation treatments).

Keywords: Nitrate, leaching, soil, denitrification, immobilization, wastes, pulp and paper industry

INTRODUCTION

Paper mills produce large quantities of wastes which pose a significant disposal problem for the paper industry. Application of paper waste to land has been investigated as a method of disposal, as opposed to landfill or sea disposal. Aitken & Lewis (1994) suggested that N immobilization after paper mill sludge application could in some circumstances be useful in reducing nitrate leaching. The rapid initial decomposition of the waste, particularly after ploughing, may give rise to significant denitrification loss as particles of waste act as anoxic 'hotspots' for denitrification. This would result in a net loss of N from the system but, under some conditions this may be preferable to retaining the nitrogen in the soil, only to be leached to groundwater. For example, vegetable cropping leaves substantial amounts of mineral N and readily decomposable crop residue N in the soil in autumn. Rahn *et al.* (1992) found up to 388 kg N/ha after cauliflower harvest comprising both crop residue and soil mineral N.

Experiments were established in autumn/winter 1994 to examine the fate of nitrate following vegetable cropping in soil amended with paper mill waste. The experimental system is similar to the many experiments that have been performed to investigate the effect of crop residues on the nitrogen cycle (e.g. Aulakh *et al.*, 1991; Green *et al.*, 1995) but differs in the larger amounts of organic material being added than is typical for crop residue experiments with, for example, straw.

MATERIALS AND METHODS

Field experimental sites

Two field experiments were established at Balmalcolm Farm, Cupar, Fife, Scotland (National Grid Reference GR 318084). Mean annual rainfall in this part of eastern Scotland is about 800 mm and potential evapotranspiration is about 500 mm. The mean annual soil temperature at 30 cm depth is about 8.5 °C (Soil Survey of Scotland, 1982). The nitrate concentration in discharge from a public water supply on the farm, has steadily increased from 4.5 mg/l NO_3^--N/l in the early 1970s to 10.0 mg/l NO_3^--N/l in 1993. Frost & MacDonald (1993) estimated an equilibrium concentration of 14 mg/l NO_3^--N, based on current land use in the 200 ha catchment and consequently the area has recently been designated a Nitrate Vulnerable Zone under the EC Nitrate Directive (Commission of European Communities, 1991). The Mackies field experiment was established on 10 October 1994 and the Dipper field experiment on 6 December 1994 (Table 1). The soils are of the Hexpath series (sandy loam or loamy sand) developed on fluvioglacial sands and gravels derived mainly from Upper Old Red Sandstone sediments. At the lower end of Mackies field, the soil texture is heavier (sandy clay loam). The site is 40 m above sea level and has a long history of intensive vegetable cropping. Mackies field was double cropped with iceberg lettuce in 1994 and Dipper field with calabrese in 1994 and double cropped with iceberg lettuce in 1995. Both fields had been cropped with leafy vegetable crops in six of the previous ten seasons.

Field experimental design

At both sites, the effects of paper mill waste application and cultivation on nitrate leaching were examined. A strip-plot experimental design was applied. This is a variation on a split-plot design, where each block is divided into plots in one direction for one treatment factor and again into plots at right angles for a second treatment factor (Little & Hills, 1978; Pearce, 1983). The removal of crop residues on some plots provided a subtreatment.

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Table 1. Experimental measurements and plot layout for the two field sites

(a) Mackies field — Cultivation block — ↓direction of beds

Waste Block	Waste treatment	Crop residues	1 DP	1 R	1 C	2 C	2 DP	2 R	3 DP	3 C	3 R
I	W2	–	G	G	SG						
	W2	+	sSG	sSG	sSG	K	K	K	HN	HN	HN
	W1	+	S	S	S				HN	HN	HN
	W0	–	G	G	sSG						
	W0	+	sSG	sSG	sSG	K			HN	HN	HN
II	W2	–				S					
	W2	+	HN	HN	HN	sSG	sSG	sSG	K	K	K
	W1	+	HN	HN	HN	S	S	S			
	W0	–				sS					
	W0	+	HN	HN	HN	sSG	sSG	sSG	C		
III	W2	–							G	SG	G
	W2	+	K	K	K	HN	HN	HN	sSG	sSG	sSG
	W1	+				HN	HN	HN	S	S	S
	W0	–							G	G	sSG
	W0	–	K			HN	HN	HN	sSG	sSG	sSG

H = 3 m × 1 bed width (1.83 m) of total and harvestable fresh yield. N = DM% and N% of crop. G = N_2O emissions. s = preplanting soil sampling (0–0.6 m). K = deep soil cores, 28/4/95. S = suction cups.

(b) Dipper field — Cultivation block — ←direction of beds

Waste Block	Waste treatment	Crop residues	1 R	1 C	1 DP	2 R	2 DP	2 C	3 C	3 R	3 DP
I	W2	–	G	G	G						
	W2	+	G			sKN	sKN	sKN	H	H	H
	W1	+	G	G	G				H	H	H
	W0	+	G			N	N	sKN	H	H	H
	W0	–	G	G	G						
II	W2	–				G	G	G			
	W2	+	H	H	H	G			sKN	sKN	sKN
	W1	+	H	H	H	G	G	G			
	W0	+	H	H	H	G			N	N	sKN
	W0	–				G	G	G			
III	W2	–							G	G	G
	W2	+	sKN	sKN	sKN	H	H	H	G		
	W1	+				H	H	H	G	G	G
	W0	+	N	N	sKN	H	H	H	G		
	W0	–							G	G	G

H = total and harvestable fresh yield 8.5 m × 1 bed width (3 or 4 rows/bed). Blocks I and III 13/6/95; Block II 21/6/95 (9.9 m). N = Total and harvestable N content and DM% for fertilised micro and Zero N plots. G = N_2O emissions. s = preplanting soil cores (0–0.6 m). K = deep soil cores 2/10/95 and ff.

Paper mill waste treatment

Paper mill waste was applied at three different rates. The waste was acquired from GB Papers Ltd, Guardbridge, St Andrews, Fife in several batches and stockpiled in the field without mixing. Analyses on samples from the paper mill were carried out to assess nutrient and potentially toxic element content during 1993–94 (Paterson, 1995). The waste typically had a pH of around 7, dry matter content of 35%, carbon content of 25% in dry matter and a neutralizing value of 3% (Table 2). The C:N ratio of the waste was extremely variable, with a mean of 25:1 but ranging up to 46:1 for secondary waste and 95:1 for the primary waste which is sometimes produced. In a more recent study, C:N ratios from the same mill varied from 37–161 (A. Sinclair, unpublished). The N content is partly from the paper pulp, but is strongly influenced by the N content of the polyacrylamide flocculant used in the waste treatment process (and possibly also by dyestuffs and surfactants used in the manufacturing process). Polyacrylamides are used as soil conditioners and are known to be highly resistant to attack by microorganisms (Quastel, 1954; Fuller & Gairaud, 1954), and therefore the C:N ratio of the paper waste may not be a reliable indication of the effect of the waste on soil nitrogen mineralization/immobilization.

Table 2. Paper waste analysis (after Paterson, 1995)

		Mean	Max.	Min.	S.D.
Dry Matter	(%)	35	47	22	7
pH		6.9	7.6	6.3	0.4
Total N	(% FW)	0.48	0.64	0.25	0.12
Total C	(% FW)	11.8	14	10	1.4
Neutralizing value as CaO	(% FW)	3	6.1	1.8	1.8

FW = fresh weight.

At Mackies field, waste treatments were applied to the previous crop residues using a rear delivery manure spreader on 10 October 1994. This paper waste was applied at a 0, 12.7 (S.D. = 8.8) and 44.4 (7.1) t DM/ha (W0, W1 and W2 respectively). The distribution of paper waste was uniform up to one metre from the centre line of the spreader. Insufficient waste was available for complete application of both W1 and W2 treatments, so W1 rates were located 2.5 m from the centre line of the W2 treatments. At Dipper field, waste was applied on 6 December 1994 at 0, 24.4 (5.7) and 38.6 (9.3) t DM/ha paper mill waste. In this experiment sufficient waste was available to use separate runs of the spreader for the W1 and W2 treatments.

Cultivation treatment

We considered that the paper mill waste might adversely affect subsequent crop yields, so we included the effect of cultivation depth in the experimental design. We expected that shallower waste incorporation would lead to the risk of N shortage for the following crop, and that denitrification of excess mineral nitrate might be promoted by incorporation by deep cultivation. Three cultivation subtreatments to incorporate the waste were applied perpendicular to the paper waste treatments. Deep mouldboard ploughing (DP) inverted the plough layer to about 350 mm depth, conventional mouldboard ploughing (CP) inverted the plough layer to about 150 mm depth, and reduced cultivation with a power harrow (R) disturbed the surface soil to a nominal depth of about 50 mm. Figure 1 shows the field layout.

Crop residue treatment

Crop residues, which may constitute 30–40% of the previous crop dry matter, remained on the plots. Residues were removed on small subplots of the W0 and W2 treatments. In Mackies field, the measured lettuce crop residue returns were 1.6 t DM/ha at 5.3% N. In Dipper field, the measured calabrese residue returns were 5.4 t DM/ha at 2.0% N.

Mineral N content of the soil was measured on 30 September to 7 October 1994 at Mackies. It was 59 mg N/kg (S.D = 56 mg/kg) for the W0 treatment and 114 (29) for the (0–50 cm) W2 treatment.

Initial mineral N contents at Dipper field were not measured. The primary effect of the paper waste was expected to be on nitrate leached from the following crop, therefore initial conditions were not relevant.

Measurement of nitrate leaching using ceramic cups

Porous ceramic cup samplers, 63 mm in diameter and 750 mm in length, were installed at a depth of 550 mm in Mackies field (the root system of iceberg lettuce at this site does not extend below 25–30 cm (A. Samson, pers. comm.). One cup was sited in each of three waste levels, for three cultivation treatments and three replicates. Additional cups were installed where residues had been removed (see Table 1a). Samples of soil solution were collected by creating a partial vacuum of 70 kPa within the cup. The first set of soil solution samples were collected on 26 October 1994 five days after zero soil moisture deficit (estimated by tensiometry) was attained. The ceramic cups were sampled at intervals of approximately one week in the early part of the drainage period when nitrate concentrations were at their highest. Samples were collected at approximately fortnightly intervals thereafter, unless rainfall was considerably below average. These samples were stored in a refrigerator at 8 °C, and chemical analysis was executed within a week of sampling. Nitrate and ammonium concentrations were determined by continuous flow analysis following the methods of Henriksen & Selmer-Olsen (1970), and Crooke & Simpson (1971) respectively. Nitrate leaching was estimated for each sampling. The quantity of nitrate-N leached from the soil profile was calculated as the product of the measured nitrate-N concentration of the soil solution at successive sampling events and the soil drainage between these samplings, calculated by water balance. The total loss of nitrate-N is the integral of the curve relating concentration to cumulative water loss during winter, and can be approximately evaluated using the trapezoidal rule (Lord & Shepherd, 1993). Ceramic cups did not work on Dipper field, because of the coarseness of the subsoil texture.

Measurement of nitrate leaching using deep soil cores

Soil cores were taken to depths of up to 5 m using a 'Stiboka' volumetric intact corer for the first metre and a conventional gouge auger (with extension rods) of 66 mm reducing to 27 mm diameter for below one metre depth. Samples from three replicates of the W0CP, W2R, W2CP and W2DP treatments were taken at Mackies field on 28 April 1995 and at Dipper field on 2 October 1995. Soils were extracted with 1 M KCl for one hour and nitrate-N and ammonium-N concentrations were determined. The soil gravimetric moisture content was measured, and this was converted to a volumetric water content using dry bulk density estimated from the dry mass and volume of each core section. If any compaction was observed during the soil coring process, the effect of this was corrected for evenly across the whole 0.8 to 1.0 m length of the auger used, except in the case of the 'Stiboka' corer, for which the compaction was assumed to be distributed over the top 0.4 m.

Nitrous oxide emissions

Closed chambers of 400 mm diameter by 200 mm height were inserted 50 mm into the soil on W0 and W2 treatments. Gas samples were taken after the chambers had been covered with an airtight lid for one hour (Clayton *et al.*, 1994). These samples were analysed for N_2O content by gas chromatography using an electron capture detector. Measurements were made at Mackies field from 14 October 1994 to 13 December 1994, and at Dipper field from 2 December 1994 to 5 January 1995. Daily measurements were made immediately after paper mill waste incorporation, reducing to weekly measurements later.

Soil biomass nitrogen

Measurements of soil biomass carbon and nitrogen were made by fumigation-extraction (Voroney & Paul, 1984) of samples obtained on 23 February 1995 from 0–400 mm depth on the W0 and W2 waste treatments and the R and CP cultivation treatments.

RESULTS

Estimates of nitrate leaching using suction cups

At Mackies field, the nitrate leached from each plot was calculated for a 160 day winter period, based on nine sampling dates from 26 October 1994 to 29 March 1995. A summary of the data obtained is given in Table 3a. Analysis of variance showed a significant effect of paper waste ($P < 0.05$) on nitrate leached but no effect of cultivation ($P < 0.1$). There was no significant interaction between paper waste and cultivation treatments. However, the reduction in nitrate loss by waste treatment W2 was larger for the deep ploughed treatment (136 kg N/ha, S.E.$_d$ = 37 kg N /ha) than for the CP (65 kg N/ha) or R (48 kg N/ha) treatments. The smallest leaching loss (76 kg N/ha) was from the W2CP treatment.

There was a non-significant ($P < 0.1$) reduction in nitrate loss after removal of residues.

Nitrate leaching estimates using soil cores

Nitrate profiles for the W0CP and W2CP treatments at Mackies field in April 1995 are shown in Figure 1a. There was a clear peak of nitrate-N concentration in the soil profile in the W0 treatments. This peak was much reduced in two out of the three replicates of the W2 treatments. In the first block, however, the W2 profile had higher nitrate-N concentrations than the W0 profile. This may be the result of uneven application of paper mill waste or the result of variable composition. All measured nitrate-N concentrations showed a marked decrease at around 2.5 m depth, which coincided with a layer of buried peat. Below this layer nitrate-N concentrations increased again.

Interpretation of these profiles is impeded by the differences in soil moisture storage in each profile. The mean pore water nitrate-N concentration and nitrate-N storage in the profiles have therefore been recalculated, using the trapezoidal rule, as a function of cumulative storage of moisture in the profile in 50 mm increments of equivalent depth of water storage. This allowed means and standard errors of pore water nitrate-N concentration and cumulative nitrate-N storage to be calculated as a function of cumulative pore water storage down the soil profile. Figure 1b shows the nitrate-N profiles for the W0CP and W2CP treatments as a function of cumulative moisture storage.

Estimation of the amount of nitrate leached over the period between waste application and sampling depends on

Table 3. N balance sheet data for Mackies field (kg N/ha)

		Cultivation				
	Waste	R	CP	DP	mean	S.E.$_d$
(a) Leaching past suction cups (26/10/94–29/3/95)	0	138	141	253	177	
	1	89	93	165	116	
	2	90	76	117	94	
	mean	106	104	178		
	+Residues				117	
	−Residues				93	
	Wastes					23
	Cultivation					27
	W × C					37
	Residues					6
(b) Storage in pore water (100–500 mm storage) (28/4/95)	0		179			
	1					
	2	192	132	178		
	Pooled S.E.$_d$					43
(c) Total plant N uptake (11/9/95)	0	61	56	58	58	
	2	65	63	51	60	
	mean	63	60	55		
	Waste					1.3
	Cultivation					7.9
	W × C					8.1
(d) Nitrous oxide emission (14/10/94–13/12/94)	0	1.14	0.93	1.02	1.02	
	2	0.9	1.21	3.66	1.92	
	mean	1.02	1.07	2.39		
	+Residues				1.47	
	−Residues				0.79	
	Waste					0.69
	Cultivation					0.69
	W × C					0.89
	Residues					0.48
(e) Biomass N content (0–400 mm) (23/2/95)	0	35	30		33	
	2	45	49		47	
	mean	40	40			
	Waste					0.13
	Cultivation					0.72
	W × C					0.62

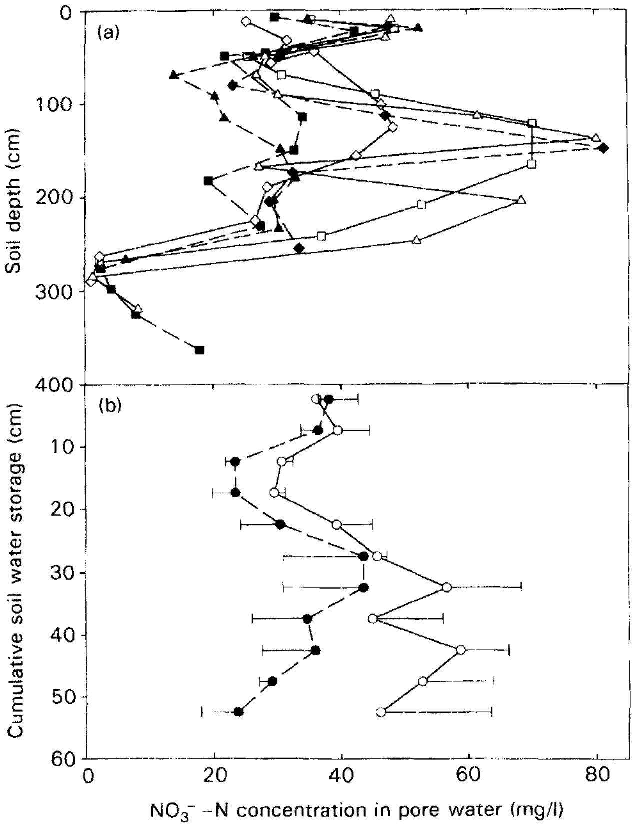

Fig 1(a) Pore water nitrate concentrations in soil cores extracted from Mackies Field on 26 April 1995. -◇-, -□-, -△- W0 for blocks 1, 2 and 3 respectively; -◆-, -■-, -▲- W2 for blocks 1, 2 and 3 respectively. (b) Pore water nitrate concentrations as a function of cumulative water stored in the soil profile. Open symbols—W0; closed symbols—W2. Error bars show standard errors.

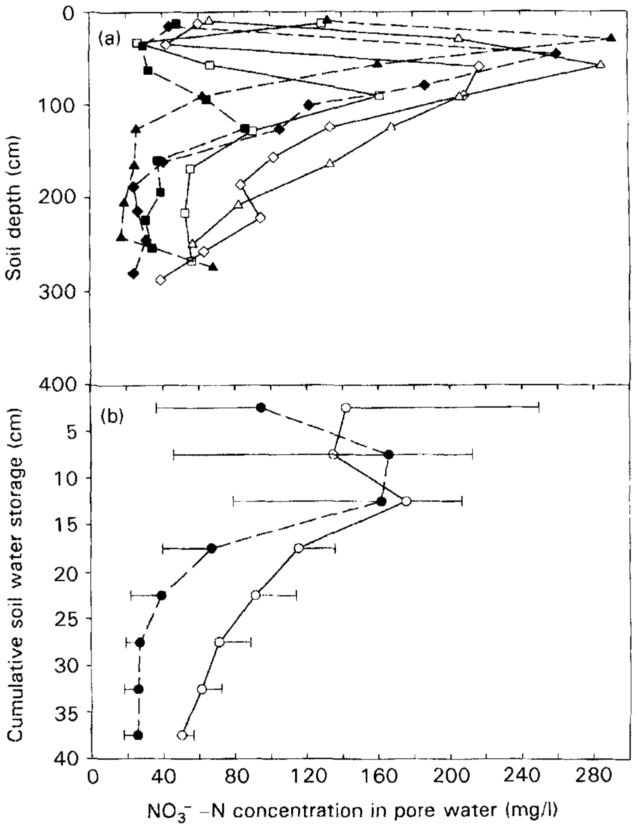

Fig 2(a) Pore water nitrate concentrations in soil cores extracted from Dipper field on 2 October 1995. -◇-, -□-, -△- W0 for blocks 1, 2 and 3 respectively; -◆-, -■-, -▲- W2 for blocks 1, 2 and 3 respectively. (b) Pore water nitrate concentrations as a function of cumulative water stored in the soil profile. Open symbols—W0; closed symbols—W2. Error bars show standard errors.

three assumptions: the amount of excess rainfall passing through the root zones; the amount of hydrodynamic dispersion of the solute pulse as it moves through the profile; and the depth of the root zone, below which any nitrate is presumed to be leached. The shape of the peak of nitrate suggests that little nitrate has leached below the maximum sampling depth, although the presence of the peat layer may obscure this. However, if we assume a field dispersion length of 50 mm (Jury *et al.*, 1991), the root mean square displacement of solute around a mean displacement of 1500 mm would be about $\sqrt{2} \times 50 \times 1500 \cong 390$ mm, confirming that little displacement of solute below the maximum measured depth is likely. Site rainfall for the period from 24 Ocober, the time of return to field capacity (measured with tensiometers), to 29 March 1995 was 420 mm and potential evapotranspiration was 45 mm, giving an excess rainfall of 375 mm. We assumed that the nitrate in the top 100 mm of moisture storage was available for uptake. This corresponds to the top 0.4–0.6 m of soil, which, given a certain amount of capillary rise during the growing season, would be within the range of the crop root system (about 0.3 m for lettuce). The nitrate stored in the profile from 100 to 500 mm cumulative storage gave a reasonable estimate of winter nitrate leaching, assuming hydrodynamic dispersion could be neglected as small. The values obtained for treatments W0CP, W2R and W2DP are given in Table 3b. Values were larger than those observed with suction cups but the effect of waste treatment was less clear.

Nitrate-N profiles from the Dipper field experiment were not taken until after the following summer, during which two crops of iceberg lettuce were grown. It was hoped that this would give information about the nitrate leaching for the second half of the winter of 1994/95 (after paper waste incorporation) and the leaching during the following summer. However, the extraction of soil cores from below about 2.5 m proved very difficult. The subsoil below one metre on this field was almost pure sand, and the friction forces set up on the gouge augers were too great to allow extraction using the jacking device, and a tractor had to be used to pull the cores out. Besides this problem, the soil moisture storage was much lower than at Mackies field. A profile of about 5 m depth would therefore be needed to observe a full winter's leaching. Nevertheless, a wet September meant that some of the residual nitrate-N left in the root zone after the summer had leached sufficiently for treatment effects to be observed. Figure 2a shows the W0CP and W2CP treatment pore water nitrate-N profiles, as a function of soil depth and Figure 2b shows the means and standard errors as a function of cumulative soil moisture storage. Tables 4a and 4b give the estimated nitrate-N storage in all treatments for the 0–100 mm and 100–300 mm increments of cumulative soil moisture storage. There were very high concentrations

Table 4. N balance sheet data for Dipper field (kg N/ha)

		Cultivation (+Residue)				
	Waste	R	CP	DP	mean	S.E.$_{d}$
(a) Storage in pore water	0		199			
(0–100 mm) Sampled 2/10/95	2	91	123	164		
	mean					
	Pooled S.E.$_{d}$					72
(b) Storage in pore water	0		227			
(100–300 mm) Sampled 2/10/95	2	153	146	157		
	mean					
	Pooled S.E.$_{d}$					22
(c) Total plant N uptake 21/6/95	0	87	67	75	77	
	1	81	80	57	72	
	2	76	76	62	73	
	mean	82	75	65		
	Waste					17
	Cultivation					9
	W × C					20
(d) Nitrous oxide emission	0	0.1	0.47	0.21	0.25	
2/12/94–5/1/95	2	0.28	0.32	0.19	0.26	
	mean	0.19	0.4	0.2		
	Waste					0.06
	Cultivation					0.07
(e) Biomass N content	0	45	44		44	
(0–400 mm) 23/2/95	2	47	71		59	
	mean	47	57			
	Waste					28
	Cultivation					6
	W × C					29

in the top 100 mm, because the lettuce crops of summer 1995 were diseased, so the amount of harvestable crop was very low in places, leading to high N returns in crop residues. Significantly more ($P < 0.05$) nitrate-N was leached in the 100–300 mm increment of the W0CP treatment (227 kg N/ha) than in the W2CP treatment (146 kg N/ha). The effect of paper waste in the other two cultivation treatments was smaller. There was no significant effect of cultivation treatment on the nitrate leaching from the W2 plots.

Residual nitrate N before planting

Soil mineral N contents from 0–0.6 m soil depth were measured at Mackies field in April 1995. The following lettuce crop was planted in June. Levels of mineral N were low and no significant differences between treatments were observed. Soil mineral N contents from 0–0.6 m soil depth were measured at Dipper field on 15 February 1995, shortly before planting of the first lettuce crop. Levels were low (10 mg/kg in both W0 and W2 treatments) and no significant differences between treatments were observed.

Crop yield and N uptake following paper waste treatment

The total N uptake of the crop of iceberg lettuce grown in Mackies field was measured and results are recorded in Table 3c. There was no significant effect of the paper waste on the N uptake of the following crop. However, a significant ($P < 0.05$) interaction effect between cultivation and paper waste occurred.

Two crops of iceberg lettuce were grown in the summer following paper waste application at Dipper field. Measurements of yield and N uptake were only made for the first of these two crops. This was considered the most likely crop to show yield deficits due to N immobilization by the paper waste or the presence of toxins such as acetic acid, formed by anaerobic decomposition. The second lettuce crop of the summer was seriously affected by fungal disease, so very little was harvested. This led to exceptionally high mineral and crop residual N contents in the soil after the second lettuce crop, and high variability in leaching data resulted. Table 4c shows the total N uptake for the two (W0 and W2). The effect of waste treatment level on total N uptake in the fertilized plots was not statistically significant (Table 4c). The variance of N uptake increased with waste application, particularly on the reduced cultivation plots.

Nitrous oxide emission

At both sites there was no significant effect of individual treatments on N_2O emissions. However, the N_2O emissions from the W2DP plots at Mackies field (Table 3d) were significantly higher than from other plots, immediately after waste incorporation.

Soil biomass N

There was a small but not significant ($P = 0.13$) increase in biomass N measured at Mackies field in April 1995 (Table 3c), where paper waste had been applied. There were no significant effects of paper waste or cultivation at Dipper field (Table 4e), although there was a trend of increased nitrogen content with increased paper waste.

DISCUSSION

The field results suggest that a significant reduction in nitrate-N leaching occurred as a result of the paper waste treatment, and there is some suggestion, at least at Mackies field, that the best cultivation to achieve this effect was conventional ploughing. The waste did not have a significant effect on the yield of the following crops. The removal of nitrate N from the pool available for leaching by paper waste application could have been achieved by either denitrification or immobilization. Although denitrification has the advantage for groundwater protection in that N is completely removed from the system, production of N_2O contributes to the greenhouse gas budget. One could argue, however, that where groundwater or surface water pollution with nitrate occurs, such as in Nitrate Vulnerable Zones, groundwater protection should take priority. The advantage of immobilization is that the N is conserved in the soil, but some of this is only temporary, and careful management to allow for the re-release of the N from organic fractions must be practised.

The field experiments showed trends for both higher N_2O emissions (Mackies field only) and higher biomass N content after W2 application, but the data do not enable total denitrification or immobilization to be quantified. The contribution of denitrification in reducing NO_3^- — leaching would depend on the respiration rate of the soil organic matter, the soil physical properties and the availability of nitrate at anoxic sites. The contribution of immobilization would depend on the availability of organic C and N to soil microflora, the growth and turnover rate of the soil biomass and the efficiency of conversion to stable organic matter. Green *et al.* (1995) found 50% reduction in mineral N due to immobilization after 90 days laboratory incubation of N-rich soils at 24 °C, when maize stover (8 g DM/kg soil) was present. Such a long period of immobilization would be effective in reducing winter nitrate leaching in the context of our field experiments. Greenwood *et al.* (1996) devised a model for predicting the effects of fertilizer on N-dynamics in vegetable crops. They assumed that 75% of added C was lost as CO_2 and that the C:N ratio of the resulting organic products of decomposition was 10. Table 5 shows estimates of the potential for N-mineralization/immobilization from the various treatments using these assumptions. The paper waste contains highly variable amounts of N, some of which, as discussed above, may be resistant to decomposition. We therefore assumed that the effective N content in the organic matter was 0.65%, similar to that of straw, giving a C:N ratio of 90:1. The rest of the nitrogen was assumed to be associated either with polyacrylamide flocculant (see Materials and Methods) and subject to microbial degradation at a rate much slower than straw degradation (Fuller & Gairaud, 1954) or with dyestuffs in the paper. If the effective C:N ratio of the paper waste is assumed to be the same as for straw, 133 and 148 kg N /ha is estimated to have been immobilized by the paper waste + lettuce residues treatment and the paper waste + calabrese residues treatment respectively. On the other hand, laboratory incubations over 90 days suggested that denitrification was the primary route for depletion of the nitrate pool and that immobilization played only a minor role (H. Luo, pers. comm.). Incubation data also showed that nitrification was being inhibited. A similar effect was observed by Aulakh *et al.* (1991). This may have been due to partial anoxia, to chemical properties of the paper waste, or to the use of acetylene for estimating denitrification.

Effects of cultivation

The effectiveness of the paper waste in reducing nitrate leaching depended on the cultivation treatment, in Mackies field. The largest decrease in nitrate leaching as a result of paper waste addition, was observed in the DP treatment (Table 3a). However the W0DP treatment resulted in the highest nitrate leaching. This was probably because the highest nitrate concentrations in early autumn were at the soil surface. Deep ploughing moved much of this high nitrate soil to deeper in the soil profile, and hence accelerated leaching past the suction cups. The pattern was less clear from the soil core data, but it still appears that the W2CP treatment was most effective in reducing nitrate leaching. However, the deep ploughing is probably undesirable as subsoil material would be mixed with the topsoil, lowering overall cropping potential. When residues and paper waste were left close to the soil surface (in the R treatment), nitrate leaching, measured by suction cups, was little affected by paper waste, but plant N uptake in the following crop was slightly lower and showed greater variability. Increases in N_2O emissions and biomass N accumulation as a result of paper waste addition tended to be lower in the R cultivation treatment at Mackies field.

A major effect of ploughing-in the paper waste could be to limit the supply of oxygen for decomposition of the paper waste. This would encourage denitrification and immobilization, and inhibit nitrification. Aulakh *et al.* (1991) studied denitrification losses following incorporation or surface placement of crop residues and found similar losses over a 35 day period in laboratory incubations of soil and crop residues.

Table 5. Estimation of C and N additions and potential mineralization/immobilization with different treatments (negative values in final columns indicate immobilization)[1]

Treatment	Organic matter (%)	C in organic matter (%)	N in organic matter (%)	C : N	Amount of waste residue added (t/ha)	C added (t/ha)	N added (kg/ha)	Potential N mineralized/ immobilized
Paper waste	55	48	2.36	25	40	12.8	519	334
Paper waste[2]	55	58	0.65	90	40	12.8	135	−202
Lettuce	100	40[3]	5.3	8	1.6	0.64	85	69
Calabrese	100	40[3]	2.0	20	5.4	2.16	108	54
Lettuce + paper waste[3]	–	–	–	–	–	13.73	220	−133
Calabrese + paper waste[3]	–	–	–	–	–	15.93	243	−148

[1] assuming 75% of added C is lost as CO_2 and C : N ratio of product of decomposition is 10 : 1.

[2] N% adjusted to that for straw (assumes that the dyestuff and polyacrylamide-derived N is not decomposed in the timescale of the experiment).

[3] derived from Vigil & Kissel (1991).

However, most of their denitrification occurred early in the incubation period in their residue incorporation treatment, which agrees with our field observation of very high N_2O fluxes immediately after deep ploughing of paper waste with crop residues. Onset of anaerobic conditions is very dependent on the soil physical condition following incorporation and on the efficiency of mixing of the carbon-rich residue with the soil by cultivation, factors not readily simulated in laboratory incubations.

Long-term considerations

In the long-term, application of paper waste to soils may result in two potential problems. Firstly the soil organic matter level will gradually increase with continuous use of the paper mill waste, so there will be more net mineralization. Allowance for higher mineralization could be made, through downward adjustment of the fertilizer recommendations but this would not help with prevention of out-of-season mineralization. Secondly, application rates should not be so high as to cause contamination with potentially toxic elements. The maximum annual amount of waste that can be applied was calculated, based on maximum permissible average annual loads of potentially toxic elements (Department of the Environment, 1993). The limiting elements are Ni (maximum waste application 67 t/ha/y over ten years) and As (64 t/ha/y). Patterson (1995) suggested that applications should not exceed 10 t/ha/y of dry matter over a ten year period but these calculations suggest this is a little conservative. Application of 40 t /ha every year would bring the Ni and As additions to about 60% of the recommended maximum application over ten years, but would be effective in reducing nitrate leaching, enabling intensive horticulture to continue over a significant portion of the catchment, without causing the nitrate concentrations in the well water to exceed the limits set by the EC. Another proposed method of decreasing nitrate leaching from crop residues is incorporation of straw (Catt *et al.*, 1992), but at the much lower application rates which are feasible with straw, the evidence is that reduction in nitrate leaching is only transitory.

CONCLUSIONS

The use of autumn/winter applied paper mill waste reduced nitrate leaching over the winter period in one field and over winter and the following summer at another field. There is some evidence of paper waste causing increased N_2O loss (suggesting denitrification may be an important N loss mechanism), particularly in the deep cultivation treatments. Increased immobilization and decreased nitrification are also important. Further, more detailed measurements of these processes are needed in the field. There is some evidence that a cultivation depth of 0.1–0.2 m will achieve the best reduction in nitrate leaching. Care must be taken that the paper waste is not present in sufficient quantities close to the soil surface to cause immobilization of fertilizer N applied to subsequent crops.

Given appropriate quality controls on the C:N ratio and potentially toxic element content of the waste, the results of this work indicate that application of the waste at 40 t/ha/y to the residues of intensive vegetable crops, followed by incorporation at normal ploughing depth, would be effective in reducing nitrate leaching to the extent that intensive horticulture could continue over a significant portion of the catchment. The longer-term influence of the paper waste on N cycling processes and on potentially toxic element accumulation needs further study. It may be necessary to adjust N fertilizer recommendations in the longer term, if significant long-lived organic matter accumulation occurs.

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