The relation between fertilizer nitrogen applications and nitrate leaching from grazed grassland

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INTRODUCTION

THE EXPORT of nitrogen in 'useful' outputs (milk, beef, etc.) from grazed grassland is equivalent to 15–20% of nitrogen input as fertilizer (Henzell & Ross, 1973; Van der Meer & Van uum Lohoyzen, 1986). This estimate, if correct, implies that in older swards, where soil total nitrogen is not increasing markedly, annual losses could be equivalent to 80–85% of the fertilizer additions. Using deep coring, Ryden *et al.* (1984) estimated that nitrate leaching from a grazed grass sward receiving 420 kg N per hectare per year was 160 kg N per hectare per year. Other studies have also indicated large losses from grass swards receiving heavy applications of nitrogen (Scholefield *et al.*, 1988; Macduff *et al.*, 1990). This contrasts with results from cut swards which suggest smaller losses (Dowdell & Webster, 1980; Garwood *et al.*, 1980; Barraclough *et al.*, 1983). Assessing the effect of changes in land use and fertilizer use on nitrate leaching requires an adequate database on the relation between fertilizer applications and nitrate leaching. The aim of this work was to measure nitrate leaching from grazed grass on various soil types receiving a range of fertilizer applications. Annual leaching losses were estimated using ceramic cup samplers. Soil cores taken from some of the experimental plots were used to provide estimates of nitrate leaching into the profile in years immediately before the period covered by the ceramic cup sampling. This work accompanied studies on losses by denitrification from the same plots (Jarvis *et al.*, 1991).

MATERIALS AND METHODS

Sites and soils

Initially five sites were selected for denitrification (Jarvis *et al.*, 1991) and soil mineral-N measurements (Jarvis & Barraclough, 1991). These covered a range of soil types and climatic conditions. Two were in Berkshire at the Institute for Grassland and Environmental Research (IGER) at Hurley and ICI Jealotts Hill, one in Devon at IGER North Wyke, one in Cheshire at the ICI experimental farm, Ravenscroft and one at Drayton EHF in Warwickshire (ADAS). Preliminary measurements indicated that the ceramic cup sampling method used to estimate leaching (see later) was not suitable at North Wyke and Drayton. At North Wyke substantial lateral water flow at 10–20 cm depth meant it was not possible to calculate the vertical water flux required to estimate leaching losses (see later). At Drayton EHF, no soil solution was extracted into the ceramic cups at the sampling suction of 550 kPa. Consequently, results are presented only for the other three sites. Details of the soils and climate at these three sites are given in Table 1.

At Jealotts Hill and Hurley, the fertilizer rates were 100, 250, 450 and 750 N kg per hectare. At Ravenscroft there was an additional rate of 350 kg N per hectare. Fertilizer was applied in equal additions at regular intervals through the growing season. The sites formed part of the GM24 grazing trial in which cattle production responses to a range of fertilizer applications had been studied over the period 1981–1985 (Baker, 1985). At Hurley the experiments had been relocated to a similar, neighbouring site in 1985. The ceramic cup measurements were made on this new site but the soil coring was performed on the original GM24 site. All measurements at the other sites were on the original GM24 plots. Measurements were made over the drainage periods of the years 1985/86–1987/88 at Jealotts Hill and over the period 1986/87–1987/88 elsewhere. The swards were grazed by cattle, their numbers adjusted in accordance with assessments of sward growth.

Leachate sampling method

None of the three sites had artificial under-drainage. Accordingly it was decided to estimate current nitrate leaching using ceramic cup samplers, despite reservations about this technique (Debyle *et al.*, 1988). The main reservations centre on the disturbance involved in initial installation, solute adsorption on the ceramic and the small volume of soil actually sampled. The last necessitates many replicates to obtain reliable estimates of the mean loss over a given area. In the present study, sixfold replication was employed.

The samplers were based on 19-mm diameter tensiometer tubes obtained from Soil Moisture Inc. (Santa Barbara, California, USA). These were already fitted with a porous ceramic cup but were fitted with an extra tube, reaching to the bottom of the ceramic cup, to permit flushing of the sampler (Fig. 1). The additional tube (b) was led to a metal reservoir with a screw cap from which another

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Table 1. Soil characteristics and climate details at the three sites

Site (grid reference)	Average rainfall (mm/yr)	Soil series	Texture	Particle size distribution* Fine sand (60–200 μm)	Silt (2–60 μm)	Clay (< 2 μm)	Total pore space*
Hurley (SU 825830)	694	Frilsham	Loam	22	23	20	44.1
Jealotts Hill (SU 875735)	692	Wickham	Silt loam	7	66	22	54.3
Ravenscroft (SJ 501508)	786	Crewe	Clay	27	37	36	56.1

*Soil physical data from the Soil Survey of England and Wales (now Soil Survey and Land Research Centre).

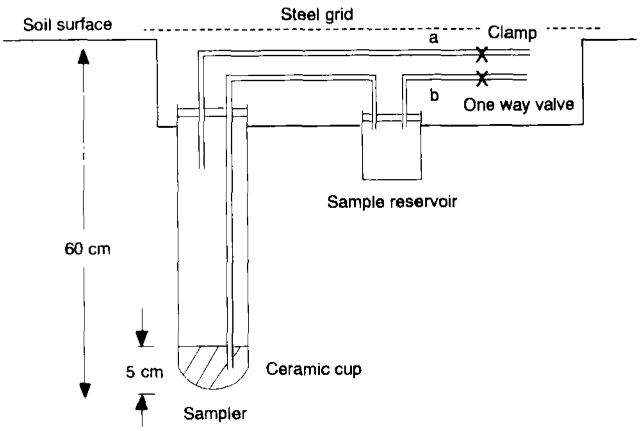

Fig. 1. Diagram of ceramic cup sampler system.

tube ended in a one-way valve (a bicycle tyre valve). The other tube ended in a clamp (a). To obtain a sample, the cup was evacuated to a suction of 550 kPa using a pump connected to the one-way valve. After a suitable interval, clamp (a) was released, causing the sample to be displaced into the metal reservoir by the incoming air. The sample was decanted into a plastic vial and stored in a refrigerator at 2°C prior to colorimetric analysis for nitrate by auto-analyser (Henriksen & Selmer-Olsen, 1970).

Samplers were installed at a depth of 60 cm into a hole fractionally narrower than the sampling tube. Back-filling was avoided to minimize disturbance during installation. All the samplers were installed some weeks before the expected start of the drainage season. All sampling tubes and the metal reservoir were concealed under the sward and protected with a metal grid, to avoid excessive trampling of the surrounding sward by curious cows. Samples were obtained at weekly intervals when soil conditions permitted (i.e. matric potentials at 60 cm were < 550 kPa).

Calculation of losses

Nitrate leaching losses were calculated by assuming that the nitrate concentration recorded at the sampler depth represented the concentration in the mobile (i.e. draining) water. The flux of water at the 60 cm depth was calculated from the rainfall (R) over the preceding week minus estimated evapotranspiration (Et) minus the soil moisture deficit at the beginning of the week (SMD). Thus:

$$\text{Loss} = (R - Et - SMD).\ \text{concentration}/100. \quad (1)$$

If R, Et and SMD are in mm and the concentration is in mg N per litre, the loss is in kg N per hectare. If the soil moisture deficit remained greater than zero over the whole week, there was no nitrate loss. Rainfall and evapotranspiration data were obtained from the MORECS service of the Meteorological Office, Bracknell.

Soil coring

Cores were taken to a depth of 3 m in the summer of 1987. Six cores were taken at random from one experimental plot at each fertilizer rate at each of the sites. The cores (5 cm diameter) were obtained with a power-driven flighted auger drill (Mobil Drilling Co., Indianapolis, USA) mounted on the rear of a Land Rover. Samples were taken every 20 cm down the profile; care was taken to avoid contamination between depths. After removal the cores were sealed in polythene bags and extracted in 2 M potassium chloride (100 g sample: 200 ml KCl solution) within 2 h for subsequent ammonium and nitrate analysis. At Ravenscroft no laboratory facilities were available. To avoid the need to transport cores over considerable distances, with the possible risk of mineralization and nitrification, a temporary laboratory was set up for extractions.

RESULTS AND DISCUSSION

Leaching losses from ceramic samplers

Table 2 summarizes the results obtained with the ceramic cup samplers. As expected, given the variability of excretal returns, differences between individual samplers on most sampling dates were considerable. When arithmetic means were calculated for the cumulative loss from each sampler, the coefficients of variation (CV) were large. Large CVs often indicate skewed distributions (Biggar, 1978). Although replication was insufficient to identify population distributions reliably, it was assumed that soil nitrate was log-normally distributed (Cameron & Wild, 1984). Accordingly all means for both the leachate and core data were based on log-transformed data, although the geometric means obtained in this way often differed markedly from the simple arithmetic means used in preliminary data analyses (Barraclough & Jarvis, 1989).

Table 2. Annual nitrate leaching (kg N/ha) from grazed swards estimated from ceramic cup samplers. Figures are means of six replicates; standard errors in brackets; all data based on log-transformed results

Year	Drainage (mm)	Fertilizer applied (kg N/ha) 100	250	350	450	750
Jealotts Hill						
1985/86	230	0.6 (5.5)	5.9 (7.2)	—	21.1 (3.3)	151.9 (1.6)
1986/87	167	1.4 (12.6)	0.7 (6.7)	—	16.4 (8.4)	100.2 (2.1)
1987/88	177	0.2 (3.7)	0.1 (1.4)	—	14.0 (4.7)	139.6 (1.4)
Hurley						
1986/87	167	2.1 (2.7)	12.3 (1.5)	—	47.9 (1.7)	·31.1 (4.9)
1987/88	177	6.7 (4.1)	6.5 (1.9)	—	37.1 (2.0)	42.0 (1.9)
Ravenscroft						
1986/87	244	2.5 (7.7)	4.3 (13.7)	50.5 (11.3)	10.9 (11.5)	279 (2.0)
1987/88	223	0.3 (1.7)	0.5 (3.9)	11.7 (5.8)	30.3 (2.7)	84.0 (2.5)

The results in Table 2 indicate marked differences between sites in the response of nitrate leaching to fertilizer application. In addition, at Ravenscroft, there is a large difference in the results for the two years even though annual drainage was similar. At Jealotts Hill, the results support the breakthrough concept suggested by Barraclough & Jarvis (1989). This relies on the identification of two distinct sections in the response of nitrate leaching to fertilizer application. The first shows little or no increase in leaching with fertilizer application, the second shows sharply increasing losses. In theory, the sharp increase occurs when the combined mineral nitrogen supplies to the plant (i.e. both fertilizer and soil-derived nitrogen and any excretal returns) exceed the nitrogen requirement of the crop growing at the maximum rate allowed by the environmental conditions. Further increases in nitrogen application result in a build-up of unused mineral nitrogen in the profile, increasing the potential for loss by either leaching or denitrification.

Figure 2 compares the envelope of leaching from grazed swards at Jealotts Hill, reported in Table 2, with the losses from cut swards, also at Jealotts Hill, measured over the period 1978–81 (Barraclough *et al.*, 1983). The differences at small fertilizer applications are not marked but, at greater applications, losses from the grazed sward seem to increase more sharply than those under the cut sward. For example, losses from the grazed sward receiving 750 kg N per hectare are comparable with those from the cut sward receiving 900 kg N per hectare.

The response curve of losses to fertilizer applications is flatter at Hurley than at the other sites so that at 100 and 250 kg N per hectare losses are greater at Hurley than at the other sites, but at 450 and 750 kg N per hectare they are less. As the Frilsham soil at Hurley is better drained than either the Wickham series at Jealotts Hill or the Crewe series at Ravenscroft, this is not an obvious result. Denitrification losses at Hurley were small (Fig. 3), so most surplus nitrate

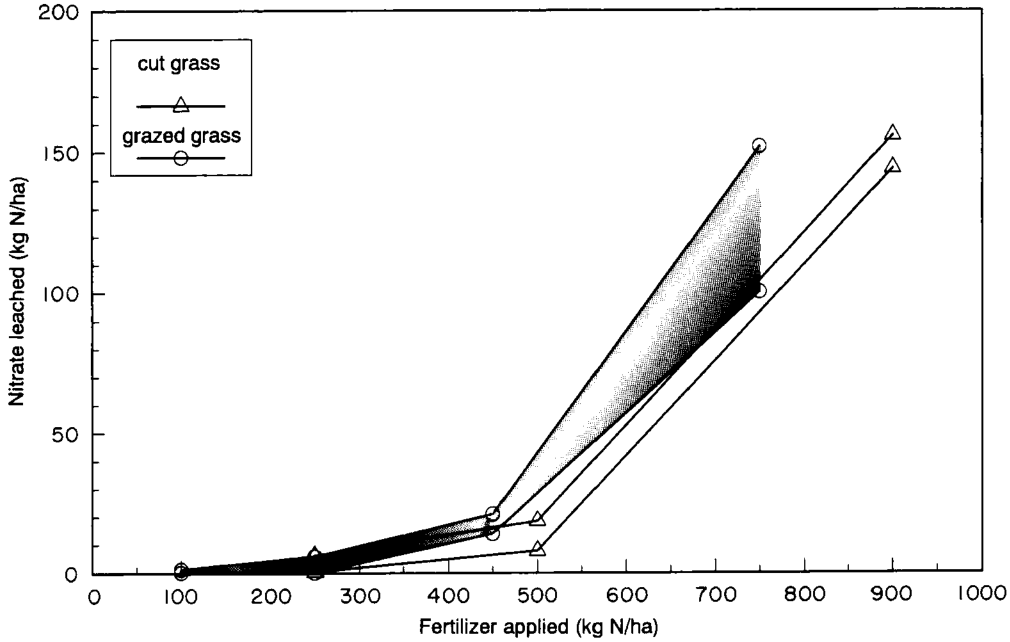

Fig. 2. Relationship between fertilizer application and annual nitrate leaching losses from grazed (1986–1988) and cut (1978–1981) plots at Jealotts Hill. For clarity, the envelope of results from the grazed plots is shaded.

Table 3. Animal production at the three sites expressed as (A) liveweight carried (t/ha) and (B) grazing days. Data from Baker (1985)

			Fertilizer applied (kg N/ha)				
Site	Production	Year	100	250	350	450	750
Hurley	A	1986	288	311	—	361	400
		1987	300	446	—	387	437
	B	1986	525	580	—	660	750
		1987	560	780	—	710	830
Ravenscroft	A	1986	312	383	370	412	368
		1987	281	281	397	407	436
	B	1986	604	738	708	799	727
		1987	537	704	774	798	880

should be lost by leaching. This apparently does not happen.

At Ravenscroft, losses in the two years differed considerably. In both years, losses were modest at applications up to 250 kg N per hectare (Fig. 2). In 1986/87 losses were greater at 350 kg N per hectare than at 450 kg N per hectare. The livestock production results (Table 3) show that in 1986 grazing days at 350 kg N per hectare were similar to those at 250 kg N per hectare, suggesting that the sward at 350 kg N per hectare was not using nitrogen as efficiently as at 250 kg N per hectare, possibly because of severe frost damage in the preceding winter. In 1987 no frost damage occurred and the response of leaching to fertilizer applications does not show the same minimum at 450 kg N per hectare. The losses at 750 kg N per hectare were greater in 1986/87 than in 1987/88. This is reflected in the animal production data (Table 3) which show that production was greater in 1987. However, an inverse relation between animal production and the amount of nitrate leached does not hold generally. At Hurley an increase in animal production between 1986 and 1987 was accompanied by a slight increase in nitrate leaching.

Surprisingly, denitrification losses at Ravenscroft were small (Fig. 3), suggesting either better aeration in the Crewe soil than its classification indicates or problems with the acetylene inhibition technique on this soil resulting in under-estimates of denitrification (Jarvis *et al.*, 1991).

Overall losses (leaching and denitrification) were smallest at Hurley, suggesting that less denitrification potential is not compensated by an increase in leaching loss. However, the leaching losses obtained at this site in the present work are much less than those reported by Macduff *et al.* (1990) on the same soil type, also at Hurley. The sward they used had

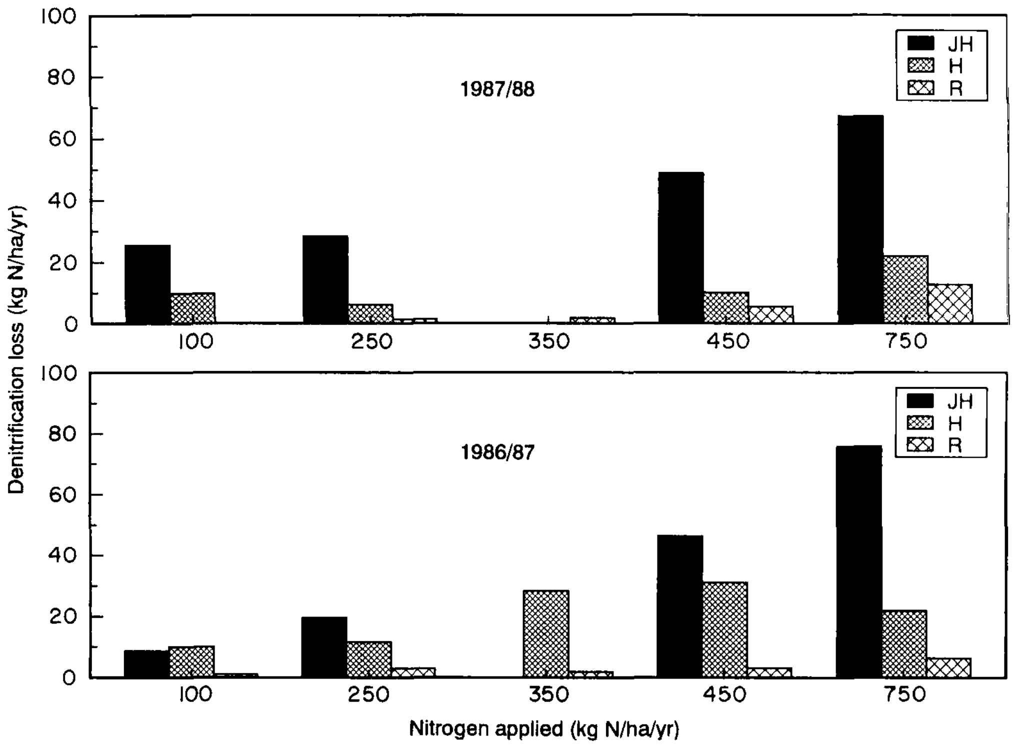

Fig. 3. Annual denitrification losses from grazed swards at the three sites at different rates of fertilizer application obtained over two years using the acetylene inhibition technique. JH is Jealotts Hill, H is Hurley and R is Ravenscroft.

been under the same management since 1976, and was probably approaching equilibrium with respect to the storage of nitrogen in soil organic matter. The sward at our site is much younger and probably still accumulating nitrogen. Losses at Jealotts Hill by both leaching and denitrification were the largest of all three sites, with those at Ravenscroft intermediate. Both the swards at these sites are probably near equilibrium, with the potential for immobilization small.

Deep coring

The ammonium and nitrate contents of the soil cores are shown in Table 4. The results for Hurley are from the original GM24 plots from which treatments were removed in 1985. All the figures are based on log-transformed data, as for the ceramic cup results.

At application rates less than 250 kg N per hectare soil nitrate to 3 m at Jealotts Hill and Hurley was not closely related to fertilizer application. At greater rates levels rise sharply. At Ravenscroft amounts of nitrate increase with fertilizer application rates over the whole range. Amounts of ammonium to 3 m do not reflect fertilizer applications at Hurley and Ravenscroft, but at Jealotts Hill they increase with fertilizer applications greater than 450 kg N per hectare. These results confirm that soil nitrate:ammonium ratios increase with increasing fertilizer applications (Jarvis & Barraclough, 1991). At Hurley, the nitrate:ammonium ratio changes from 0.17 at 100 kg N per hectare to 2.66 at 750 kg N per hectare. At Jealotts Hill the ratio changes from 0.43 to 1.2 over the same range, and at Ravenscroft from 1.38 to 5.77. Whether this change results from increased nitrification at greater application rates, or from preferential uptake of ammonium as application rates increase is not clear.

Amounts of nitrate in lower parts of the soil profile reflect nitrate leached below the rooting zone in the years up to and including that in which the cores were taken. If leaching were predominantly by piston displacement (i.e. there was little by-pass or preferential flow), it should be possible to determine the average annual displacement down the profile from the annual drainage and the volumetric moisture content of the soil in the profile while drainage is occurring. For example, if an average annual drainage of 200 mm flows through a soil with a nominal field capacity of 0.4 cm^3/cm^3, the average annual displacement is 50 cm. Estimates of the annual drainage in the years immediately before the soil coring were used in this way to calculate displacements down the profile. They were then used to apportion the nitrate in the profile to leaching in each year. Table 5 gives the 'historical' leaching losses estimated in this way.

Table 5. 'Historical' nitrate leaching estimated from the nitrate content of soil cores

Site and year	Fertilizer applied (kg N/ha) 100	250	350	450	750
Jealotts Hill					
1987/88	3.0	3.0	—	25.2	31.6
Hurley					
1984/85	1.6	2.7	—	18.4	42.2
1985/86	2.7	9.1	—	17.8	42.2
1986/87	1.0	2.2	—	4.8	18.8
1987/88	3.5	0.3	—	1.9	2.6
Ravenscroft					
1983/84	3.0	3.4	—	5.2	6.0
1984/85	4.3	4.4	—	13.4	12.7
1985/86	12.5	14.3	—	21.1	40.2
1986/87	7.8	29.3	—	39.3	84.6
1987/88	35.6	62.5	—	107.7	300.0

The relatively small losses at Hurley in 1987/88 and 1986/87 reflect the withdrawal in autumn 1985 of treatments from the original GM24 plots from which the soil cores were taken. The estimates for 1984/85 and 1985/86, when the treatments were still in place, agree well with the losses determined by the ceramic cup samplers on neighbouring plots in later years (Table 2). At Jealotts Hill it is only possible to estimate historical leaching for one year because of the profile discontinuity resulting from the occurrence of London Clay at about 40 cm depth (Barraclough, 1989). The agreement between the 'historical' leaching for 1987/88, determined for the soil cores, and the current losses, determined by ceramic cups, is reasonable up to an application rate of 450 kg N per hectare. At greater rates the agreement is poor. At Ravenscroft the greater annual drainage (~ 250 mm) means that nitrate from only the two previous years leaching is still in the upper 3 m. There are therefore both ceramic cup estimates of leaching for 1986/87 and 1987/88 (Table 2) and loss estimates for the soil cores

Table 4. Nitrate and ammonium contents of soil cores to 3 m (kg N/ha). Figures are means of six cores; standard errors in brackets; all figures based on log-transformed results

Fertilizer applied (kg N/ha)	Hurley NO_3	Hurley NH_4	Jealotts Hill NO_3	Jealotts Hill NH_4	Ravenscroft NO_3	Ravenscroft NH_4
100	17.3 (2.2)	96.6 (1.4)	36.9 (2.9)	86.3 (1.9)	78.8 (1.7)	57.1 (1.4)
250	19.8 (1.8)	37.8 (1.4)	30.1 (1.9)	96.1 (1.5)	138 (2)	71.8 (1.5)
350	—	—	—	—	136 (3)	105 (4)
450	56.2 (2.9)	34.6 (1.5)	164.1 (2.2)	146 (2)	233 (2)	68.4 (1.4)
750	115 (2)	43.1 (1.7)	263 (4)	219 (2)	507 (2)	87.8 (2.1)

(Table 5). The agreement between the two methods is poor.

It seems that where water and solute flow is predominantly piston-type displacement, as at Hurley for example, ceramic cup samplers and soil coring give similar estimates of nitrate leaching. In more structured soils, such as the Wickham series at Jealotts Hill and the Crewe series at Ravenscroft, the more complex flow paths may result in the ceramic cups sampling only the more mobile pore water.

CONCLUSIONS

It is clear that the spatial variability of soil nitrate under grazed swards makes reliable estimation of nitrate leaching difficult unless under-drainage can be employed to obtain measurements integrated over a large area. Despite this variability, trends were apparent in this work. The data broadly support the concept of a breakpoint in the relation between nitrate leaching and fertilizer application, although they indicate how difficult it would be to predict it accurately in a given year. They do not, however, support the hypothesis that leaching losses from well-drained soils necessarily exceed those from heavier soils where more denitrification would be expected to occur. The results from Hurley indicate that other factors, such as the age of the sward, may influence nitrate loss. The soil core data confirm earlier conclusions based on studies of the surface layers of the soil that nitrate:ammonium ratios widen as fertilizer applications increase. The comparison between the losses estimated by ceramic cups and by soil coring indicate that the two methods only give comparable results on soils where flow is predominantly piston type.

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Nitrate leaching and intensive outdoor pig production

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Abstract. The production of pigs in outdoor units is gaining in popularity in the United Kingdom and is often concentrated on free-draining soils over important aquifers. Originally, stocking rates were sufficiently low to ensure the maintenance of a grass crop, but recently they have increased. Pigs are natural 'rooters' and wallowers and so cause damage to vegetation and soil structure. With overstocking these natural activities lead to considerable areas of bare, uncropped ground for much of the year. This paper assesses the potential for leaching of nitrate from such land, and makes recommendations for decreasing it.

INTRODUCTION

THE UK PIG INDUSTRY is noted for its cyclical profitability. One recent feature has been the ascendancy of the outdoor pig herd, a major advantage being less capital requirement than with housed intensive pigs. Savings of £200 per sow in capital costs have been reported (Ridgeon,

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