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A comparison of animal output and nitrogen leaching losses recorded from drained fertilized grass and grass/clover pasture

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SUMMARY

Annual liveweight gain of beef cattle (steers) grazing grass pasture fertilized with 200 kg N/ha was compared over a period of 7 years (1989–95) with that of steers grazing grass/white clover pasture given no artificial N fertilizer at North Wyke, Devon, UK. Nitrogen lost by leaching over the ensuing winter drainage periods was monitored from both pastures. Nitrogen leaching loss from the fertilized pasture over an extended period of 13 years (1983–95) is also reported.

The average annual liveweight gain of the steers grazing the grass/clover pasture (0·81 t/ha) was 19% lower than that of the steers grazing the N-fertilized grass pasture (1·00 t/ha). The average annual loss of nitrate-N by leaching in winter drainage from the grass/clover pasture (13 kg/ha) was only 26% of that recorded from the fertilized grass (50 kg/ha). A possible reason for this difference may arise from the previous history of the grass/clover pasture which had been ploughed in 1982, causing a flush of N mineralization and consequently greater immobilization of N in the soil in subsequent years.

Losses of N each winter by leaching measured over a 13-year period from the fertilized grass were highly correlated ($P < 0·001$) with the preceding summer's soil moisture deficit, with the highest losses following dry summers. The nitrate-N concentration in the drainage water exceeded the European Union limit in drinking water (11·3 mg/l) in the initial 25 mm of drainage during 11 of the 13 autumns. The average loss of N each winter (53 kg/ha) was equivalent to 26% of the fertilizer-N applied annually. Immediate losses of N by leaching of fertilizer applied in early spring and throughout one very wet summer (1993) were minimal.

INTRODUCTION

In previous papers describing the grassland drainage experiment at North Wyke, Devon (Tyson *et al.* 1992*a*; Scholefield *et al.* 1993), we have shown that drainage of these impermeable clay soils, known locally as the Culm Measures, increased annual liveweight production of grazing cattle by only 11%. This increase in output was not statistically significant and was unlikely to be economic for beef production in the short term because of the high initial capital cost of drainage schemes. Drainage of these soils was also shown to have potentially serious environmental side-effects. Nitrogen (N) leached from the grazed pastures was more than three times greater from the drained pasture compared with that recorded from undrained pasture receiving the same annual input of fertilizer-N. Nitrogen lost to drainage as nitrate (NO_3-N) from pasture receiving an annual fertilizer-N input of 200 kg/ha was increased over the ensuing winter periods from an average of 16 kg/ha from undrained paddocks to 56 kg/ha from drained paddocks (Scholefield *et al.* 1993; Tyson *et al.* 1993).

In lowland southern and eastern England, clover is generally accepted as being capable of fixing some 74–280 kg/ha of atmospheric N annually (Cowling 1982) and therefore the productivity of pastures with a substantial clover content could be expected to be comparable to that of a grass pasture supplied with moderate rates of fertilizer-N. In this experiment, steer production and N leaching losses from grass/clover pasture were compared with those recorded from the grass pasture receiving 200 kg N/ha. During 1988, two drained paddocks sown originally to perennial ryegrass (*Lolium perenne* L.) in 1982 and receiving 400 kg N/ha annually over the 5-year period 1983–87 were converted to grass/white clover (*Trifolium repens* L.) pastures and have since received no fertilizer-N. This paper reports on the 7-years' data on steer production and N losses by leaching

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from this and the drained grass pasture with 200 kg N/ha. Also reported are the N leaching losses from the fertilized grass pasture recorded over a longer period of 13 years.

MATERIALS AND METHODS

The Rowden drainage experiment has been fully described in previous papers. The soils of the experimental area were surveyed by Harrod (1981) and a full description of the drainage treatments and hydrological instrumentation, together with the results of drainage on the soil water regimes, are given by Armstrong & Garwood (1991). Agronomic results obtained during the first 5 years of the experiment (1983–87) were reported by Tyson *et al*. (1992*a*) and a further paper by Scholefield *et al*. (1993) provided detailed information and analysis of the N losses recorded in drainage water from the various experimental treatments during 1983–89. A technical report by Tyson *et al*. (1993) provided the historic record, scientific data obtained and conclusions derived over the 10-year period, 1983–92. A 'popular' article (Tyson *et al*. 1992*b*) summarized the main practical implications obtained from the experiment.

Two drained 1 ha sized paddocks previously sown to perennial ryegrass (cv. Melle) and receiving 400 kg N/ha were converted to grass/clover pastures during 1988 using a Hunter rotary strip seeder (Pascal & Sheppard 1985) as follows. Nitrogen was applied on 14 March, 11 April and 5 May in equal amounts, giving a total of 132 kg/ha. The paddocks were cut for silage on 1 June and then sprayed on 8 June with paraquat (at 1·4 litres/ha) to suppress grass regrowth. On 13 June, white clover (cv. Menna) was strip-seeded into the sward at 4·8 kg/ha. Slug pellets at 3·6 kg/ha, lime at 63 kg/ha, phosphorus at 30 kg/ha and potassium at 60 kg/ha were also strip-seeded into the sward with the clover seed. The summer of 1988 was one of the wettest recorded at North Wyke and consequently both germination of clover seed and subsequent clover growth were good. The pastures were sprayed on 22 June with chlorpyrifos (Dursban, Dow Elanco) to prevent any possible attack by Sitona weevils on the germinating clover seedlings. No further N was applied in 1988 or during the subsequent 7 years. The grass/clover pastures were lightly grazed by steers from mid-July until late October during this establishment year.

The fertilized grass pastures were originally established in 1982 on a permanent pasture known to be at least 50 years old and treatments remained substantially unchanged throughout the course of the present measurements. Total annual N input (200 kg/ha) remained unchanged. Between 1983 and 1992, fertilizer was applied in nine equal amounts of 22·2 kg/ha starting in mid-March and thereafter at 3-weekly intervals. During the last 3 years (1993–95), 40 kg/ha was applied in the first and second applications in mid-March and mid-April followed by four equal applications of 30 kg/ha at monthly intervals until mid-August. Each spring, 25 kg P/ha and 50 kg K/ha was applied to the grass treatments and for the first 3 years (1989–91) 50 kg P/ha and 100 kg K/ha was applied each spring to the grass/clover treatments. This rate was reduced in 1992 to 40 kg P/ha and 80 kg K/ha and subsequently to 25 kg P/ha and 50 kg K/ha during 1993–95 in response to the increase in available P and K. Soil pH remained in the range 6·0–6·5 in the 0–10 cm soil horizon of both grass and grass/clover pastures and so no lime was applied after 1988. Each of the paddocks had been mole drained (at 2 m spacing) in 1982. They were re-moled during the summer of 1987 and again in August 1993. All plots were grazed by Limousin × Friesian beef steers (average weight 275–300 kg at turnout). Animal numbers were adjusted as required throughout each season, to maintain sward heights in the range 50–60 mm (rising-plate sward stick; Holmes 1974).

Herbage production was estimated at 3-week intervals during the period 1989–92 by taking sample cuts from under exclusion cages as described by Tyson *et al*. (1993). To allow for variable soil contamination, subsamples of herbage were analysed for ash content and herbage yields were expressed as ash-free organic matter (OM). Estimates of clover content were made on hand-separated subsamples of fresh herbage. Estimates of herbage organic matter (OM) yield and clover content were discontinued after 1992. Steer liveweight gain (LWG) from the two contrasting pastures was measured by the regular weighing of five core steers allocated to each paddock as described by Tyson *et al*. (1992*a*). The steers used in 1989–91, but not subsequently, were each given a 'Romensin' ruminal delivery device containing monensin sodium to comply with current farm practice at that time.

Each paddock was hydrologically isolated from its neighbours with drainage water directed through a weir. Samples of drainage water were collected daily from the outfall of the weirs throughout the winter period when the soil was at field capacity. These samples were analysed for nitrate + nitrite-N (Hendriksen & Selmer Olsen 1970) and ammonium-N (NH_4-N) (Searle 1984), and the quantities of N lost to drainage calculated by the methods described by Scholefield *et al*. (1993) using weekly values of drainage calculated from incoming rainfall less the estimate for evapotranspiration.

A measure of each growing season's wetness or dryness can be inferred from the maximum potential soil water deficit (SWD). This value was derived from the daily rainfall and evaporation of surface water from a 4 m^2 tank, using seasonal correction factors to adjust to transpiration by a grass sward freely supplied with water (Penman 1952). Drainage data have been

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derived from rainfall minus evapotranspiration from the date drainage first commenced each autumn until its cessation the following spring.

RESULTS

Rainfall and water balances

North Wyke Research Station received an average 1054 mm rain each year for the 30-year period, 1966–95. The wettest months were December (130 mm) and January (134 mm) whereas the driest month was July (54 mm). Despite the high annual rainfall, a considerable SWD often built up during the growing season, causing periods of restricted grass growth during some summers (Table 1). The years with a large potential SWD (i.e. > 250 mm) were 1983, 1984, 1989, 1990 and 1995. Wetter summers with a low potential SWD (i.e. < 105 mm) were 1986, 1988 and especially 1993, when drainage was recorded during periods of all the summer months except August.

Herbage organic matter (OM) yield

Organic matter yields of both grass+N and grass/clover pastures were low during the two dry summers of 1989 and 1990 (Table 2). Although over the 4-year period of measurements, the grass+N pasture out-yielded the grass/clover pasture by 19%, in 1991 (the year with the highest clover content) the grass/clover pasture produced the larger OM yield. Clover content of the grass/clover pasture, averaged over the 4 years, increased from 15% of the total OM yield in mid-April, reaching a peak of 49–50% from late June to early August before declining to 15% by early October. During this peak of clover growth in mid-summer, the grass/clover pasture marginally out-yielded the grass+N pasture over a 6-week period.

Table 2. *Annual organic matter (OM) yield from grass+200 kg N and grass/clover pasture (t/ha) and percentage contribution of clover (in parentheses) to the grass/clover yield. Values are means of two replicates*

Year	Grass+N	Grass/clover
1989	6·88	4·28 (9%)
1990	6·75	5·30 (28%)
1991	8·09	8·59 (40%)
1992	7·79	6·61 (28%)
Mean	7·38	6·20 (31·6%)
S.E. (D.F. = 3)	0·663	1·860

Productivity of pastures as measured by steer liveweight gain (LWG)

Spring turnout of steers onto the pastures was determined as described by Tyson *et al.* (1992*a*), i.e. by the amount of herbage available and the load-bearing capacity of the ground as measured by a hand-held shear vane (Serota & Jangle 1972) and varied between 29 March and 20 April (Table 3). The

Table 1. *Annual rainfall, maximum potential soil water deficit (SWD), drainage volume and duration*

Year (1 April–31 March)	Rainfall (mm)	Maximum potential SWD (mm)	Maximum potential SWD Date reached	Volume (mm)	Drainage duration First autumn	Drainage duration Last spring
1983/84	1144	268	1 Aug	555	28 Nov	8 Apr
1984/85	970	308	21 Aug	655	18 Oct	16 Apr
1985/86	851	140	26 Jul	410	8 Nov	26 Apr
1986/87	1091	85	30 Jul	670*	20 Oct*	9 Apr
1987/88	1103	198	2 Oct	620	10 Oct	4 Apr
1988/89	930	104	26 Jun	510	27 Sep	1 May
1989/90	1199	347	8 Sep	730	28 Oct	2 Mar
1990/91	929	302	18 Sep	480	20 Nov	10 Apr
1991/92	729	210	21 Sep	270	31 Oct	1 May
1992/93	993	141	10 Aug	535†	20 Oct	28 Apr†
1993/94	1441	76	7 Sep	875‡	12 Sep	11 Apr‡
1994/95	1340	173	29 Aug	830§	25 Oct§	31 Mar
1995/96	893	278	5 Sep	480	11 Nov	25 Apr
Mean	1047	203	25 Aug	585	25 Oct	13 Apr

* Includes 50 mm of drainage recorded between mid-August and early September 1986.
† An additional 144 mm drainage was recorded in May, June and July 1993.
‡ An additional 32 mm drainage was recorded between 17 and 22 May 1994.
§ Includes 30 mm of drainage recorded between 14 and 22 September 1994.

Table 3. *Length of grazing season, steer grazing days (per ha) and annual liveweight gain (t/ha) from grass+200 kg N/ha and grass/clover pasture. Values are means of two replicates*

		Grazing days		Liveweight gain	
Year	Length of grazing season	Grass+N	Grass/clover	Grass+N	Grass/clover
1989	3 Apr–7 Nov (218 d)	1021	926	0·96	0·78
1990	29 Mar–7 Nov (223 d)	1201	929	1·01	0·89
1991	11 Apr–5 Nov (208 d)	1118	1028	1·07	0·96
1992	8 Apr–23 Oct (198 d)	1153	1032	1·02	0·85
1993	31 Mar–20 Oct (202 d)	1081	921	0·96	0·70
1994	20 Apr–1 Nov (195 d)	1110	874	0·98	0·81
1995	5 Apr–17 Nov (226 d)	1238	943	0·97	0·69
Mean	6 Apr–3 Nov (210 d)	1132	950	1·00	0·81
S.E. (D.F. = 6)		73·1	58·4	0·040	0·098

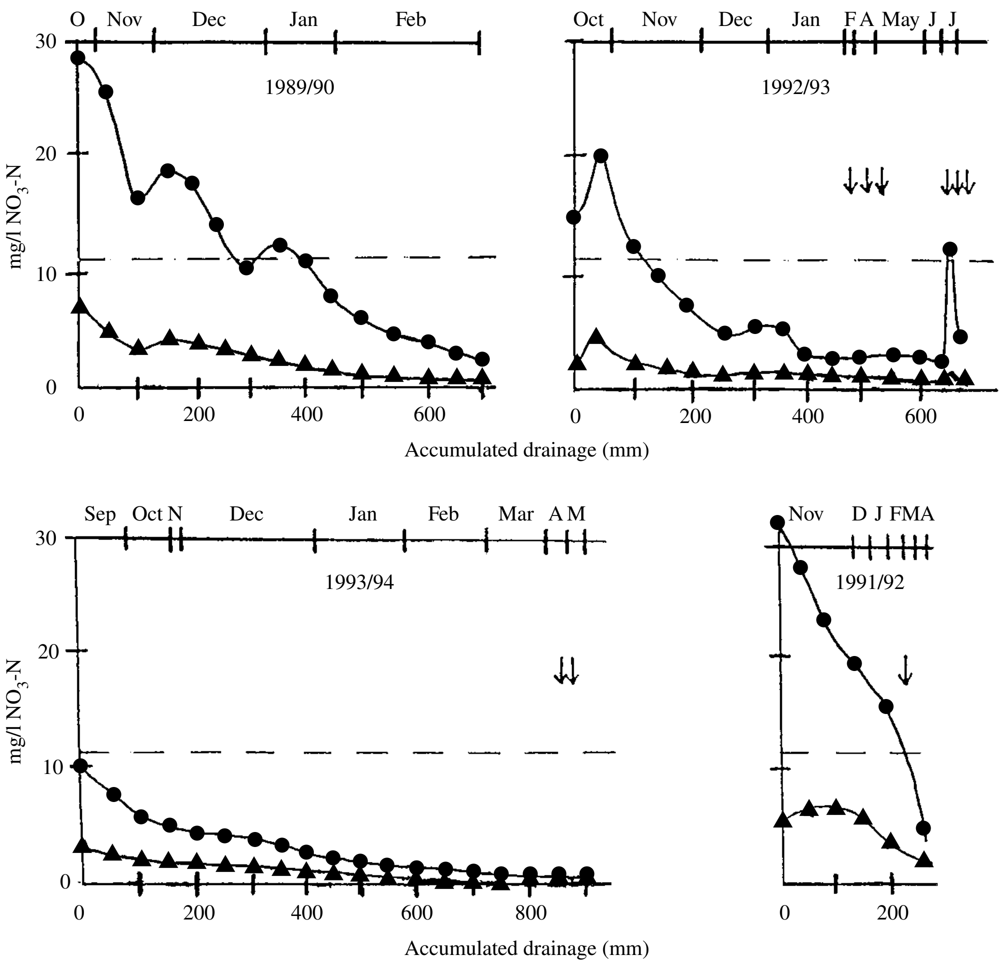

Fig 1. Concentrations of NO_3-N (mg/l) in selected winter drainage periods from a grazed grass pasture receiving 200 kg N/ha per annum (●) and a grass/clover pasture receiving no artificial N (▲). Fertilizer added when indicated by arrows. Mean values from 2 × 1 ha paddocks for each treatment for the periods 1989/90, 1991/92, 1992/93 and 1993/94. The EU limit in drinking water is also indicated (--). There was no drainage in March 1993.

Table 4. *Loss of N (kg/ha) by drainage from grass + 200 kg N/ha and grass/clover pasture between 1988 and 1996. Values are means of two replicates*

Year	Grass + N	Grass/clover
1988/89	38·3	10·4
1989/90	83·5	17·9
1990/91	54·3	9·1
1991/92	51·6	15·4
1992/93	40·4	12·2
1993/94*	29·6	10·2
1994/95	31·8	11·2
1995/96	72·5	16·6
Treatment mean	50·2	12·9
S.E. (D.F. = 7)	19·38	3·28

* During the exceptionally wet summer of 1993 (Table 1) an additional 6·2 kg N/ha was leached from the grass + N pasture and 1·7 kg N/ha was leached from the grass/clover pasture. These values are included in the 1993/94 totals, i.e. in addition to winter drainage losses.

Table 5. *Loss of N (kg/ha) by drainage from grass + 200 kg N/ha pasture between 1983 and 1988 prior to the comparison with grass/clover pasture. Values are means of two replicates*

Year	Grass + N
1983/84	62·0
1984/85	69·4
1985/86	61·8
1986/87	35·3
1987/88	62·8
Treatment mean	58·2
S.E. (D.F. = 4)	13·23

end of the grazing season was usually dictated by lack of available herbage rather than by soil condition. Annual liveweight production (Table 3) on the grass + N pasture was remarkably consistent from year to year, only varying over the 7 years between 0·96 and 1·07 t/ha. Animal production on the grass/clover pasture varied more from year to year (range 0·69–0·96 t/ha) and over the first 4 years mirrored the clover content of the swards. Individual steer LWG values were also more consistent from year to year on the grass + N pasture (0·78–0·96 kg/day, mean 0·88 ± 0·044 kg/day) but over the 7-year period were not significantly different from those of the steers grazing the grass/clover pasture (0·73–0·96 kg/day, mean 0·85 ± 0·090 kg/day).

Nitrogen leaching losses from grass + N pasture compared with grass/clover pasture

Nitrogen as NH_4-N was recorded at concentrations of *c.* 1 mg/l in the initial drainage each autumn but rapidly declined to < 0·1 mg/l throughout the remainder of the winter, so that only NO_3-N concentrations are reported. Nitrite-N concentrations were assumed to be negligible. The mean concentrations of NO_3-N in the drainage waters from both pastures are shown in Fig. 1 for selected winters. The NO_3-N in the drainage water of winter 1989/90 illustrates the high concentrations recorded after a hot, dry summer with a large potential SWD (Table 1) and can be contrasted with the lower NO_3-N concentration in the drainage water of 1993/94 following a cool, wet summer with a small potential SWD. The winter of 1991/92 was dry, with less than half the average winter drainage and illustrates a rapid decline in NO_3-N concentration from late February 1992. The final illustration shows the NO_3-N concentration in the drainage water during the very wet spring and summer of 1993, with monthly inputs of N to the grass pasture and intermittent drainage recorded from April to July. Each winter there was a similar trend in the NO_3-N concentrations in the drainage water from both treatments (Fig. 1). Highest concentrations of NO_3-N occurred in the first 50 mm of drainage each autumn and then declined throughout the winter to reach < 5 mg/l from the grass + N pasture and < 1 mg/l from the grass/clover pasture by late March, provided that > 500 mm of winter drainage had occurred. Also shown in Fig.1 is the maximum permissible level of NO_3-N (11·3 mg/l) allowed in drinking water by the European Union (EU).

The quantity of N lost to drainage was calculated by using the values for weekly drainage volume and mean NO_3-N concentration recorded in each week's drainage (Table 4). It was valid to use mean concentrations, as variable flow rates have been shown to have only a small effect on NO_3-N concentration over short periods at this site (Scholefield *et al.* 1993). There were large annual variations in N loss from the grass + N treatment, ranging from 29·5 kg/ha (1993/94) to 83·5 kg/ha (1989/90). Nitrogen loss from the grazed grass/clover pasture over the 8 years was 26% of that recorded from the grass + N treatment.

The two grass replicate pastures being used in the current comparisons of animal output and N leaching loss with that recorded from grass/clover pasture had received the same treatment for 13 consecutive years (1983–95). The N losses by drainage from the grass + N pasture for the 5-year period prior to those reported in Table 4 are given in Table 5.

DISCUSSION

Farmers in the UK, as elsewhere in Europe, are under increasing pressure from the EU, National Governments and environmental organizations to reduce losses or outputs of agricultural chemicals into the environment. The increasing concern over NO_3 in river and ground water has led to the EU upper limits of 11·3 mg N/l for the NO_3-N content of drinking water. The UK government has recently declared NO_3 vulnerable zones with voluntary restrictions on N inputs to crops by farmers. There is a financial and environmental benefit in being able to maintain high levels of animal output by using minimum inputs of fertilizer, or by relying on clover-based pastures to fix the N required to maintain productive pastures with minimal contamination of rivers and ground waters. However, Jarvis (1992) argued that if animal output from a clover-based pasture was similar to that from N-fertilized grass pasture, this would imply that similar quantities of N were circulating around the two systems, so that NO_3 leaching losses would be similar. Macduff *et al.* (1990) demonstrated that under a sheep-grazed clover monoculture, the concentration of NO_3-N in the soil solution below the rooting zone was comparable to that below highly fertilized grass pastures (400 kg N/ha). Cuttle *et al.* (1992) studied NO_3-N leaching losses from sheep-grazed pastures over a period of 3 years and recorded a winter loss of 2–24 kg N/ha from grass plots fertilized with 150–200 kg N/ha per year compared with 6–33 kg N/ha from grass/clover plots.

It has already been demonstrated (Tyson *et al.* 1993) that increasing N input from 200 to 400 kg/ha led to only a marginal, uneconomical, increase in animal output. The additional N lost to drainage from the drained pasture given 400 kg N/ha, however, caused the NO_3-N in the drainage water to exceed the EU limit throughout most winters. Initial concentrations of NO_3-N were as high as 70 mg/l in October 1989 and averaged 55 mg/l at this time over 7 years. The total loss of N by leaching averaged 194 kg N/ha each winter, the equivalent of 48·5% of that applied as fertilizer N. In contrast, when no fertilizer N was applied to a grass-only pasture, losses were much lower, averaging 5 kg N/ha annually (Scholefield *et al.* 1993; Tyson *et al.* 1993)

Estimates of herbage production on grazed pastures are notoriously difficult to make and the use of exclusion cages, as used in this experiment, has been criticized (Parsons *et al.* 1984). Although they do not give a measure of herbage consumed by the grazing animal, cages give a measure of the productivity of a pasture which has been previously grazed with returns of animal excreta. Estimates of the clover content of a grazed pasture can also be criticized if based on non-grazed areas under exclusion cages, even if the grazing animal is excluded for only 21 days. Accepting these criticisms, estimates of herbage production in the present study revealed a 15% lower OM yield from the grass/clover pasture over a 4-year period when compared with the grass + N pasture. Clover content, averaged over the 4 years, increased as the growing season progressed, reaching a peak contribution of *c.* 50% of the total yield in mid-summer.

The 15% lower OM production from the grass/clover pasture resulted in a corresponding reduction of 16% in grazing days (or 0·7 steers/ha per day) compared with the grass + N pasture (Table 3). This lower stocking density on the grass/clover pasture might have been compensated for by an enhanced daily LWG. Increased growth rates have been demonstrated by cattle fed on forages made from white clover compared with those from grass in indoor feeding trials (Cook & Wilkins 1981; Thomson 1984). However, in grazing experiments with steers on grass/clover pastures, such responses are more difficult to demonstrate (Clark 1988). In the present experiment, growth rates by steers on the grass/clover pasture, averaged over the 7-year period (0·85 kg/day), were similar to the growth rates of steers grazing the N-fertilized grass pasture (0·88 kg/day).

Although annual steer production per hectare from the grass pasture was 190 kg greater than that achieved from the grass/clover pasture, in monetary terms when the cost of buying and applying 200 kg N/ha to the grass pasture is taken into consideration, the value of this extra animal production is reduced. Using late 1995 prices (Nix 1995), the additional LWG produced annually from the grass + 200 kg N pasture was valued at £218 (£1.15/kg). Set against this extra income, the cost of 200 kg N (£72.50) and the £41/ha cost of applying N fertilizer on six occasions reduced the advantage of the grass + 200 kg N pasture to £105/ha, with no allowance being made for the higher working capital involved in the more heavily stocked grass + N treatment.

The major advantage shown by the clover-based pasture over the N-fertilized grass pasture was the very much lower loss of N by leaching. Approximately four times as much N leached from the N-fertilized grass each winter (50 kg) than from the grass/clover pasture (13 kg). The concentration of NO_3-N in the leachate from the grass/clover pasture never exceeded the EU limit for drinking water at any time, whereas in all but two of the years the NO_3-N concentration from the grass + N pasture was above the EU limit at the onset of drainage in autumn. Concentration of NO_3-N in the leachate from the grass + N pasture was as high as 30 mg/l in October 1989 (Fig. 1) and in November 1991.

A possible explanation for the large difference in NO_3-N loss from the two contrasting pastures could be their previous history. The N-fertilized grass pasture has, to our knowledge, not been ploughed for at least 50 years. The organic matter status in the top soil horizons was high (5·7% C and 0·51% N in the upper 10 cm of the soil profile). Soil sampling each October revealed only small differences in total soil N to 10 cm depth from year to year with no obvious changes (Tyson *et al.* 1993). Therefore, organic matter accumulation was apparently at or approaching

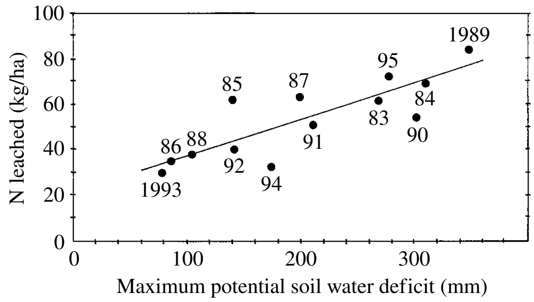

Fig 2. The relationship between the maximum potential soil water deficit (mm) recorded each summer over a 13-year period (1983–95) and the subsequent loss of NO_3-N (kg) by leaching from grazed grass pasture receiving 200 kg N/ha per annum. $y = 21{\cdot}7 + 156x$, $r = 0{\cdot}814$, $P < 0{\cdot}001$.

equilibrium. Surplus N not removed either in the animal LWG, by denitrification or by ammonia volatilization would have been leached in the following winter's drainage. The grass/clover paddocks had, in contrast, originally been ploughed and reseeded with perennial ryegrass in August 1982. A flush of mineralization occurred after ploughing, causing a drop in the soil organic matter status of the top 10 cm of the soil profile to 4·0% C and 0·37% N, a loss of *c*. 17 t/ha of C and 1·4 t/ha of N (Tyson *et al*. 1993). Since ploughing in 1982, the soil N to 10 cm depth increased at a rate of *c*. 80 kg N/ha annually. This increase in soil N under a newly sown grass pasture was similar to the annual increase measured elsewhere during the first 10 years under a newly established grass/clover pasture on a free draining sandy-loam soil of the Frilsham series (Tyson *et al.* 1990). Since conversion in 1988 to a grass/clover pasture, soil N at the North Wyke site has continued to increase so that approximately half of the original loss of organic N had been restored by 1995. It seems likely, therefore, that as the high N values found in the soil under the old grass pasture are approached under the grass/clover pasture, a decreasing quantity of N will be incorporated into the soil organic matter, leaving more surplus N to be leached. Comparison of undisturbed and reseeded grass pastures at the same site (Scholefield *et al*. 1993) showed that over the 5 years after reseeding, NO_3-N leaching losses were, on average, 50% lower from the reseeded pasture than from the permanent pastures. This effect may also be the case for the present treatments over an extended period.

Another important effect may be through the difference in stocking rates, i.e. the higher stocking rate with the grass + N pasture may have given rise to greater excesses and leaching losses of N. Differences in the quantities of N leached from other pastures in the experimental area (Scholefield *et al*. 1993) receiving 200 or 400 kg N/ha demonstrate that only relatively small differences in animal output may result in large differences in leaching losses. Other studies with grazing sheep (Cuttle *et al*. 1992) have also shown that there is a strong positive relationship between livestock carried and leached NO_3-N, regardless of whether N is supplied through fertilizer addition or by biological fixation.

Leaching losses from N-fertilized grazed grass pasture over the long term

It was apparent that a greater loss of NO_3 followed dry summers and a lower loss followed wet summers. There was an approximately three-fold difference between the lowest and the highest winter loss recorded in the 13-year period. In Fig. 2, the loss of N measured each winter is plotted against the maximum potential SWD recorded in the preceding summer (from Table 1). The average throughput of winter drainage (585 mm) resulted in low concentrations of NO_3-N by early spring (Fig. 1) and in the leaching of 90% or more of the residual NO_3 remaining in the soil profile at the end of the grazing season (Scholefield *et al*. 1993). The quantity of N leached each winter was highly correlated ($P < 0{\cdot}001$) with the maximum potential SWD recorded during the preceding summer. (A similar relationship ($P < 0{\cdot}1$) was also shown by the grass/clover pasture.) The greater loss during winters following a dry summer could result from some of the N applied as fertilizer remaining in the soil during drought conditions. Much lower rates of denitrification would occur in drought conditions and if the soil wetting up process occurred while soil temperatures were still optimal, a burst of mineralization could occur, releasing yet more mineral N, surplus to the sward's need, to be in the soil profile and at risk of leaching loss.

Using Fig. 2, it is possible to predict with a high degree of accuracy the quantity of N to be leached each winter. Exceptions will occur during some winters, as illustrated by the greater N loss than predicted in 1985/86 and the lower than predicted loss in 1994/95. During March 1986 up to 10 kg N from the first spring fertilizer application was leached from the soil profile during a very cold month, with minimal grass growth, so adding to the total loss. During the autumn of 1994, however, the reverse was true when exceptionally mild weather after the removal of the steers on 1 November resulted in considerable grass growth and uptake of N continuing until mid-December, thereby reducing the pool of NO_3-N in the soil profile at risk of loss. When winters are abnormally dry, as was the case in 1991/92, incomplete leaching of N occurs. The very rapid fall in NO_3-N concentration in the drainage water measured during late February and March 1992 (Fig. 1) was probably caused by N uptake by a rapidly growing sward that followed a mild early spring.

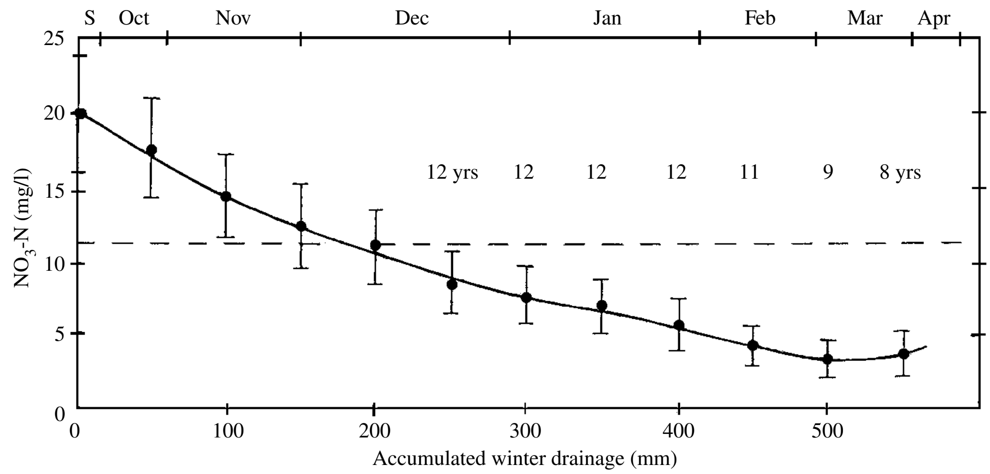

Fig 3. Mean concentration of NO_3-N (mg/l) in winter drainage from the grazed grass pasture receiving 200 kg N/ha per annum. Based on the 13-year period 1983–95 unless otherwise indicated. The EU limit in drinking water is also indicated (--). Vertical bars represent S.E.S.

Nitrogen losses from spring applications of fertilizer-N

Data presented in Fig. 1 and confirmed in several other years demonstrate that there was little effect of the first spring application of N in mid-March on the NO_3-N concentration in the drainage water. A small increase in NO_3-N concentration occurred in March 1985, a larger increase in March 1986 (see above) and a small increase in March 1988. Applications of N in April 1985, March 1991 and March 1992 caused no increase in the NO_3-N concentration. These first spring applications of N during March, at rates of 22–25 kg/ha and at a time when grass growth was beginning, could be expected to be taken up fairly rapidly and therefore not to be at risk of loss by leaching during further wet spells of weather in March and April. Even the two applications of 40 kg N/ha on 14 April and 6 May 1994 (Fig. 1) caused only a small increase in NO_3-N in the 46 mm of drainage that occurred between 17 and 27 May 1994.

The spring and early summer of 1993 was an exceptionally wet period, with 432 mm of rain recorded during April–July compared with the 30-year mean rainfall for these months of 240 mm. The soil was restored to field capacity on no fewer than seven occasions between April and July and a total of 188 mm of drainage recorded (Fig. 1). However, despite the 174 kg N/ha applied during these months, only 6·9 kg N/ha was leached through the soil profile.

The small, or negligible, reaction to applications of early spring N in the NO_3-N concentration in the drainage water during some wet springs and throughout the very wet summer of 1993 indicates that moderate inputs of N fertilizer were rapidly used by an actively growing sward or denitrified in the wet and warm soil. The converse would be true in dry summers, when poor grass growth and low denitrification due to drought allows a build up of unused NO_3-N, leading to a large loss of N by leaching during the ensuing winter (Fig. 2).

Generalized nitrate leaching pattern

The 8 years' data on average NO_3-N leaching concentrations throughout each winter from the two N-fertilized grazed grass pastures used in conjunction with the previous 5 years' data from these pastures allow values to be estimated for the average NO_3-N concentration to be expected from a grazed grass pasture fertilized with 200 kg N/ha under the site-specific conditions of soil type, sward age, drainage status and climate relating to North Wyke, Devon (Fig. 3).

At North Wyke, the average maximum potential SWD of 203 mm (*c.* 100 mm actual SWD), recorded over the 13-year period, was reached in late August (Table 1) followed by a 2-month soil wetting up period, so that first drainage occurred during late October (Table 1). This initial drainage contained on average 20 mg/l NO_3-N. The NO_3-N concentration declined steadily throughout the winter period, dropping below the EU limit in drinking water after *c.* 150 mm of accumulated drainage in early December and continued to decline to *c.* 3 mg/l NO_3-N by early March after 500 mm of accumulated drainage. The first spring application of N fertilizer in mid-March resulted in a very small increase in NO_3-N by the end of winter drainage during early April. Over the 13-year period, on average, 53 kg N/ha was leached each winter, equivalent to 26 % of that applied annually as fertilizer-N.

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