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Management options to limit nitrate leaching from grassland

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Abstract

Nitrate leaching can be reduced by the adoption of less intensive grassland systems which, though requiring a greater land area to achieve the same agricultural output, result in less nitrate leaching per unit of production than do intensively managed grasslands. The economic penalties associated with reductions in output can be partly offset by greater reliance on symbiotic nitrogen fixation and the use of clover-based swards in place of synthetic N fertilisers. Alternatively, specific measures can be adopted to improve the efficiency of nitrogen use in intensively managed systems in order to maintain high outputs but with reduced losses. Controls should take account of other forms of loss and flows of nitrogen between grassland and other components of the whole-farm system and, in most instances, should result in an overall reduction in nitrogen inputs. Removing stock from the fields earlier in the grazing season will reduce the accumulation of high concentrations of potentially leachable nitrate in the soil of grazed pastures but will increase the quantity of manure produced by housed animals and the need to recycle this effectively. Supplementing grass diets with low-nitrogen forages such as maize silage will reduce the quantity of nitrogen excreted by livestock but may increase the potential for nitrate leaching elsewhere on the farm if changes to cropping patterns involve more frequent cultivation of grassland. Improved utilisation by the sward of nitrogen in animal excreta and manures and released by mineralisation of soil organic matter will permit equivalent reductions to be made in fertiliser inputs, provided that adequate information is available about the supply of nitrogen from these non-fertiliser sources.

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1. Introduction

The temperate climate of western Britain is well suited to the growth of grass and supports a wide range of beef, dairy and sheep production systems. Pastures range from extensively grazed areas of unfertilised semi-natural vegetation to intensively managed grassland receiving up to 400 kg ha^{-1} N annually. Although little nitrate is leached from the more extensive, moderately fertilised swards, greater quantities may be leached from intensively managed pastures. Annual leaching losses ranging from 30 to >200 kg ha^{-1} N have been reported from pastures receiving 300–400 kg ha^{-1} fertiliser-N (Ryden et al., 1984; Macduff et al., 1990; Barraclough et al., 1992; Scholefield et al., 1993) and nitrate concentrations in drainage water from these pastures may be considerably in excess of the European Union limit of 11.3 mg L^{-1} N for drinking water. The development of strategies for reducing nitrate losses has concentrated on these intensively managed pastures where the problem is seen to be most acute.

2. Factors contributing to nitrate leaching

In Britain, particularly in lowland areas, the evaporative demand in summer is generally sufficient to restrict drainage to infrequent events at this time of year and most leaching occurs during late autumn and winter when drainage volumes are greater. Significant leaching of nitrate is generally associated with conditions which lead to an accumulation of nitrate in the soil which may then be transported from the profile by percolating water. Given suitable conditions during the growing season, grass swards are relatively efficient at taking up mineral-N. Where herbage is cut and removed from the field, application of fertiliser at rates of up to ~ 400 kg ha^{-1} yr^{-1} N leaves little residual mineral-N in the soil (Prins, 1980) and, as a result, there is little nitrate available to be leached over the following winter. Where significant losses do occur from cut swards, these are most frequently associated with excessive applications of fertiliser or slurry at times when plant uptake of nitrogen is restricted, for example, in autumn and winter or during periods of drought (Garwood and Tyson, 1977; Dowdell and Webster, 1980). Direct losses of nitrogen may also occur in drainage water or surface runoff when heavy rain follows shortly after application of fertiliser or slurry to well-structured or wet, impermeable soils (Cuttle et al., 1992; Scholefield et al., 1993).

Introduction of the grazing animal has a major impact on flows of nitrogen in grassland and significantly increases the potential for loss. Of the nitrogen consumed by ruminants, 75–95% is excreted (Whitehead, 1970) and, in the case of grazing stock, is returned directly to the pasture in localised patches of dung and urine. The uneven distribution of excreta provides particularly large inputs of nitrogen to the areas of pasture that are affected, equivalent to between 30 and 100 g m^{-2} N (Ball and Ryden, 1984) and considerably in excess of the sward's immediate requirements. In the soil, urine-N is rapidly hydrolysed to create zones containing high concentrations of ammonium and nitrate from which large losses of nitrogen may occur as gaseous emissions and by leaching. Nitrogen in dung is present in organic forms that are less rapidly mineralised and is less susceptible to loss (Ball and Ryden, 1984). Nitrate leaching from grazed pastures is therefore characterised by a high degree of spatial heterogeneity with high concentrations from a randomly distributed pattern of urine patches superimposed on a lower background concentration from the pasture as a whole (White et al., 1987; Afzal and Adams, 1992). The background loss is likely to contribute proportionally more to leaching from intensively managed pastures where fertiliser inputs and mineralisation rates may in themselves be sufficient to provide significant accumulations of mineral-N in the soil.

The relative importance of the different processes that determine nitrate contents in the soil and the subsequent mechanisms of leaching are influenced by soil properties and climate and, as a result, there may be considerable variation between the quantities of nitrate leached at different sites and in different years, even where nitrogen inputs are similar. However, where data from separate studies have been considered together, variations in nitrate losses could be only partly explained in terms of soil and climatic factors (Macduff et al., 1990). Water quality standards are generally expressed in terms of nitrate concentrations, rather than absolute quantities, and these too are influenced by soil properties and climate. Studies on soils ranging from loamy sands to drained clay loam indicate that for a given quantity of nitrogen leached, peak concentrations may vary 5-fold according to soil type (Scholefield et al., 1994). Nitrate concentrations increased with decreasing clay content, presumably as a result of reductions in soil water capacity and the degree of preferential flow. The sensitivity of losses to differing conditions demonstrates the potential that exists for controlling leaching through an understanding and manipulation of nitrogen flows but also indicates that control measures that are effective in some instances may be less so in others.

3. Strategies to reduce nitrate leaching

Measures to control nitrate leaching seek to minimise immediate losses and prevent the occurrence of excess nitrate concentrations in the soil, generally by matching the supply of nitrogen more closely to the demands of the sward and by minimising the impact of the grazing animal. Although leaching is largely associated with diffuse losses from fields, controls should also take account of other components of the farming system which influence the flows of nitrogen into and out of grassland. For example, much of the nitrogen fed to housed stock in silage and purchased feed will ultimately be transferred to the fields as manure or slurry and will contribute to the pool of potentially leachable nitrogen in the soil. Similarly, leaching cannot be considered in isolation from other forms of nitrogen loss. Gaseous emissions of ammonia and nitrous oxide are also of environmental concern and strategies that reduce nitrate leaching by redirecting the loss to these other pathways cannot be considered to be acceptable, except perhaps as a short-term expedient in circumstances where the impact of nitrate leaching is particularly acute.

Strategies to control nitrogen leaching must therefore be developed within the context of the whole-farm system and take account of all forms of nitrogen loss. In any agricultural system, the total output of nitrogen in products and as losses to the wider environment will be equal to the overall input of nitrogen to the farm unless there is a

Table 1
Measures that have been proposed for reducing nitrate leaching from grassland (Frame, 1992, pp. 107–108)

Measures to reduce nitrate leaching
● Improved precision of rate and timing of fertiliser use
● Balanced fertiliser use
● Use of good quality fertilisers
● Improved accuracy of spreading
● Use of ammonium-based fertiliser in spring
● Application of slurry in spring or summer
● Emphasis on cutting in late season
● Use of grass/clover swards
● Reliance on long-term grassland
● Reseeding leys in spring

change in the quantity of nitrogen stored within the system. It is apparent, therefore, that if this balance is to be maintained, any reductions in nitrogen losses must be accompanied by either a reduction in inputs, increased recovery in products or increased storage of nitrogen. As most agricultural systems have a finite capacity to accumulate nitrogen, measures that rely on increases in storage are only likely to be effective in the short term.

A wide range of measures have been proposed for controlling nitrate losses, either directed specifically at grassland itself (e.g., Table 1) or involving wider changes to the farming system as a whole (Aarts et al., 1992). All can be shown to satisfy one or more of the above requirements. In considering the options that are available, a distinction can be made between strategies that achieve a reduction in leaching simply as a result of reductions in nitrogen inputs, without involving specific measures to modify nitrogen flows, and those strategies that seek to maintain a high level of production while controlling losses through the adoption of specific practices to improve the efficiency of nitrogen use. In the context of this paper, an improvement in efficiency is defined as an increase in the proportion of the total nitrogen input ultimately recovered in farm products.

3.1. Control of losses through reducing nitrogen inputs

As large nitrogen losses are particularly associated with intensive grassland systems, it follows that losses may be reduced by reducing the intensity of the farming operation and limiting inputs of nitrogen as fertiliser and in the form of purchased feeds. The effectiveness of reductions in fertiliser inputs is demonstrated by data from an experiment on a clay loam soil in Devon in which nitrate losses were measured in drainage water from hydrologically isolated plots grazed by beef cattle (Tyson et al., 1992; Scholefield et al., 1993). N fertiliser was applied to both drained and undrained plots at rates of either 200 or 400 kg ha^{-1} N annually. Over a 7-yr period, the mean quantity of nitrate leached from plots receiving 200 kg ha^{-1} N was only 27% of that leached from the 400-kg-ha^{-1}-N treatments (Table 2). Although the lower fertiliser rate was effective at reducing leaching, animal output was also reduced. As a result, a greater area of land

Table 2
Effects of fertiliser input on animal production and quantities of nitrogen leached from undrained and drained pastures grazed by beef cattle (mean values 1983–1989)

	Undrained		Drained	
	200 kg ha^{-1} N	400 kg ha^{-1} N	200 kg ha^{-1} N	400 kg ha^{-1} N
Liveweight gain of cattle (kg ha^{-1} yr^{-1})	784	879	878	965
N removed in cattle (kg ha^{-1} yr^{-1} N)	20	22	22	24
N leached (kg ha^{-1} yr^{-1} N)	18	74	59	194

Data from Tyson et al. (1992) and Scholefield et al. (1993). Quantities of nitrogen removed in cattle are estimated from liveweight gains, assuming a nitrogen content of 2.5% (Blaxter, 1980).

would be required to achieve the same total output as that produced by the more intensively managed pasture. In this respect, the shape of the response curve linking nitrogen losses to inputs is of particular importance. There is evidence from a number of studies that this is not a linear relationship (Kolenbrander, 1981; Barraclough et al., 1992). Nitrate losses appear to increase disproportionately with increasing input, indicating that, though distributed over a greater area, the overall quantity of nitrogen leached from more extensively managed grassland will be less than if the same output was produced intensively on part of the area. In the experiment above, the average liveweight gain from the pasture receiving fertiliser at a rate of 200 kg ha^{-1} N was equivalent to 90% of that achieved with 400 kg ha^{-1} N (Table 2). It would only be necessary to increase the area of the 200-kg-ha^{-1}-N treatment by 10% to produce the same liveweight gain as that with the intensive management. This would result in an absolute loss of 65 kg N from an area of 1.1 ha, compared with 194 kg N from 1 ha of intensively fertilised pasture.

This comparison ignores the economic arguments in favour of more intensive production systems. The economic viability of many agricultural units is dependent on maximising production from the land area that is available. In these cases, significantly reducing inputs below what is considered to be an economic optimum is not a viable option, except perhaps where compensation is available from Government. However, there may be greater opportunities for adopting less intensive grassland systems if the changes include more widespread use of grass/clover swards. In clover-based swards, where nitrogen is supplied by symbiotic fixation, there will be savings in fertiliser costs which to some extent will offset the loss of income arising from reductions in output (Ryan, 1989; Frame, 1992, pp. 262–263).

It has also been suggested that less nitrate is leached from clover-based swards than where nitrogen is supplied as inorganic fertiliser. Although leaching losses from grass/clover pastures have been shown to be smaller than those from grassland receiving large inputs of N fertiliser (Ryden et al., 1984), the former are usually of lower productivity. Where comparisons have been made between clover- and fertiliser-based swards of similar stock carrying capacity, there appears to be little difference in the

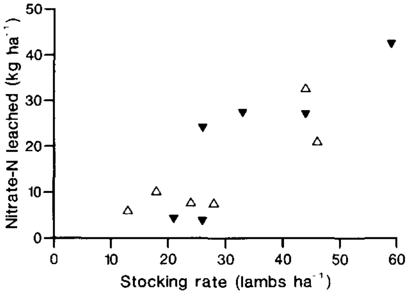

Fig. 1. Relationship between quantities of nitrogen leached annually and mean stocking rates (post-weaning) for a ryegrass sward receiving 150–200 kg ha^{-1} fertiliser-N (*solid symbols*) and an unfertilised grass/clover sward (*open symbols*): 1987–1993 (Cuttle et al., 1992; S.P. Cuttle, unpublished data, 1995).

quantities of nitrate leached (Cuttle, 1992). Fig. 1 shows results obtained over 6 consecutive years from sheep-grazed plots in Wales in which nitrate losses from perennial ryegrass (*Lolium perenne* L.) pasture receiving 150–200 kg ha^{-1} fertiliser-N were compared with those from ryegrass/white clover (*Trifolium repens* L.) pasture that received no N fertiliser (Cuttle et al., 1992; S.P. Cuttle, unpublished data, 1995). Both sward types had been established at the start of the experiment as replicate plots within what had previously been a uniformly managed field and, with the exception of nitrogen applications, were managed similarly during the course of the experiment. The number of sheep on the plots was adjusted throughout the grazing season to match the rate of herbage production. Data from both treatments demonstrate a similar positive relationship between stocking rate and the quantity of nitrogen leached during the following winter, indicating that stocking rate and, it is assumed, the proportion of pasture affected by excreta, was the main factor determining losses, irrespective of whether the origin of the nitrogen was as fertiliser or by fixation. Baber and Wilson (1972) and Ball (1982) also report that considerable losses of nitrogen can occur from highly productive, clover-rich pastures. The contribution that clover-based systems may make towards reducing nitrate leaching would therefore appear to be associated with their economic advantages which favour the adoption of less intensive management systems, rather than to any direct benefits in terms of the relative quantities of nitrogen leached from clover- and fertiliser-based swards.

3.2. Strategies to improve the efficiency of nitrogen use

Although there is increased awareness and concern about the environmental impact of intensive grassland systems, the economic pressures that have encouraged their adoption have not diminished. Alternative strategies therefore seek to improve the utilisation of nitrogen in order to develop intensive production systems that maintain a high level of animal output but with reduced losses. In these circumstances, measures that improve the efficiency of nitrogen use should be seen primarily as means of reducing the nitrogen input required for a particular level of output, rather than providing opportunities for further increasing production. For example, application of animal manures in spring and autumn rather than winter will improve utilisation of nitrogen by the sward and reduce leaching from this source (Pain et al., 1986) but in doing so, will retain more nitrogen within the actively cycling pool. This will ultimately contribute to increased losses unless the increased recovery of nitrogen from manure is matched by an equivalent reduction in the net input of nitrogen, most probably in the form of reduced fertiliser applications. In practice, this requires that better information be made available to farmers about the effective nutrient content of manures and the responses that are likely to be obtained from their use.

In addition to the input of nitrogen to grassland in manures from housed stock, excretion by grazing animals and mineralisation of soil organic matter also make available large amounts of nitrogen and significantly influence the optimum fertiliser requirements of intensively managed swards (van der Meer and van Uum-van Lohuyzen, 1986). The supply of nitrogen from these non-fertiliser sources is influenced by management, soil conditions, climate and sward age. Improvements in the precision of fertiliser rates to avoid excessive applications will require more accurate information from soil tests and from predictive models incorporating information about these variables to determine the quantities of nitrogen available from excreta and from mineralisation. Accurate predictions of fertiliser requirements are particularly important in intensively managed swards. These are already close to their maximum output and as there is little opportunity for further increases in utilisable production, any surplus nitrogen input will be largely directed towards increasing losses.

A recent study has attempted to improve the efficiency of fertiliser use by means of a rapid test to determine the mineral-N content of the soil at intervals during the grazing season and adjusting fertiliser rates on the basis of these measurements to avoid excessive applications and accumulation of mineral-N in the soil (Titchen and Scholefield, 1992). N fertiliser was applied to grazed plots as fortnightly dressings with the rates adjusted on the basis of the soil test as described above. This tactical strategy was compared with a conventional fertiliser treatment on similar plots to which 200 kg ha^{-1} N was applied as 9 equal dressings at 3-week intervals. In these initial studies, adoption of the tactical fertiliser strategy had little effect on the total quantity of fertiliser applied compared with the conventional treatment (Table 3) or on the quantities of nitrogen that were leached. In more recent trials on commercial farms (N. Titchen, pers. commun., 1994), the use of the tactical strategy was more successful and resulted in reductions in fertiliser inputs while maintaining herbage production at a similar level to that achieved with the conventional fertiliser treatment (Table 3). It was only in these cases, where nitrogen inputs were reduced, that the tactical strategy was effective in reducing leaching losses.

Direct returns of nitrogen to pasture in the excreta of grazing animals also contribute to the build-up of mineral-N in the soil. Pastures are normally grazed from spring to late autumn and studies with simulated urine patches (Sherwood and Fanning, 1989; Cuttle and Bourne, 1993) have shown that it is urine deposited in the later part of this period that makes the greatest contribution to nitrate leaching. The later the deposition date, the smaller was the proportion of urine-N recovered by herbage and the greater the proportion remaining in the soil and available for leaching at the start of winter (Fig. 2). In more intensively managed pastures where a greater proportion of the potential uptake

Table 3
Comparison of the effect of conventional and tactical fertiliser strategies on fertiliser inputs, productivity and nitrogen leaching: (a) from experimental plots (Titchen and Scholefield, 1992); and (b) from trials on commercial farms (N. Titchen, pers. commun., 1994)

	Conventional strategy	Tactical strategy
(a) Experimental plots (mean values 1990/1991 and 1991/1992):		
Fertiliser-N applied (kg ha^{-1} N)	214	201
Animal liveweight gain (t ha^{-1})	1.04	1.06
Soil mineral-N in autumn (kg ha^{-1} N)	39	27
N leached (kg ha^{-1} N)	52	65
(b) Commercial farms (mean values for 6 farms):		
Fertiliser-N applied (kg ha^{-1} N)	301	211
Herbage growth (t ha^{-1})	5.77	5.88
N leached (kg ha^{-1} N)	22.3	14.2

1 t = 1 metric tonne = 10^3 kg.

will be met by nitrogen from fertiliser and from mineralisation of soil organic matter, urine-N in the soil will be depleted less rapidly so that nitrogen from urine deposited earlier in the season would be expected to persist for longer and to make a greater contribution to leaching during winter.

In both cases, the removal of stock from fields earlier in the grazing season would limit the accumulation of urine-derived nitrogen in the soil and may provide a further means of reducing nitrate leaching. The effectiveness of this approach has been investigated in studies which compared nitrate leaching from pastures that were either grazed up to October or from which cattle were removed in July and further herbage growth removed by cutting. In initial studies on a clay soil site, the early removal of stock and removal of herbage reduced the accumulation of mineral-N in the soil in

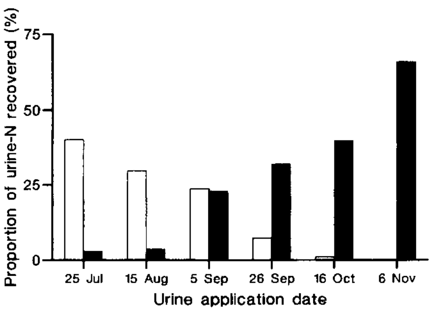

Fig. 2. Proportions of urine-N recovered in grass (*open bars*) and remaining in the soil in November 1990 (*solid bars*) following applications of urine (equivalent to 300 kg ha^{-1} N) on different dates during the growing season (Cuttle and Bourne, 1993).

October 1986 from 31.4 to 4.4 kg ha^{-1} N (Titchen et al., 1989). When repeated in the following year, there was a similar reduction from 36.2 to 13.5 kg ha^{-1} N. However, results from later trials on more freely drained soils were more variable (Lord, 1992), possibly reflecting the greater susceptibility of these soils to drought conditions which restricted growth and nitrogen uptake in late summer. Although reducing the duration of the grazing season may under suitable conditions reduce the immediate leaching loss from pasture, housing stock for longer also increases the quantity of nitrogen passing to manure or slurry and the overall effectiveness of these measures will be determined by the fate of this nitrogen. Adoption of this strategy would require increased storage capacity to contain the additional manure and sufficient safeguards to minimise losses during the handling and spreading of manures, otherwise the measures merely serve to redirect the loss of nitrogen to other pathways. The overall effectiveness will be determined by the extent to which the return of nitrogen to pasture as manure, rather than as direct excretion during grazing, increases the recovery of nitrogen by herbage and permits an equivalent reduction in external inputs.

The poor utilisation of ingested nitrogen by ruminants and subsequent excretion of the surplus are largely a result of an imbalance between the contents of rumen-degradable nitrogen and carbohydrate in the diet. Although highly fertilised grass is of high nutritive value, its nitrogen content is approximately double what the animal requires and can utilise efficiently. Supplementing grass diets with low-nitrogen forages or concentrates such as maize silage or beet pulp would lead to an improvement in nitrogen utilisation by the animal and a reduction in the nitrogen excreted (Tamminga and Vestegen, 1992).

On a whole-farm basis, substituting areas of highly fertilised grass with maize silage would permit a reduction in the overall fertiliser input to the farm and would thus appear to reduce the potential for nitrogen loss. However, changes in cropping patterns may influence losses in other ways. Nitrogen in soil organic matter represents a major storage pool within the grassland nitrogen cycle. Disturbances, such as cultivation for arable cropping, increase the rate of net mineralisation of soil organic matter, increasing the supply of mineral-N in the soil and the potential for loss. In this case, increases in the quantity of nitrogen lost would be associated with reductions in nitrogen storage within the system and would be independent of balances between inputs and outputs. The net effect on losses would be determined by how efficiently the nitrogen that was mineralised following cultivation was recovered by the subsequent maize crop and, on a whole-farm basis, by the balance between the benefits of feeding a reduced-nitrogen diet and the risk of increased leaching from that part of the farm area brought into cultivation.

In addition to the direct effects of cultivation, more widespread adoption of ley/arable rotations would result in a greater proportion of temporary grass leys and younger swards which may also influence the quantities of nitrate leached. In recently-established grassland, particularly after a period of arable cropping, a major component of the nitrogen balance is the net accumulation of nitrogen in soil organic matter. The annual rate of increase in total nitrogen content for grassland soils has been reported to be between 50 and 150 kg ha^{-1} N (Clement and Williams, 1967; Tyson et al., 1990). As swards age, the organic matter content normally approaches an equilibrium and the rate of nitrogen accumulation declines. If nitrogen inputs remain constant over this period, any reduction in net immobilisation of nitrogen in soil organic matter must be matched by a corresponding increase in nitrogen outputs. Although some of this may be accounted for in increased animal production, the remainder is presumed to contribute to a pattern of increasing nitrogen losses with increasing sward age.

Evidence of an interaction between nitrate loss and sward age is provided by data from the grazing experiments referred to above. In the experiment described by Scholefield et al. (1993), quantities of nitrate leached from permanent pasture receiving 400 kg ha^{-1} N were consistently greater than those from similarly fertilised plots where the pasture had been ploughed and reseeded at the start of the experiment in 1982. In the case of undrained plots, annual leaching losses between 1983 and 1987 averaged 80 kg ha^{-1} N from permanent pasture compared with 27 kg ha^{-1} N from reseeded plots. Losses from corresponding treatments on drained plots were 199 and 85 kg ha^{-1} yr^{-1} N. Although measurements of the total nitrogen content of these soils were confined to the 0–10-cm soil depth, rather than the full plough layer, they provide an indication of the effect of cultivation on nitrogen contents and how this may influence losses. In 1983 the topsoil in the reseeded plots contained 0.38% N (K. Tyson, pers. commun., 1995). By 1987, contents had increased to 0.41% and 0.44% in the drained and undrained plots, respectively. These values are equivalent to annual increases of 86 and 121 kg ha^{-1} N, respectively, and are sufficient to account for a large proportion of the nitrogen input that was not recovered in the animal product and would otherwise have been available for loss. There was no comparable increase in the nitrogen content of the topsoil in the drained permanent pasture plots which remained at 0.50% throughout this period. Although the content in the corresponding undrained plots increased by the equivalent of 50 kg ha^{-1} yr^{-1} N, this is still considerably less than the increase measured in the undrained reseeded plots. The quantities of nitrate leached from the ploughed soils showed no tendency to increase during the period of the investigation; however, other studies indicate that changes in nitrate leaching associated with sward age may occur over a relatively short time scale (Cuttle et al., 1992; S.P. Cuttle, unpublished data, 1995). In this instance, leaching from a grass ley sown after a period of arable cultivation was minimal in years 2 and 3 after establishment but increased appreciably in

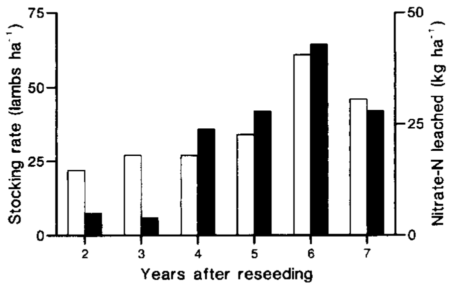

Fig. 3. Influence of sward age on stocking rate (*open bars*) and quantities of nitrogen leached (*solid bars*) from a recently established ryegrass ley receiving 150–200 kg ha^{-1} fertiliser-N (Cuttle et al., 1992; S.P. Cuttle, unpublished data, 1995).

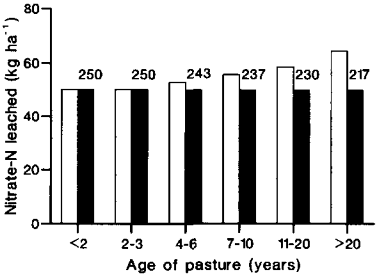

Fig. 4. Predictions (Scholefield et al., 1991) of changes in the quantities of nitrogen leached from pasture of increasing age when fertiliser inputs are: (a) fixed at 250 kg ha^{-1} N (*open bars*), or (b) adjusted to maintain a constant animal output (*solid bars*). The *solid bars* are labelled with the annual fertiliser inputs (kg ha^{-1} N) used in deriving prediction (b).

subsequent years in spite of fertiliser inputs remaining unchanged at 200 kg ha^{-1} N (Fig. 3). The greater leaching losses from year 4 onwards were assumed to result from an increased supply of nitrogen from mineralisation of soil organic matter and/or reduced immobilisation of fertiliser nitrogen, leading to increased herbage production, higher stocking rates and greater returns of urine-N to the soil. The total nitrogen content of the 0–30-cm soil depth was measured in years 4 and 7 and increased from 0.26% to 0.29%, equivalent to an annual increase of 170 kg ha^{-1} N (Cuttle and Bourne, 1992). Although the measurements relate to the period following the increase in nitrate leaching, it is unlikely, in view of the nitrogen inputs to the site, that the rate of accumulation would have been much greater than this in the years immediately after reseeding.

A computer model entitled "NCYCLE" has been developed by Scholefield et al. (1991) to describe flows of nitrogen through the different components of grazed grassland and can be used to demonstrate this interaction between sward age, productivity and nitrogen leaching. For the example of a beef grazing system receiving a fixed input of 250 kg ha^{-1} yr^{-1} fertiliser-N, the model predicts that over a 20-yr period there will be a gradual increase in animal output with an accompanying increase in the quantity of nitrogen leached (Fig. 4). The increased productivity as the sward ages is associated with a gradual increase in the supply of soil-N through mineralisation. If the model is re-run with the fertiliser input for each time increment progressively reduced so as to maintain animal output at the same value as for the newly-sown pasture, then over the 20-yr period the annual fertiliser requirement falls from 250 to 217 kg ha^{-1} N and the leaching loss remains constant.

These considerations indicate that any effects of increases in nitrogen losses associated with sward age can be avoided, provided that fertiliser inputs are adjusted to take account of the increasing supply of nitrogen from mineralisation of soil organic matter or from reductions in nitrogen immobilisation. They also indicate that N fertiliser is used relatively inefficiently in younger swards as a greater proportion of the nitrogen that is applied contributes to the build-up of organic matter in the soil rather than contributing to production. However, in these circumstances, the apparent inefficiency of nitrogen use in recently established swards adds to the pool of stored nitrogen rather than contributing to immediate losses from the system. The extent to which incorporation of nitrogen into soil organic matter affects the overall efficiency of nitrogen use cannot be satisfactorily assessed on the basis of short-term annual balances. Although not contributing to current production, the accumulation of organic-N in the soil will in the longer term lead to increased mineralisation of soil-N and is an essential prerequisite to the apparently greater efficiency of fertiliser use in longer established swards. In the case of grass leys, this process will be interrupted and the return of nitrogen from storage to the actively cycling pool will be hastened by their periodic cultivation.

4. Conclusions

Nitrate leaching from grassland cannot be considered in isolation from other components of the farm system nor from other forms of nitrogen loss which are equally unacceptable and also need to be controlled. Measures to control losses should therefore be assessed in terms of whole-farm nitrogen balances. The examples in this paper demonstrate that in most cases control strategies will only be effective where they result in reductions in overall nitrogen inputs to the farming system. Simply reducing inputs without specific measures to improve the efficiency of nitrogen use can markedly reduce losses but this is at the expense of reduced productivity. The majority of specific measures to control nitrogen losses from intensive grassland rely on more efficient recycling and greater retention of nitrogen in the system. Measures to increase the sward's recovery of nitrogen from animal excreta and from mineralisation of soil organic matter permit equivalent reductions in external inputs to be made without affecting productivity. However, this requires accurate information about the quantities of nitrogen supplied by these non-fertiliser sources. Measures that involve changes in cropping patterns and the frequency of cultivation of grassland influence the relative rates of mineralisation and immobilisation of soil-N and thus promote changes in the quantity of nitrogen stored in the soil organic matter pool. Significant reductions in nitrogen storage disturb the short-term equivalence between inputs and outputs and can increase the potential for loss independently of other controls over nitrogen inputs.

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