SOLVING THE NITRATE PROBLEM

Progress in research and development

MAFF ENVIRONMENT *matters*

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Introduction

The 1980 EC Directive on the Quality of Water Intended for Human Consumption set a maximum allowable concentration of 50 mg/l of nitrate in drinking water. An increasing number of water sources exceed this concentration. For instance, in 1989, 154 sources exceeded the limit while, in 1990, 192 sources did so. The water supply companies have introduced water blending and treatment programmes to help them comply with the drinking water requirement. Meeting the limit by blending high nitrate water with low nitrate water, or by chemically purifying it, can be expensive. Moreover, programmes can be undermined if nitrate levels continue to rise.

Agriculture is the main source of nitrate in drinking water. The loss of nitrate from agricultural land is, however, a complicated process. Nitrate loss, or "leaching", will occur throughout a water catchment area. It is therefore a "diffuse" source of pollution rather than being attributable to one or more "point sources" such as a leak or spill.

Moreover, there is often a delay of many years if not decades, before water leaving agricultural land reaches underground water sources. There can therefore be a considerable time lag before changes in land use affect nitrate concentrations in groundwater supplies. This makes precise causes and effects of nitrate leaching difficult to pin down.

In 1989, the Government announced its decision to introduce the Pilot Nitrate Scheme in order to examine the practical implementation of controls on nitrate leaching from agriculture in drinking water catchment areas. Following consultation with farmers, water companies and other interested parties, 10 Nitrate Sensitive Areas and 9 Nitrate Advisory Areas were set up during 1990.

In December 1991, the European Community Nitrate Directive was adopted by Member States. This requires them to introduce restrictions on agriculture in the catchment areas of water which either already exceeds the 50 mg/l limit, or is at risk of so doing. Future UK and Community policy will be governed by this Directive which will be implemented from December 1995 onwards.

The Ministry of Agriculture, Fisheries and Food funds a major R & D programme on nitrate. Its aim is to provide information both on the causes of high nitrate leaching, and on effective ways of reducing it. In 1992/93 the total cost of this programme is £6.9m.

The purpose of this report is to summarise the progress made in recent years towards understanding the nitrate problem. In doing so it will provide background information on nitrate, consider different aspects of the Ministry's nitrate R & D programme and discuss the Pilot Nitrate Scheme.

Chapter 1

Background to the nitrate problem in the UK

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Summary

The movement of water, and hence nitrate, from the soil zone to groundwater is influenced both by the depth of the aquifer and the characteristics of the rocks forming it. Water passes most quickly through fissured rocks, such as limestone, and less quickly through the fine matrix of sandstone and chalk. The nitrate concentration in groundwater is influenced by, among other things, the amount of rainfall. Areas of high rainfall tend to have lower nitrate concentrations due to increased dilution. There are many sources of nitrate including the atmosphere, leaking sewers and septic tanks, airfield runway de-icers, sewage sludge applications to land and urban waste water treatment plants. However, the main source is agriculture. Losses of nitrate from agriculture are dependent on the type of farming system being operated. In turn, losses from a particular farming system are, to a large extent, influenced by the balance between nitrogen inputs (fertilisers or feedstuffs) and nitrogen outputs (harvested crops or animal products). This means that the nitrate concentration at a point of abstraction depends on the overall balance of agriculture in the catchment. A maximum allowable concentration of 50 mg/l of nitrate in drinking water was set by the 1980 EC Directive on the Quality of Water Intended for Human Consumption. The EC Nitrate Directive was agreed in December 1991. This Directive requires member states to monitor waters, set up nitrate vulnerable zones and produce a Code of Good Agricultural Practice by December 1993. Action plans for vulnerable zones are to be established by December 1995 and fully implemented by December 1999.

Introduction

This chapter provides background information on the nitrate problem. It discusses the loss of nitrate to ground and surface waters and the effect of geology and rainfall on this process. The sources of nitrate are given and the influence of different agricultural farming systems and practices on the amount of nitrate leaving the land is considered. Developments under the EC Directive, such as the timetable for the establishment of vulnerable zones and the preparation of a Code of Good Agricultural Practice and of Action Programmes for vulnerable zones, are detailed.

Fig 1.1. Location of principal aquifers

Nitrate levels in groundwaters

Groundwater is the water held underground in the pore spaces and fissures of rocks which form aquifers. The map in Figure 1.1 gives the location of the principal aquifers. The areas where groundwater sometimes already exceeds the 50 mg/l EC nitrate limit are located mainly in the south, east and centre of the country, where important agricultural areas are underlain by the chalk, limestone and sandstone which provide most of our groundwater supplies. These rocks are important aquifers because less permeable materials beneath them, such as clay, stop further downward movement of water and allow the pore spaces to become saturated with water originating from infiltration at the land surface.

The time taken for water to move from the agricultural zone of the soil to the water abstraction borehole varies depending on the depth of the aquifer and the characteristics of the rock. Water can move through soil and rock by two principal flow paths. Intergranular flow occurs when water moves slowly through the pore spaces between the grains of the matrix of soil or rock. This type of flow predominates in sandstone and chalk. Vertical movement of water through the matrix of the unsaturated zone from the soil to the water table is often a metre per year or less. When the intergranular pore spaces are small, and may be made even smaller by compaction and cementing, flow through the matrix is restricted and fissure flow becomes dominant. This is the case in the limestones of Lincolnshire. Much of the water in these rocks moves rapidly through cracks and fissures.

All groundwater systems take several years for a new equilibrium nitrate concentration in abstracted water to be achieved following a change in nitrate loss from the agricultural soil. This can be in excess of 40 years for some deep chalk aquifers but is typically 10-20 years for groundwaters in the UK. As shown in the graphs in Figure 1.2 the response depends very much on the geology. Some rocks with predominantly intergranular flow show a smooth trend in nitrate concentration with little annual variation. By contrast, limestone with predominantly fissure flow shows a marked annual variation in concentration, indicating that some effects are noticeable within months, although it may still take several years for a new equilibrium to be fully established.

The amount of rainfall, and more specifically the amount passing through the soil during the winter, is a major factor in determining nitrate concentration in groundwater. The main problems of high concentration occur in drier parts of eastern and central England. In western and northern areas, dilution of nitrate lost from the soil profile is greater, resulting in a lower nitrate concentration in water from a comparable farming system.

Nitrate levels in river waters

A few surface drinking water abstractions direct from rivers exceed the 50 mg/l nitrate limit during some periods of the year. The peak concentration usually occurs in late autumn when the first run-off water reaches the river. The characteristics of the catchment have a major influence on the shape of the nitrate concentration graph during the year. If the groundwater contribution to the river flow is substantial, the nitrate peak in the autumn will be less obvious.

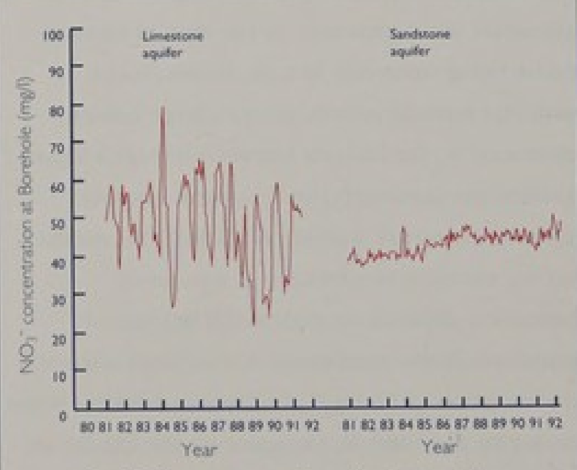

Fig 1.2. Nitrate concentrations at boreholes under a limestone aquifer and a sandstone aquifer

By contrast, a catchment of predominantly clay soils, particularly where a high proportion contain land drains, will usually show a very marked autumn peak concentration when the first substantial re-wetting of the soil occurs.

Sources of nitrate

Agricultural land is the main source of nitrate in rural catchments. The quantity of nitrate lost from an area of land is related to the cropping or intensity of livestock farming. Hence, the concentration of nitrate in a groundwater or river drinking water source, depends on the overall balance of agriculture in the catchment. This means that the presence of some fields with high losses will not necessarily result in the overall water concentration exceeding 50 mg/l. The quantity of nitrate lost from a farming system depends very much on the balance between inputs of nitrogen in the form of fertilisers and imported animal feeds and the quantity removed in crops and animal products from the farm. It is also dependent on whether the farming system protects the soil from over-winter leaching, using for example mainly autumn sown crops, or whether the soil is bare during the main leaching season.

No agricultural system can be 100% efficient in its use of nitrogen. Nitrate leaching is a natural process and some loss each year is inevitable. Most systems, however, can be improved with a resulting reduction in the quantity of nitrate lost each winter. Two particular practices can result in unnecessarily high leaching from any farming system. One is where nitrogen fertiliser use is in excess of crop requirement. The other is where nitrogen in animal manures, sewage sludge or other organic wastes is applied at excessive rates or inappropriate times.

Even in rural catchments, some nitrate may reach water from non-agricultural sources. Nitrogen is deposited both in rainfall and directly from the atmosphere in the form of ammonia, nitrogen oxides and nitrate. This contributes to nitrate loss from the soil. Nitrogen oxides and atmospheric nitrate are mainly non-agricultural in origin but most of the atmospheric ammonia originates from agriculture. Nitrate may also reach groundwaters from leaking sewers and septic tanks although the quantity is usually small compared to the loss from agriculture, at least in rural catchments. Use of urea for de-icing runways on airfields can also contribute, as can the application of nitrogen-containing wastes to land, for example sewage sludge. In the case of surface waters, discharges from urban waste water treatment plants account on average for about one quarter of the nitrate present. Most nitrogen-containing compounds can be oxidised to nitrate in the soil. So, for instance, ammonia, which does not readily leach in the dissolved ammonium form, easily leaches once it is converted to nitrate within days or weeks of being added to the soil.

Recent European Community developments

The implementation timetable for the Nitrate Directive requires that, by December 1993, waters are monitored and vulnerable zones set up covering land which contributes to a drinking water quality or eutrophication nitrate problem. Eutrophication of water is an enrichment of the water with nutrients to a level above that occurring naturally. It is often associated with algal blooms and can result in a disturbance of the biological balance. It is this disturbance which constitutes eutrophication under the Directive. Nutrient concentrations of both nitrogen and phosphorus in the water are factors in determining the risk of eutrophication occurring. On present knowledge we do not consider eutrophication that is limited by nitrogen to be a major problem in the UK. However, limited problems in our estuary waters, which are not necessarily specifically related to agricultural nitrate, are under investigation. Fresh water eutrophication is normally limited by phosphate rather than by nitrate. Nonetheless, several river and groundwater drinking water sources are likely to show nitrate levels and trends which will require vulnerable zones to be designated. The extent of these will be established over the next year.

The Directive requires a Code of Good Agricultural Practice to be prepared and promoted throughout the country, again by December 1993. This will apply on a voluntary basis to UK farms in the same way as the current MAFF Code of Good Agricultural Practice for the Protection of Water. Indeed a new, substantial document may not be necessary.

The next stage is to draw up Action Programmes plans describing the measures needed to meet the objectives in the vulnerable zones. These Action Programmes, which will be obligatory for farmers, must be established by December 1995 and fully implemented by December 1999. They must include rules on the timing and quantity of chemical and organic fertiliser applications based on Good Agricultural Practice. Their detail will depend on national discretion. The main additional rule specified in the Directive is the limit of 170 kgN/ha total nitrogen loading in organic manures. This figure can be higher initially and, if an objective case for this can be sustained, thereafter.

A factor that will need to be taken into account when determining the Action Programmes under the Nitrate Directive is the extent to which changes to the EC Common Agricultural Policy (CAP) both in the market regimes and under the proposed agri-environment measures will affect nitrate leaching. One change already made to the price support system for oilseed rape could well reduce nitrate leaching. Under the new system, the price received by the farmer for his produce is greatly reduced but his income is supplemented by a payment per hectare made irrespective of production level. Most oilseed farmers will therefore use less nitrogen fertiliser. This will be particularly beneficial as nitrate leaching from oilseed rape is currently higher than from many other crops.

The recent agreement that farmers wanting to receive support payments for cereals and other main arable crops from 1992 onwards must set aside about 15% of their land should also reduce overall nitrate loss.

Chapter 2

Fertiliser nitrogen for arable crops

Roger Sylvester-Bradley (ADAS) and David Powlson (IACR, Rothamsted)

Summary

Nitrogen (N) is needed for photosynthesis which, in turn, is essential for crop growth. Amounts of fertiliser N needed to meet crop requirement have been determined by field trials and are published as the recommendations which form the basis of 'Good Agricultural Practice'. Differences between crops, and mismatches between amounts of N applied and taken up by crops, can result in varied N residues in soil after most arable crops have been harvested. Although these residues can provide some of the next crop's needs, a portion is normally leached. This may be sufficient to give nitrate concentrations in excess of the EC limit for drinking water. This underlines the need for all farmers to take particular care to avoid excessive or untimely applications of nitrogen fertilisers.

Introduction

Since 1905 the Government has offered guidance to farmers on how best to use N fertilisers. This guidance has been steadily improved through continuing programmes of research. The fertiliser recommendations published by MAFF form the basis of the 'good practice' which farmers need to adopt in order to avoid unnecessarily high nitrate leaching.

MAFF's recommendations, as well as those published by other governments and by members of the Fertiliser Manufacturers Association advocate that farmers adjust their fertiliser applications according to three factors :

(i) the crop's requirement, which depends on the species, expected yield and (sometimes) the required quality of the crop,

(ii) the soil supply of N, the N released from soil organic matter, or left from growing the last crop, or from any livestock manures, and

(iii) the extent to which the available N will be lost before the crop takes it up.

These three factors are discussed in the following three sections.

Crop requirement

Crops mainly need N to form leaves. N taken up by crops directly affects the size of the green canopy through which they absorb sunlight and carbon dioxide for photosynthesis. Cereals use about 30 kg N to form a hectare of green surface; sugar beet uses about 40 kgN/ha. In order to intercept most of the available sunlight, crops must maintain a green canopy with a surface area of at least three times their land area. Thus a significant amount of N is needed for crops to grow optimally. The amounts of fertiliser which result in optimal crop growth have largely been determined by 'trial and error' in the field.

The value of most crops is based on features such as starch, sugar or oil content which do not contain N. For these crops, there is no specific requirement for N other than to enable the plant to grow. However, a few crops also require N specifically to form proteins that are needed in the harvested produce. For instance, wheat grown to make bread needs to contain at least 11% protein to form a satisfactory dough. This amount of protein requires a nitrogen concentration in the grain of about 1.9%.

Soil supply

The N that has been used to maintain the leaf canopy is eventually distributed between the storage organs (be they grains, tubers or tap-roots), the straw or haulm, and the roots. The proportion of a crop's N that is removed from the field at harvest ranges widely. For instance, in cereals and field legumes 75% and 65% respectively of the crop's N is removed, while for oilseed rape and sugar beet the figures are 40% and 35% respectively. This means that, combined with their differing success in acquiring the N from fertiliser, the species of crop grown can make a large difference to the amount of N remaining in a field after harvest.

N in crop residues or 'unused' fertiliser left in the soil after harvest can become available for the next crop. The considerable differences between crops in the residues they could leave are found by calculating the difference between what is normally applied as fertiliser and what is normally harvested.

Amounts of residual N are additionally influenced where the N applied as fertiliser does not match well the N needed by the crop, particularly if the fertiliser application exceeds what the crop requires. It appears that crops take up what they require for optimal growth, but any excess supply is used inefficiently, resulting in a larger proportion of the fertiliser remaining in the soil as nitrate (Figure 2.1).

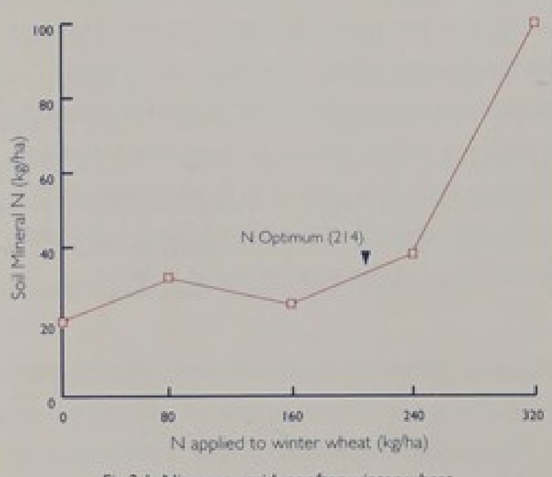

Fig 2.1: Nitrogen residues after winter wheat

Mineralisation of soil organic matter

This is often the major source of the nitrate present in arable soils in autumn. Agricultural soils contain several thousand kg N/ha in soil organic matter, sometimes referred to as humus, and a few percent of this is mineralised to nitrate each year. A proportion of the N mineralised during the year is available to the crop during the main growing season of spring and early summer. However, a significant proportion is produced too late in the growing season for crop uptake - for example, winter wheat usually absorbs little additional N after flowering in mid-June. Any nitrate formed too late for uptake will remain in the soil until leaching begins in the following winter unless removed from the soil by other processes earlier.

Some soils, particularly those derived from peat or where grassland has played a significant part in their history, retain large reserves of N in organic matter. Although there are only a minority of arable fields in the UK with such an organic content, it is particularly important that they be recognised because the amounts of N which become available for crop uptake can be very considerable, even to the extent of providing all of the N that is required to grow a crop.

Where there are large levels of soil organic matter, or where animal manures (see Chapter 3) have recently been applied, it often proves worthwhile making a soil analysis of the N available, in order to identify cases where normal fertiliser rates would be excessive.

Losses

N may easily be lost from the soil before it can be taken up by a crop and it is important to minimise these losses. Field experiments have found that most of the nitrogen applied in the autumn may be leached due to poor utilisation by crops at this time of the year (Figure 2.2). This data has led to changes in recommendations on fertiliser use and hence a gradual but major decline in autumn nitrogen applications (Figure 2.3).

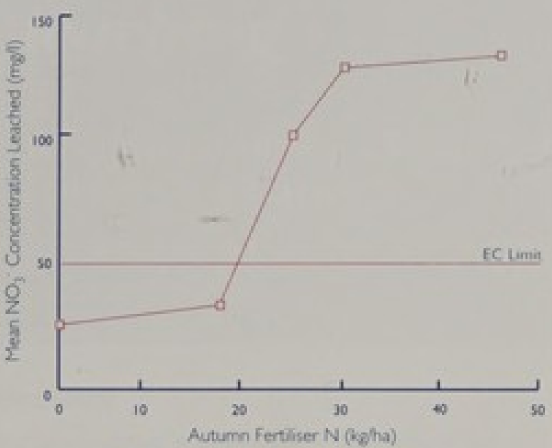

Fig 2.2: Autumn applications of fertiliser nitrogen lead to high levels of nitrate leaching

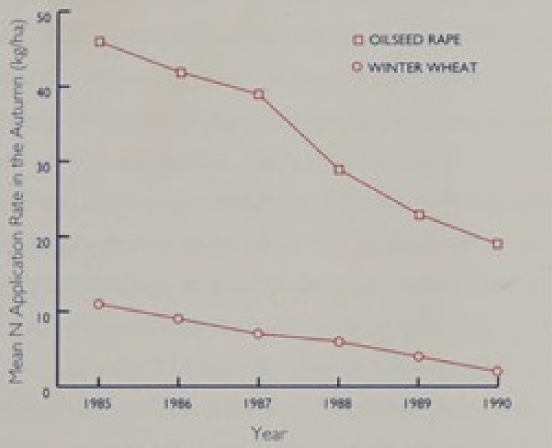

Fig 2.3: Autumn nitrogen applications have steadily declined in recent years

Losses by leaching depend on soil type and rainfall. The lightest arable soils only retain about 80 mm water per metre depth; so nitrate in these, and the shallow soils which are so extensive in the UK, are much more easily leached than nitrate in deep clay or silt soils which may retain more than 200 mm of water per metre. The amount of rain which is in excess of evaporation and crop transpiration, and which therefore causes leaching, varies from about 150 mm per annum in the east to more than 300 mm in some western and northern arable regions and to more than 1,000 mm in some grassland regions. Particularly on the less well drained clay soils, significant losses of N to the atmosphere may be caused by denitrification (the process by which nitrate is converted to the gases nitrogen and nitrous oxide), in addition to any leaching losses.

Experiments appear to show that 10 to 60% of fertiliser N is not taken up by the crop for which it was applied. Direct losses of fertiliser N occur when there is high rainfall soon after the fertiliser is applied. If not lost or taken up by the crop, most fertiliser N is absorbed and metabolised by soil organisms. This new soil N helps to maintain the capacity of the soil to supply N over future seasons but, inevitably, some of the nitrogen is mineralised during the autumn or winter when crop uptake is small and the risk of leaching is large. With a succession of N applications over seasons, fertilisers tend to increase the amount of nitrate that can be leached from soils by over-winter rainfall.

The application of fertiliser N at rates at or below the economic optimum results in relatively low residual quantities of N in the soil at harvest. For instance, sub-optimal applications of fertiliser N result in averages of 10 kg soil nitrate N residue per 100 kg N applied after cereals, 13 kg/100kg after oilseed rape

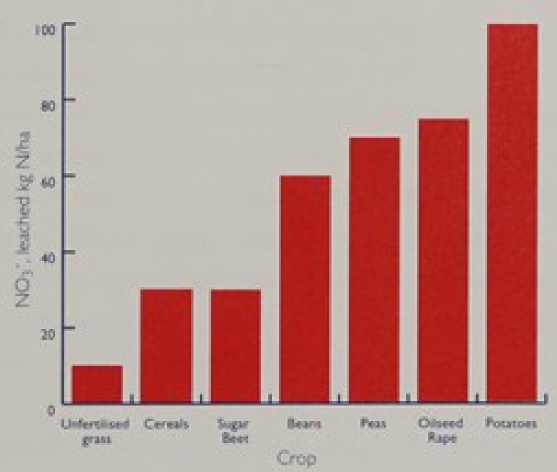

Fig 2.4: Nitrate leaching loss from different crops, without use of manures

and 26 kg/100kg after potatoes. However, when fertiliser rates much in excess of the economic optimum are used, the levels of residual soil nitrate N available for leaching are considerably higher (Figure 2.1). Measurements of the nitrate that is actually leaching from arable soils are difficult to make, so reliable estimates are only now becoming available (see Figure 2.4 for typical arable crops).

It would seem vital for the continuing sustainability of arable agriculture in the UK, that ways of reducing nitrate losses are found. Novel, scientifically-based, management practices must either preclude fertilisers from contributing to soil N reserves or else ensure that nitrate uptake by autumn-sown crops precedes the over-winter leaching period.

Chapter 3

Organic manures and nitrate leaching

Brian Pain (IGER, North Wyke) and Ken Smith (ADAS)

Summary

The risk of nitrate leaching from land which has received organic manures is considerable because they are commonly applied in amounts and at times not related to optimal uptake of N by crops. Nitrate leaching may be increased when manures are applied to arable land rather than grassland. In the short term, manures containing much water soluble N, for example slurries and digested sewage sludges, pose a more serious threat than farm yard manures. However, release of nitrate into the soil may continue for a longer period from the latter. Relating time and rate of application of organic manures more closely to crop requirements are vital ways of reducing nitrate leaching. The use of cover crops on arable land and the use of nitrification inhibitor chemicals may also reduce leaching from organic manures.

Nature of the problem

The main organic manures applied to agricultural land originate from housed livestock in the form of semi-liquid slurries of faeces, urine and water or as more solid material containing straw, wood shavings etc. such as farm yard manure (FYM) and poultry litter. Sewage sludge is applied to land as a means of disposal and, like livestock wastes, has value as a fertiliser. The potential for nitrate loss from these manures is greater than from inorganic fertilisers because of difficulties in making timely, accurate applications of readily available nitrogen. These manures are often applied to arable stubbles and grassland throughout the autumn or winter as and when convenient and soil conditions permit, or at rates well in excess of crop uptake. Substantial nitrate leaching is likely to result.

The quantity of excreta produced from livestock and its N content vary widely with class of stock, diet and water intake, building design and environment. Using average values of excreta output per animal, together with typical N content and June animal census data, it is possible to estimate the annual output of N by housed livestock in the UK. For cattle, pigs and poultry these figures are 0.32, 0.08 and 0.11 million tonnes of N respectively. The N contained in these manures is approximately equivalent to 30% of the 1.5m tonnes of N in chemical fertiliser used in 1991. However, as might be expected, nationally the distribution is uneven and reflects variations in livestock density.

Treatment of sewage yields a range of different types of sludge which vary in physical consistency and N content. Currently, about 30 million wet tonnes of sewage sludge are produced each year, 40% of which, containing 15,000 tonnes of N, is applied to agricultural land.

Nitrogen transformations and losses

Unlike most purchased fertilisers, N in organic manures is present in both inorganic, most commonly as ammonium - N (NH_4^+ - N) derived from hydrolysis of excreted urea, and organic forms. The proportion of NH_4^+ - N varies widely, ranging from 10-70% in the majority of livestock wastes and from 5-60% in sewage sludges. The occurrence of nitrate in organic manures, especially in slurries, is rare due to the prevalence of anaerobic conditions which inhibit nitrification.

Following application to land, NH_4^+ - N is subject to rapid loss through ammonia volatilisation from the surface and, in the soil, rapid transformation by nitrification to nitrate (see page 37). As is the case for mineral fertilisers, nitrate derived from organic manures is rapidly removed from the soil by actively growing crops but, at other times, may be subject to denitrification (the process by which nitrate is converted to nitrous oxide and/or nitrogen gas) or leaching. The organic N fraction must first be mineralised (see box, Chapter 2), the extent and rate of this process depending mainly on the composition of the manure, soil and weather conditions. Mineralisation of N in water soluble material is more rapid than in water insoluble forms. However, the latter can also increase nitrate concentrations through mineralisation over a prolonged period of time, whilst the reverse process of immobilisation may reduce nitrate concentrations.

Factors influencing nitrate leaching

Early studies on both grassland and arable land highlighted the importance of rate and timing of application for the utilisation of nitrogen from manures and slurries. These studies also indicated that nitrate losses from grassland, especially after cattle slurry applications, were relatively low but that more significant losses were likely from arable land. More recently, direct measurements have been made of N losses, including nitrate leaching, following the application of organic manures to land. It is clear that their addition to soils can increase the risk of nitrate leaching on two counts, both of which are associated with lack of synchrony between release of nitrates into the soil and uptake by crops. Leaching can occur during the winter after application in autumn, due to the rapid mineralisation of readily degradable organic matter and nitrification of NH_4^+ - N and, in subsequent winters, through prolonged mineralisation of residual organic matter. The extent and rate of leaching is influenced by a wide range of factors, many of which are still poorly defined.

Time of application

The data in Figure 3.1 are from a fallow site which received manure containing approximately 200 kg/ha

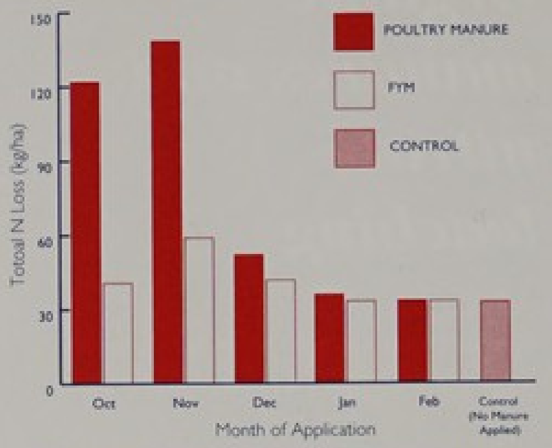

Fig 3.1: Total nitrogen losses from poultry manure and FYM applied at monthly intervals from October to February

N at monthly intervals between October and February. Although this may be considered a 'worst case' situation, a very light soil with no crop cover, they give a clear indication of the extent to which nitrate loss is dependent upon time of application. For poultry manure, peak soil water nitrate concentrations reached over 400 mg/l in the winter after application in October and November. Peak concentrations from December applications were just approaching maxima when drainage ceased in February.

Crop

Application of manures before December generally results in higher nitrate losses than applications made from January onwards. In an experiment on arable land in 1990/91, uptake of N by an autumn

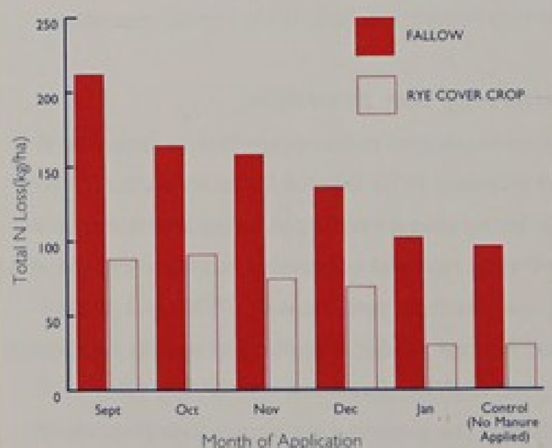

Fig 3.2 Total N losses from fallow land or land planted to rye following slurry applications at monthly intervals from September to January

sown cover crop markedly reduced these losses from cattle slurry (Figure 3.2).

Similar results were obtained with FYM. Losses following application to a nearby grassland site were generally lower than those from the cultivated land.

Composition of manure

Elevation of soil mineral N content following application of manures is closely related to their soluble-N content in the form of NH_4^+ - N for slurries and FYM or NH_4^+ - N plus uric acid for poultry wastes. This, in turn, will be related to the risk of nitrate leaching from non-retentive soils following application of manures outside the normal growing season. The current results (see Figures 3.1 and 3.2) support this view, with losses from slurry and poultry manure, where soluble N represents 40-60% of the total, being consistently greater than those from N supplied as FYM and containing only 10% soluble material. In this respect, those sewage sludges with a high soluble N content, could be expected to behave similarly to animal slurries.

The carbon to nitrogen (C:N) ratio of the manure is also important. In some recent studies, over a relatively short period (33 weeks), immobilisation and mineralisation were approximately in balance for slurries with a C:N ratio of about 20:1 whereas higher ratios resulted in net immobilisation of nitrogen. Nevertheless, it is generally true that addition of organic material to soils eventually increases the potential for nitrate leaching. This has been demonstrated in long term experiments, on arable land using annual applications of either mineral fertiliser or FYM, which have found greater quantities of nitrate to be leached from the FYM treatment than from the inorganic fertiliser treatment.

Interactions between N loss pathways

Evidence for increased leaching potential following organic manure applications is well illustrated by soil nitrate concentrations at 13 and 72 days after applying pig slurry in October at 250 kg N/ha (140 kg NH_4^+ - N/ha) to winter barley (Figure 3.3). At the end of the winter it was estimated that losses from pig slurry through nitrate leaching amounted to over 70 kg/ha N which is approximately double the amount that would normally be expected from winter barley grown only with chemical fertiliser. In contrast, results from lysimeter experiments suggest that nitrate loss following application of cattle slurry to grassland is lower (Figure 3.4), although dependent upon soil type. Other field plot experiments on a sandy loam soil showed that gaseous losses of N, through ammonia volatilisation and denitrification, were very high and that this may explain the lower leaching losses from cattle slurry.

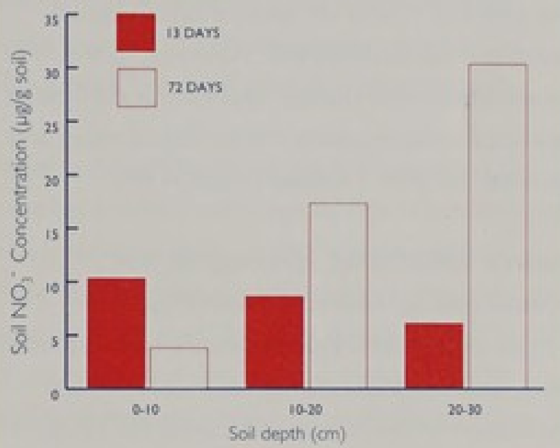

Fig 3.3: Soil nitrate concentrations at 13 and 72 days after application of pig slurry at 250 kg N/ha to winter barley in early winter

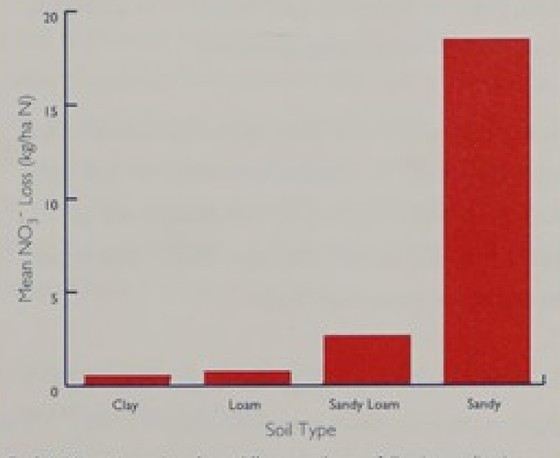

Fig 3.4: Mean nitrate loss from different soil types following applications of cattle slurry to grassland lysimeters at 300 kg/ha total N in November

Furthermore, the large amounts of freely available carbon in cattle slurry provide a substrate for denitrifying bacteria, so enhancing losses via this pathway even under cold, winter conditions. Pig slurry is generally more dilute than cattle slurry so rates of infiltration into soil are more rapid, particularly on cultivated soil, and hence losses through ammonia volatilisation are relatively low. Similarly, denitrification rates appear to be lower in this situation than for application of more viscous cattle slurries to grassland.

Much permanent grassland is on clay or clay-loam soils where pollution of surface waters through run-off is more likely than leaching to groundwater. Preliminary experiments indicate that, over the year, total losses of N from the application of organic wastes may be relatively low. However, incidents of run-off shortly after manure applications can lead to high nitrate concentrations in the run-off water and can therefore pose a serious pollution risk.

Future R&D and strategies for reduction of nitrate leaching

In order to provide a sound scientific basis for future codes, guidelines and regulations, we need clear information on the factors influencing the extent and rate of nitrate leaching from organic manures. Control strategies require further development and evaluation. Attention must also be paid to interactions between leaching and loss of N in other forms, such as ammonia and nitrous oxide, which are also of environmental concern.

It is important that any strategies implemented to comply with the EC Nitrate Directive are not only effective in reducing nitrate concentrations in waters, but also ensure that agriculture can remain sustainable in economic terms.

Nitrification inhibitors (e.g. dicyandiamide 'DCD') suppress the microbial transformation of NH_4^+ - N to nitrate in the soil and so have potential for reducing denitrification losses and leaching during the winter on both grassland and arable crops. Recent studies have recorded a 50% reduction in leaching losses from cattle slurry applied to grassland and from pig slurry applied to winter barley. But results to date are inconsistent, possibly due to wide variation in the rate of breakdown of the inhibitor in the soil, so further work is needed before widespread use can be recommended.

Currently, restricting the time and rate of application is the simplest and most reliable way of reducing the risk of nitrate leaching from organic manures. Limiting application rates to ensure that supply of plant nutrients does not exceed crop requirements is consistent with good agricultural practice and has long been advised. The Code of Good Agricultural Practice for the Protection of Water recommends a maximum application rate for organic manures of 250 kgN/ha although lower limits may be appropriate in Nitrate Vulnerable Zones. The new EC Nitrate Directive described in Chapter 1 will ultimately limit rates of application of organic manures to 170 kg N/ha unless an objective case for higher rates can be sustained. The environmentally best time for application is during the spring when N uptake by the crop is likely to be high. The use of cover crops as part of a planned management strategy may however make earlier applications acceptable (see Figure 3.2).

Chapter 4

Autumn and winter land management

David Powlson (IACR, Rothamsted) and Bryan Davies (ADAS)

Summary

Most nitrate leaching in the UK occurs during the autumn and winter due to the soil reaching full water saturation during this period. Careful management of the land at that time is therefore important to reduce the quantity of nitrate that is leached. For instance, ploughing in the autumn rather than direct drilling leads to increased mineralisation of organic matter in soil and hence increased nitrate leaching. The nitrate released from incorporated crop residues or residual nitrate from fertiliser applications will also influence the quantities leached, as will autumn applications of organic manures and inputs of N from the atmosphere. The presence of an autumn-sown crop or a winter cover crop can greatly decrease nitrate leaching as these absorb nitrate from the soil and decrease the amount left exposed to leaching. However, this strategy is only effective if the crop is sown early.

Introduction

Although some nitrate leaching can occur in spring, soon after nitrogen fertiliser application, the major period of leaching under UK conditions is during winter after soils return to full water saturation (field capacity). In autumn or early winter arable soils often contain around 30-50 kg N/ha as nitrate and greater quantities (100 kg N/ha or more) are not uncommon. In designing agricultural practices that will decrease nitrate leaching it is vital to understand the sources of the nitrate present in soil in autumn and winter and the factors that influence its production and fate.

Sources of nitrate and factors influencing their importance

1. Mineralisation of soil organic matter (see box, Chapter 2)

The quantity of N mineralised in a year, and not taken up by the current crop, is affected by weather and by the history of the soil. As a rough guide, the amount might be 50 kg N/ha or less in a low organic matter soil (say 2% organic matter) that has been in arable cropping for many years. It might be 100 kg N/ha or more for a soil of high organic matter content (6% organic matter or higher) or which has a history of grass or organic manures.

It can be helpful to regard soil mineralisation as composed of two components. First, a baseline rate which reflects organic matter content and past cropping and management practices. Onto this are superimposed more transient factors such as method of cultivation and crop residue disposal, recent organic inputs and residues from fertiliser. These influences are discussed below.

2. Effect of cultivation

Mineralisation of soil organic matter is stimulated to some extent by cultivation. This has been observed at the Brimstone Experiment in Oxfordshire, where nitrate leaching from a heavy clay soil is measured directly in hydrologically isolated plots.
Nitrate concentration in drainage water from direct-drilled plots is generally smaller than from ploughed ones (Figure 4.1) and total leaching losses are generally 5-10 kg N/ha less.

3. Mineralisation of organic N from residues of current year's crop

All crop residues, both roots and above ground material, contain some nitrogen. The rate at which

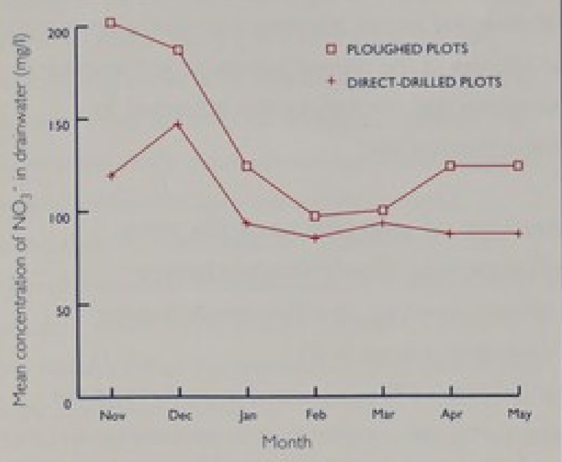

Fig 4.1: Flow-weighted mean monthly concentrations of nitrate in drainwater from ploughed and direct drilled plots

this is converted to nitrate is affected by the properties of the residue, especially its decomposability (sometimes expressed as the inverse of lignin content) and C:N ratio. It also depends on the extent of incorporation, and hence the intimacy of contact with soil microorganisms, and on weather conditions. Microbial activity is favoured by warm and moist conditions but is slow if the soil is cold and either very dry or excessively wet. A certain proportion of the organic material in crop residues is broken down fairly rapidly, say within a few weeks or months of incorporation, and contributes to the short-term production of nitrate. Part will add to the reserves of organic matter in soil and thus contribute to the baseline mineralisation in future years.

Cauliflower tops are an example of a crop residue that is highly decomposable and rich in nitrogen and can lead to production of 100 kg/ha of nitrate within two weeks of incorporation during mid-summer. By contrast, cereal straw has a high lignin content and wide carbon-to-nitrogen ratio: in the initial stages of decomposition very little N is released as nitrate and, in fact, the opposite process occurs. Some inorganic N is tied up, or immobilised, in the soil micro-organisms responsible for decomposition, thus decreasing the soil nitrate content slightly: decreases of about 10 kg N/ha have been observed in a number of experiments. However, the nitrogen immobilised adds to the soil reserves of organic matter and, in time, will lead to a slightly greater baseline mineralisation.

Crops grown under high fertiliser conditions over many years will have returned larger residues of stubble and root to the soil, and these contain more N than residues from crops grown with smaller fertiliser applications. These residues will have added to the soil's reserves of organic N and will inevitably lead to some additional mineralisation.

There are important interactions between the times of harvest and of cultivation. For example, incorporation of oilseed rape residues following harvest in July can lead to considerable nitrate production before winter leaching begins, whereas tops of sugar beet harvested in November or December will probably release rather little because of colder weather at that time of year. Work by ICI at their Lincolnshire site at Ropsley showed that mineralisation of organic N following oilseed rape may be halved by delaying ploughing for 3 weeks. When measured in late autumn, soil nitrate content was only 55 kg N/ha in soil that had been ploughed in mid-October compared to 110 kg N/ha in soil ploughed in mid-September.

Nitrate production can be especially large when a grass or grass/legume ley is ploughed up. For example, between 100 and 200 kg N/ha is likely to be released following ploughing of a 3-year ley and the figure can be even higher for very old grassland. This is an important factor to be considered when including a ley in a rotation or, indeed, when ploughing up set aside land. However, the large flush of nitrate released at this stage is, at least partly, offset by low leaching during the ley phase provided it is not intensively fertilised and grazed.

4. Fertiliser residues

For cereals given recommended rates of inorganic nitrogen fertiliser in spring, nitrate coming directly from the fertiliser usually makes a very small contribution to that present in the soil when leaching begins in the following winter. It will usually be less than 5 kg N/ha although there are exceptions. For example if crop growth was inhibited by drought or disease or if the crop was over-fertilised. With shallow rooting vegetables, given high rates of N that are used inefficiently (but still giving an economic return), direct residues of nitrate from fertiliser can be a major source. Residual nitrate from fertiliser is of intermediate importance for some other crops: for example, up to 50 kg N/ha from potatoes and up to 20 kg N/ha from oilseed rape, though this is not always the case. With sugar beet, direct residues from fertiliser nitrogen are small, as with cereals.

5. Organic manures (see also Chapter 3)

Organic manures applied in the autumn period frequently lead to large accumulations of nitrate in the profile during winter. Some organic materials (such as farmyard manure) have undergone greater decomposition before application to land, so the short-term production of nitrate is much less and the added organic matter contributes to soil organic reserves and hence to baseline nitrate production in future years. It is no coincidence that most of the largest nitrate concentrations found in the monitoring of NSAs are in fields with a history of organic manure applications.

6. Atmospheric inputs

Current inputs of N from the atmosphere in central and south-eastern England are around 40-50 kg N/ha/yr. Roughly one third of this is in the form of ammonia gas or ammonium dissolved in rain which largely originates from agriculture. The remainder is non-agricultural in origin and is mainly a mixture of oxides of nitrogen and nitrate dissolved in rain. Some of the atmospheric nitrogen enters soil organic matter, some is taken up by the crop, some is returned to the atmosphere in gaseous losses and some is leached. Recent calculations using a mathematical model for soil N turnover suggest that about 30% of the input (roughly 15 kg N/ha) is leached during the winter. On arable land receiving inorganic fertiliser at recommended rates, N originating from atmospheric inputs could amount to 15-50% of the total nitrate leached depending on soil type and crop, amongst other things.

Crop cover during winter

This is the main factor determining the fate of the nitrate present in soil in autumn. An early-sown and well-established autumn crop can take up a substantial amount of N (e.g. 30-50 kg/ha) during autumn and early winter and thus decrease the amount left in soil and exposed to leaching; Figure 4.2 is an example of this. In the Brimstone Experiment, where nitrate leaching is measured directly, it was at least 20 kg N/ha less in plots sown to a winter cereal compared to bare fallow. In general, autumn sowing is one of the most useful practical strategies for decreasing nitrate leaching. It is not, however, a panacea. Autumn sowing is not effective in decreasing leaching if emergence or sowing is late; the early sowings in Figure 4.2 were in mid-September, earlier than is practical in many situations and, indeed, such early sowing can exacerbate disease and weed problems. Where N uptake by an autumn crop is low it may be little more than the additional mineralisation caused by autumn cultivations.

There are some situations where it is not possible to grow a commercial crop during winter and where

Fig 4.2: Sowing winter wheat early reduces the amount of mineral nitrogen in the soil and at risk to leaching in autumn and winter

high nitrate leaching often occurs as a result. For example, in the winter prior to growing potatoes, sugar beet, maize or other crops that are not frost-hardy, or in the autumn following a crop that is harvested late, such as potatoes. One option is to grow a winter cover crop where, as with a normal autumn-sown crop, the aim is to absorb as much nitrate as possible during autumn, before winter leaching begins. Recent experiments have shown that cover crops that are sown very soon after harvesting a cereal (e.g. in August) can sometimes absorb 50-90 kg N/ha within a few months though this is not always achieved, especially if sowing is later (e.g. in October) or if germination is delayed because of dry soil conditions. In some cases, cover crops have completely failed to establish. However, the relatively few measurements of the effect of successfully established cover crops on nitrate leaching under UK climatic conditions all show a considerable decrease compared to bare soil (Figure 4.3). In the Brimstone Experiment, where conditions for growing cover crops are far from ideal, they decreased leaching by 15 kg N/ha in two separate years.

An alternative to sowing cover crops is to allow weeds and volunteers to grow. Such growth can sometimes absorb as much N as a sown crop but the agronomic impact of this practice, especially in relation to future weed control, requires careful assessment, as does the wider question of how cover

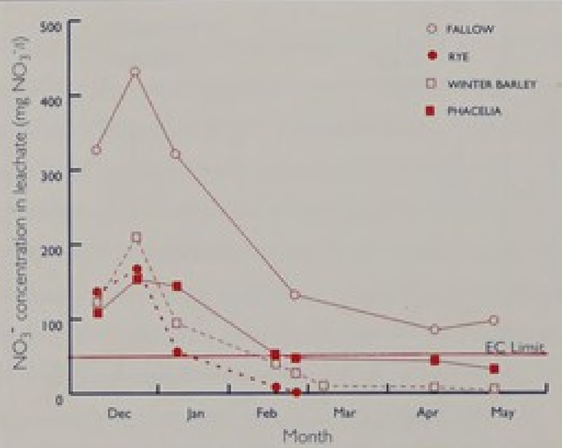

Fig 4.3: Effect of cover cropping on nitrate leaching

crops will affect pest and disease incidence. The use of cover crops is much easier on light-textured soils; on clays, seedbeds have to be made after harvest and spring crops drilled direct into the dead remains of winter killed cover crops.

Other ways of using cover crops are currently being evaluated. These include very short-term cover between harvest and drilling of an autumn-sown crop, undersowing before harvest to achieve earlier establishment of the cover crop, and growing a cover crop in combination with an autumn-sown commercial crop, to enhance the removal of nitrate from soil during winter.

A potential problem with a very vigorously growing cover crop is its use of water. This will decrease the volume of water draining during winter and therefore reduce the recharge of underground aquifers. A balance needs to be struck between the need to absorb sufficient nitrogen and the risk of removing excessive water. In the driest parts of the country this might also lead to a shortage of water available to the following crop.

Questions still remain over the fate of N from cover crops after incorporation. N mineralised fairly quickly will be available for the following crop, although there is a risk of some nitrate being leached before crop uptake commences. It is likely that a substantial proportion of the incorporated N will be mineralised slowly and make a small contribution to mineralisation over a number of years. At the Brimstone Experiment there is an indication of increased nitrate leaching in the winter following cover crop incorporation in the previous spring due to this slow mineralisation. This effect may be alleviated to some extent by taking into account the mineral N released from incorporated cover crops when applying inorganic fertiliser.

Conclusion

R&D to date has provided much useful information on the autumn and winter management of land to reduce nitrate leaching. This R&D indicates that methods for reducing nitrate leaching include: reduced cultivation rather than ploughing in the autumn; early sowing of autumn crops; planting cover crops where soils would otherwise be bare during winter and delaying the ploughing in of crop residues, especially the easily mineralised ones such as oilseed rape, even by a few weeks between September and October. The last method needs to be balanced against the benefits of early autumn sowing. Further information is still needed in particular with regard to the long-term influence of these practices on nitrogen mineralisation and the resulting effect on leaching.

Chapter 5

Progress in grassland nitrogen management

Steve Jarvis (IGER, North Wyke) and Peter Dampney (ADAS)

Summary

Ungrazed grassland, even with very high fertiliser inputs, is unlikely to result in substantial nitrate leaching if applications of fertiliser are made to match closely the needs of the growing grass crop. However, once grazing animals are introduced, grassland swards may become a significant source of nitrate leaching and of gaseous losses of N e.g. ammonia and nitrous oxide under many situations. This, in large part, is related to the poor utilisation of dietary N by ruminants and its recycling in excreta. Recent research has enabled a much greater appreciation of the extent of losses and of the processes (and their interaction with management, environmental and soil factors) involved in the complex grassland N cycle. This enhanced understanding is helping to formulate improved advice and new approaches for farmers to help them meet current economic and environmental targets.

Introduction

Grasslands play a major role in the agricultural economy of the UK and contribute much to the general aesthetic and ecological qualities of our countryside. Grassland farmers have achieved considerable success over recent decades in meeting the levels of production of dairy and meat products which people want to eat. Much of this success can be attributed to the use of N fertilisers. The economic responses that have been obtained from fertiliser N have meant that high rates of application have been used in intensive grassland management. In recent years, increases in fertiliser inputs have levelled off, but a significant proportion (11%) of intensively managed grassland in the UK receives more than 300 kg N/ha. The current maximum recommended rates for dairy systems range from 300 - 380 kg N/ha for grazed and from 340 - 420 kg N/ha for cut swards.

Increasingly, questions are being raised about the efficiency of N utilisation within grassland management primarily because of the possibility of leaching of excess nitrate to waters and the emission of gaseous N compounds to the atmosphere but also because, with the narrowing of profit margins, farmers need to pay closer attention to the cost of inputs. Until recently, grassland systems had been generally perceived as having a high capacity for absorbing added N with less leaching than arable counterparts. This misconception arose because assessments had been based on cut swards and little account had been taken of the grazing ruminant which returns much of the N that it ingests (and which may have been accumulated very effectively by the plant crop) back to pasture in dung and urine rather than being removed from the field in harvested forage. The impact of the grazing animal on leaching and other losses has been clearly demonstrated in many situations. Much recent research has therefore addressed problems of losses in grazed swards in order to reduce their environmental impact and to enhance the efficiency of N utilisation within grassland systems.

The grassland nitrogen cycle

The nitrogen cycle is complex, especially in grassland environments, with interactions and flows of N between soils, plants, animals and the wider environment (see page 37). Grasslands differ from tillage systems in many respects: the crop is perennial, there are major differences in the patterns of organic matter accumulation and mineralisation and, most importantly, they differ in the extent of recycling that occurs through excretal returns from the animal. Fertiliser inputs are used not because there is any deficiency on the part of the animal but to stimulate plant dry matter growth. Recent analysis of data from 133 replicated ADAS/IGER field trials to examine responses of cut grass to fertiliser N has established a strong relationship between economic optimum levels of addition (i.e. when the rate of response became 7.5 kg dry matter per ha per kg N applied) and yield response. The mean value for optimum N over all the sites was 407 kg N/ha. Where grass is cut, even very high fertiliser rates are unlikely to result in substantial nitrate leaching if applications are made which closely match the crop's needs. However, once animals are involved, very large proportions of the N consumed in the herbage are excreted and recycled back to pastures; increasing inputs of N increases ingestion by the ruminant and in turn, this increases the total amount of N excreted and the proportion in urine (Figure. 5.1). That in urine is particularly important and the pattern of deposition is such that there will be an extremely skewed distribution of mineral N in the soil with much mobile N accumulated into urine patches or 'hot spots'. This results in N supplies exceeding the potential for plant uptake and the excess being vulnerable to transformation and loss.

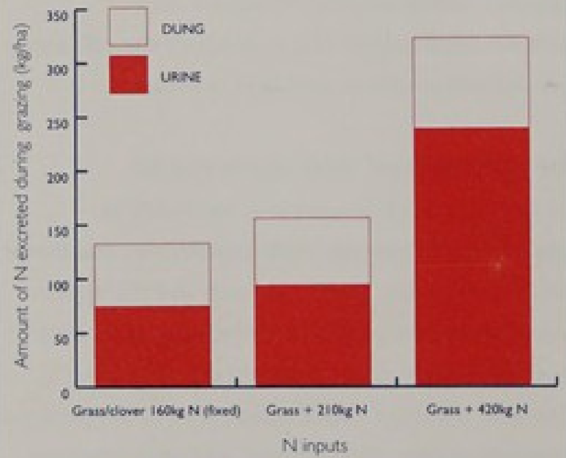

Fig 5.1: Excretion of nitrogen by grazing cattle

Mineralisation and immobilisation

(see also box, Chapter 2)

One very poorly defined component of the grassland system is that which relates to the movement of N into and out of soil organic matter. Changing organic matter contents with time result in a changing balance of mineralisation and immobilisation and as swards age so the potential for mineralisation and release of nitrate increases. Cultivation, especially of old swards, disturbs balances through effects on soil aeration levels and promotes the release of mineralised N: a band of high nitrate concentration water deep in the chalk and limestone aquifers is thought to have resulted from ploughing grassland during the Second World War. Recent studies have shown the considerable extent of leaching losses during the first year after cultivation on some sites, despite being cropped by cereals. Leaching losses of up to 876 kgN/ha have been recorded in the first year after autumn ploughing of grassland swards with a mean value of 252 kgN/ha over 8 field trials. There was a considerable reduction in the second year when the impact of uptake and immobilisation had taken effect and there were major differences between sites with past and present agronomy also having an important impact on losses. Other recent studies of the effects of previous fertiliser inputs to grazed swards on responses of subsequent cereal crops have demonstrated the importance of an accurate knowledge of previous fertiliser use if leaching losses are to be avoided.

After cultivation and reseeding grass swards there is an initial depletion of soil organic matter, but it then accumulates and there is a shift in the balance towards immobilisation with less mineral N so that leaching losses decrease (see Figure 5.2). There are, however, few measurements available to provide estimates of the changing flows to and from soil organic matter. Research is tackling the difficult task of quantifying the flows of N to and from this large and important soil pool so that prediction of its impact on N release can be determined with a greater degree of confidence.

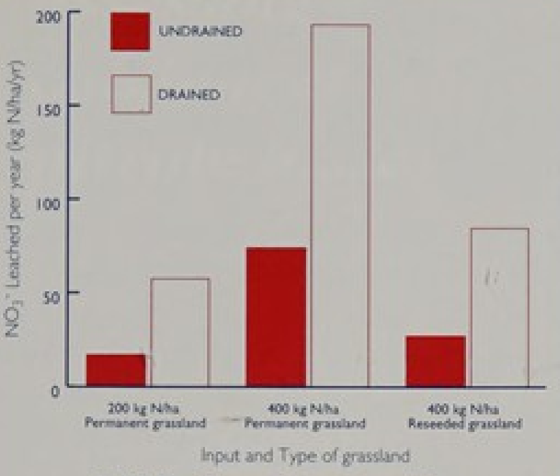

Fig 5.2: The influence of nitrogen input levels, drainage and reseeding on nitrate leaching from grazed swards

Losses of nitrate from grassland

A number of recent studies have demonstrated the extent of nitrate leaching under grazing. Generally leaching losses increase with increasing inputs (see Figure 5.2) but it is difficult as yet to provide firm relationships. When information from several sites in England, Wales and the Netherlands was considered recently, a wide scatter in the relationship between inputs and nitrate leaching rates was demonstrated. This is not surprising given the major differences between the sites with respect to their drainage, soil type, past histories and current management. Where comparisons have been made on the same soil type, there have been indications of an increased rate of loss as some critical rate of fertiliser addition is exceeded.

Because of the extent of losses from grazed systems, the concentration of nitrate in leachate is often high and in excess of the EC limit for drinking waters, especially under long term swards (Figure 5.2). Even relatively low fertiliser additions of 200 kg N/ha result in substantial proportions of the drainage having concentrations greater than 50 mg/l of nitrate. Many grassland systems are based on 'structured' soils such as clays and clay loams rather than on 'unstructured' soils such as sandy soils. The way that water, and solutes such as nitrate, flow in structured soils is not as easy to predict as it is for unstructured soils. Research effort is being directed at quantifying and understanding some of the pathways of solute flow vertically as leaching and also horizontally as surface runoff.

The description of N flows in grassland systems of the form depicted on page 37 has been developed into a mathematical computer model to describe the annual fluxes of N within grazed grassland and has been widely adopted to help define flows in different systems. This NCYCLE model has now been extended and modified to enable the prediction of annual leaching loads of rivers on a catchment basis. Further model development will enable better prediction of flows of nitrate from grassland soils into rivers and aquifers.

Avoidance of leaching problems in grassland

The research that has been undertaken over recent years has enabled a far better comprehension of the extent and the likely causes of nitrate leaching from grassland. Research funded by MAFF has already resulted in an updating of advice provided for farmers which will help to allow them to grow grass efficiently while reducing excessive risk of leaching. Whilst there is still considerable opportunity to fine tune existing systems, other approaches have also been investigated. In one investigation, accumulation

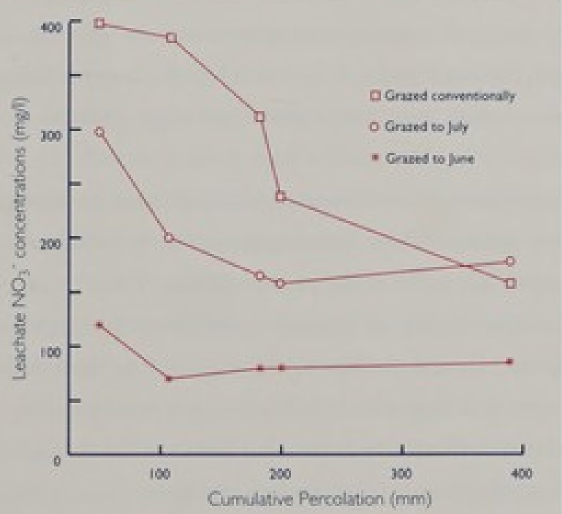

Fig 5.3: Removing cattle early from grassland reduces the concentration of nitrate in the leachate

of nitrate in the profile in autumn was reduced when grazing cattle were removed early and a late silage cut was taken. This method has been investigated further at two other sites and substantial reductions in leaching have been recorded: the earlier the removal, the more consistent and greater the effect (Figure 5.3). However the usefulness of this approach is restricted where drought limits late season grass growth.

Another more recent attempt to make more logical utilisation of the available N in the soil profile has developed a field method of measuring nitrate and ammonium so that fertiliser adjustments can be made in a tactical manner to avoid accumulation. Tests on grazed experimental plots have looked promising and significant reductions in mineral N accumulation have been achieved. This approach of a more complete knowledge of soil mineral N, coupled with better utilisation of other information (especially that relating to rainfall, evapotranspiration and soil water content and storage capacity) should enable much greater efficiency in use of soil N, from wherever it originates.

Use of clover

There has recently been a considerable revival in interest in the use of clover based swards as a means of sustaining animal production. This has been prompted by economic considerations and also by the fact that leaching and other losses have been demonstrated to be very much less from many mixed swards than from highly fertilised grass systems. However, where studies have tried to match N inputs from fertiliser and clover, leaching losses are very similar. Whilst many mixed swards have low losses, this reflects the presence of sufficient N-deficient grass to provide a sink for any adjacent excess mineral N. Where that capacity is exceeded, and where opportunities for fixation increase, the system can become leaky. For instance, nitrate concentration in leachate below clover mono-cultures grazed by sheep have been shown to be similar to that beneath highly fertilised grass.

Conclusions and future progress

The R&D to date has shown that ungrazed systems are generally unlikely to pose serious nitrate leaching problems but that significant leaching may occur under grazing grassland.

Nitrate leaching generally increases with increasing fertiliser inputs and the extent of leaching is influenced by drainage, soil type, past history of the site and current management practices. The results from R&D have been used in updating advice and recommendations to farmers in order to increase fertiliser efficiency, improve grass production and to reduce leaching. Results also suggest that taking cattle off grassland early and making a late silage cut will reduce leaching. The measuring of soil mineral N so that fertiliser adjustments can be made during the growing season to avoid accumulation of nitrate in the soil has also shown significant reductions in nitrate leaching in preliminary experiments.

For the future, because of the complexity of the grassland N cycle, a greater understanding of all N transformations and flows within the cycle is needed. Current MAFF-funded research in grassland systems is tackling this area. It will be important to appreciate the consequences of measures taken to reduce leaching for other losses of nitrogen from the grassland system.

Chapter 6

Assessing catchment nitrate losses

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Summary

In order to assess the effectiveness of measures to reduce nitrate leaching it is not sufficient simply to measure the nitrate in water abstracted for drinking, since nitrate leached from agricultural land may take many decades to reach the borehole. It is therefore necessary to estimate nitrate leaching using information on current agricultural practices and models of the various processes involved. Models have been developed to estimate the current nitrate leaching risk, the overwinter drainage volume, the effect of drainage volume on nitrate losses, the movement of nitrate to the borehole and the fate of nitrate within streams. By using these models it is possible to estimate the amount of nitrate that will be leached in different situations, to identify the most effective and cost-effective ways of reducing nitrate leaching and to estimate the timescale for changes to be reflected in abstracted water.

Introduction

Nitrate leached from agricultural land today may not reach the borehole at which drinking water is abstracted for many years, if not decades. On the way, it will mix with water from other fields and other years. This makes it difficult to predict the exact effect of surface activities on nitrate concentrations in abstracted water at a given time. In order to ensure that measures implemented to reduce nitrate leaching are as effective, and cost-effective, as possible, we need to assess both the extent of the problem at present, and the likely effect of proposed measures. The problem at present depends on i) farming practice, which determines the amount of nitrate likely to be available for leaching, ii) climate, which determines the quantity of water draining through the soil with the nitrate, and hence the concentration and iii) subsequent processes, which determine the rate at which the nitrate reaches the point of abstraction, and how much of it does so, i.e. the extent of any losses on the way, due to denitrification (i.e. the conversion of nitrate to nitrous oxide and/or nitrogen gas).

Estimating current nitrate leaching risk

For any given cropping system, the nitrogen leaching under economic optimum fertiliser inputs and management can be estimated from experimental data for similar situations. This potential may be greatly increased if excessive fertiliser or manure is applied, or if manures are applied in autumn or winter.
It may be decreased by measures which maintain green cover over winter to mop up soil nitrogen; by ensuring that fertiliser inputs are fully adjusted for other sources of nitrogen such as soil residues or manures; and by reducing fertiliser inputs, especially if these are above the economic level. If the balance of cropping is known for an area it is possible to estimate the potential nitrate leaching load under typical current practice. These estimates may be refined in the light of more detailed local data.

In order to develop and test methods of estimating potential losses of nitrate under current farming practice, data from the Nitrate Sensitive Areas (NSAs) (see Chapter 7 for further details) have been used. The information required was collected from farmers in the course of providing them with field-by-field nitrogen fertiliser recommendations. The factors taken into account included recent history (crops, manure and nitrogen inputs); soil type; and husbandry of the crop immediately preceding the winter of interest. The leaching expected after harvest of a given crop was adjusted according to fertiliser inputs and yield (i.e. nitrogen balance); residues from previous crops and manure inputs; and green cover in autumn. For grassland, the NCYCLE model developed by IGER provided an estimate of leaching potential based on fertiliser (and manure) inputs, grass management (cutting or grazing), soil type and climatic area.

This estimate, combined with the expected drainage volume, gives an indication of the expected concentration of nitrate at the borehole if current practice were to continue for long enough for equilibrium to be established and if no denitrification occurs between the soil zone and the groundwater. It is possible to identify the cropping systems with the greatest impact on leaching losses within a particular catchment.

In order to check that the derived values are a fair reflection of the situation in practice, estimates have been compared with measurements made on selected fields and have been found to be in reasonable agreement (Figure 6.1).

Fig 6.1 Comparison between NCYCLE model predictions of nitrate leaching under 3 grassland management systems, and actual measured rates of leaching

Estimates from the models, of nitrate leaching over the last 20 years indicate that in several NSAs nitrate concentrations leaving the soil zone have been, and still are, well above the 50 mg/l Drinking Water Directive limit. However, nitrate concentrations in the water abstracted from the boreholes in these areas, which have been monitored over the same period, are below 50 mg/l on average. For instance, at Branston Booths NSA the estimated nitrate concentrations leaving the soil zone from 1970 to 1990, range from 120 to 141 mg/l while the nitrate concentration in abstracted water for this area has varied between 20 and 50 mg/l over the same period. One explanation for this discrepancy could be the delay between water leaving the soil and arriving in the groundwater, although in the case of Branston Booths at least some of the water will reach the aquifer quickly through the rock fissures. It is also possible, however, that some nitrate is being denitrified during its passage through underground rock. Further R&D and NSA Scheme monitoring should provide an explanation for this discrepancy between observations and predictions.

Estimating overwinter drainage volume

Overwinter drainage determines not only the quantity of nitrate leaching, and its dilution, but also the total water resource available for abstraction. Changes in cropping could affect this recharge, especially if they result in the land being left under growing crops for a larger proportion of the year and therefore using more water, or if they lead to an increase in afforestation. For instance, of all farm crops, grass results in the smallest recharge because it is present all year; perhaps 20-50mm less than spring cereals depending on the weather. Coniferous forest can reduce aquifer recharge by over 100mm compared to cereals, which means that affected parts of Eastern England would have no recharge at all in many years. Estimates of these values for standard crops and locations are provided by the Meteorological Office model MORECS, both as averages and for current weather data. However, these estimates cannot allow for variations in husbandry (e.g. cover cropping) or local rainfall, and the differences can be important in dry areas or winters, and in experimental work. For this reason the principles in the model have been further developed in collaboration with ADAS, to provide a flexible model called IRRIGUIDE which can calculate site-specific drainage, using local rainfall, husbandry information and soil types.

Effect of drainage volume on nitrate losses

In most winters, enough water drains through the soil to leach most of the nitrate present in autumn to beyond the reach of crops roots, at least on the light soils which overlie most groundwater sources. However in a dry winter such as winter 1991/2, drainage may be insufficient to remove all the nitrate. The questions then arise: how much nitrate has been leached; and will the remaining nitrate be recovered by crops, or contribute to greater losses next winter?

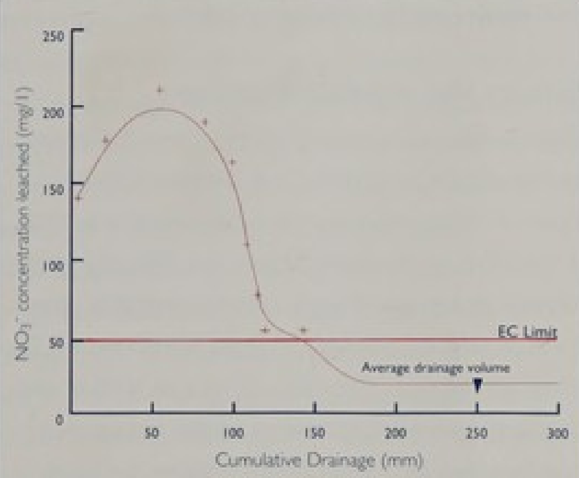

Fig 6.2 Effect of drainage volume on concentration of nitrate leached in winter 1990/91

Figure 6.2 shows a typical curve of nitrate concentration against drainage volume for a light soil over sandstone. The nitrate concentrations were measured at 90 cm, using porous ceramic cups. In the early part of the winter concentrations are high, and rising. After 50 - 100 mm of drainage, concentrations start to fall again, and after 150 - 200 mm drainage they are usually low. Thus the later drainage serves to dilute the nitrate in the earlier drainage. If drainage were under 100 mm, as happened in many areas in 1991/2, little dilution would have occurred. Furthermore some of the water below 90 cm is accessible to a well-developed cereal, sugar beet or oilseed rape crop. After a normal winter the concentrations at this depth are low, but after a dry winter concentrations could be high enough for even moderate water uptake from depth to have a significant impact on nitrate leached to the aquifer. The SACFARM nitrate leaching model developed at IACR Rothamsted is being used to assess how drainage volume affects nitrate loss, concentrations in the drained water, and the fate of nitrogen remaining in the subsoil, for a range of soil types and crops.

Nitrate movement to the borehole

Estimates of water and nitrate loss in any given year do not tell us what the concentrations of nitrate are at the borehole many metres underground. Some groundwater systems, such as the limestone aquifer, have large fissures which mean that changes at the surface may have some effect within months. However, even here the full impact may not be felt for many years because of the possibility that some water mixes with the water stored in the limestone rock, and equilibrium is reached only slowly. Scientists at WRc have developed an aquifer model which takes into account the location of sources of nitrate in relation to the borehole, the rock type (whether fissured or not, and how porous), and annual recharge and abstraction rates, to estimate the timecourse of changes in nitrate concentration at the borehole. Since current concentrations at the borehole will reflect activities over previous decades, the model has been calibrated using estimates of nitrate losses in previous decades. For example in the NSAs, farmers were asked what crops they were growing 10 or 20 years ago, what livestock manures and fertilisers they applied to those crops, what yields they generally achieved, and other details of crop husbandry. From this information, nitrate losses in previous decades were estimated by ADAS. These were then input to the WRc hydrological model, and the nitrate concentrations through time at the borehole were modelled. The results have been compared with actual borehole data. The models have then been run forward to predict concentrations beyond the year 2000. In most cases, the model (which takes no account of possible denitrification or other losses) predicts concentrations continuing to rise at the borehole for some years, whatever changes are introduced at the surface. It could therefore take many years if not decades for the full benefit of measures introduced now to be realised.

Surface waters

Nitrate concentrations in rivers fluctuate much more rapidly than those at boreholes, because there is less opportunity for mixing with water from other areas and other times (Figure 6.3).

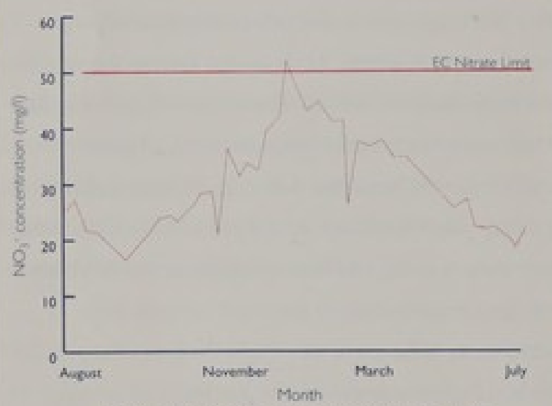

Fig 6.3 Fluctuations in nitrate concentrations in a river

Once the soil is saturated, water usually reaches a river within hours or at most days of the rainfall event. The EC Nitrate Directive requires agricultural measures to be put in place where surface water used for drinking fails the standard of 50 mg/l nitrate. This means that any assessment of the effects of farming on nitrate concentrations in the river must take into account peak concentrations, rather than averages as is usually the case with groundwaters. Peak nitrate concentrations normally occur during winter, and efforts are being directed at finding what changes in farm practice will have greatest impact on the height of this peak. The Institute of Hydrology has developed models of the fate of nitrate within rivers, and is applying them to catchments for which detailed agricultural and water quality data are available, including the Nitrate Advisory Area, Bourne Brook.

River water is largely supplied by clay soils, in which water moves mainly through cracks. After a heavy rainfall event, water may move so fast that incomplete exchange of solutes occurs with the soil matrix, and concentrations of nitrate and other salts are low. During periods of slower, steadier drainage concentrations will more closely reflect those in the soil. If a heavy rainfall event occurs shortly after applications of manure or fertilisers, concentrations may be very high, because the water dissolves the soluble nitrogen at the soil surface, and moves rapidly to the river without losing very much on the way. Development of models of the behaviour of water and nitrate within clays, taking account the effect of cracks, is underway at several institutes in collaborative studies funded by MAFF.

Putting the models together

When legislation to reduce nitrate losses is planned, the first step is to identify areas where action is required. This means assessing the nitrate available for leaching, on the basis of land use; the overwinter drainage and hence the concentration of that nitrate in water; and the mixing and delay which occurs before abstraction. The same factors, as well as any subsidiary effects of legislation on the farm system, must be taken into account in assessing the likely impact of proposed measures. The models discussed above help Government to estimate the effectiveness of the measures.

Results from the Pilot Nitrate Scheme

John Archer
and Eunice Lord (ADAS)

Summary

The Pilot Nitrate Scheme consisted of the Nitrate Sensitive Areas (NSA) Scheme and the Nitrate Advisory Areas (NAA) Scheme. In the NSAs farmers were invited to alter crop management practices in return for payments whilst in the NAAs detailed advice was given but no payments made. The NSAs are being monitored in several ways. The groundwater nitrate concentration is being measured; farmers are providing data to be fed into models to predict nitrate loss; and direct measurements of soil nitrate are being taken. Cover crops have been found to reduce nitrate losses considerably in some cases and the conversion of arable land to grass has generally also been found to reduce leaching substantially. In the NAAs farmers were given individual advice including field by field fertiliser recommendations. The results showed that they did not generally take sufficient account of the advice given on the nitrogen value of manures, crop residues and ploughed out grass. Potatoes and sugar beet were often given more fertiliser than the economic recommendation. Farmers generally accepted recommendations to establish green cover over winter, to target fertiliser applications more carefully, to delay cultivations after early-harvested high-residue crops, to plant autumn rather than spring cereals, to limit manure applications to 170kg N/ha/year and to delay these applications to the spring.

Introduction

The Pilot Nitrate Scheme was set up in 1990 to test the effectiveness in practice of measures to reduce nitrate leaching, to find out how well they could be integrated into commercial farming practice, and to gain experience in administering such a scheme on a catchment basis. The Scheme consisted of two main parts: the NSA Scheme, in which farmers were invited to make major changes to crop management over a 5-year period in return for payments; and the NAA Scheme, in which farmers were offered a detailed advisory visit on good agricultural practice but no payments. Desk studies were first carried out to identify water sources with high and/or rising nitrate levels, and to estimate the likely impact of proposed changes on these levels. For the NSA Scheme, ten catchments were selected, over sandstone, chalk or limestone groundwater sources. In order to help ensure that the measures to be implemented were practicable, that they were based on sound local information and that the payments reflected the likely costs, the proposed areas and measures to be implemented were discussed in detail with local farmers and landowners, local authorities, nature conservation bodies and other interested parties.

Fig 7.1 Locations of the NSAs and NAAs

A further nine catchments were identified as NAAs. Two of these were surface water catchments, and seven were groundwater catchments. The sites of the NSAs and NAAs are shown in Figure 7.1.

The Nitrate Sensitive Areas Scheme

Within the NSAs, a 5-year voluntary scheme was offered to farmers in return for standard payments. Farmers joining had to put all their land within the NSA boundary into the Scheme, for 5 years starting in 1990 or 1991. In addition, they could opt for higher payments under a 'Premium' Scheme, by putting part or all of their arable land down to grass receiving zero or 150 kg N/ha nitrogen annually.

The Basic Scheme, which now involves over 85% of agricultural land in the NSAs, has four main requirements: application of the correct (economic optimum) amount of nitrogen fertiliser to each field, with reductions in fertiliser input for winter cereals and oilseed rape; a limit of 170 kg N/ha/yr as livestock manure; a ban on the autumn application of slurry or poultry manures; and use of cover crops where land would otherwise be bare during autumn and winter. These measures were designed to minimise nitrate available for leaching during autumn and winter. In addition, under the Premium options, which were taken up on 12 % of the agricultural land, farmers could elect to put a part of their land previously under arable crops into grass for 5 years, with a limit on nitrogen inputs of zero or 150 kg N/ha. Losses of nitrogen from Premium Scheme land were expected to be considerably smaller than under arable cropping.

Monitoring of the Nitrate Sensitive Areas Scheme

The NSA Scheme is monitored in several ways. The concentration of nitrate in groundwater within NSAs is being measured by the National Rivers Authority (NRA). However, despite the large uptake of the Scheme, it is not practical to monitor the effect of the Scheme within its 5 year life solely by reference to nitrate concentrations in the borehole because the water leaving agricultural land may take many years to travel to it. Even in so-called fast response aquifers, where some of the water may arrive within weeks or months, there will be several years before full equilibrium is reached. In order to assess the effectiveness of the Scheme more quickly and reliably, two other main types of monitoring are being carried out. Firstly, farmers are required to provide details of crop and husbandry on each field registered in the Scheme. Information supplied includes fertiliser and manure inputs and dates of application, drilling and harvest dates, yields and main cultivations. The data are used to estimate nitrate losses, and identify any changes during the life of the Scheme, as described in Chapter 6.

Second, nitrate losses are being measured directly on a few representative sites, for comparison with expectation. Ten to twenty fields within each NSA have had porous ceramic cups installed at about 90 cm depth, through which water moving down to the aquifer can be sampled and the concentration of nitrate measured throughout the life of the Scheme. On some of these sites in the 6 sandstone and chalk NSAs, rock cores have been taken to about 10 m depth, and the water in these cores analysed for nitrate and other solutes. The change in nitrate concentration down the profile gives a historical snapshot of nitrate which was leached from the land over about the last 10 years. It is intended that coring should be repeated at the end of 5 years, to test the impact of the Scheme on nitrate within the rock. The microbial activity in the rock is being investigated to find out whether denitrification (loss of nitrate by conversion to nitrogen gas or nitrous oxide gas) could be occurring as water moves down to the abstraction point.

Effects of the NSA Scheme on farming practice

The aim of the Basic Scheme in the NSAs was to allow present cropping systems to continue, while achieving significant reductions in nitrate leaching. Changes in cropping have in fact been relatively small, and difficult to distinguish from the year-to-year variation in crop areas caused by normal rotational practice. The main exception is conversion of arable land to grass under the Premium Scheme.

Where there are large areas of spring crops, the requirement for cover crops has been an important extra workload. Farmers have had problems in the two dry autumns since the start of the Scheme, and a range of approaches has been tried. In some cases the managed use of naturally-germinating shed grain has been as successful as purpose-sown species, and is, of course, considerably cheaper.

Where heavy applications of pig or poultry manures had been made, these have generally stopped or greatly reduced to within the requirements of the Scheme. In most cases the export of these manures outside the NSA has increased. However a requirement of the Scheme is that disposal even outside the NSA should comply with the MAFF Code of Good Agricultural Practice for the Protection of Water or, if the land is over a vulnerable groundwater source, with the rules of the NSA Scheme. Dairy farms producing cattle slurry have often found compliance with the Scheme difficult. On the light, freely draining soils found in the NSAs, it has been traditionally possible to dispose of slurry to land throughout the winter. The introduction of a closed season in autumn has meant the need for increased storage, at high capital investment.

Measurements of nitrate concentrations

Measurements of nitrate leaving the subsoil were started in the winter of 1990/91, when the effects of the Scheme were expected to be very small. These results therefore provide a baseline. Results generally confirmed expectations from experiments that nitrate losses were high after crops such as potatoes and oilseed rape, and moderate after cereals (see Figure 2.4). Losses after sugar beet were often particularly low, especially if no manure had been applied. Extremely high losses were measured, as expected, in areas which had been used for disposal of large amounts of manure from housed livestock over several years.

Where cover crops were introduced as a result of the Scheme, losses were sometimes very low. However this was not always the case, because establishment was delayed in many cases by unusually dry conditions. Farmers and researchers are experimenting with practical ways of improving establishment without increasing costs and time requirements in the very busy autumn period.

Conversion to grass under the Premium Scheme resulted in some very low losses of nitrate even in the first winter. Exceptions were due to poor establishment, in the very dry conditions, but by the second winter, losses were invariably small.

The Nitrate Advisory Areas Scheme

The objective of the NAA Scheme was to find out whether farmers could make enough changes to their systems to have a significant impact on nitrate losses, without financial detriment to their business. Farmers were offered a detailed advisory visit on good agricultural practice, but no payment. All farms within each NAA were visited in order to discuss details of current cropping and management, and to identify areas where changes in practice could reduce nitrate losses. A letter was then sent confirming desirable changes, and giving field-by-field economic nitrogen fertiliser recommendations. One year later, a sample of farmers was revisited in order to find out what changes they had in fact made, whether they had followed the fertiliser recommendations, and what their reasons had been if they had decided that they could not follow the advice given.

The study found that most farmers were using nitrogen fertiliser in quantities similar to or below recommendations, but there were situations where higher amounts were being used. Nitrogen from other sources such as manures, previous crop, and ploughed-out grass were often not allowed for sufficiently. Potatoes were often given more fertiliser than the economic recommendation, especially when manure inputs were taken into account, because farmers were anxious to ensure that there was no limitation to yield. Sugar beet also often received higher N inputs than recommended. This was partly because of insufficient allowance for organic manures applied before the crop, but also possibly because fertiliser recommendations have fallen over the last 20 years, and not all farmers had adjusted to the newer advice. In some cases, farmers were reluctant to reduce fertiliser inputs in response to ADAS advice, because they perceived an economic risk. Further thought will have to be given to tackling this problem.

Other potential improvements in practice included establishment of green cover over winter before spring crops; ensuring that fertiliser nitrogen was not applied before February; splitting large applications into two separate dressings; delaying cultivations after early-harvested high-residue crops such as peas until the next crop was due to be drilled; and planting autumn instead of spring cereals where possible.
In general farmers were receptive to these suggestions, which in most cases carried little or no financial penalty. They complied with advice on 44% to 75% of the area involved (depending on the measure). Green cover, where established, usually consisted of the cheapest option: natural regeneration.

Where applications of manure exceeded 170 kg N/ha/yr, farmers were asked to reduce them by spreading the manure over more land. Where poultry manure or slurries were applied to arable land in autumn, advice was given to delay application until winter or spring. In spite of the costs of complying with these proposals, the advice was followed on over 60% of the affected land. These changes could have a considerable impact on leaching losses.

Overall, changes achieved by the NAA Scheme were smaller than in the NSA Scheme, as was to be expected. However farmer awareness of the issues was raised, and many were prepared to change practices which cause unnecessary loss of nitrogen.

Conclusion:

What farmers can do now and the way forward

This brochure has provided an introduction to the extent and nature of the nitrate problem. It has given up-to-date information on the ways in which nitrate losses from agriculture can be reduced. Where appropriate it has also indicated areas where our knowledge is limited and where further R&D is needed.

In the Introduction it was noted that nitrate loss to groundwater is a complex process. There are no simple remedies to the problem. However, through MAFF's R&D programme, a number of methods and practices have been identified, each of which will have an important role to play in reducing nitrate leaching from agriculture.

We have seen that processes beyond our control, such as soil type, geology and rainfall, affect the rate of nitrate leaching and subsequent concentrations in groundwater. For instance, groundwater below light soils in areas of low rainfall are particularly susceptible to high nitrate concentrations. This is due to rapid leaching through the soil and low dilution by rainfall.

What the farmer can do now

There are several courses of action farmers can take now to reduce nitrate leaching. These include:

1. The careful targeting of fertiliser (both inorganic and organic) to avoid exceeding the crop requirements.
2. Avoiding excessive slurry and other organic manure applications and minimising autumn applications.
3. Planting autumn rather than spring cereals.
4. Establishing autumn crops as early as possible.
5. Avoiding unnecessary autumn cultivations.
6. Establishing green cover over winter where spring crops are to be planted.

The R&D challenge

Further R&D is needed:

1. To improve recommendations for inorganic fertiliser applications by taking better account of crop requirements and soil mineralisation.
2. To characterise organic manures more precisely and convince farmers to regard them as a valuable resource rather than a waste.
3. To evolve systems for establishing cheap and effective autumn crop cover.
4. To improve the evaluation of nitrate losses at the whole farm and catchment level.
5. To increase our understanding of the fate of nitrate after leaving the soil.

Increased knowledge in these areas along with the information we already possess will provide a solid base for future policies.

Further reading

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