CAS Paper 29

Water services and agriculture: key issues and strategic options

Proceedings of a conference organised by the Centre for Agricultural Strategy, held at the One Great George Street Conference Centre, Westminster, London SW1P 3AA on 14 December 1993

Edited by B J Marshall & F A Miller

Centre for Agricultural Strategy
University of Reading
1 Earley Gate
Reading RG6 2AT

May 1994

Marshall B J & Miller F A (Eds)(1994) *Water services and agriculture: key issues and strategic options.* CAS Paper 29.
Reading: Centre for Agricultural Strategy.

6 Water quality and fertiliser use - understanding the nitrate problem

D S Powlson

SUMMARY
It is clear that concentrations of nitrate in many groundwaters and surface waters have increased in recent decades and that agricultural activities have been a prime cause. What is less clear is the extent to which nitrate is a real problem, as opposed to a legal one. Medical reasons for being concerned about nitrate in public water supplies above the European Community (EC) limit of 50 mg per litre appear to be weak. There are, however, sound environmental and economic reasons for wishing to minimise losses of nitrate, and phosphate, from soil to aquifers. A clear and quantitative understanding of the processes comprising the nitrogen cycle, and the impact of different agricultural operations, is a necessary prerequisite for designing less leaky agricultural systems.

Direct loss of nitrate from fertiliser is not generally a major source of the nitrate leaching from agricultural land, although there are exceptions to this and also indirect long-term effects of fertiliser. The major source is usually the breakdown of organic matter in soil by micro-organisms - the process of mineralisation. Part of the nitrate produced is taken up by plants but part is formed in the late summer, autumn or early winter when crop uptake is minimal. In the climatic conditions of north-west Europe, nitrate in soil during this period is at great risk of being leached during winter. A key factor in decreasing leaching is to decrease the quantity of nitrate present in soil during the winter period. In many situations the most practical way of achieving this is to ensure that a crop, such as grass or an autumn-sown cereal, is present but this is not always possible and is not necessarily effective.

Various measures, including incorporation of cereal straw or growing winter cover crops, can decrease leaching in the short-term but cause a build-up of organic nitrogen in soil and, later, some of this will be released as nitrate. The use of animal manures, or other organic 'wastes' such as sewage sludge, adds to the problem of untimely nitrate production.

Mathematical models of the nitrogen cycle in agricultural systems are being developed. By calculating the quantity, and time course, of nitrogen coming from mineralisation they can help farmers to make rational decisions on the nitrogen fertiliser requirements of crops on a field specific basis. They can also help farmers and planners to design cropping patterns such that the impact of leaky, but profitable, crops are diluted by less leaky ones at the catchment level. Although many of the principles underlying the nitrate problem are now understood, translating these into practical management systems that will decrease leaching to the extent necessary under current legislation presents a formidable challenge.

INTRODUCTION

It is undeniable that concentrations of nitrate have increased in many groundwaters and rivers in the past few decades. It is also undeniable that agricultural activities have been a prime cause of this increase. Beyond these points it becomes more difficult to separate fact from conjecture. Is nitrate really a hazardous substance to be kept out of water at all costs? Is the limit of 50 mg nitrate per litre in drinking water and in many surface waters justified on medical or environmental grounds?

The exact ways in which agricultural operations influence the movement of nitrate from soil to water are often not appreciated by practitioners in the agricultural and water industries. Indeed, some of the processes are only partly understood by soil scientists, agronomists and hydrologists. A sound understanding of the processes comprising the nitrogen cycle, and the complex interactions between them, is essential if effective (as opposed to cosmetic) strategies to decrease leaching are to be devised. There has been at least one benefit from the move to a lower limit for nitrate in water. It has stimulated considerable research on aspects of the nitrogen cycle and highlighted the need to manage plant nutrients in a more conservative and sustainable way. This research has greatly increased our level of understanding and we are now in a position to make logical recommendations regarding agricultural practices that will decrease nitrate leaching. The regulations now in force in the Nitrate Sensitive Areas (NSAs)in the UK generally reflect this increased level of knowledge; without the recent increases in understanding of nitrogen transformations the regulations could well have been more difficult for farmers to apply and also less effective. However, the research has highlighted a number of difficulties and gaps in our knowledge. First, the interactions between different processes are even more complex than we had thought; changes in agricultural practice can sometimes have unexpected knock-on effects elsewhere in the soil/plant/water/atmosphere system. For example, a change in practice which decreases nitrate leaching in the short-term may be less beneficial in the long-term or lead to a different environmental problem. Second, although we have a good idea of the key processes involved, we are still short of good quantitative measurements made under realistic field conditions representative of a wide range of environments. Third, although a number of strategies can now be adopted which certainly decrease nitrate leaching, at least in the short- or medium-term, it is quite possible that the resulting decreases will not be sufficient to meet the very stringent limit of 50 mg nitrate per litre.

This paper considers the key processes involved and gives examples of how current research is aiding our understanding. It also highlights some of the complexities and uncertainties and reviews current ideas on how to decrease nitrate loss. Many publications are available giving more detailed information. These include a book entitled *'Farming, fertilizers and the nitrate problem'* by Addiscott *et al* (1991) and a Ministry of Agriculture, Fisheries and Food (MAFF) publication entitled, perhaps optimistically, *'Solving the nitrate problem'* which comprises essays by many of the researchers involved in this field in the United Kingdom (UK).

WHY WORRY ABOUT NITRATE?

Medical reasons

High concentrations of nitrate are implicated in the disease methaemoglobinaemia, or blue baby syndrome, which affects babies of less than 1 year old. Nitrate, NO_3^-, is converted to nitrite, NO_2^-, in the baby's stomach and this combines with haemoglobin in the bloodstream. The result is that less oxygen can be transported around the body. The unfortunate baby suffers what might be described as chemical suffocation, a very severe condition that can prove fatal. Fortunately this is a very rare condition. A re-examination of all reported cases throughout the world showed that almost all were associated with water from shallow wells where there is good reason to believe that the water was bacterially contaminated by either human or animal excreta (Addiscott *et al*, 1991). Thus, blue baby syndrome appears to be associated with a combination of high nitrate concentration and bacterial contamination - not a combination that occurs in public water supplies in Western Europe.

It has also been suggested that there is a connection between nitrate in water and stomach cancer. This is a complex subject and it would be unwise for an agricultural scientist to attempt an authoritative discussion. Suffice to say that present evidence is against such a link. One UK study (Forman *et al*, 1985) compared the incidence of stomach cancer in areas of high or low nitrate in the water supply. The results showed a higher incidence in the low nitrate area. This does not necessarily disprove the existence of a link between stomach cancer and nitrate but it does suggest that, if it does exist, it is extremely weak and over-ridden by other factors. Other studies have examined the number of cases of stomach cancer in workers at fertiliser factories who received large intakes of nitrate in dust. Cancer levels were not found to be above the level in the surrounding population, not exposed to fertiliser dust (see Addiscott *et al*, 1991 for further details).

Environmental reasons

Nitrate, together with phosphate, that enters rivers or wetland areas can alter the balance of plant species present. Thus, if natural habitats are to be preserved in their present condition it is necessary to keep nutrient inputs to a minimum. Excessive nitrate and phosphate in rivers, lakes and estuaries can lead to the growth of algal blooms; either nitrate or phosphate may be the most important factor in different situations. When the algae die they are subjected to decomposition by bacteria and this leads to deoxygenation of the water which, in turn, causes the death of fish and other forms of aquatic life.

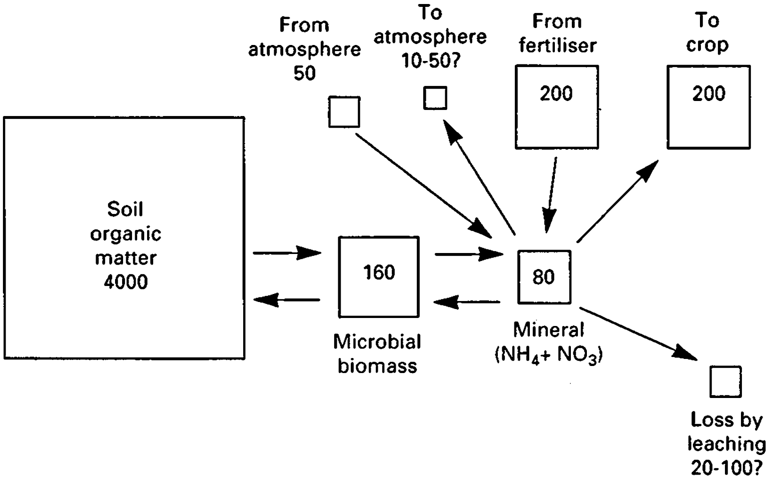
An additional reason for wishing to limit unnecessarily high concentrations of nitrate in soil is that under certain conditions it is subject to a process called denitrification. In this process bacteria convert nitrate to a mixture of the gases nitrous oxide, N_2O, and nitrogen, N_2, which are evolved to the atmosphere. Although N_2 is environmentally benign, N_2O is a greenhouse gas. Furthermore, if it reaches the stratosphere it is involved in reactions leading to ozone destruction.

Thus, the environmental reasons for wishing to limit the occurrence of excess nitrate in soil, and its movement from soil to aquifers, are probably stronger than the medical, but whether the strict limit of 50 mg nitrate per litre is justifiable is open to debate.

THE NITROGEN CYCLE

Table 1, taken from a recent review (Jenkinson, 1990a), shows current estimates of the quantities of nitrogen in different forms on a global scale. Soil organic nitrogen is the dominant pool in terrestrial ecosystems, being an order of magnitude greater than the nitrogen in plant biomass.

Figure 1
Pools and pathways of nitrogen in arable fields



Note: The figures (in kg N/ha) are based on arable fields at Rothamsted Experimental Station and the areas of the squares are proportional to the quantity of N in the pool or undergoing the process annually.
Source: Addiscott *et al* (1991)

Figure 1 shows this diagrammatically for an arable field; the figures are based on data from experimental fields at Rothamsted but are broadly representative of many arable fields throughout northwest Europe. Again, an obvious feature is the very large size of the soil organic nitrogen pool: the surface layer of an arable soil typically contains between 2000 and 6000 kg N/ha in organic matter. The amount reflects the past history of the soil and its mineral composition, being greatest in soils that have had long periods under grass or forest and those containing much clay which can stabilise organic matter. Some fractions of soil organic matter are very stable, having half-lives measured in hundreds or even thousands of years. Other fractions, such as remnants of fresh plant or animal material, are easily broken down by micro-organisms to yield carbon dioxide and inorganic nitrogen over periods of days or weeks. Thus, several sources of nitrate can be identified and will be considered in turn. These are:

- inorganic fertiliser;
- mineralisation of soil organic matter, animal manures and crop residues;
- atmospheric inputs.

Table 1
Estimates of the active pools in the global nitrogen cycle

	N (million tonnes)
Air	
N_2	3 900 000 000
N_2O	1 400
Land	
Plants	15 000
Animals	200
of which people	10
Soil organic matter	150 000
of which microbial biomass	6 000
Sea	
Plants	300
Animals	200
In solution or suspension	1 200 000
of which NO_3-N	570 000
of which NH_4-N	7 000
Dissolved N_2	22 000 000

Source: Jenkinson (1990a)

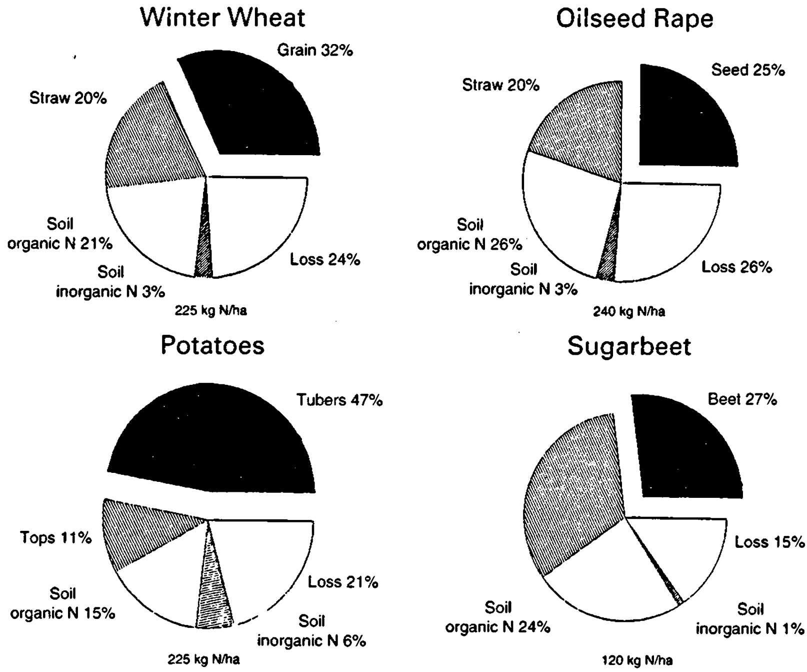
THE FATE OF N FROM INORGANIC FERTILISER

During the growing season

The loss of fertiliser N during the growing season of a crop can be quantified using ^{15}N-labelled fertiliser. ^{15}N is the heavy isotope of nitrogen; it is not radioactive and must be measured in samples of crop, soil or leachate using a mass spectrometer. The particular benefit from its use in agricultural experiments is that the relatively small quantity of fertiliser residue left in soil can be measured, even against the background of the large amount of native soil N. In such experiments the amounts of fertiliser-derived N taken up by the crop and retained in soil are measured and the amount not accounted for at the time of harvest, or some earlier sampling time, can be calculated. Figure 2 shows some examples of ^{15}N balances for a range of crops (Macdonald, Poulton and Powlson, unpublished data).

In another series of experiments in which ^{15}N-labelled fertiliser was applied, in spring, to winter wheat on three different soil types, recovery of fertiliser N in the above-ground parts of the crop ranged from 46 to 87% with a mean of 68%. The proportion retained in the soil was remarkably constant, averaging 18% where N was applied as double-labelled ammonium nitrate ($^{15}NH_4{}^{15}NO_3$), but less (7-14%) where it was applied entirely in the nitrate form. The proportion not recovered in either crop or soil varied greatly between years from 2%

Figure 2
Fate of ^{15}N from inorganic fertiliser applied to different crops in spring

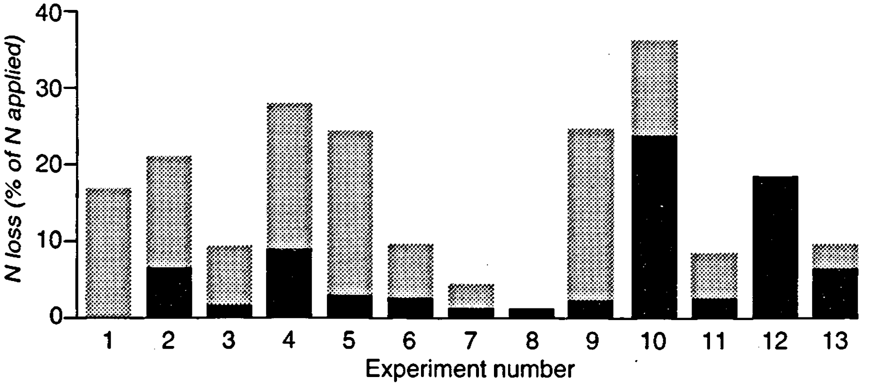


Source: Macdonald *et al* (1990)

to over 35% (Powlson *et al.*, 1992). There was a linear relationship between loss of fertiliser N and rainfall in the three-week period following application; each additional 10 mm of rain increased loss by 2.6%. On the basis of this relationship it was suggested that the second part of a divided dressing could be adjusted to take account of whether or not significant losses would have affected the first application.

Rainfall could favour loss by increasing leaching, denitrification, or both. A limitation of ^{15}N-balance experiments is that they give no direct information on the cause of loss unless other measurements of specific processes are conducted concurrently. Addiscott & Powlson (1992) proposed a method for distinguishing between the two loss processes based on the use of a mathematical model for leaching (see Figure 3). In 3 of the 13 experiments leaching appeared to have made a significant contribution to the total loss, but in the other cases there was too little movement of water down the soil profile after the time of spring fertiliser application to cause substantial leaching. There was good circumstantial evidence that the non-leaching loss was caused by denitrification except in two cases where small losses of ammonia, probably from crop foliage, may have occurred.

Figure 3
Partitioning of N fertiliser loss between leaching and gaseous losses



Note: ^{15}N-labelled fertiliser was applied, in spring to winter wheat in 13 different experiments and leaching loss calculated using a mathematical model for leaching ▩ gaseous losses; ■ leaching.
Source: Addiscott & Powlson (1992)

These studies indicate that leaching of fertiliser N shortly after its application to arable crops in spring is not the major cause of loss nor, indeed, the major source of nitrate reaching aquifers. This conclusion is consistent with 14 years of data from the Brimstone Experiment in Oxfordshire. Water passing into a drainage system beneath the clay soil is collected from hydrologically separated plots and analysed for nitrate, phosphate and a range of pesticides. Again, significant leaching of nitrate in the spring period, after fertiliser application, was rare - by far the most nitrate leaching occurred during winter (Goss *et al*, 1993). In regions to the north and west of Britain, with higher rainfall and where the main leaching season extends further into the spring, the situation could well be different; direct loss of fertiliser N by leaching may be more common.

Applications of N to spring-sown crops at the time of sowing will often be at greater risk of loss than equivalent applications to autumn-sown crops, as nitrate will remain in the soil for several weeks before uptake begins. However, this risk does not always materialise. In the lysimeter studies of Dowdell & Webster (1984), in which ^{15}N-labelled fertiliser was applied to spring barley, leaching of fertiliser N in spring was very small.

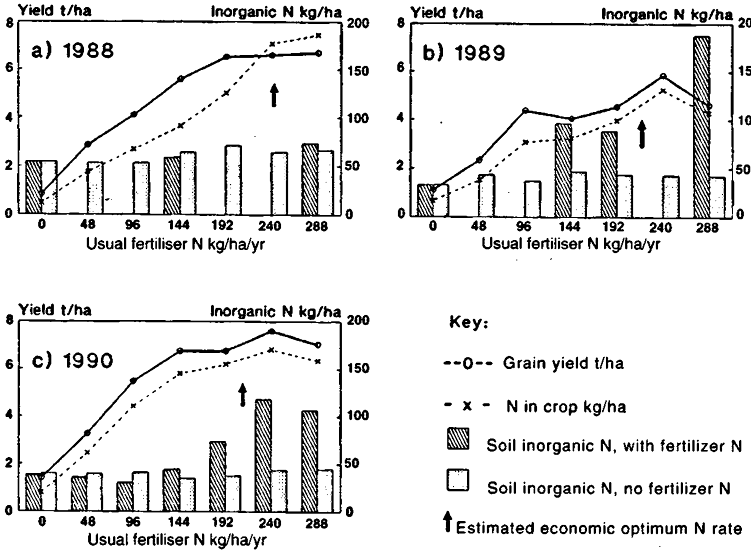
After harvest

The use of ^{15}N allows the forms of residual fertiliser-derived N in soil to be identified and their subsequent fate studied. For example, in some experiments with winter wheat (Macdonald *et al*, 1989) at least 80-90% of the fertiliser-derived N in soil at harvest was in *organic* forms - roots, stubble, root exudates, microbial cells, metabolites and humus. For crops given fertiliser N at currently recommended rates it was rare for more than 5 kg/ha of fertiliser-derived N to be left in soil as nitrate unless severe drought or disease greatly decreased crop growth. In most cases more than 90% of the inorganic N in soil at this time was unlabelled indicating that it was derived from sources other than fertiliser, mainly mineralisation of soil organic matter. The exact values obtained in such experiments have to be treated with some caution because of complications in the interpretation of experiments with ^{15}N arising from changes in the ^{15}N enrichment of the soil inorganic N pool caused by concurrent immobilization and mineralisation (so-called pool substitution see Jenkinson *et al*, 1985). However, under field conditions, the magnitude of these effects is often small (Hart *et al*, 1986) and does not alter the overall conclusion that nitrate derived directly from fertiliser is generally not a major source of the nitrate in soil following harvest of cereal crops. This is consistent with other results that do not rely on the use of ^{15}N. With winter wheat it is commonly observed that soil which received no fertiliser N in spring has the same nitrate content, when sampled after harvest, as that which received the usual application (eg Macdonald *et al*, 1990).

The relationship between fertiliser N application rate and residual nitrate in soil after harvest is illustrated in Figure 4 showing results from the Broadbalk Wheat Experiment (Glendining *et al*, 1992). The results illustrate some general principles but also some difficulties in giving improved advice on N fertiliser use. In 1990 there was no significant increase in crop yield with rates of N above 192 kg N/ha. For N rates below this the quantity of residual nitrate in soil (to a depth of 100 cm) was the same as in the plot that never received N fertiliser; a decrease in fertiliser N application was completely ineffective at decreasing residual nitrate (Figure 4). Chaney (1990) observed a similar pattern in experiments on a range of soil types in the UK although, in contrast to the Broadbalk results in 1990, the increase in residual nitrate did not occur until well after the estimated optimum economic N rate. Results from Broadbalk in 1988 were more similar to those of Chaney. In this year there were few constraints to crop growth and, although grain yield did not increase at N rates above 192 kg N/ha, N uptake by the crop increased over the entire range tested. Even at the highest rate of 288 kg N/ha the amount of residual nitrate in soil was only slightly greater than in the plot never receiving fertiliser N. Withholding N fertiliser in that year did not decrease residual nitrate in soil, even at the highest rate.

Figure 4

Inorganic N in soil (0-100 cm) at harvest (August) with and without the usual fertiliser N application



Note: Grain yield (85% DM) and N uptake (in grain and straw) are for the parts of the plots where fertiliser N was applied at the usual rates

Source: Glendining *et al* (1992)

Considerable effort is now being directed towards developing computer models to better predict the optimum N application for crops, on a field-specific basis, based on a knowledge of soil type, previous management and a realistic estimate of expected yield (eg Bradbury *et al*, 1994; Jenkinson, 1990b; Whitmore *et al*, 1991). The use of improved fertiliser advice systems, based on well-founded yet easily usable computer models of the soil N cycle, should greatly decrease the number of cases where excessive quantities of fertiliser N are applied. They are not, however, infallible as illustrated by the data for 1989 in Figure 4. Wheat yield on Broadbalk was below average because of excessively dry soil conditions. Nitrate residues from fertiliser were left in soil at a fertiliser rate of 144 kg N/ha, not normally considered an excessive application for winter wheat on this field. Clearly, studies are required to better quantify the opposing risks of over-fertilisation, leading to excess nitrate in soil, and under-fertilisation which has adverse economic consequences for the farmer.

With crops other than winter cereals it is more common for N from fertiliser to have a direct influence on residual nitrate and hence on subsequent leaching. For example, Macdonald *et al* (1990) found twice as much nitrate left in the profile of a sandy loam soil after potatoes given 220 kg N/ha (the recommended rate) as in the control treatment given no N. A similar situation exists with some short-season horticultural crops such as leafy brassicas which give an economic return from high rates of N fertiliser but use it inefficiently (Rahn, 1992). In catchments that are particularly vulnerable to nitrate leaching it may be necessary to restrict the area used for such crops.

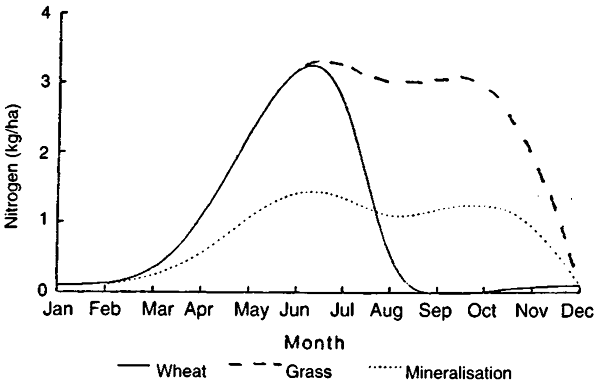
Long-continued applications of N fertiliser over many years can have a significant impact on the soil N cycle. Crops grown with larger rates of N leave larger quantities of N in organic residues (eg straw, stubble, roots) than impoverished crops. These residues tend to increase the content of soil organic N and, eventually, increase the amount of nitrate formed from mineralisation, some of which will be leached. There is preliminary evidence from the Broadbalk Experiment that, in the very long term, there may be a more linear relationship between N fertiliser rate and nitrate leaching (Glendining *et al*, 1992; Goulding, KWT & Webster, CP, unpublished data). The total amount of N now mineralised in the Broadbalk plot that has received 144 kg N/ha, as inorganic fertiliser, annually since 1852 appears to be about twice that in the unfertilised plot (Glendining *et al*, 1992).

MINERALISATION OF ORGANIC NITROGEN

The reason that N derived from mineralisation of soil organic matter is usually the predominant source of nitrate in soil in the autumn and winter is the lack of synchronisation between mineralisation and crop uptake: this is illustrated diagrammatically in Figure 5 which shows the situation in a temperate maritime environment such as north-west Europe. What is shown is net rate of mineralisation, ie the excess of mineralisation over immobilisation. In reality both processes occur concurrently, some parts of the soil microbial population releasing inorganic N from the decomposition of organic matter while other parts absorb inorganic N, together with carbon, for protein synthesis.

During winter, mineralisation is limited by low temperature but as soil warms in spring the rate increases rapidly, roughly coinciding with increased crop growth (for comparison Figure 5 includes typical rates of N uptake by winter wheat and grass). Nitrogen mineralised during spring has a reasonable chance of being absorbed by the crop, although some losses will occur as with fertiliser applied at this time. Mineralisation usually continues long after uptake by an arable crop has ceased, causing a considerable accumulation of nitrate during the late summer, autumn and early winter: values of 30-100 kg N/ha as nitrate to a depth of 1 m are common in arable fields. Only a small fraction of this is absorbed by an autumn-sown crop and the remainder is exposed to leaching throughout the late autumn, winter and early spring when soil is generally saturated. In soils under grass, the late flush of growth removes some residual nitrate, thus decreasing winter leaching, but if the grass is grazed nitrate formed from mineralisation and nitrification of N in animal excreta adds considerably to the quantity present and can lead to large leaching losses (Jarvis & Pain, 1990).

Figure 5
Diagrammatic representation of the time course of N uptake by winter wheat and grass and of nitrate formed from mineralisation of organic N in soil.



Source: Addiscott *et al* (1991)

Post-harvest mineralisation of crop residues has a major effect on the quantity of nitrate at risk to leaching. The extent of mineralisation is dependent on the composition of these residues and the method and timing of incorporation or disposal. The use of ^{15}N permits these transformations to be studied and quantified, even in the presence of a very large background of soil organic N. In the experiments of Macdonald *et al* (1990) the rate of release tended to be least following winter wheat with straw removed: 29% of the labelled residue was mineralised and either lost from the soil:plant system or absorbed by the following crop. The corresponding values were 46% for potatoes (residues incorporated) and 36% for oilseed rape (residues removed) and 39% for sugarbeet (tops incorporated).

Addition of organic manures to either grassland or arable soil in autumn can greatly increase the amount of nitrate formed by mineralisation, the magnitude of the effect depending on the composition of the material and the timing of its application. For example, slurry and poultry manure have a large effect because they are high in ammonium and readily mineralisable organic N, whereas farmyard manure has a smaller immediate effect because it has undergone greater decomposition (and loss of N) before application.

Measurements of nitrate in the profile of soils with a long history of organic manures invariably show greater quantities than in soils given only inorganic fertilisers (Powlson *et al*, 1989; Glendining *et al*, 1992; Wadman & Neeteson, 1992; Chambers & Smith, 1992). Delaying application of organic manures may ensure that a larger proportion of the nitrate is formed in spring, and is more likely to be absorbed by a crop. However, the benefits must be weighed against the risk of surface runoff if materials such as slurry are applied to wet or frozen land during winter. Application of slurry to a growing crop in spring is a particularly valuable way of utilising this material in a less wasteful way, and one that increases the possibility of recycling nutrients more efficiently.

Incorporation of cereal straw, which generally has a wide C:N ratio, in the range 50-100, causes some immobilisation of N into microbial cells, leaving less inorganic N at risk to leaching (eg Bertilsson, 1988; Powlson *et al*, 1985). Although the short-term impact will generally be beneficial, if small, in the long-term the opposite effect may well occur. The additional N immobilised following each incorporation of straw will add to the organic N reserves in the soil and, in time, lead to greater mineralisation. Evidence of this was detected in soils from two sites in Denmark where barley straw had been incorporated for 18 years (Powlson *et al*, 1987). This is an example of a more general point - any agricultural practice that increases the organic matter content of the soil will eventually lead to an increase in the background rate of N mineralisation. Part of the N mineralised will be absorbed by crops, but part will be produced at times of the year when crop uptake is minimal and will contribute to increased nitrate leaching.

The ploughing up of grass or grass/legume leys is another example of where it is necessary to consider both long- and short-term effects and to consider them on a catchment basis. Ploughing such leys in autumn stimulates mineralisation and can lead to very large losses of nitrate by leaching; the longer the ley, the greater the effect. For example, losses in excess of 200 kg N/ha were detected following the ploughing of a 6-year ley on a sandy loam soil; even after a 1-year ley losses exceeded 100 kg N/ha (Johnston *et al*, 1993). Enhanced mineralisation is not necessarily restricted to the period immediately following ploughing; Macdonald *et al* (1989) found additional nitrate in soil that had been ploughed out of leys one year previously compared to that in continuous arable treatments. However, the very large release of nitrate at this point in the rotation will be offset by small losses at other times provided the ley phase has been managed in a way that minimises leaching - low rates of N fertiliser and the grass either cut or grazed at very low stocking rates. There is a lack of quantitative data on the overall amount of nitrate leaching from ley/arable rotations.

Even in continuous arable cropping, cultivation has a significant effect on mineralisation and, hence, nitrate leaching. This is illustrated by results from the Brimstone Experiment; winter leaching losses averaged 24% less from land that had been direct-drilled instead of ploughed (Goss *et al*, 1993). Delaying cultivation during the autumn period can also decrease mineralisation (Stokes *et al*, 1992) but this is incompatible with early sowing of autumn crops which can be a very effective means of decreasing leaching.

FATE OF N FROM ATMOSPHERIC INPUTS

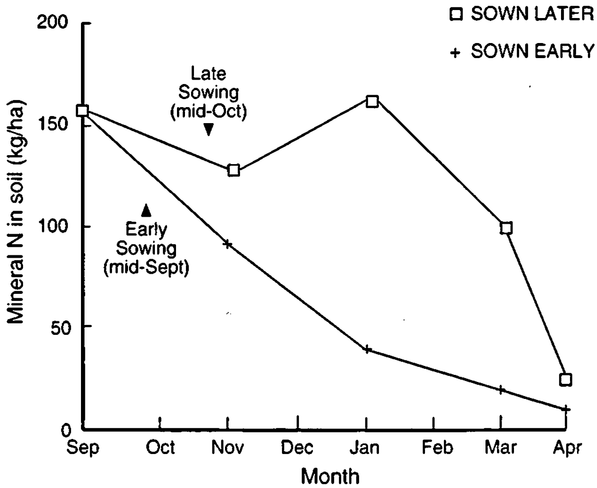
It has been known since the beginning of this century that rain contains nitrogen in the forms of ammonium and nitrate. It has only been established more recently that there are substantial inputs of N to the crop/soil system from dry deposition of gases such as ammonia and oxides of nitrogen. It is now estimated that 50-60 kg N/ha enters cereal growing systems at Rothamsted annually (Goulding, 1990). These inputs are partly offset by gaseous losses giving a net input of about 40 kg N/ha. The fate of this input has been calculated using mathematical models for the nitrogen cycle of the Broadbalk Experiment (Whitmore & Goulding, 1992). These show that 51% of the atmospheric input is taken up by the wheat crop on the plot receiving 192 kg N/ha as fertiliser, but 29% is leached and 20% is evolved back to the atmosphere as gases. The fraction that is leached represents 29% of the estimated total leaching from the system - a high proportion considering atmospheric inputs are only 17% of total inputs.

EFFECTS OF 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 (eg 30-50 kg/ha) during autumn and early winter and thus decrease the amount left in soil and exposed to leaching; Figure 6, taken from Widdowson *et al* (1987), is an example of this. Table 2 shows some data from the Brimstone Experiment, where nitrate leaching is measured directly. The presence of an autumn sown crop decreased winter leaching by at least 50% compared with that from bare soil. In general, autumn sowing is probably the most useful practical strategy for decreasing nitrate leaching, but it does have limitations. It is not effective if emergence or sowing is late; the early sowing in Figure 6 was 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 equivalent to little more than the additional mineralisation caused by autumn cultivations.

Figure 6

Effect of sowing date of winter wheat on the quantity of nitrate in the soil profile.



Source: Widdowson *et al* (1987)

Table 2

Nitrate-N losses (kg/ha) in winter drainflow at the Brimstone Experiment in 1988-89

Crop	Mean loss
Grass	9.8
Fallow/Spring wheat	25.0
Mustard/Spring wheat	10.6
Winter oats (straw burnt, ploughed)[a]	10.2
Winter oats (straw incorporated, ploughed)[a]	6.3
Winter oats (straw burnt, shallow tines)[a]	6.1

a Operations before sowing winter oats

Source: Catt *et al* (1992)

Where soil would normally be bare during winter, prior to sowing a crop in spring, a winter cover crop provides a means of decreasing leaching by absorbing N that would otherwise be leached. Recent experiments have shown that cover crops sown very soon after harvesting a cereal (eg in August) can sometimes absorb 50-90 kg N/ha within a few months (Christian *et al*, 1992) though this is not always achieved, especially if sowing is later (eg October) or if germination is delayed because of dry soil conditions. In some cases, cover crops have completely failed to establish.

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 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 cover crops killed by frost or herbicide. There is, however, a strong possibility that the extra N mineralised as a result of cultivation will equal or exceed that taken up by a cover crop. Other ways of applying the principle of cover cropping are currently being considered. 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. This procedure, which has been termed 'companion cropping' (Christian, DG, personal communication), relies on the cover crop being killed, either by frost during winter or by herbicide in spring.

Questions still remain over the fate of N from cover crops after incorporation. Nitrogen 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 (Catt *et al*, 1992).

THE WAY FORWARD

In all future farming systems the tighter cycling of nutrients will be a key feature for legislative, environmental and economic reasons. It is also sensible from the viewpoint of utilising plant nutrients in a more efficient and sustainable way. There are, however, considerable difficulties to be overcome in attempting to achieve this laudable aim. Even under ideal conditions, with best management practices, decreasing nitrate leaching is difficult because much nitrate is derived from the mineralisation of soil organic matter or crop residues and is poorly synchronised with crop uptake. The greater use of animal manures, sewage sludge, or other organic wastes, whilst desirable on the grounds of improved nutrient recycling, will inevitably exacerbate the problem. Even the use of legumes in a rotation, which decreases the need for inorganic N fertiliser, may increase the potential for nitrate loss or, at least, be nitrate-neutral. Again, the release of N from residues of the legume crop is dependent on soil microbiological activity and can be poorly synchronised with crop uptake. There is an urgent need for reliable quantitative information on N-cycle processes under a wider range of realistic field situations than is currently available. These data can be used to evaluate the effectiveness of different management strategies and extend the scope of mathematical models which are being developed as aids to farmers, policy makers and those concerned with environmental protection.

To be of practical value, mathematical models of N-cycle processes must utilise field data and information on soil properties that are readily available. At the same time they must include some mechanistic description of the processes, even if in a simplified way. If this aspect is ignored the 'model' becomes merely an empirical relationship that is likely to give misleading predictions if used outside the range of values from which it was constructed. Most models were originally designed for use at the scale of an individual field. There is an urgent need to combine them with data on the distribution of different soil types and hydrological characteristics at the catchment scale so that the overall effect of changes in cropping pattern or management can be evaluated at this scale.

A number of general principles for decreasing nitrate leaching are already clear. These include:

- the achievement of maximum crop cover during winter;
- providing farmers with the best possible advice on the likely supply of N from the soil in a given field as a basis for rational decisions on the amount of fertiliser N required. It may be helpful to provide this information on a probability or risk basis;
- being extremely careful with organic manures or wastes in an effort to minimise the problem of poor synchronisation between nitrate production and crop uptake. Similar considerations apply to the use of grass leys;
- a reconsideration of crop rotations to achieve maximum 'capture' of residual nitrate in soil, but without ignoring other aspects of good husbandry;
- catchment planning so that profitable, but nitrate-leaky, crops are grown on a restricted area within a catchment.

Continued agronomic studies are needed in order to translate these principles into practical management techniques. It seems very likely, on the basis of present evidence, that even the best management practices that would currently be considered practicable may be insufficient to decrease nitrate leaching to the extent required to meet the new water quality regulations.

The role of soil as both a source and sink for gases which are of importance in atmospheric chemistry requires further research of a more fundamental nature, as many of the processes, and factors controlling them, are still poorly understood. The gases of concern include N_2O, NO, and NH_3. It is quite possible that measures designed to decrease nitrate leaching will increase the risk of gaseous loss, especially denitrification, and there are some preliminary indications of this. In addition, aerobic soils act as a sink for CH_4, through its oxidation by soil bacteria, but their activity can be modified by certain N cycle processes. Any modifications to farming systems designed to decrease nitrate leaching must also be considered from the viewpoint of their impact on these gaseous fluxes. In the long-term the effects of agriculture, and other human activities, on the composition of the atmosphere may be of greater environmental significance than the effects on water.

REFERENCES

Addiscott, T M, Whitmore, A P & Powlson, D S (1991) *Farming, fertilisers and the nitrate problem.* 170 pp. Wallingford: CAB International.

Addiscott, T M & Powlson, D S (1992) Partitioning losses of nitrogen fertilizer between leaching and denitrification. *Journal of Agricultural Science, Cambridge* **118**, 101-107.

Bertilsson, G (1988) Lysimeter studies of nitrogen leaching and nitrogen balances as affected by agricultural practices. *Acta Agriculturae, Scandinavica* **38**, 3-11.

Bradbury, N J, Whitmore, A P, Hart, P B S & Jenkinson, D S (1994) Modelling the fate of nitrogen in crop and soil in the years following application of ^{15}N-labelled fertilizer to winter wheat. *Journal of Agricultural Science, Cambridge* (in press).

Catt, J A, Christian, D G, Goss, M J, Harris, G L & Howse, K R (1992) Strategies to reduce nitrate leaching by crop rotation, minimal cultivation and straw incorporation in the Brimstone Farm Experiment, Oxfordshire. In: *Nitrate and Farming Systems, Aspects of Applied Biology* **30**, 255-262.

Chambers, B J & Smith, K (1992) Soil mineral nitrogen arising from organic manure application. In: *Nitrate and Farming Systems, Aspects of Applied Biology* **30**, 135-143.

Chaney, K (1990) Effect of nitrogen fertilizer rate on soil nitrate nitrogen content after harvesting winter wheat. *Journal of Agricultural Science, Cambridge* **114**, 171-176.

Christian, D G, Goodlass, G & Powlson, D S (1992) Nitrogen uptake by cover crops. In: *Nitrate and Farming Systems, Aspects of Applied Biology* **30**, 291-300.

Dowdell, R J & Webster, C P (1984) A lysimeter study of the fate of nitrogen in spring barley crops grown on a shallow soil overlying chalk: denitrification losses and nitrogen balance. *Journal of Soil Science* **35**, 183-190.

Forman, P, Al-Dobbagh, A & Doll, R (1985) Nitrate, nitrite and gastric cancer in Great Britain. *Nature, London* **313**, 620-625.

Glendining, M J, Poulton, P R & Powlson, D S (1992) The relationship between inorganic N in soil and the rate of fertilizer N applied on the Broadbalk Wheat Experiment. In: *Nitrate and Farming Systems, Aspects of Applied Biology* **30**, 95-102.

Goss, M J, Howse, K R, Lane, P W, Christian, D G & Harris, G L (1993) Losses of nitrate-nitrogen in water draining from under autumn-sown crops established by direct drilling or mouldboard ploughing. *Journal of Soil Science* **44**, 35-48.

Goulding, K W T (1990) Nitrogen deposition to land from the atmosphere. *Soil Use and Management* **6**, 61-63.

Hart, P B S, Rayner, J H & Jenkinson, D S (1986) Influence of pool substitutions on the interpretation of fertilizer experiments with ^{15}N. *Journal of Soil Science* **37**, 389-403.

Jarvis, S C & Pain, B F (1990) Ammonia volatilisation from agricultural land. *Proceedings of the Fertiliser Society* **298**, 35 pp.

Jenkinson, D S (1990a) An introduction to the global nitrogen cycle. *Soil Use and Management* **6**, 56-61.

Jenkinson, D S (1990b) The turnover of organic carbon and nitrogen in soil. *Philosophical Transactions of the Royal Society, London B* **329**, 361-368.

Jenkinson, D S, Fox, R A & Rayner J H (1985) Interactions between fertilizer nitrogen and soil nitrogen - the so-called "priming effect". *Journal of Soil Science* **36**, 425-444.

Johnston, A E, McEwen, J, Lane, P W, Hewitt, M V, Poulton, P R & Yeoman, D P (1994) Effects of one to six year old rye grass-clover leys on soil nitrogen and on the subsequent yields and fertilizer nitrogen requirements of the arable sequence winter wheat, potatoes, winter wheat, winter beans *(Vicia faba)* grown on a sandy loam soil. *Journal of Agricultural Science, Cambridge* **122**, 73-89.

Macdonald, A J, Powlson, D S, Poulton, P R & Jenkinson, D S (1989) Unused fertilizer nitrogen in arable soils - its contribution to nitrate leaching. *Journal of the Science of Food and Agriculture* **49**, 407-419.

Macdonald, A J, Poulton, P R & Powlson, D S (1990) Sources of nitrate leaching from arable soil to aquifers. In: *Fertilization and the Environment* (eds R. Merckx, H. Vereecken & K. Vlassak), Leuven University Press, pp. 281-288.

Ministry of Agriculture, Fisheries and Food (1993) *Solving the nitrate problem.* London: MAFF.

Powlson, D S, Brookes, P C & Christensen, B T (1987) Measurement of soil microbial biomass provides an early indication of changes in total soil organic matter content due to straw incorporation. *Soil Biology and Biochemistry* **19**, 159-164.

Powlson, D S, Jenkinson, D S, Pruden, G & Johnston, A E (1985) The effect of straw incorporation on the uptake of nitrogen by winter wheat. *Journal of the Science of Food and Agriculture* **36**, 26-30.

Powlson, D S, Poulton, P R, Addiscott, T M & McCann, D S (1989) Leaching of nitrate from soils receiving organic or inorganic fertilizers continuously for 135 years. In: Hansen, J A & Henriksen, K (Eds) *Nitrogen in organic wastes applied to soils* pp. 334-345 London: Academic Press.

Powlson, D S, Hart, P B S, Poulton, P R, Johnston, A E & Jenkinson, D S (1992) Influence of soil type, crop management and weather on the recovery of ^{15}N-labelled fertilizer applied to winter wheat in spring. *Journal of Agricultural Science, Cambridge* **118**, 83-100.

Rahn, C (1992) Nitrogen residues from brassica crops. In: *Nitrate and Farming Systems, Aspects of Applied Biology* **30**, 263-270.

Stokes, D T, Scott, R K, Tilston, C H, Cowie, G & Sylvester-Bradley, R (1992) The effect of time of soil disturbance on nitrate mineralization. In: *Nitrate and Farming Systems, Aspects of Applied Biology* **30**, 279-282.

Wadman, W P & Neeteson, J J (1992) Nitrate leaching losses from organic manures - the Dutch experience. In: *Nitrate and Farming Systems, Aspects of Applied Biology* **30**, 117-126.

Whitmore, A P, Bland, G J & Addiscott, T M (1991) The Rothamsted soil and crop nitrogen service on Viewdata 1985-1989. *Soil Use and Management* **7**, 14-21.

Whitmore, A P & Goulding, K W T (1992) *AFRC Institute of Arable Crops Research Report for 1991*, p 36.

Widdowson, F V, Penny, A, Darby, R J, Bird, E & Hewitt, M V (1987) Amounts of NO_3-N and NH_4-N in soil, from autumn to spring, under winter wheat and their relationship to soil type, sowing date, previous crop and N uptake at Rothamsted, Woburn and Saxmundham. *Journal of Agricultural Science, Cambridge* **108**, 73-95.