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**Minimising losses of nitrogen from UK agriculture**  
**Professor K.W.T. Goulding, B.Sc., M.Sc., Ph. D., F.I.Soil Sci.**

*Head: Agriculture and the Environment Division, Rothamsted Research, Harpenden, Hertfordshire, AL5 2JQ, UK*

### **Summary**

The nitrogen cycle is essentially 'leaky'. Small amounts of nitrate must leach into waters, and ammonia and nitrous oxide be emitted to the atmosphere to maintain natural ecosystems. However, in many parts of the world, intensive agricultural production has contributed, with industry and vehicle use, to the global doubling of 'reactive' nitrogen (N) in the environment, resulting in eutrophication (nutrient enrichment), ecosystem change and health concerns. This has resulted in increased pressures on farmers to reduce those losses, including legislation such as the EU Nitrate Limit of 50 mg l<sup>-1</sup>, the reductions in ammonia and nitrous oxide emissions required by the UNECE Convention on long-range Transboundary Air Pollution and the all-embracing Water Framework Directive.

A very large amount of research has identified practices that cause large losses of N from agriculture, including the particular problems of livestock farming caused by the inefficiency with which animals transfer N in feed into saleable produce. Best Management Practices for minimising losses can be prescribed. These include calculating fertiliser requirements with a recommendation system, allowing for soil mineral N and manures applied, spreading fertilizers evenly with a properly calibrated spreader, minimising pest and disease infestation, and effective scheduling of irrigation. Computer models of the N cycle have been constructed and used as the core of new, dynamic fertiliser recommendation systems. This paper discusses the problems of maintaining productivity while reducing N losses, compares conventional with low input (integrated) and organic systems, and reviews some of the impacts of recommended practices on losses.

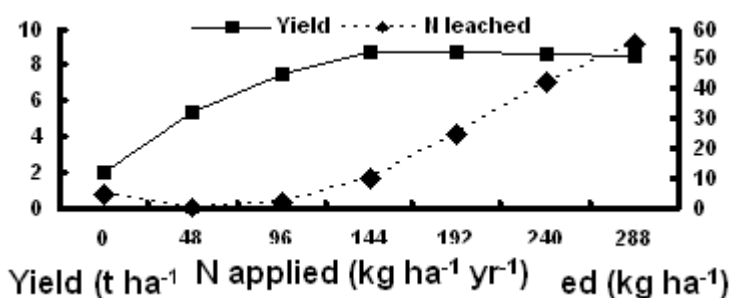
### **Introduction: nitrogen as a nutrient and pollutant**

The 1980 European Union (EU) Drinking Water Directive (80/778/EEC) set a Maximum Admissible Concentration for nitrate (NO<sub>3</sub><sup>-</sup>) in drinking water of 50 mg l<sup>-1</sup>. The EU Nitrate Directive (91/676/EEC) reinforced this by requiring EU member states to reduce NO<sub>3</sub><sup>-</sup> pollution through controls on agriculture in water catchments where NO<sub>3</sub><sup>-</sup> concentrations exceed 50 mg l<sup>-1</sup> or are at risk of doing so. In the UK, the Ministry of Agriculture, Fisheries and Food (now the Department for Environment, Food and Rural Affairs, Defra) conducted a major programme of research into the problem. Ideas to reduce losses of nitrogen (N), specifically of NO<sub>3</sub><sup>-</sup> leaching, were tested in the 32 Pilot Nitrate Sensitive Areas (NSAs) established in 1990 in which farmers were paid to participate. These were viewed as successful and so 68 Nitrate Vulnerable Zones (NVZs), with a total area of 600,000 ha, were established in the UK in 1998. However, in December 2000, the European Court of Justice ruled that the Nitrate Directive had not been fully implemented in the UK. In response to this ruling, Defra has consulted and concluded that 55% of England will be designated as an NVZ (Defra 2001). Farmers in these areas are required by law to follow certain practices, with no

financial compensation but rather the threat of prosecution if they fail to meet the requirements.

However,  $\text{NO}_3^-$  leaching is not the only process impacting on the environment. Future legislation on phosphate (P), the Climate Change Convention on nitrous oxide emissions, the likely EU and UNECE measures to control ammonia emissions and the all-embracing Water Framework Directive will result in a multiplicity of targets. Nitrate and various forms of nitrogen have also been implicated in health concerns. Recent medical research suggests that, far from being harmful,  $\text{NO}_3^-$  is beneficial to health (Addiscott & Benjamin, 2004; L'hirondel & L'hirondel, 2002). However, publications continue to appear that list ever-increasing concerns over health and possible environmental impacts (e.g. Townsend *et al.*, 2003). It is very difficult and time-consuming to rebut such claims and they generate continued pressure to minimize all emissions of N to the environment. Unfortunately, practices that minimize one form of loss often exacerbate another. For example, the early sowing of an autumn crop may increase the uptake of N, decreasing  $\text{NO}_3^-$  leaching, but it is also likely to increase pest and disease transmission and thus increase pesticide use; incorporating slurry or manure into soil reduces ammonia volatilization but an equivalent amount of N may then be lost by leaching or denitrification or both.

Trying to meet the various targets already, or soon to be, set is a major problem for UK agriculture. Nitrogen is usually the yield-determining nutrient. The application of N fertilizer is very cost-effective. However, as Figure 1 shows, the application of more N than required, in this case for winter wheat, greatly increases the risk of N loss.



**Figure 1** A nitrogen response curve for winter wheat and corresponding leaching losses from the Broadbalk Experiment at Rothamsted, in which N treatments have been repeated on the same plots since 1843.

In addition, measurements and models have shown a major contribution to N losses from ploughing out permanent grassland, leys and Set-aside, and from atmospheric deposition. Set-aside and leys can release 200-300 kg N ha<sup>-1</sup> over 1-2 years, but permanent grassland 4 t N ha<sup>-1</sup> over 20 years: model calculations suggest that the ploughing of grassland during the 1940s and 1950s contributed >50 mg l<sup>-1</sup>  $\text{NO}_3^-$  to the water supplies of much of central England (Whitmore *et al.*, 1992). Nitrogen deposited onto cereal crops from the atmosphere may total over 40 kg ha<sup>-1</sup> yr<sup>-1</sup> (Goulding *et al.*, 1998b) and comprise > 40% of the N leached from arable land (Goulding *et al.*, 1998a). The problem of reducing the impact of N on the environment is clearly complex, with no simple solutions. The current UK approach to minimising N losses was summarised in a special edition of the journal *Soil Use & Management* (SUM, 2000), on which much of this paper is based.

### Measuring and modelling losses of N

The first step to minimizing losses is to make reliable measurements of them. This can require considerable research effort. For leaching, the relatively simple and cheap porous ceramic cups were compared with more complex and expensive methods using lysimeters and field-scale drainage facilities (Goulding, 2000;

Jarvis, 2000). The research showed that no technique was suitable for every situation. Porous cups are the best practicable method for freely-draining, structureless soils, but leaching losses from clayey, well structured soils cannot be measured simply and cheaply. Measuring losses of ammonia and nitrous oxide or total denitrification is more challenging. Techniques usually involve the incubation of soil in the laboratory, some kind of chamber placed over the soil to capture the gases, or the use of micrometeorological techniques in which wind speed and direction are combined with measurements of gas concentrations at different heights above the ground to measure average fluxes over many hectares of land (Goulding, 2004). Using these techniques, N losses and their spatial and temporal variability have been measured at a range of scales, soil types and crops, and on conventional, low-input and organic systems.

### **Minimizing losses of N: understanding the nitrogen cycle**

Mineralisation, the microbially-facilitated conversion of organic N to ammonium and then nitrate, is a key process controlling the availability of mineral N for crop uptake and loss (Jarvis *et al.*, 1996). Much effort has gone into understanding mineralisation and its controlling factors. Methods for measuring net mineralisation in the field have been developed and techniques using the non-radioactive isotope,  $^{15}\text{N}$ , to 'label' fertilizers were used to measure overall N use efficiency and gross rates of mineralisation and nitrification.

Using these data, mathematical, computer-based models have been constructed to describe all or parts of the N cycle. Some models, such as CRACK-N are specific to particular problem soils, in this case cracking clays, and provide a partial solution to the problem of measuring losses from such soil; other models such as SUNDIAL, N-ABLE and WELL-N are for general use (Goulding, 2000; Jarvis, 2000; Chambers *et al.*, 2000; Lord & Anthony, 2000).

Recent research has identified significant amounts of soluble organic forms of N in agricultural soils. Murphy *et al.* (2000) have shown that amounts of soluble organic N extracted from a range of arable soils are of the same order of magnitude as those of mineral N. Its dynamics are affected by mineralisation, immobilization, leaching and plant uptake in the same way as those of mineral N, but its pool size is more constant than that of mineral N. Small but significant amounts of organic N are leached, carrying other nutrients (calcium, magnesium, trace elements), toxic metals and pesticides.

While such basic research increases our understanding of the system and its predictability, much simpler methods remain invaluable for indicating the potential for N loss. Nutrient budgets measure or estimate the inputs and outputs of nutrients to a field, farm or farm system (Watson & Atkinson, 1999). 'Farm Gate' nutrient budgets usually include inputs of N (and P and K) in feed, fertilisers, manures, composts and bedding, and outputs in saleable produce. By their nature they cannot improve N use efficiency but are valuable as they highlight problems and raise awareness of the need for better techniques. For many farmers and agronomists, raising awareness of a problem is an essential first step to solving it.

### **Minimising N losses from conventional systems**

Results from the 160-year old Broadbalk Experiment at Rothamsted show the importance of good all-round management, i.e. BMP. For the same application of N fertilizer, about half as much N is leached from modern varieties of wheat compared with those grown 100 years ago (1878-1883; Goulding *et al.*, 2000). Adequate pest and disease control is essential (Cussans, 1992). In 1996-97 estimates of N leached from wheat treated with fungicide were two-thirds of those from an untreated, and thus poorer-yielding crop; other experiments have shown that, the greater the incidence of the disease 'Take-all' (*Gaeumannomyces graminis*), the poorer the crop and the greater the leaching loss; modelling studies of these data predicted that the extra  $\text{NO}_3^-$  leached from the crop infected with 'Take-all' was mostly unused fertilizer.

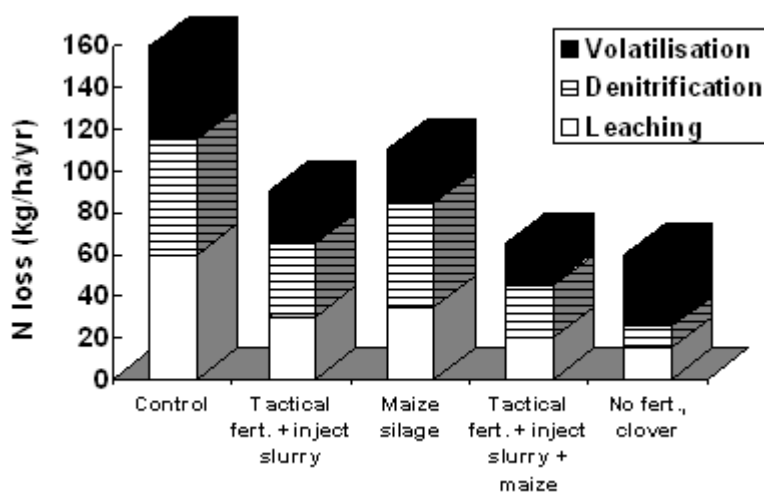
Whole farm 'System Studies' that measure a detailed N budget over an entire farm allow alternative management practices to be tested. These have identified 'leaky' practices (e.g. Table 1) and highlighted the importance, especially for grassland and mixed arable and livestock farms, of making the best use of N returns in excreta and of N released by soil organic matter (Figure 2; Jarvis, 2000). Major steps forward

have been made merely by helping farmers to estimate the nutrient content and availability of manures (Chambers *et al.*, 2000).

**Table 1** Nitrogen applied and leached ( $\text{kg ha}^{-1} \text{ yr}^{-1}$ ) from the Coates Farm system study in dry (1996-1997) and wet (1997-1998) seasons (Allingham *et al.*, 2003c).

Crop	N Applied	N leached	
		1996-1997 (dry season, 570 mm rain)	1997-1998 (wet season, 850 mm rain)
Winter barley	170	5	23
Winter wheat	200	7	52
Grass ley	250	25	188
Stubble turnips/linola	50	40	190
Kale/forage maize	250	49	199

More generally, the factors that determine losses have been clarified (SUM, 2000): the weather dominates through the impact of rainfall and temperature on drainage, plant growth and N utilization; rainfall in the weeks following N application is especially important. Besides the weather, losses are determined by (i) the amount of residual mineral N present in the soil and the amount mineralized through the autumn – the more there is and the less taken up by the plant the greater the leaching loss; (ii) the amount and timing of N fertilizer applied (iii) cultivation, for arable crops or reseeding grass, which stimulates mineralisation; (iv) drilling date; for arable crops and reseeded grass early drilled crops take up more soil N.



**Figure 2** N losses from five different dairy management systems (Jarvis, 2000).

Many countries have nationally-approved recommendation systems and interactive, internet-based systems, with remote sensing, yield mapping and crop canopy measurements to fine-tune N applications (Kitchen & Goulding, 2001). Using strategies such as these, fertilizer applications to brassica rotations can be reduced by 50% without loss of yield, and by using starter or banded fertilizers leaching losses from vegetables can be reduced by up to 75% (Rahn *et al.*, 1993).

Direct measurement of the spatial variation in yield has been available since the early 1990s (Stafford *et al.*, 1999). Knowing yield variation across a field offers the prospect of variable-rate N applications, but yield maps are confounded by many potential causes of yield variability as well as errors. Using yield maps alone to predict crop production for N management without measuring other potential and often transient yield-limiting factors (e.g., pest incidence, nutrients, and management variation) may be futile. However, relatively inexpensive tools such as Global Positioning Systems (GPS) enable the within-field availability of soil N to

be determined. Variable-rate N application maps can result in a 60% increase in the area correctly fertilized compared to a fixed-rate application (Ferguson *et al.*, 1996). A recent review of the potential for uptake of precision agricultural practices in Northern Europe (Sylvester-Bradley *et al.*, 1999) concluded that the technology was most likely to be adopted where prior knowledge identified large heterogeneity and predicted treatment zones, but that the main obstacle was the lack of appropriate sensors.

Nitrification inhibitors have often been suggested as a means of reducing N loss but they have not been extensively adopted. Prasad & Power (1995) pointed out that the need for a 0.3-0.5 t ha<sup>-1</sup> increase in yield to cover the costs had prevented their adoption. At the moment the low cost of N fertiliser and the high cost of inhibitors make it unlikely that they will play a major role in improving N efficiency. However, legislative moves such as a N tax (see below) could change the economics.

Experiments have shown that planting a Cover Crop such as rye, white mustard, or *phaecelia* between harvest and sowing a late winter or spring crop such as peas, beans and sugar beet is the single most effective way of retaining N over the following winter. However, when the cover crop is killed its N is released back into the soil at a rate that depends on climate and management. This re-mineralized N can be effectively used by the following crop but can also be leached in subsequent seasons (Harrison & Peel, 1996).

The introduction of buffer strips between agricultural land and water courses or boreholes can prevent the movement of nitrate, phosphate and pesticides into water courses at some sites (Leeds-Harrison *et al.*, 1999). However, buffer strips remove nitrate by denitrification, increasing nitrous oxide emissions and swapping one pollutant for another (Burt *et al.*, 1999). Such measures are at best short-term and are better replaced by actions that reduce all emissions at source.

### **Integrated and Organic farm systems**

At the farm scale, a change of rotation or farm system can reduce losses. Models such as SUNDIAL have been used to predict losses from different rotations and so suggest management strategies to minimize the risk of loss (Smith *et al.*, 1997). Integrated and, especially, extensive farming systems are another way to reduce losses. Some integrated and organic systems from the UK are considered below.

*LIFE*. In common with all integrated farm systems, the LIFE (Less Intensive Farming and the Environment) system aims to maintain farm income by balancing reduced outputs against reduced inputs, and through the latter to reduce environmental impact; ultimately its aim is to be environmentally benign (Jordan *et al.*, 1997). The system utilizes a 7-phase rotation to minimize pest, disease and weed problems and to improve soil structure and fertility. Minimum cultivation techniques are used to counteract N losses from late sowing. Crop residues are incorporated into the topsoil immediately after harvest to encourage weed and 'volunteer' cereal growth and thus N uptake. The growth is killed with glyphosate prior to drilling with one-pass, non-inversion tillage (NIT). This creates an adequate seedbed whilst minimizing autumn mineralisation, reducing erosion and energy input and encouraging soil biota; it can, however, exacerbate weed and slug problems. Nitrogen is applied to give a sub-optimal yield.

On a deep loam soil at Long Ashton Research Station, LIFE produced a small increase in gross economic margins. Nitrate loadings in drainage waters from NIT were 80% less than those from conventionally tilled land. In contrast, on a shallow (less than 30 cm deep) stony clay loam soil over limestone at the Royal Agricultural College, Cirencester, losses of N from an equivalent LIFE system were identical to those from a nearby conventional farm, and there was a reduction in gross margins. Site-specific management seems to be essential.

*Organic Farming Study*. The Organic Farming Study at the Duchy of Cornwall's Home Farm near Tetbury, UK, measured N, P and K budgets, N losses, and the economics and environmental benefits of this organically based farming system (Cobb *et al.*, 1999). As expected in any rotational system, the critical point

for  $\text{NO}_3^-$  leaching was the ploughing out of grass-clover leys; measured losses in the winter after ploughing were 119-132 kg N ha<sup>-1</sup>. Leaching was estimated across the whole rotation and for a comparable conventional system. On average,  $\text{NO}_3^-$  leaching on the organic system was 66% of that in the conventional system; other studies have found no difference between comparable organic and conventional systems (Goulding, 2000). A farm N budget calculated that 55% of the N entering the organic system was exported in saleable product. However, measurements of losses indicated a net loss of soil N (a mining of soil reserves); including this in calculations made efficiency only 34%, about the same as that at a conventional, mixed farm on the same soil type, 20 km away.

*Focus on Farming Practice.* In the UK, CWS Agriculture have been comparing 'Organic', 'Integrated' and 'Conventional' farms since 1989 (Leake, 1996). Yields on the organic system are, on average, 40% those of the conventional system but premium prices sustain profitability. Yields on the integrated system are a little less than the conventional but the integrated system is 8% more profitable because of reduced costs. On the integrated system, minimum tillage reduced autumn and winter nitrate concentrations by 25-50% and prevented soil erosion. Grass leys are an integral part of this and many rotational systems. They reduce leaching losses until ploughed, but then any gains are lost. Choosing the drilling date is difficult: early drilling and associated cultivation increased N uptake but also stimulated mineralisation; later drilling reduced mineralisation but the crop was much less able to utilize the N already present. Another conflict arises from weed control: on the integrated system a combination of low dose (25%) herbicide to check weeds and N fertilizer to stimulate crop growth shaded out weeds and reduced herbicide usage; i.e. adding N reduces herbicide use. This is not possible in the organic system. Using mineral N measurements and a chlorophyll meter to calculate N requirements more precisely, and splitting N applications, prevented growth spurts and lodging without the need for growth regulators. The conclusion of this work was that IFM is more flexible and better able to meet the continually changing needs of farming than highly regulated organic systems.

### **BMP for minimising losses of N**

The factors that determine N losses are clear: the weather dominates through the impact of rainfall and temperature on drainage, crop growth and N utilization; rainfall in the weeks following N application is especially important. Besides the weather, losses are determined by the amount and timing of fertilizer applied, cultivation and sowing date for arable and reseeded grass, and the patterns of cutting and grazing and of manure utilization for cut or grazed grass systems. The results of the considerable amount of research done in the developed world shows some clear principles with regard to BMP to minimize emissions in conventional agricultural systems. Losses of N are best minimized by using a modern, N-efficient crop variety with effective pest and disease control. A green cover should be maintained for as long as possible. Minimum tillage also reduces leaching losses, but must be balanced against effective weed and pest control, and thus the increased use and possible loss of pesticides in non-organic systems. Manures should be effectively utilized and greater efforts made to reduce losses during storage and spreading. However, this is likely to require capital input, and it is still not possible to precisely predict the timing and rate of release of N from manures.

There are ecological as well as environmental benefits from integrated and organic systems. NIT, a key part of IFM, can be very beneficial on some soils, encouraging soil biota, providing a food source for earthworms, creating semi-natural habitats for beneficial species, reducing erosion and conserving N. However, NIT is not practicable on all soils, especially on heavy clays, and it can increase perennial weed and slug problems. Crop rotations play a vital part in integrated and organic systems but need careful management. Some parts of the rotations, e.g. potatoes or the ploughing out of a ley, can produce large N losses, and fine seed bed preparation for potatoes can impact severely on soil organisms. Integrated and organic systems can reduce losses but require very careful, site-specific management to optimise the system to the local climate and soils.

The opposite approach to integrated and organic systems must also be considered. Even more intensive

systems with transgenic (GM) crops for better nutrient use efficiency are being researched. The debate on the release of transgenic organisms complicates the issue but scientists must consider all possibilities.

A fertilizer tax is often suggested as a way of reducing inputs and therefore, it is assumed, losses.

Economic models suggest that fertiliser taxes must be very high, >100%, before they become effective.

Policy to date has taken the view that inputs and management practices should be regulated (Romstad *et al.*, 1997). For example, in the early 1990s the N surplus of The Netherlands was >320 kg ha<sup>-1</sup> yr<sup>-1</sup>. In an attempt to reduce this a compulsory nutrient budgeting policy was introduced. This requires budgets to be made on all farms with >2.5 livestock units per hectare and gives allowed surpluses: for arable land 175 kg ha<sup>-1</sup> yr<sup>-1</sup> in 1998 decreasing to 100 kg ha<sup>-1</sup> yr<sup>-1</sup> after about 2008; for grassland 300 kg ha<sup>-1</sup> yr<sup>-1</sup> in 1998 decreasing to <200 kg ha<sup>-1</sup> yr<sup>-1</sup> in about 2008. If these values are exceeded, farmers are taxed about 1 Euro or £0.5 or each kg N above the limit. Approaches such as this seem to be slowly reducing N losses, but not without painful changes for farmers: some farm systems, such as intensive pig production (Lauwers, 1997) and crop production in some dry areas (Goulding, 2000) may be impossible if emission limits are to be met.

### Progress in reducing losses

In the UK, concerns about emissions of N to the environment, and changes in practice and increasing yields, have reduced the N surplus (excess of inputs over outputs in produce) for winter wheat from > 50 kg ha<sup>-1</sup> in the early 1980s to < 20 kg ha<sup>-1</sup> today (Table 2; Goulding, 2000), so progress is being made.

Dampney *et al.* (2000) reported a very large and rapid decrease in the areas of winter wheat and winter barley receiving fertilizer N in the autumn after this was shown to be uneconomic – a real ‘win-win’ solution as the autumn-applied fertilizer was easily leached. But surpluses and losses to the environment have not been eliminated. Residues of more than 300 kg N ha<sup>-1</sup> remain after brassica production, two-thirds of which may be leached from the root zone of the following crop on sandy soils, even in an ‘average’ year (Rahn *et al.*, 1992). Farmers and growers are never likely to be able to reduce surpluses to zero, and even where no fertilizer N is applied there is always some leaching, from 5-10 kg ha<sup>-1</sup> yr<sup>-1</sup> under winter wheat on the Broadbalk Experiment at Rothamsted (Figure 1).

Despite this, there is good evidence that improved agricultural practice generally and specific actions are reducing emissions of N. Measurements and model calculations suggest that practices introduced in Nitrate Sensitive Areas and now Nitrate Vulnerable Zones will decrease leaching losses and nitrate concentrations by 20% (Dampney *et al.*, 2000). Insalaco (2002) reported an approximate doubling in the length of river waters described as having ‘Good’ chemical and biological quality and a more than halving of those of ‘Bad’ quality.

**Table 2** Average amounts (kg ha<sup>-1</sup> yr<sup>-1</sup>) of nitrogen fertilizer applied and removed in grain (assuming 20 kg N t<sup>-1</sup> grain) for winter wheat in England and Wales, 1974-1997 (modified from Goulding, 2000).

Year	Nitrogen (kg ha <sup>-1</sup> )		
	Applied	Removed in grain	Surplus
1975	95	85	10
1980	150	110	40
1985	185	130	55
1990	180	140	40
1995	175	160	15

To reduce losses of N and maintain profitable farming, participatory research is needed that includes all stakeholders, but especially farmers, from the beginning. Farmers then have the opportunity to inform the

research debate and are more likely to be 'on board' with any suggested changes to management.

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### References

- Addiscott, T.M., and N. Benjamin. 2004. Nitrate and human health. *Soil Use and Management* (in press).
- Allingham, K.D., Cartwright, R., Donaghy, D., Conway, J.S., Goulding, K.W.T. & Jarvis, S.C. 2003. Nitrate leaching losses and their controls in a mixed farm system in the Cotswold Hills, England. *Soil Use & Management*, **18**, 421-427.
- Burt, T.P., Matchett, L.S., Goulding, K.W.T., Webster, C.P. & Haycock, N.E. 1999. Denitrification in riparian buffer zones: the role of floodplain hydrology. *Hydrological Processes*, **13**, 1451-1463.
- Chambers, B.J., Smith, K.A. & Pain, B.F. 2000. Strategies to encourage better use of nitrogen in animal manures. *Soil Use & Management*, **16** (Supplement) 157-161.
- Cobb, D., Feber, R., Hopkins, A., Stockdale, L., O'Riordan, T., Clements, B., Firbank, L., Goulding, K., Jarvis, S. & Macdonald, D. 1999. Integrating the environmental and economic consequences of converting to organic agriculture: evidence from a case study. *Land Use Policy*, **16**, 207-221.
- Cussans, G.W. 1992. The implications for weeds and weed control of practices to reduce nitrate leaching. *Aspects of Applied Biology*, **30**, 351-358.
- Dampney, P.M.R., Lord, E.I. & Chambers, B.J. 2000. Development of improved advice for farmers and advisers. *Soil Use & Management*, **16** (Supplement) 162-166.
- Defra. 2001. Implementing the Nitrates Directive. 20 December 2001. Department for Environment, Food & Rural Affairs.
- Ferguson, R.B., C.A. Gotway, G.W. Hergert, & T.A. Peterson. 1996. Soil Sampling for Site-Specific Nitrogen Management. In P.C. Robert *et al.* (ed.), *Precision Agriculture* (3rd International Conference). ASA, CSSA, and SSSA, Madison, WI, pp 13-22.
- Goulding, K.W.T. 2000. Nitrate leaching from arable and horticultural land. *Soil Use & Management*, **16** (Supplement) 145-151.
- Goulding, K.W.T. 2004. Pathways and losses of fertilizer nitrogen at different scales. In Mosier, A. *et al.* (eds) Nitrogen fertilizer rapid assessment project workshop, Kampala, January 2004. Island Press, in press.
- Goulding, K.W.T., Bailey, N.J. & Bradbury, N.J. 1998a. A modelling study of nitrogen deposited to arable land from the atmosphere and its contribution to nitrate leaching. *Soil Use & Management*, **14**, 70-77.
- Goulding, K.W.T., Bailey, N.J., Bradbury, N.J., Hargreaves, P., Howe, M., Murphy, D.V., Poulton, P.R. & Willison, T.W. 1998b. Nitrogen deposition and its contribution to nitrogen cycling and

associated soil processes. *New Phytologist*, **139**, 49-58.

- Goulding, K.W.T., Poulton, P.R., Webster, C.P. & Howe, M.T. 2000. Nitrate leaching from the Broadbalk Wheat Experiment, Rothamsted, UK, as influenced by fertilizer and manure inputs and the weather. *Soil Use & Management*, **16**, 244-250.
- Harrison, R. & Peel, S. 1996. Nitrogen uptake by cover crops and its subsequent fate in arable systems. *Aspects of Applied Biology*, **47**, 51-58.
- Insalaco, R. 2002. *National Statistics*. Annual Abstract of Statistics No 138. TSO, London.
- Jarvis, S.C. 2000. Progress of studies in nitrate leaching from grassland soils. *Soil Use & Management*, **16** (Supplement) 152-156.
- Jarvis, S.C., Stockdale, E.A., Shepherd, M.A. & Powlson, D.S. 1996. Nitrogen mineralisation in temperate agricultural soils : process and measurement. *Advances in Agronomy*, **57**, 187-237.
- Jordan, V.W.L., Hutcheon, J.A., Donaldson, G.V. & farmer, D.P. 1997. Research into and development of integrated farming systems for less-intensive arable crop production: experimental progress (1989-1994) and commercial implementation. *Agriculture, Ecosystems & Environment*, **64**, 141-148.
- Kitchen, N.R. & Goulding, K.W.T. 2001. On-farm technologies and practices to improve nitrogen use efficiency. In *Nitrogen in the environment: sources, problems and management*, eds Follett, R.F. & Hatfield, J.L. Elsevier, Amsterdam, pp335-369.
- Lauwers, L.H. 1997. Effects of policy measures regarding the manure problem and pig production structure in Flanders. In *Controlling mineral emissions in European agriculture*, eds E. Romstad, J. Simonsen & A. Vatn, CAB International, Wallingford, UK, pp 193-208.
- Leake A R 1996. The effect of cropping sequences and rotational management: an economic comparison of conventional, integrated and organic systems. *Aspects of Applied Biology*, **47**, 185-194.
- Leeds-Harrison, P.B., Quinton, J.N., Walker, M.J., Sanders, C.L. & Harrod, T. 1999. Grassed buffer strips for the control of nitrate leaching to surface waters in headwater catchments. *Ecological Engineering*, **12**, 299-313.
- L'hirondel, J., and J.-L. L'hirondel. 2002. *Nitrate and Man. Toxic, harmless or beneficial?* CABI Publishing, Wallingford, Oxon., 186 pp.
- Lord, E.I. & Anthony, S.G. 2000. MAGPIE: a modelling framework for evaluating nitrate losses at a national and catchment scales. *Soil Use & Management*, **16** (Supplement) 167-174.
- Murphy, D.V., Macdonald, A., Stockdale, E.A., Goulding, K.W.T., Fortune, S., Gaunt, J.L., Poulton, P.R., Wakefield, J.A., Webster, C.P. & Wilmer, W.S. 2000. Soluble organic nitrogen in agricultural soils. *Biology & Fertility of Soils*, **30**, 374-387.
- Prasad, R. & Power, J.F. 1995. Nitrification inhibitors for agriculture, health, and the environment. *Advances in Agronomy*, **54**, 233-281.
- Rahn, C. R., Vaidyanathan, L. V. V. & Paterson, C. D. 1992. Nitrogen residues from brassica crops.

- Rahn, C. R., Paterson, C. D. & Vaidyanathan, L. V. V. 1993. Improving the use of nitrogen in brassica rotations. *Acta Horticulturae*, **339**, 207-218.
- Romstad, E., Simonsen, J. & Vatn, A. 1997. *Controlling mineral emissions in European agriculture. Economics, policies and the environment*. CAB International, Wallingford, UK, 292 pp.
- Smith, J. U., Bradbury, N. J., Glendining, M. J. & Smith, P. 1997. Simulation of nitrogen turnover in crop rotations. *Quantitative Approaches in Systems Analysis*, **10**, 87-92.
- Stafford, J.V., R.M. Lark, & H.C. Bolam. 1999. Using Yield Maps to Regionalize Fields into Potential Management Units. In P.C. Robert *et al.* (ed.), *Precision Agriculture* (4th International Conference). ASA, CSSA, and SSSA, Madison, WI, pp 225-237.
- SUM (Soil Use & Management) 2000. Tackling nitrate from agriculture. **Vol 16**, June 2000, Supplement.
- Sylvester-Bradley, R., Lord, E., Sparkes, D.L., Scott, R.K., Wiltshire, J.J.J. & Orson, J. 1999. An analysis of the potential of precision farming in Northern Europe. *Soil Use & Management*, **15**, 1-8.
- Townsend, A.R., R.W. Howarth, F. A. Bazzaz, M. S. Booth, C. C. Cleveland, S. K. Collinge, A. P. Dobson, P. R. Espstein, E. A. Holland, D. R. Keeney, M. A. Mallin, C. A. Rogers, P. Wayne, and A. H. Wolfe. 2003. Human health effects of a changing global nitrogen cycle, *Frontiers in Ecology and the Environment*, **1**, 240-246.
- Watson, C. A. & Atkinson, D. 1999. Using nitrogen budgets to indicate nitrogen use efficiency and losses from whole farm systems: a comparison of three methodological approaches. *Nutrient Cycling in Agroecosystems*, **53**, 259-267.
- Whitmore, A. P., Bradbury, N. J. & Johnson, P. A. 1992. Potential contribution of ploughed grassland to nitrate leaching. *Agriculture, Ecosystems & Environment*, **39**, 221-233.