Note: This is a reference cited in *AP 42, Compilation of Air Pollutant Emission Factors, Volume I Stationary Point and Area Sources.* AP42 is located on the EPA web site at www.epa.gov/ttn/chief/ap42/

The file name refers to the reference number, the AP42 chapter and section. The file name "ref02_c01s02.pdf" would mean the reference is from AP42 chapter 1 section 2. The reference may be from a previous version of the section and no longer cited. The primary source should always be checked.

AP42 Section:	9.2.1
Background Ch	4
Reference:	55
Title:	C. Ramos, "Effect of Agricultural Practices on the Nitrogen Losses to the Environment," *Fertilizer Research,* 43(1-3):183-189, 1996.

Sect 4 #55

Fertilizer Research 43: 183–189, 1996.

© 1996 *Kluwer Academic Publishers. Printed in the Netherlands.*

Effect of agricultural practices on the nitrogen losses to the environment

C. Ramos
Instituto Valenciano de Investigaciones Agrarias, Moncada, Spain

Key words: agriculture, environment, nitrogen cycle

The environmental significance of nitrogen emissions from agriculture

Nitrogen losses from agricultural fields affect the quality of both water and air. In relation to water quality the main concerns are the nitrate concentration in groundwater and total N concentration in surface waters. Nitrate concentrations above 50 mg l^{-1} make water not appropriate for drinking because it can produce methaemoglobinaemia in infants (Fraser and Chilves, 1981); another health problem associated to high nitrate concentration in drinking water is stomach cancer (Joossens and Geboers, 1981) although the evidence is not conclusive (Addiscott *et al*, 1991).

Eutrophication or nutrient enrichment of surface waters, mainly in nitrogen and phosphorus, is an important environmental problem in many areas because it produces excessive algal growth that can cause death of fish by creating anoxia conditions when the algae die and bacteria decompose them using the dissolved oxygen; also, algal growth is a nuisance for the recreational uses of these waters. In addition, eutrophication changes the proportion of aquatic organisms: macrophytes decrease and algae proliferate; some of the latter are toxic to fish and mammals and can cause taints in drinking water (O'Riordan and Bentham, 1993).

The main gaseous nitrogen compounds produced in agricultural soils that have atmospheric relevance are the nitrogen oxides and ammonia. Nitrous oxide (N_2O) and nitric oxide (NO) are produced in the denitrification reaction, mostly a microbial mediated process, and also in the nitrification reactions.

Nitrous oxide has, indirectly, a negative effect on the stratospheric ozone layer since there it can be converted to nitric oxide that, in turn, reacts with ozone.

The concentration of N_2O in the atmosphere was 310 ppbv in 1990 and its rate of increase has been estimated in 0.25% yr^{-1}. Although N_2O absorbs infrared radiation, its contribution to global warming has been estimated to be only 6% (Houghton *et al.*, 1990). NO and NO_2 (nitrogen dioxide) are also involved in acid rain (Fowler *et al.*, 1982).

Atmospheric ammonia plays a key role in atmospheric acidity and therefore in the 'acid rain' problem; it has been estimated that NH_3 emissions to the atmosphere are capable of neutralizing about 70% of the acid originally present in acid rain in large parts of Europe (EMEP/CEC, 1984). More complex effects of NH_3 on atmospheric chemistry are discussed in Derwent *et al.*, 1988).

Direct toxic effects of ammonia in plants, mainly conifers, have been observed especially when high NH_3 concentrations are combined with low temperatures (Roelofs and Houdijk, 1990).

Ammonia in the atmosphere is rapidly dissolved in the water microdroplets and converted to NH_4^+ with SO_4^{2-}, Cl^- and NO_3^- as the main counterions. Land deposition of NH_3/NH_4^+ from the atmosphere may provide about 10–20 kg N ha^{-1} yr^{-1} (Derwent *et al*, 1988), although values of 35–40 kg N ha^{-1} yr^{-1} have been reported (Goulding, 1990).

The contribution of fertilizers to total NH_3 emissions from agricultural systems (including livestock operations) is small; in a study in U.K. this contribution was estimated to be about 5%, in comparison to about 33% from land spreading of livestock wastes (Jarvis and Pain, 1990).

The nitrogen cycle in agricultural soils

To understand the effect of agricultural practices on nitrogen losses to the environment it is necessary to know the various processes that interact in the transport and transformation of N in soils, also known as

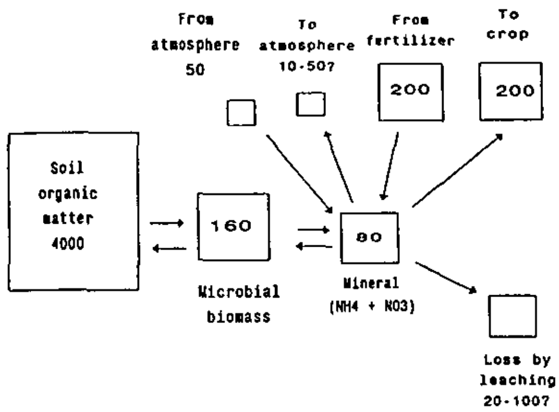

Fig. 1. The nitrogen cycle in soil for an arable field. The quantity of N in each pool (kg ha^{-1}) or in each process (kg ha^{-1} yr^{-1}) is proportional to the size of the square (after Powlson, 1993)

the 'nitrogen cycle'. Two recent reviews of this cycle are in Powlson (1993) and Vinten and Smith (1993). On a global scale the N cycle has been discussed by Jenkinson (1990).

Some important points to consider in the N cycle in agricultural soils are:

1) In most soils, organic matter contains about 95% or more of the total N. This implies that the amount of organic N in the first 50 cm of soil ranges from 6000 to 8000 kg ha^{-1}.

2) Small changes in the organic N pool by mineralization or immobilization result in significant amounts of mineral N in comparison to N fertilizer inputs.

3) The main processes of N loss from soil are nitrate leaching, denitrification and ammonia volatilization.

4) Plant growth has an important role in the N cycle since it can be the main sink of soil N and also affects the soil water balance that, in turn, influences directly nitrate leaching.

Fig. 1 shows a diagram of the N cycle for an arable field in U.K. that could be representative of many arable fields from northern-west Europe (Powlson, 1993). In this example, the main unknown values correspond to nitrate leaching and gaseous losses, that are difficult to measure (Powlson, 1993).

Next, the effects of agricultural practices on the main processes in the N cycle will be discussed.

Nitrate leaching

This is one of the main leaks of the N cycle in soils. Its importance depends on type of crop, cultivation practices, soil and climate. Recent reviews on nitrate leaching are those by Smith *et al.* (1990), Addiscott *et al.* (1991), Vinten and Smith (1993), Parkinson (1993), Powlson (1993) and Shepherd *et al.* (1993).

Fertilizer effects

Three main aspects will be considered: fertilizer rate, chemical form, and timing.

Fertilizer rate

The general relationship between fertilizer rate and nitrate leaching potential is presented in Fig. 2. In this figure, residual nitrogen is that nitrate remaining in soil at the end of the cropping period (harvest time); this nitrate can be leached by the winter rains. Fig. 2 shows that residual nitrate increases rapidly when fertilizer rates are above those that give maximum yield and N uptake by the plant. Similar evidence to that in Fig. 2 has been obtained by others (Bock and Hergert, 1991; Chaney, 1990; Pratt, 1984).

The assumption that the residual nitrate in soil after harvest is related to nitrate leaching induced by rain during the following months is supported by the results of Bergström and Brink (1986). In some cases, the observed increment in the residual mineral N at harvest with N fertilizer application rate is not as high as that in Fig. 2 (Neeteson, 1995).

Chemical form

There are not many studies on the effect of the chemical form of N in fertilizer on nitrate leaching, probably because the more reduced forms of N (ureic, ammonium) are converted to nitrate in the soil quite rapidly, depending on climate and soil factors. In temperate climates, transformation of urea or ammnonium fertilizers to nitrate is fast enough to prevent observing any difference in nitrate leaching, except when some important rain or irrigation occur shortly after fertilizer application.

Dilz (1988) reviewed the effect of timing and N source type on the N-use efficiency for several important crops in the Netherlands and concluded that calcium ammonium urea was, in general, superior to urea, and that splitting of applications tended to increase N-use efficiency and/or reduce nitrate leaching. Baud-

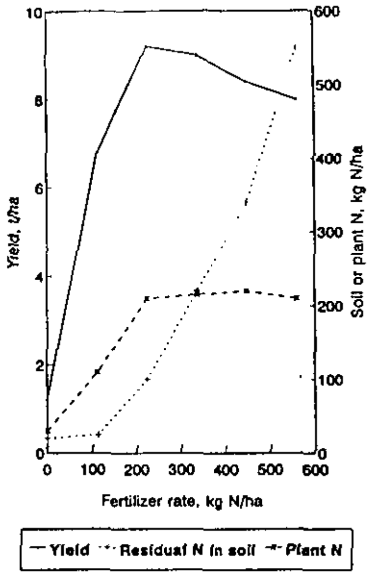

Fig. 2. Yield and N uptake by a maize crop, and residual nitrate in soil (0–240 cm) at harvest in relation to fertilizer application (after Broadbent and Carlton, 1978).

er and Montgomery (1979) reported greater leaching losses when fertilizing with nitrate than with NH_4^+ or urea.

The use of nitrification inhibitors such as nitrapyrin and dicyandiamide (DCD) can delay nitrification of urea and ammonium fertilizers and reduce nitrate leaching (Owens, 1987; Serna *et al.*, 1994).

Timing

This is an important factor for two main reasons: 1) it can increase nitrate leaching if the N fertilizer application is before the rain season and, 2) it can greatly influence N utilization by the crop and, indirectly, nitrate leaching. Juergens-Schwind (1989) reviewed the evidence on the advantages of split N applications to match crop needs in cereals, in relation to nitrate accumulation in soil and, therefore, nitrate leaching potential.

Varshney *et al.* (1993) found that a single application of 175 kg N ha^{-1} to maize resulted in a higher amount of residual nitrate than three applications totalling 125 kg N ha^{-1}, and no difference in yield between these two treatments was observed.

Organic manures

The production of organic manures has increased in the last decades considerably (Wadman *et al.*, 1987) and its inappropriate use on agricultural land can cause important nitrate leaching problems due to (Prins and Wadman, 1990):

- the large amounts of manure applied to land on farms with a high manure/land ratio (i.e. pig and poultry farms).
- the variable N content of manures (average values in U.K. are given by Archer (1991)).
- the uncertainties in mineral N content and mineralization rate of the organic N.
- the uneven distribution at land spreading.
- the time of application.

The effectiveness of N in manure in comparison to that in fertilizer is variable but ranges about 30 to 60% (Smith and Chambers, 1992; Wadman and Neeteson, 1992). Typical values for the fraction of total N in manures that is available for the plant in the season of application are 25% for farmyard manure and 60% for pig slurry (Davies and Archer, 1990).

Nitrate leaching can be one of the main losses from the soil when large amounts of N are applied with slurry or poultry manure, mostly if applied to good drainage soils in autumn (Smith and Chambers, 1993).

Factors that affect the efficiency of manure application and, indirectly, nitrate leaching are: type of application (surface or injected, and delay in incorporation to soil when surface applied), time of application in relation to the rain season, and dry matter content of slurry (Smith and Chambers, 1992).

Irrigation

Irrigation influences nitrate leaching because it determines the amount of water flowing down below the root zone. Experimental evidence relating nitrate leaching to the amount of drainage or deep percolation is given by Pratt (1984) and shows that nitrate leaching increases with drainage. The effects of water management on nitrate leaching have been reviewed by Ferguson *et al.* (1990). In a study on irrigated maize, Ritter *et al.* (1991) found that nitrate leaching was related to drainage volume and that it occurred mainly during the fall and winter months, when most drainage took place; leaching losses during the growing season varied from 34 kg N ha^{-1} for the less irrigated treatment (about 50% of maximum crop evapotranspiration) to 139 kg N ha^{-1} for the well irrigated treatment.

The importance of fall and winter rains for nitrate leaching prompted Smith *et al.* (1990) to propose that irrigation should be managed to obtain a soil water deficit at harvest as high as possible (without reducing yield), since this would reduce drainage in the following rainy months.

Cover crops

Cover crops are legumes, cereals or other crops grown to protect the soil from erosion, to improve soil physical properties, to reduce insects and pathogens through increasing biodiversity, and to reduce groundwater pollution by nutrients or pesticides. These crops are not grown for harvest but to fill periods of time when cash crops would leave the ground bare (Lal *et al.*, 1991).

In a review on the effects of cover crops on nitrate leaching, Meisinger *et al.* (1991) concluded that these crops can reduce the mass of N leached and the nitrate concentration of the leachate by 20–80% in comparison with no cover crop, and that grasses (mainly rye) and brassicas (i.e. mustard, rape, radish) are two to three times more efficient than legumes. However, there are reports showing no effects of cover crops on nitrate leaching (Vinten *et al.*, 1991).

Green manure cover crops contain adequate N to be mineralized shortly after incorporation to soil; the amount of available N that these crops can provide to the following crops ranges about 20–100 kg ha^{-1} (Smith *et al.*, 1990).

Crop residues management

Crop residues contain variable amounts of N that should be taken into account when planning the fertilization rates. A review of the N content of plant residues was made by Meisinger and Randall (1991). Residues of non-leguminous crops do not usually contribute significantly to N supply for the following crops because of their low N content and high C/N ratio. Straw incorporation to soil reduced leaching up to 30–40% (Jarvis *et al.*, 1989) but the long term use of this practice to reduce nitrate leaching has been questioned (Powlson *et al.*, 1987; Catt *et al.*, 1992). Bremer and van Kessel (1992) studied the lentil and wheat residues as a source of N for subsequent crops and found that only the lentil green manure provided a significant amount of N (40% of its N content). Similarly, Smith and Sharpley (1993) found that mineralization of sorghum and wheat residues provided less than 18 kg N ha^{-1} whereas alfalfa residues gave 55 kg N ha^{-1}.

Residues with less than 1.0–1.2% N usually immobilize mineral N (Smith *et al.*, 1990; Vigil and Kissel, 1991); this reduces the potential for nitrate leaching but can create temporary N deficiency.

Tillage

Tillage can affect nitrate leaching because it can modify the soil water balance and soil mineralization rate. Vinten and Smith (1993) suggested that the main effect of tillage on nitrate leaching is that it promotes soil aeration and, therefore, increases mineralization and decreases denitrification. Vinten *et al.* (1991) measured higher nitrate leaching losses from plots that had been cultivated (chisel ploughed and subsoiled) than from plots left in stubble over the winter. Similarly, Goss (1990) found that shallow cultivation or direct drilling reduced leaching losses compared to ploughing. Other researchers have observed small differences in nitrate leaching between conventional tillage and no-till treatments (Ritter *et al.*, 1993).

Denitrification

This is the major biological process by which the nitrogen cycle is completed and fixed N_2 is returned to the atmosphere as NO, N_2O and N_2. Reviews on N losses from soil by denitrification have been published (Aulakh *et al.*, 1992; Smith and Arah, 1990). Measured denitrification losses range from 5 to 50% of the applied N (Nieder *et al.*, 1989).

Denitrification requires the presence of nitrate metabolizable carbon compounds, and anaerobic conditions. In some cases, anaerobic conditions can occur inside soil aggregates even when the bulk soil oxygen content is adequate. Denitrification rates increase with temperature up to 40 °C or higher, and the optimum pH range is 6 to 8. From the environmental point of view, the relevant value is not the absolute denitrification rate but the N_2O production. The ratio of N_2O to N_2 in the gaseous products of denitrification depends on soil water content, amount of available C, and nitrate concentration (Weier *et al.*, 1993). Nitrous oxide can also be produced in the nitrification process, and there are different opinions about the relative importance of these two processes in the production of N_2O: some scientists think that denitrification is a more important source (Wild, 1993), whereas others argue that the relative importance of these pathways may depend on soil conditions, so that, in wet soils, denitrification would be more important but, in well aireated soils, nitrification would be the main source (Smith and Arah, 1990). Recent evidence for this latter view was obtained by Hutchinson *et al.* (1993), who found that, in soils with water potentials ranging from -10 to -1000 kPa (implying good aeration), denitrification made no significant contribution to nitrogen oxide emissions that were attributed to a chemoautotrophic NH_4^+ oxidation by nitrifying microorganisms.

N_2O emissions from soils are weakly related to nitrogen fertilizer application rates (Eichner, 1990). Denitrification losses of 20–40 kg N ha^{-1} yr^{-1} were measured in vegetable fields receiving large amounts of fertilizer N and frequently irrigated (Ryden and Lund, 1980). In another field experiment, farmyard manure application resulted in N losses by denitrification about six times those of the untreated control (Webster and Goulding, 1989).

Tillage also can influence denitrification. Aulakh *et al.* (1992) concluded that denitrification losses from conventional fallow fields are two to seven times higher than from conventional cropped fields, and that, generally, conventional cultivated cropped soils have lower denitrification losses than reduced or no-till soil management.

Straw incorporation to soil stimulates denitrification by supplying high energy material to the denitrifying microorganisms and by increasing soil moisture (Ball, 1990).

Ammonia volatilization

Ammonia volatilization can be an important loss of N to the atmosphere in calcareous soils where high pH conditions are frequent. N losses by NH_3 volatilization when using urea can be very high; losses up to 80% of the N applied as urea have been reported (Fenn and Hossner, 1985; Gould *et al.*, 1986). The more effective way to reduce NH_3 emissions after urea application is by injecting it into the soil (Stevens and Laughlin, 1989). Surface application of an urea solution did not reduce volatilization losses in comparison to prilled urea (Watson *et al.*, 1992). NH_3 volatilization losses of up to 35% of the applied N have been observed after urea application to rice in flooded soils (Buresh *et al*, 1993).

Ammonia losses can be very important when adding organic wastes and manures to the soil. The kind of machinery used in the field influences the volatilization losses during the application of slurry to land but, the more important losses occur after the application (Phillips *et al.*, 1990). Up to 70% of the total loss can occur within the first 24 hr (Jarvis and Pain, 1990). The main factors involved in NH_3 losses after land application of slurry are soil moisture and total solids content of the slurry (Smith and Chambers, 1992). Some of the proposed methods to decrease NH_3 volatilization include: slurry dilution (Sommer and Olsen, 1991), soil incorporation immediately after application (Bless *et al.*, 1991), removal of slurry solids by filtration, acidification, and dilution with water (Stevens *et al.*, 1992).

Nitrogen losses in runoff water

Nitrogen in runoff can be in organic form, associated with the eroded soil, or in soluble form, mostly nitrate. Therefore, all practices that affect soil erosion will have an impact on N losses in runoff. These losses are small, in general, and can be lower than the N input in precipitation (Keeney, 1983). Important losses, however, may occur when a major runoff event takes place shortly after surface application of N fertilizer (Smith *et al.*, 1990).

Tillage is one of the agricultural practices that has a major influence on N losses in runoff. In a six year study to compare no-till and conventional chisel-till soil management in relation to runoff, Chichester and Richardson (1992) found that N losses in runoff were, on average, 4 and 8 kg ha^{-1} yr^{-1}, for no-till and conventional till, respectively. Sharpley *et al.* (1991) measured N in runoff in sorghum watersheds during five years for conventional tillage, reduced tillage, and no-till, and found losses of 7.3, 1.0 and 0.8 kg N ha^{-1} yr^{-1}, respectively.

Conclusions

It is difficult to predict in a given situation the appropriate agricultural practices to reduce N losses, without decreasing yield, because of the complex interactions of the processes involved in the N cycle in soil. To integrate all these phenomena many models have been developed, (i.e. Addiscott *et al.*, 1991; Groot *et al.*, 1991; Hutson and Wagenet, 1991; Shaffer *et al*, 1991) but their practical application is still rare due to different reasons including the high number of data they require, and their limited testing. However, this is a field of active research and good advances in the robustness of these models and in their user 'friendlines' are to be expected. In the mean time, the judicious application of the more general knowledge of the different aspects of the nitrogen cycle in soils should help in making possible a profitable agriculture with a low degradation of the environment.

Acknowledgement

Thanks are due to A.L. Lidón and R. Gazzola for their help in preparing the typescript.

References

Addiscott TM, Whitmore AP and Powlson DS (1991) Farming, Fertilizers and the Nitrate problem. CAB International, Wallingford, UK

Archer JR (1991) Management of livestock wastes for nitrate control. In: Pollution - the New Standard. RASE/ADAS Conference, 6 Feb 1991 (Cited in Parkinson, 1993)

Aulakh MS, Doran JW and Mosier AR (1992) Soil denitrification - Significance, measurement, and effects of management. Adv Soil Sci 18: 1–57

Ball BC (1990) Straw incorporation and tillage methods: straw decomposition, denitrification and growth and yield of winter barley. J Agric Eng Res 46: 223–243

Bauder JW and Montgomery BR (1979) Overwinter redistribution and leaching of fall applied nitrogen. Soil Sci Soc Am J 43: 744–747

Bergström L and Brink N (1986) Effects of differentiated applications of fertilizer N on leaching losses and distribution of inorganic N in the soil. Plant and Soil 93: 333–345

Bless HG, Beinhauer R and Sattelmacher B (1991) Ammonia emission from slurry applied to wheat stubble and rape in North Germany. J Agric Sci 117: 225–231

Bock BR and Hergert GW (1991) Fertilizer nitrogen management. In: Follet RF, Keeney DR and Cruse RM (eds) Managing Nitrogen for Groundwater Quality and Farm Profitability, pp 139–164. Soil Sci Soc Am, Madison, Wisconsin

Bremer E and Van Kessel C (1992) Plant-available nitrogen from lentil and wheat residues during a subsequent growing season. Soil Sci Soc Am J 56: 1155–1160

Broadbent FE and Carlton AB (1978) Field trials with isotopically labeled nitrogen fertilizer. In: Nielsen DR and MacDonald JG (eds) Nitrogen and the Environment, pp 1–41. Academic Press

Buresh RJ, Castillo EG and De Katta SK (1993) Nitrogen losses in puddled soils as affected by timing of water deficit and nitrogen fertilization. Plant and Soil 157: 197–206

Catt JA, Christian DG, Goss MJ, Harris GL and Howse KR (1992) Strategies to reduce nitrate leaching by crop rotation, minimal cultivation and straw incorporation in the Brimstone Farm experiment, Oxfordshire. Aspects of Applied Biology. Nitrate and Farming Systems, pp 255–262

Chaney K (1990) Effect of nitrogen fertilizer rate on soil nitrogen content after harvesting winter wheat. J Agric Sci 114: 171–176

Chichester FW and Richardson CW (1992) Sediment and nutrient loss from clay soils as affected by tillage. J Environ Qual 21: 587–590

Davies DB and Archer JR (1990) Nitrate management in the United Kingdom. In: Calvet R (ed) Nitrates, Agriculture, Eau, pp 511–525. INRA, Paris

Derwent RG, Dollard GJ and Metcalfe SE (1988) On the nitrogen budgets for the United Kingdom and North West Europe. Quart J Royal Met Soc 114: 1127–1152

Dilz K (1988) Efficiency of uptake and utilization of fertilizer nitrogen by plants. In: Jenkinson DS and Smith KA (eds) Nitrogen Efficiency in Agricultural Soils, pp 1–26. Elsevier Applied Sci, London

Eichner MJ (1990) Nitrous oxide emissions from fertilized soils: summary of available data. J Environ Qual 19: 272–280

EMEP/CEC (1984) Summary report from the chemical coordinating centre for the second phase of EMEP rpt 2/84 (cited in Smith and Arah 1990)

Fenn LB and Hossner LB (1985) Ammonia volatilization from ammonium or ammonium-forming nitrogen fertilizers. Adv Soil Sci 1: 123–169

Ferguson RB, Eisenhauer DE, Bockstadter TL, Krull DH and Buttermore G (1990) Water and nitrogen management in Central Platte Valley of Nebraska. J Irrig Drain Eng ASCE 116: 557–565

Fowler D, Cape JN, Leith ID, Paterson IS, Kinnaird JW and Nicholson IA (1982) Rainfall acidity in northern Britain. Nature 297: 383–386

Fraser P and Chilvers C (1981) Health aspects of nitrate in drinking water. Sci Total Environ 18: 103–116

Goss MJ (1990) The effects of soil and crop management on the leaching of nitrates. In: Calvet R (ed) Nitrates, Agriculture, Eau, pp 389–394. INRA, Paris

Gould WD, Hagedorn C and McCready RGL (1986) Urea transformations and fertilizer efficiency in soil. Adv Agron 40: 209–238

Goulding KWT (1990) Nitrogen deposition to land from the atmosphere. Soil Use Manage 6: 61–63

Groot JJR, de Willigen P and Verberne ELJ (eds) (1991) Nitrogen turnover in the soil-crop system. Kluwer Acad Publ, The Netherlands

Houghton JT, Jenkins GJ and Ephraums JJ (eds) (1990) Intergovernmental Panel on Climate Change. Cambridge University Press

Hutchinson GL, Guenzi WD and Livingston GP (1993) Soil water controls on aerobic soil emission of gaseous nitrogen oxides. Soil Biol Biochem 25: 1–9

Hutson JL and Wagenet RJ (1991) Simulating nitrogen dynamics in soils using a deterministic model. Soil Use Manage 7: 74–78

Jarvis S, Barraclough D, Unwin RJ and Royle SM (1989) Nitrate leaching from grazed grassland and after straw incorporation in arable soils. In: Germon JC (ed) Management Systems to Reduce Impact of Nitrates, pp 110–125. Elsevier, Amsterdam

Jarvis SC and Pain BF (1990) Ammonia volatilisation from agricultural land. The Fertiliser Soc, Proc N° 298, London

Jenkinson DS (1990) An introduction to the global nitrogen cycle. Soil Use Manage 6: 56–61

Joossens JV and Geboers J (1981) Nutrition and gastric cancer. Proc Nutr Soc 40: 37–46

Juergens-Gschwind S (1989) Ground water nitrates in other developed countries (Europe) -Relationships to land use patterns. In: Follet RF (ed) Nitrogen Management and Ground Water Protection, pp 75–138. Elsevier, Amsterdam

Keeney DR (1983) Transformations and transport of nitrogen. In: Schaller FW and Bailey GW (eds) Agricultural Management and Water Quality. Iowa State University Press, Ames

Lal R, Regnier E, Eckert DJ, Edwards WM and Hammond R (1991) Expectations of cover crops for sustainable agriculture. In: Hargrove WL (ed) Cover Crops for Clean Water, pp 1–11. Soil and Water Conserv Soc, Ankeny, Iowa

Meisinger JJ, Hargrove WL, Mikkelsen RL, Williams JR and Benson VW (1991) Effects of cover crops on groundwater quality. In: Hargrove WL (ed) Cover Crops for Clean Water, pp 57–68. Soil and Water Conserv Soc, Ankeny, Iowa

Meisinger JJ and Randall GW (1991) Estimating nitrogen budgets for soil-crop systems. In: Follet RF, Keeney DR and Cruse RM (eds) Managing Nitrogen for Groundwater Quality and Farm Profitability, pp 85–124. Soil Sci Soc Am, Madison

Neeteson JJ (1995) Residual soil nitrate after application of nitrogen fertilizers to crops. In: Adriano DC., Iskandar AK and Murarka IP (eds) Contamination of Groundwaters, pp 347–365. Science Reviews, Northwood, UK

Nieder R, Schollmayer G and Richter J (1989) Denitrification in the rooting zone of cropped soils with regard to methodology and climate: a review. Biol Fertil Soils 8: 219–226

O'Riordan T and Bentham G (1993) The politics of nitrate in the UK. In: Burt TP, Heathwaite AL and Trudgill ST (eds) Nitrate: Processes, Patterns and Management, pp 403–416. John Wiley, Chichester, UK

Owens LB (1987) Nitrate leaching losses from monolith lysimeters as influenced by nitrapyrin. J Environ Qual 16: 34–38

Parkinson RJ (1993) Changes in agricultural practice. In: Burt TP, Heathwaite AL and Trudgill ST (eds) Nitrate: Processes, Patterns and Management, pp 321–339. John Wiley, Chichester, UK

Phillips VR, Pain BF and Klarenbeek JV (1990) Factors influencing the odour and ammonia emissions during and after the land spreading of animal slurries. In: Nielsen VC, Pain BF and Hartung J (eds) Odour and Ammonia Emissions from Livestock Production, pp 98–106. Elsevier Appl Sci, London

Powlson DS (1993) Understanding the soil nitrogen cycle. Soil Use Manage 9: 86–94

Powlson DS, Brookes PC and Christensen BT (1987) Measurement of soil microbial biomass provides an early indication of changes in total soil organic matter due to straw incorporation. Soil Biol Biochem 19: 154–164

Pratt PF (1984) Nitrogen use and nitrate leaching in irrigated agriculture. In: Hauck RD (ed) Nitrogen in Crop Production, pp 319–333. Am Soc Agron, Madison, Wisconsin

Prins WH and Wadman WP (1990) Management of animal manures to reduce nitrate pollution of groundwater. In: Calvet R (ed) Nitrates, Agriculture, Eau, pp 313–322. INRA, Paris

Ritter WF, Scarborough RW and Chirnside AEM (1991) Nitrate leaching under irrigation on coastal plain soils. J Irrig Drain Eng ASCE 117: 490–502

Ritter WF, Scarborough RW and Chirnside AEM (1993) Nitrate leaching under irrigated corn. J Irrig Drain Eng ASCE 119: 544–553

Roelofs JGM and Houdijk ALFM (1991) Effects of ammonia. In: Nielsen VC, Voorburg JH and L'Hermite P (eds) Ammonia and Odour Emission from Livestock Production, pp 10–16. Elsevier Appl Sci, London

Ryden JC and Lund LJ (1980) Nature and extent of directly measured denitrification losses from some irrigated vegetable crop production units. Soil Sci Soc Am J 44: 505–511

Serna MD, Legaz F and Primo-Millo E (1994) Efficacy of dicyandiamide as a soil nitrification inhibitor in citrus production. Soil Sci Soc Am J 58: 1817–1824

Shaffer MJ, Halvorson AD and Pierce FJ (1991) Nitrate leaching and economic analysis package (NLEAP): model description and application. In: Follet RF, Keeney DR and Cruse RM (eds) Managing Nitrogen for Groundwater Quality and Farm Profitability, pp 85–124. Soil Sci Soc Am, Madison

Sharpley AN, Smith SJ, Williams JR, Jones OR and Coleman GA (1991) Water quality impacts associated with sorghum culture in the Southern Plains. J Environ Qual 20: 239–244

Shepherd MA, Davies DB and Jonhson PA (1993) Minimizing nitrate losses from arable soils. Soil Use Manage 9: 94–99

Smith KA and Arah JRM (1990) Losses of nitrogen by denitrification and emissions of nitrogen oxides from soils. Fertilizer Soc Proc No. 299, 34 p

Smith KA and Chambers BJ (1992) Improved utilization of slurry nitrogen for arable cropping. In: Archer *et al.* (eds) Aspects of Applied Biology No. 30. Nitrate and Farming Systems, pp 127–134

Smith KA and Chambers BJ (1993) Utilizing the nitrogen content of organic manures on farms - problems and practical solutions. Soil Use Manage 9: 105–112

Smith SJ, Schepers JS and Porter LK (1990) Assessing and managing agricultural nitrogen losses to the environment. Adv Soil Sci 14: 1–43

Smith SJ and Sharpley AN (1993) Nitrogen availability from surface-applied and soil-incorporated crop residues. Agron J 85: 776–778

Sommer SG and Olsen JE (1991) Effects of dry matter content and temperature on ammonia loss from surface-applied cattle slurry. J Environ Qual 20: 679–683

Stevens RJ and Laughlin RJ (1989) A microplot study of the fate of ^{15}N-labelled ammonium nitrate and urea applied at two rates to ryegrass in spring. Fert Res 20: 33–39

Stevens RJ, Laughlin RJ and Frost JP (1992) Effects of separation, dilution, washing and acidification on ammonia volatilization from surface-applied cattle slurry. J Agric Sci 119: 383–389

Varshney P, Kanwar RS, Baker JL and Anderson CE (1993) Tillage and nitrogen management effects on nitrate-nitrogen in the soil profile. Trans ASAE 36: 783–789

Vigil MF and Kissel DE (1991) Equations for estimating the amount of nitrogen mineralized from crop residues. Soil Sci Soc Am J 55: 757–761

Vinten AJA, Howard RS and Redman MH (1991) Measurement of nitrate losses from arable plots under different nitrogen input regimes. Soil Use Manage 7: 3–13

Vinten AJA and Smith KA (1993) Nitrogen cycling in agricultural soils. In: Burt TP, Heathwaite AL and Trudgill ST (eds) Nitrate: Processes, Patterns and Management, pp 39–73. John Wile Chichester UK

Wadman P and Neeteson JJ (1992) Leaching losses from organic manures - the Dutch experience. In: Archer *et al.* (eds) Aspects of Applied Biology No. 30. Nitrate and Farming Systems, pp 117–126

Wadman WP, Sluijsmans CMJ and de la Lande Cremer LCN (1987) Value of animal manures: changes in perception. In: Van der Meer HG, Unwin RJ, Van Dijk TA and Ennik GC (eds) Animal Manures on Grassland and Fodder Crops. Fertilizer or Waste pp 1–16. Dordrecht, Martinus Nijhoff Publ.

Watson CJ, Stevens RJ, Laughlin RJ and Poland P (1992) Volatilization of ammonia from solid and liquid urea surface-applied to perennial ryegrass. J Agric Sci 119: 223–226

Webster CP and Goulding KWT 1989 Influence of soil carbon content on denitrification from fallow land during autumn. J Sci Food Agric 49: 131–142

Weier KL, Doran JW, Power JF and Walters DT (1993) Denitrification and the dinitrogen/nitrous oxide ratio as affected by soil water, available carbon, and nitrate. Soil Sci Soc Am J 57: 66–72

Wild A (1993) Soils and the Environment. An Introduction. Cambridge University Press, Cambridge, UK