ASAE Publication 05-90

AGRICULTURAL AND FOOD PROCESSING WASTES

Proceedings of the Sixth International Symposium on Agricultural and Food Processing Wastes

December 17-18, 1990
Hyatt Regency Chicago in Illinois Center
Chicago, Illinois

Published by
American Society of Agricultural Engineers
2950 Niles Rd., St. Joseph, Michigan 49085-9659 USA

AMMONIA VOLATILIZATION AND NITRATE LEACHING

AFTER ANIMAL MANURE APPLICATION TO AGRICULTURAL CROPS

J.J. Neeteson* W.P. Wadman*

During the past decades the production of animal manures per unit of agricultural land has increased considerably in a number of regions in Europe. For instance, in the Netherlands the total production of manure from housed cattle (during the winter period only), pigs, poultry, and fattening calves increased from 10 t/ha in 1950 to 26 t/ha in 1982 (Wadman et al. 1987). In the same period, however, the need to use animal manures as fertilizers decreased due to the introduction of cheap chemical fertilizers, which have a number of advantages: their composition is known, they are easier to store, transport and apply, and have a more predictable effect on crop growth than manures. Therefore, animal manures were increasingly regarded as a waste product rather than a valuable fertilizer. This was especially so in southern and eastern regions, livestock densities are very high (De la Lande Cremer 1970; Sluijsmans et al. 1978; Van Boheemen 1987). Large amounts of slurry were dumped annually on fields where crops as maize were to be grown. As the slurries were usually surface-applied in the fall or winter, when fields are fallow or crops are unable to absorb nutrients, heavy losses of nutrients to the environment occurred. Nitrogen is lost through ammonia volatilization, nitrate leaching, and denitrification.

Since there is a growing concern about the quality of the environment, viz., atmosphere, soil, and water, much research was done during the past decade by the agricultural research establishments to minimize the environmental effects of agricultural practices. An important field of research was the reduction of the environmental side effects of fertilization, especially ammonia volatilization and nitrate leaching after application of animal manures. This paper reviews results obtained in this field. Most results presented originate from the Netherlands, but results obtained in other West-European countries are also shown.

AMMONIA VOLATILIZATION

Of the total annual ammonia emission in the Netherlands, which was estimated to be approximately 240,000 t in the period 1980-1986, about 50, 25, and 15% are contributed by manures from cattle, pigs, and poultry, respectively (Ministry of Housing, Physical Planning and Environment 1987). Ammonia emission from animal manures applied to agricultural land constitutes an estimated 50% of the total emission. A substantial part of the ammonia emitted is deposited on nearby forest sites, and contributes to soil acidification upon transformation into nitric acid through nitrification. The Dutch Government has decreed that the ammonia emission in the year 2000 should be only 30% of the emission in 1980 (Ministry of Agriculture, Nature Management, and Fisheries 1990).

*J.J. NEETESON, Head, and W.P. WADMAN, Researcher, Department of Fertilization and Plant Nutrition, Institute for Soil Fertility Research, P.O. Box 30003, 9750 RA Haren, the Netherlands

After surface-application of slurries to arable land it was found that between 20 and 70% of the applied inorganic nitrogen volatilizes (Van der Molen et al. 1989; Pain and Thompson 1989). Although there appear to be differences between slurry types in the amount of ammonia volatilized after application, the lowest being from pig slurries and the highest from poultry slurries (Pain and Thompson 1989), weather conditions probably have a dominant effect on the rate of ammonia volatilization. Temperature and global radiation are positively correlated with volatilization (Beauchamp et al. 1978, 1982; Freney et al. 1983). Rainfall suppresses volatilization (Beauchamp et al. 1978) and high wind speeds increase volatilization (Denmead et al. 1982). The actual rate of ammonia volatilization from a specific field is determined by the combination of soil properties, management practices and the various weather parameters (Van der Molen et al. 1989).

During spreading, ammonia losses are negligible when slurries are applied with a conventional vacuum tanker (Pain and Thompson 1989). Immediately after spreading, however, ammonia volatilization is generally most rapid (Van der Molen et al. 1989). A typical example of a time curve of ammonia volatilization rates is given in Fig. 1, where most of the ammonia volatilized during the first hours after application.

Measures to Reduce Ammonia Volatilization

Ammonia volatilization after slurry application to agricultural land can be reduced by immediate incorporation of the slurry into the soil and by adding chemicals to the slurry before application.

Incorporation of Slurry into the Soil: It has been found that ammonia volatilization can be reduced by incorporating the manure or slurry into the soil immediately after spreading (Blanck 1918; Heck 1931; Allison 1955; Kolenbrander and De la Lande Cremer 1967). A clear example of the reduction of ammonia volatilization by incorporation of the slurry into the soil is given by Van der Molen et al. (1990). They estimated ammonia volatilization after cattle slurry application to a fallow sandy soil (pH-KCl = 5.6) by means of measurements according to the micrometeorological mass balance method (Ryden and McNeill 1984). On 29 September 1987, 31 t slurry per ha was surface-applied. The slurry contained 85 kg ammonium per ha. Under comparable weather and soil conditions (Table 1), 30 t slurry per ha, containing 90 kg ammonium per ha, was surface-applied on 12 April 1988 and incorporated immediately after spreading into the upper 6 cm of the soil with a cultivator. During the first nine days after application, the measured rate of ammonia volatilization from the surface-applied slurry was much higher than volatilization from the slurry incorporated immediately after spreading (Fig. 2). It was calculated that in this period 57 and 14 kg N per ha were volatilized without and with incorporation of the slurry, respectively. This corresponds to 67 and 16% of the ammoniacal nitrogen applied with the slurry, indicating that substantial nitrogen losses through ammonia volatilization can be avoided by incorporation of the slurry immediately after spreading.

To be able to incorporate slurry into grassland soils machinery has been developed to inject the slurry into the soil to a depth of 10-20 cm. In Table 2 the results of a micrometeorological experiment in the UK are shown where about 100 t pig slurry per ha was either spread on the surface with a conventional vacuum tanker or injected into the grassland soil. Ammonia volatilization was drastically reduced by injection of the slurry. The total amount of ammonia volatilized during the first three days after slurry application was 15 times lower with injection than without injection (Table 2).

In the Netherlands about 35% of the grassland soils are suitable for injection of slurry (Wadman 1988). Most of the other soils lack sufficient bearing capacity for the heavy machinery required. Currently it is investigated whether ammonia volatilization is also strongly reduced when slurry is injected into the sward at less than 10 cm depth in these soils.

Table 1. Weather and soil conditions during the first nine days of the experiments of Van der Molen et al. (1990)

	Day								
	1	2	3	4	5	6	7	8	9
Av. soil temp. -2 cm (°C)									
A[a]	12	10	10	10	9	9	11	13	11
B[b]	8	7	6	8	10	11	11	13	12
Vol. soil moist. cont. 0-5 cm (%)									
A	28	26	21	23	22	-	18	24	24
B	26	22	24	22	21	-	24	23	21
Av. air temp. 1.5 m (°C)									
A	9.4	7.6	9.1	9.2	8.7	9.6	12.5	14.5	11.1
B	8.4	6.2	5.3	8.6	11.8	12.0	10.8	13.1	12.7
Av. wind speed at 10 m (m/s)									
A	3.1	2.8	4.8	5.1	4.7	3.8	2.9	4.5	6.6
B	4.5	5.4	2.9	3.9	3.3	3.2	2.2	2.4	5.3
Rainfall (mm)									
A	1.8	0.0	0.0	0.0	0.0	0.0	1.3	14.8	2.4
B	0.0	0.0	0.0	0.0	1.0	1.2	0.0	0.0	0.0
Av. rel. humidity (%)									
A	79	88	76	78	78	83	85	95	84
B	79	69	64	50	74	89	82	81	83
Radiation (J/cm²) per day									
A	1030	1380	1270	1310	1270	1022	920	220	790
B	1300	1710	2150	2270	810	780	2130	1570	1060

[a] Day 1 = 29 September 1987
[b] Day 1 = 12 April 1988

Table 2. Rates of ammonia volatilization following surface application or injection of pig slurry to grassland. After Pain and Thompson (1989).

Period (hours after application)	Ammonia volatilization (kg N per ha)	
	surface application	injection
0- 1	2.40	0.08
1-24	4.32	0.38
24-46	1.54	0.02
47-73	0.81	0.06
1-73	6.67	0.46
0-73	9.07	0.54

Adding Chemicals to the Slurry: Additives have been used to convert ammonium bicarbonate in slurries, from which ammonia is readily lost, to more stable ammonium compounds. In the USA, more than 50 years ago, superphosphate, phosphoric acid, or kainite were used as additives to freshly excreted manure, or land-spread at the time of manure application, to obtain ammonium phosphate or ammonium sulphate (Salter and Schollenberger 1939). More recent research in the UK has shown that adding sulphuric acid to slurry can be effective in reducing ammonia volatilization (Pain et al. 1987). Cattle slurry containing 100 kg ammoniacal nitrogen per ha with and without addition of sulphuric acid was applied to grassland. Ammonia volatilization was estimated on the basis of measurements according the wind-tunnel method (Lockyer 1984). Without acidification, about 20% of the applied ammoniacal nitrogen was volatilized during the first three days after application. With acidification, only 5% volatilized in this period (Fig. 3).

Superphosphate or phosphoric acid is not added to slurries in the Netherlands, because then the rate of phosphorus application would be too high for most soils (De la Lande Cremer and Kolenbrander 1960). It is now investigated whether addition of nitric acid is effective in minimizing ammonia volatilization from animal manures.

NITRATE LEACHING

In Western Europe, nitrate leaching from the root zone to aquifers mainly occurs in the period from late fall to early spring when precipitation exceeds evapotranspiration. The nitrate leached originates from nitrate present in the soil at the end of the growth period, i.e. residual soil nitrate, from soil organic nitrogen mineralized in the fall and winter period, and from animal manures applied in the fall and winter. When crops are fertilized according to the current recommendations, residual soil nitrate levels are low, except in the case of potatoes, some field vegetables, maize and grazed grassland (Prins et al. 1988; Neeteson 1990). It can be expected that mineralization during winter does not contribute substantially to nitrate leaching due to the low temperatures. When animal manures are applied in the fall and early winter, however, considerable amounts of nitrate can be leached. On a maize field where 300 t cattle slurry per ha was applied annually for nine years (150 t/ha in December, 100 t/ha in February, and 50 t/ha in April) it was found that 430 kg nitrate-N was leached per ha per year (Steenvoorden 1985). The EEC maximum permissible nitrate concentration of drinking water is 50 mg nitrate per litre (European Economic Community 1980). If it is assumed that nitrate is not lost from the groundwater through denitrification and that the drinking water would be made up solely of the shallow groundwater, under the Dutch conditions of an annual precipitation surplus of 300 mm the EEC standard is already reached when 34 kg N per ha is leached out. Thus, in the above-mentioned example of very heavy applications of slurry in the fall and winter, the EEC standard for the nitrate concentration of drinking water would have been far exceeded.

The Dutch government aims at a maximum nitrate concentration of 50 mg per litre in groundwater at a depth of 2 m below the phreatic level in those areas where the groundwater can be used for drinking water (National Environmental Plan of the Netherlands 1989).

Measures to Reduce Nitrate Leaching

Nitrate leaching following animal manure application can be reduced by applying the manures in spring instead of in the fall and by adjusting application rates to the nitrogen demand of the crop. When manures are applied in the fall, addition of nitrification inhibitors to the manures and growing winter crops can help to reduce the amount of nitrate leached in winter.

Spring Application: In Western Europe it has been common practice to apply slurries in the fall or winter to fields which were left fallow until spring. Since there is a precipitation surplus in this period, resulting in downward movement of water in soils, it is obvious that heavy leaching losses can then occur. In field trials where crop response to nitrogen from fall- or spring-applied slurries is determined, it is generally found that the effectiveness of nitrogen from fall-applied slurries is about half of that from spring-applied slurries (Sluijsmans et al. 1978). The lower efficiency of fall-applied slurries is attributed to nitrogen losses during winter, mainly due to nitrate leaching. In Germany, Vetter and Steffens (1981) measured the nitrate content in the upper layers of the groundwater after different times of application of 30 t pig slurry to an arable field. Although nitrate leaching without slurry application seemed to be rather high, they found lower leaching losses from spring-applied slurry than from fall-applied slurry (Table 3).

Table 3. Effect of time of slurry application on nitrate leaching from a arable field. Pig slurry was applied annually at a rate of 30 t/ha, containing 180 kg N per ha (Vetter and Steffens 1980).

Time of slurry application	Nitrate content of groundwater (mg N per litre)	Nitrate leached (kg N per ha per year)
No slurry application	34	86
February/March	41	100
October	51	125
August	56	140

To reduce the risk of excessive nitrate leaching, in the Netherlands a ban has been imposed on spreading animal manures on arable land from harvest time until 1 November (with a few exceptions) and on grassland from 1 October to 1 December. Recently, a working group has advised to extend the ban so that no manure may be applied to arable land on clay and peat soils from 1 July to 1 October, to arable land on sand, loam and reclaimed peat soils from 1 July to 1 March, and to grassland from 1 September to 1 March (Wadman and Steenvoorden 1990). It is proposed to extend the ban not only to reduce nitrate leaching, but also to reduce surface runoff of nitrogen.

Adjustment of application rates to nitrogen demand of the crop: When the amount of available nitrogen from animal manures exceeds crop demand for nitrogen, nitrate accumulates in the soil and is liable to be leached after the crop is harvested. As an example, residual inorganic nitrogen levels in a sandy soil, which were measured after application of different amounts of cattle slurry to maize, are given in Table 4.

Table 4. Residual soil inorganic nitrogen after application of different amounts of cattle slurry to maize. Average values of 8 years. The slurry was surface-applied. After Schröder and Dilz (1987)

Slurry application rate (t per ha per year)	Total amount of slurry nitrogen applied (kg N per ha per year)	Residual soil inorganic nitrogen (kg N per ha, 0-60 cm)
50[a]	252	110
100[b]	505	125
200[c]	1013	210
300[d]	1522	287

[a] 50 t/ha in March/April
[b] 50 t/ha in March/April; 50 t/ha in Jan./Feb.; 50 t/ha in Nov./Dec.
[c] 50 t/ha in March/April; 100 t/ha in Jan./Feb.; 50 t/ha in Nov./Dec.
[d] 50 t/ha in March/April; 100 t/ha in Jan./Feb.; 150 t/ha in Nov./Dec.

To prevent animal manures being dumped on agricultural fields in the Netherlands, maximum permissible application rates of animal manures, based on the so-called phosphate standard, have been set (Table 5). In the year 2000 the final level should be reached, whereby phosphorus supply, inclusive of fertilizer phosphorus, has to be in equilibrium with phosphorus removal by the crop.

Table 5. Maximum permissible annual application rates of animal manures in the Netherlands expressed as the so-called phosphate standard. From 1995 onwards, the phosphate standard also includes fertilizer phosphorus

Cropping system	Maximum permissible amount of phosphate to be applied (kg P_2O_5 per ha per year)			
	1987	1991	1995	2000[a]
Arable crops	125	125	125	70
Grassland	250	200	175	110
Maize	350	250	125	75

[a] Not yet defined. Values given are those expected by the authors

When the maximum permissible rates are applied, nitrogen supply exceeds maize demand (about 200 kg N per ha) until the year 1995. Table 6 shows the nitrogen supply to a maize crop when 250 kg phosphate per ha is applied in the form of different slurries. The calculations are based on average nitrogen contents of the slurries. Any nitrogen losses due to leaching or denitrification are disregarded, but two levels of losses due to ammonia volatilization are given.

Table 6. Total and crop available nitrogen supplied with 250 kg phosphate per ha in the form of different slurries (Wadman and Steenvoorden 1990)

Slurry type	Application rate (t/ha)	Total nitrogen (kg N per ha)	Available nitrogen (kg N per ha)	
			ammonia volatilization	
			10%[a]	35%[a]
Cattle	139	611	374	298
Fattening pigs	64	436	298	243
Poultry	32	335	232	190

[a] Expressed as a percentage of the amount of ammoniacal nitrogen contained in the slurry

Addition of nitrification inhibitors: Inorganic nitrogen contained in animal manures almost entirely consists of ammonium, which has to be nitrified before it can be leached as nitrate. By adding nitrification inhibitors to fall-applied slurry, it is attempted to prevent or retard nitrification during the fall and winter period so that losses through nitrate leaching are reduced. So far, of the many inhibitors tested, dicyandiamide (DCD) appears to be the most effective. An example of the effect of DCD added to cattle slurry on the amount of nitrate leached after slurry application to a sandy soil is shown in Table 7. The slurry was incorporated into the soil immediately after application.

Table 7. Effect of DCD added to slurry on nitrate leaching after application of the slurry (Van Enckevort et al. 1990)

Time of application	Total amount of nitrogen applied (kg/ha)	Amount of DCD applied (kg/ha)	Nitrate leached (kg N per ha)
8 November 1988	272	0	88
	298	30	59
15 December 1988	263	0	93
	287	30	67

Although DCD generally reduces nitrate leaching, it is doubtful whether leaching can be decreased sufficiently to allow slurry application in the fall and winter without causing environmental problems.

Growing of winter crops: When animal manures are applied in the early fall, winter crops are able to reduce nitrate leaching by taking up nitrogen and water. Under West-European conditions, however, a prerequisite is that the winter crops are sown early, preferably before mid-September, so that they can absorb substantial quantities of nitrogen before winter. When winter crops are sown in mid-August, nitrogen uptake can exceed 100 kg/ha (Elers et al. 1987). Nitrogen uptake by crops sown in early September is reported to be 50-100 kg/ha and that by crops sown in mid-September 10-60 kg/ha (Elers et al. 1987; Landman 1988).

Although winter crops contribute to the reduction in nitrate leaching from fall-applied animal manures, it can be expected that they will not be sufficiently effective in absorbing nitrogen. Soil nitrate in the fall also originates from residual nitrate from the previous crop and from soil nitrogen mineralized in the fall.

CONCLUSIONS

It is possible to substantially reduce ammonia volatilization and nitrate leaching after animal manure application to agricultural crops. The measures which are expected to minimize environmental side effects of manure application are application in spring and early summer only, incorporation of the manure immediately after application, and adjusting the application rates to the demand of the crop for nitrogen.

REFERENCES

1. Allison, F.E. 1955. The enigma of soil nitrogen balance sheets. In: Advances in Agronomy, Vol. VII. A.G. Norman, Editor. Academic Press Inc, New York, pp. 213-250.

2. Beauchamp, E.G., G.E. Kidd and G. Thurtell 1978. Ammonia volatilization from sewage sludge applied in the field. J. Environ. Qual. 7:141-146.

3. Beauchamp, E.G., G.E. Kidd and G. Thurtell 1982. Ammonia volatilization from liquid dairy cattle manure in the field. Can. J. Soil Sci. 62:11-19.

4. Blanck, E. 1918. Studien über den Sticksoffhaushalt der Jauche. Teil 3. Über den Stickstoffverlüst von Jauche und Harn bei der Auf- und Einbringung bezw. Kopfdüngung. Landwirtschaft. Versuchsstat. 91:271-290.

5. De la Lande Cremer, L.C.N. 1970. Probleme der beseitigung von Mistüberschüssen in den Niederlanden. Landwirtschaft. Forsch., Sh. 25/11:33-36.

6. De la Lande Cremer, L.C.N. and G.J. Kolenbrander 1960. Can superphosphate conserve nitrogen in farmyard manure and and liquid manure? (in Dutch). Landbouwk. Tijdschr. 72:470-481.

7. Denmead, O.T., J.R. Freney and J.R. Simpson 1982. Dynamics of ammonia volatilization during furrow irrigation of maize. Soil Sci. Soc. Amer. J. 46:149-155.

8. Elers, B., A. Van Brandis, H.C. Scharpf and H.D. Hartmann 1987. Winterbegrünung auf abgeernteten Gemüseflächen. Gemüse 6:290-292.

9. European Economic Community 1980. Council directive on the quality of water for human consumption. Off. J. EEC 23, 80/778 EECL 229:11-29.

10. Freney, J.R., J.R. Simpson and O.T. Denmead 1983. Volatilization of ammonia. In: Gaseous Loss of Nitrogen from Plant-Soil Systems. J.R. Freney and J.R. Simpson, Editors. Martinus Nijhoff Publ., The Hague, pp. 1-32.

11. Heck, A.F. 1931. Conservation and availability of the nitrogen in farm manure. Soil Sci. 31:335-363.

12. Kolenbrander, G.J. and L.C.N. De la Lande Cremer 1967. Farmyard manure and liquid manure. Their value and possibilities (in Dutch). Veenman en Zonen, Wageningen, 188 pp.

13. Landman, A. 1988. Ability of winter crops to conserve nitrogen after slurry application (in Dutch). Ad Fundum 6:16-24.

14. Lockyer, D.R. 1984. A system for the measurement of field losses of ammonia through volatilization. J. Sci. Food Agric. 35:837-848.

15. Ministry of Agriculture, Nature Management, and Fisheries 1990. 'Structuurnota Landbouw' (in Dutch). The Hague.

16. Ministry for Housing, Regional Development and the Environment 1987. 'Notitie Tussentijdse Evaluatie Verzuringsbeleid' (in Dutch). The Hague.

17. National Environmental Plan of the Netherlands 1989. (in Dutch). Tweede Kamer der Staten Generaal, Vergaderjaar 1988-1989, 21137, no. 1-2. SDU, The Hague, 258 pp.

18. Neeteson, J.J. 1990. Development of nitrogen fertilizer recommendations for arable crops in the Netherlands in relation to nitrate leaching. Fert. Res. (in press).

19. Pain, B.F. and R.B. Thompson 1989. Ammonia volatilization from livestock slurries applied to land. In: Nitrogen in organic wastes applied to soils. J.Aa. Hansen and K. Henriksen, Editors. Academic Press, London, pp. 202-212.

20. Pain, B.F., R.B. Thompson, L.C.N. De la Lande Cremer and L. Ten Holte 1987. The use of additives in livestock slurries to improve their flow properties, conserve nitrogen and reduce odours. In: Animal Manure on Grassland and Fodder Crops. Fertilizer or Waste? H.G. Van der Meer, R.J. Unwin, T.A. Van Dijk and G.C. Ennik, Editors. Martinus Nijhoff Publ., Dordrecht, pp. 229-246.

21. Prins, W.H., K. Dilz and J.J. Neeteson 1988. Current recommendations for nitrogen fertilisation within the EEC in relation to nitrate leaching. Proceedings no. 276. The Fertiliser Society, London, 27 pp.

22. Ryden, J.C. and J.E. McNeill 1984. Application of the micrometeorological mass balance method to the determination of ammonia loss from a grazed sward. J. Sci. Food Agric. 35:1297-1310.

23. Salter, R.M. and C.J. Schollenberger 1939. Farm manure. Ohio Agricultural Experimental Station, Ohio, 69 pp.

24. Schröder, J. and K. Dilz 1987. Cattle slurry and farmyard manure as fertilizers for forage maize. In: Animal Manure on Grassland and Fodder Crops. Fertilizer or Waste? H.G. Van der Meer, R.J. Unwin, T.A. Van Dijk and G.C. Ennik, Editors. Martinus Nijhoff Publ., Dordrecht, pp. 137-156.

25. Sluijsmans, C.M.J., T.A. Van Dijk, G.J. Kolenbrander, L.C.N. De la Lande Cremer, K.W. Smilde and C.H.E. Werkhoven 1978. The spreading of animal excrement on utilized agricultural areas of the Community. I. Scientific basis for the limitation of quantities and criteria for rules thereon. EEC, Information on Agriculture 47, 154 pp.

26. Steenvoorden, J.H.A.M. 1985. Nutrient leaching losses following application of farm slurry and water quality considerations in the Netherlands. In: Efficient Land Use of Sludge and Manure. A. Dam Kofoed, J.H. Williams and P. L'Hermite, Editors. Elsevier Applied Science Publ., London, pp. 168-176.

27. Van Boheemen, P.J.M., 1987. Extent, effects and tackling of a regional manure surplus; a case-study for a Dutch region. In: Animal Manure on Grassland and Fodder Crops. Fertilizer or Waste? H.G. Van der Meer, R.J. Unwin, T.A. Van Dijk and G.C. Ennik, Editors. Martinus Nijhoff Publ., Dordrecht, pp. 175-193.

28. Van Enckevort, P.L.A., A. Landman, H.H.H. Titulaer and E.J. Jansen 1990. Possibilities to reduce leaching of nutrients from animal manures (in Dutch). Themaboekje 10. IKC-Akkerbouw en Groenteteelt in de Vollegrond en PAGV, Lelystad, pp. 53-68.

29. Van der Molen, J., D.W. Bussink, N. Vertregt, H.G. Van Faassen and D.J. Den Boer 1989. Ammonia volatilization from arable and grassland soils. In: Nitrogen in organic wastes applied to soils. J.Aa. Hansen and K. Henriksen, Editors. Academic Press, London, pp. 185-201.

30. Van der Molen, J., H.G. Van Faassen, M.Y. Leclerc, R. Vriesema and W.J. Chardon 1990. Ammonia volatilization from arable land after application of cattle slurry. 1. Field estimates. Neth. J. Agric. Sci. 38:145-158.

31. Vetter, H. and G. Steffens 1981. Leaching of nitrogen after spreading of slurry. In: Nitrogen Losses and Surface Runn-off from Landspreading of Manures. J.C. Brogan, Editor. Martinus Nijhoff/Dr. W. Junk Publ., The Hague, pp. 251-269.

32. Wadman, W.P. 1988. Injection of animal manures. Possibilities, advantages, and problems (in Dutch). Directie Landbouwkundig Onderzoek, Wageningen, 64 pp.

33. Wadman, W.P., C.M.J. Sluijsmans and L.C.N. De la Lande Cremer 1987. Value of animal manures: changes in perception. In: Animal Manure on Grassland and Fodder Crops. Fertilizer or Waste? H.G. Van der Meer, R.J. Unwin, T.A. Van Dijk and G.C. Ennik, Editors. Martinus Nijhoff Publ., Dordrecht, pp. 1-16.

34. Wadman, W.P. and J.H.A.M. Steenvoorden 1990. 'Advies beperking uitrijperiode van dierlijke meststoffen voor de tweede fase van de mestregelgeving' (in Dutch). Directie Landbouwkundig Onderzoek, Wageningen (in press).

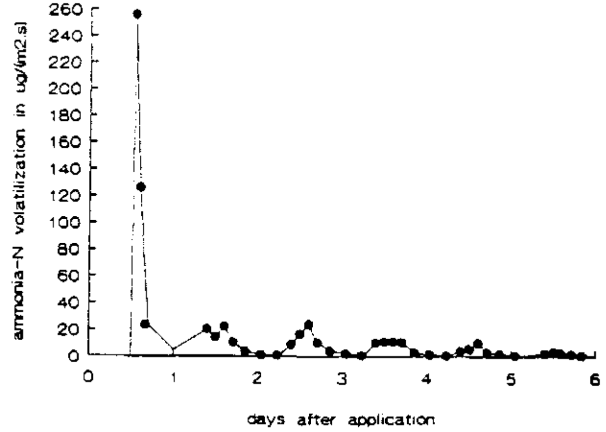

Fig. 1 Typical pattern of ammonia volatilization after surface application of cattle slurry applied to arable land (Van der Molen et al. 1989). Slurry application rate = 31 t/ha; inorganic nitrogen content of the slurry applied = 80 kg N per ha

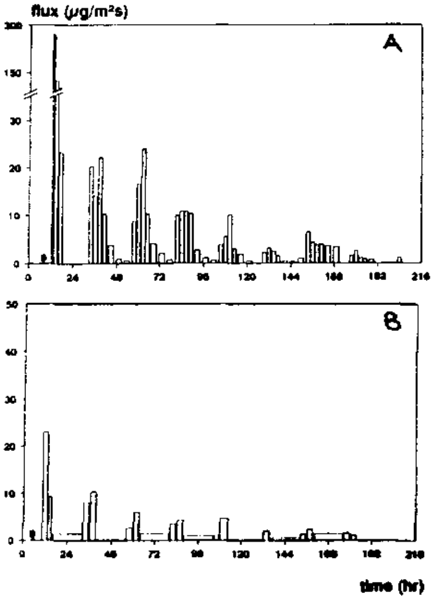

Fig. 2 Measured rates of ammonia volatilization after surface-applied cattle slurry without (A) or with incorporation into the soil immediately after spreading (B). The width of the bars indicates the duration of the measuring periods. The arrows indicate the start of slurry application on the first day. After Van der Molen et al. (1990)

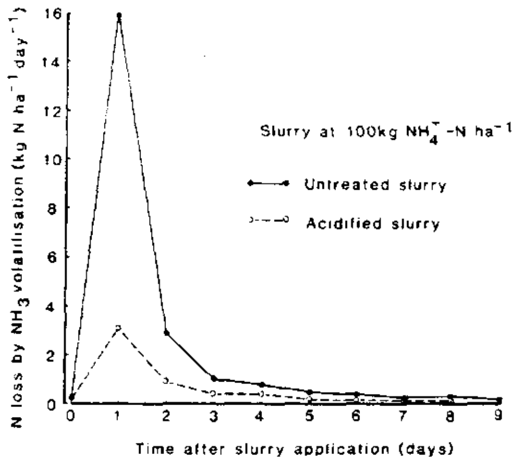

Fig. 3 Ammonia volatilization from cattle slurry, with and without added sulphuric acid, applied to grassland (Pain et al. 1987)