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Reducing N losses (NH_3, N_2O, N_2) and immobilization from slurry through optimized application techniques *

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Abstract

In model, pot and field trials the effect of C reduced slurries and different application techniques on N losses and N immobilization were investigated. The C reduced slurries were produced by mechanical separation. Ammonia losses from surface-applied and injected cattle slurry were measured under field conditions using a wind tunnel system. Injection of slurry was the most efficient way to reduce volatilization of ammonia. After 6 days the total loss from the injected slurry was only 9% of that from surface band application. Furthermore, additional losses of N may occur through denitrification, specially after injection of slurry which may create an anaerobic environment abundant in readily oxidizable C. Therefore denitrification measurements by the acetylene inhibition technique were conducted. Until 100 days after application the loss from the injected slurry was 7.3 kg compared to 4.5 kg N ha^{-1} from surface band applied slurry. After injection, denitrification was only 4.1 kg N ha^{-1} for C reduced compared to 6.5 kg N ha^{-1} for normal slurry. In pot trials the ammonium-^{15}N of normal slurry and C-reduced slurry was utilized by oats between 52 and 60%, the ammonium sulfate by 67%. The increased biomass C confirmed a greater immobilization of the NH_4-N of the normal slurry resulting in a lower initial efficiency.

Introduction

The utilization of potentially available nitrogen (NH_4-N) of slurries by growing plants is often unsatisfied, due to losses through N leaching and considerable gaseous losses through ammonia volatilization or biological denitrification. These losses are implicated with increasing costs for plant production and additionally, the emission of nitrogen gases (NH_3, N_2O) can be detrimental for natural ecosystems. The deposition of ammonia may lead beside the acidification of some forest soils in Europe (van Breemen *et al.*, 1987) also to undesired changes in oligotrophic ecosystems (Schulze *et al.*, 1989). Nitrous oxide has been shown to contribute to global warming and to the destruction of the stratospheric ozone when it is converted to nitric oxide (Crutzen, 1981).

In addition to the various losses of nitrogen an immobilization of the NH_4-N of slurry is responsible for a low efficiency (Gutser and Dosch, 1994). Therefore, the goal of best management practice for manuring is to obtain high N utilization of applied slurry in the first vegetation period. For this, strategies which minimize N losses and N immobilization are necessary.

Ammonia volatilization after application of slurry are reported to be 5–95% of applied ammonium N. The NH_3 loss rate is affected by climatic conditions, mode of application, chemical and physical soil properties (Rank *et al.*, 1987). It has also been shown, that the dry matter content of slurry affects NH_3 loss and in this way a lowered dry matter content of mechanical separated slurry lead to reduced NH_3 losses.

Immediate incorporation or the direct injection of slurry into the soil is known to minimize NH_3 losses to low values. Thompson *et al.* (1987) observed, that only 2% of the applied NH_4-N were lost by volatilization when slurry was injected to grassland. However, the injection of slurry increased the losses by denitrification up to 51 and 16% of the applied NH_4-N, after application in winter and spring, respectively.

In order to value the environmental compatibility of different strategies all losses of nitrogen must be considered, including N immobilization. The aim of the present study was to investigate the effect of C

* Dedicated to Prof. Dr. A. Amberger on his 75th birthday

Table 1. Composition of the cattle slurries (average)

Slurry	Dry matter	NH_4-N	Total N	Total C
		(% in fresh weight)		
Normal	7.6	0.21	0.37	3.3
Separated	5.3	0.22	0.36	2.3

reduced slurries in combination with different application techniques (injection, surface band application) on the extent of gaseous N losses and the N utilization by plants.

Methods

Site characteristics

Measurements were carried out on a brown earth (Dürnast soil) at the institute of Plant Nutrition in Weihenstephan near Munich. Some properties of the soil (0–25 cm): pH 6.4 ($CaCl_2$); clay 20%; silt 60%; total N 0.12%; organic C 1.11%; CEC 141 meq kg^{-1}.

Slurry

Throughout all experiments cattle slurries were used. Before each application, slurry was taken from the same tank to provide similar slurries and afterwards separated with a roller press separator. The separation resulted in a reduced dry matter and total C content but had no effect on the total N and NH_4-N content of slurry; the C/N ratio is decreased (Table 1). In each experiment slurries were applied on the basis of NH_4-N.

NH_4-N of slurries was determined with a NH_3-selective electrode (Orion model 95–12), total N by the Kjeldahl method.

Ammonia volatilization

Losses of N through ammonia volatilization were measured using a wind tunnel system like the system described by Lockyer (1984). The wind tunnel consists of an inverted U-shaped tunnel made from transparent polycarbonate, which covered an area of 1 m^2 (0.5 × 2.0 m) and a circular steel duct housing an electrically powered fan. Wind speed through the tunnels was controlled at 2.0 m s^{-1} in these experiments.

There were five wind tunnel units of which one was used for reference (measurement of the ambient ammonia level). All experiments were carried out in two treatments and two parallels.

An aliquant part of the airstream was sampled near the outlet of the steel duct using a diaphragm suction pump. The pump drew an airstream at a rate of 5 l min^{-1} through a 500 ml absorption flask fitted with a sintered gas distribution tube. The flask contained 300 ml 0.01 *M* H_2SO_4. Ammonia in the air was trapped in the sulfuric acid and determined in the laboratory by destillation and subsequent titration.

In the first experiment slurry treatments were (i) surface band application and (ii) injection of normal slurry. Injection depth was 100 to 150 mm. The normal slurry was applied at a rate equivalent to 70 kg NH_4-N ha^{-1} to the fallow experimental area. In the second experiment, slurry treatments were (i) surface application by broadly spreading the slurry (splash plates) and (ii) surface band application (trailing hoses) of separated and normal slurry. Both slurries were applied to growing winter wheat at shooting stage in a dose equivalent to 70 kg NH_4-N ha^{-1}.

Denitrification

Measurements of denitrification by the acetylene inhibition technique using a soil-cover method described by Hutchinson and Mosier (1981) were conducted in the field cropped with maize. 20-ml samples of the enclosed air were withdrawn 0, 60 and 120 min after placement and stored in vaccutainers until analysis of N_2O and CO_2 were made. Coated CaC_2 has been used as a source of C_2H_2 (Aulakh *et al.,* 1991).

Maize (*Zea mays,* L.) was planted 28 April 1993 in 66 cm rows. The first slurry application took place on 25 May 1993: surface band application with no incorporation spaced 200 mm apart and injection 100 mm deep, 200 mm apart, both as normal slurry. The second slurry application took place on 11 June 1993: injection of separated and normal slurry. In both experiments injected and surface-applied slurries were applied at a rate of 60 kg NH_4^+N ha^{-1}.

The vented chambers (diameter 120 mm) were placed directly over the surface or injection band. The measured flux can therefore be calculated for an area of 1818 m^2. Flux ha^{-1} was given additively by the measured flux of the control plot without slurry.

Soil samples (0–15 cm) were collected to each date as denitrification was measured. In order to obtain the whole slurry band (injection and surface band) a 200 mm wide soil block was sampled. The soil samples were extracted with 2 *M* KCl and 0.01 *M* $CaCl_2$ for NH_4 and NO_3, respectively. NH_4 was determined colorimetrically using the reaction with sodium hypochloride and sodium phanate and NO_3 by high pressure liquid chromatography as described by Vilsmeier (1984).

Pot trial

Field-moist soil from Dürnast was collected from the A horizon, passed through a 5 mm sieve and filled (6.5 kg) in pots (diameter 200 mm, 200 mm high). 450 mg NH_4-N as normal slurry, separate slurry or ammonium sulfate (atom% ^{15}N abundance of each treatment was 14.4) were thoroughly mixed with the soil. After one week of incubation oat (*Avena sativa*, L.) was seeded at 25 plants pot^{-1} and placed in the greenhouse. At flowering stage total N and ^{15}N analysis in soil or in plant samples were conducted with an automated mass spectrometer (Europa Scientific). Additionally, soil samples were removed 1, 4 and 8 weeks after manuring from pots without plants and analysed for microbial biomass (Anderson and Domsch, 1978).

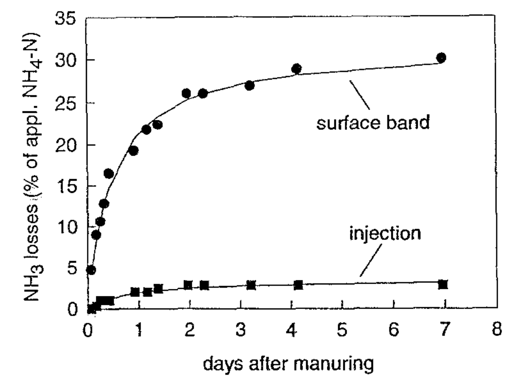

Fig. 1. Cumulative NH_3 losses after different application of slurry to soil without plants. N dose: 70 kg NH_4-N ha^{-1}.

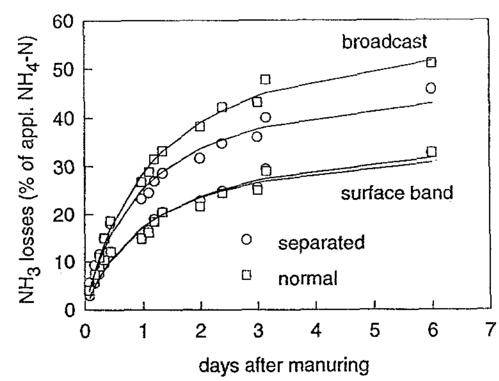

Fig. 2. Cumulative NH_3 losses after different application of normal and separated slurry to winter wheat at shooting stage. N dose: 70 kg NH_4-N ha^{-1}.

Results

Ammonia volatilization

The cumulative losses of N through volatilization after surface band application or injection of normal slurry are presented in Figure 1. The NH_3 losses of surface band applied slurry followed the typical pattern of lost ammonia after application of slurry. More than half of the total loss occuring during the 7-day period took place within the first day. The total NH_3 loss following surface application was 21.7 kg N ha^{-1} and was equivalent to 31% of the applied NH_4-N. Direct injection of slurry into the soil reduced NH_3 losses to low values. After 7 days the total loss from the injected slurry was only 9% of that from surface band application.

In growing winter wheat lower NH_3 losses were observed when slurry was applied in surface bands compared to broadcast application (Fig. 2). The total NH_3 loss following surface band application was 22.7 kg N ha^{-1}. The use of separated slurry showed in the broadcast treatments lower NH_3 emissions of 51 to 46% of the applied NH_4-N compared to normal slurry. This was equivalent to 35.8 and 32.0 kg N ha^{-1} for broadcast application of separated and normal slurry, respectively.

Denitrification

Denitrification measurements using the acetylene inhibition technique showed high N_2O-fluxes in the first 3 weeks after application of slurry (Fig. 3). The maximum rate observed was 625 g N_2O-N ha^{-1} d^{-1} from the injected slurry. After 21 days the rates of denitrification of both treatments remained < 35 g N_2O-N ha^{-1} d^{-1} in spite of high NO_3 concentrations in soil (Fig. 4a, b) and were within the range of the control plot. The total denitrification loss measured from injected slurry treatment was 7.3 kg N ha^{-1} compared to 4.5 kg N ha^{-1} from the surface banded slurry without incorporation.

The production of CO_2 followed a similar pattern as the rate of N losses by denitrification (Fig. 3). Therefore, the injected treatment led to a higher CO_2 emis-

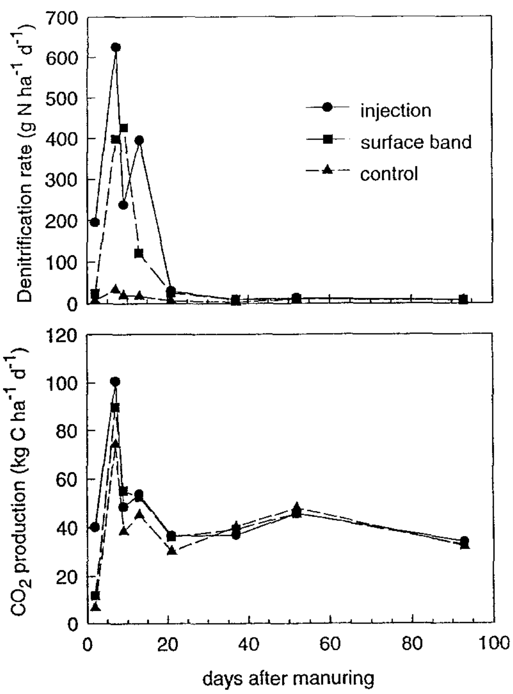

Fig. 3. Denitrification and CO_2 production rates from soil after different application of slurry to maize. N dose: 60 kg NH_4-N ha^{-1}.

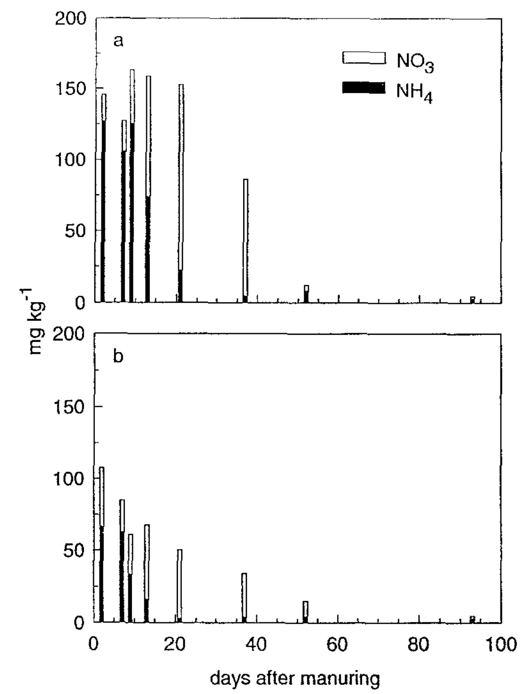

Fig. 4. Soil ammonium- and nitrate-N after injection (**a**) or surface band application (**b**) of slurry to maize.

sion than the surface band application. The similar N_2O-fluxes after 3 weeks of slurry treated and control plots may be a result of an exhaustion of added organic material, because the NO_3 content in soil was sufficiently high to allow denitrification.

Inorganic N concentrations in soil were lower after surface band application compared to injection (Fig. 4a, b). If we assume, that 2 days after manuring the N losses by denitrification were negligible, the lower N content after surface band application may probably due to higher N losses through volatilization of about 30% and confirmed the NH_3 losses measured in the wind tunnel. Decreasing inorganic N contents in the surface treated soil can be attributed to erosion of soil and nitrogen, caused by a heavy rainfall on the 4th day after manuring. After injection no decrease in anorganic N contents in the soil was observed. Therefore, surface band application demands incorporation of slurry, in order to minimize NH_3 losses as well as erosion of nitrogen.

With one exception higher denitrification rates up to 379 g N_2O-N ha^{-1} d^{-1} were observed for the injected normal slurry (Fig. 5). Afterwards the N losses by denitrification decreased strongly and reached the niveau of the control plot in day 28 after manuring. Until 90 days after injection of slurry, denitrification was only

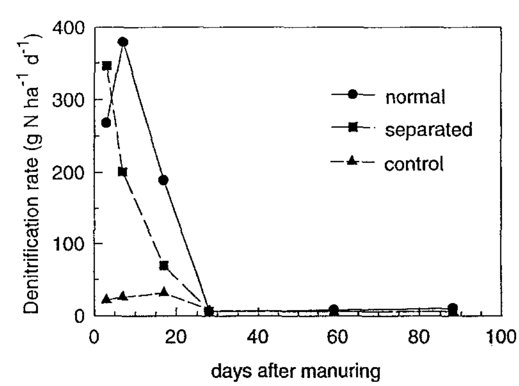

Fig. 5. Denitrification rate after injection of normal and separated slurry to maize. N dose: 60 kg NH_4-N ha^{-1}.

4.1 kg N ha^{-1} for the C reduced slurry compared to 6.5 kg N ha^{-1} for normal slurry. The rate of CO_2-C evolution at the first date was equal in both slurry treatments. But in the following dates a faster decrease was observed for the separated slurry, similar to the pattern of N_2O-fluxes. Substracting the CO_2 losses of the the control total CO_2 loss from the normal slurry was 342 kg C ha^{-1} compared to 209 kg C ha^{-1} from separated slurry.

Table 2. N utilization of slurry and mineral fertilizer (NH_4-^{15}N) in a pot trial with oat. N dose: 450 mg NH_4-N pot^{-1}

Treatment	N removal			^{15}N residue in soil
	Sum	Fertilizer	Soil*	
	(mg pot^{-1})			
Normal slurry	376^{b**}	235^{c} = 52%	141	27.2
Separated slurry	413^{ab}	272^{b} = 60%	145	19.6
$(NH_4)_2SO_4$	439^{a}	301^{a} = 67%	139	14.1

* includes N from organic N in slurry.
** Values with same letter within a column are not significantly different based on Tukey's multiple comparison test ($\alpha = 0.05$).

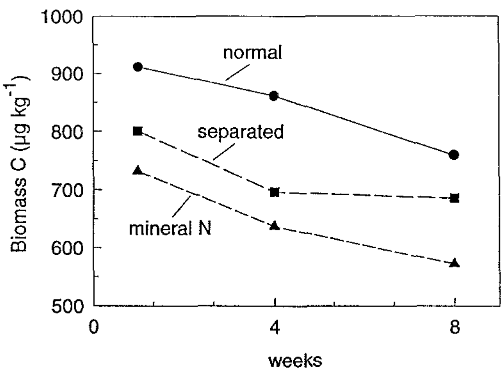

Fig. 6. Biomass C after application of slurry and $(NH_4)_2SO_4$.

Immobilization

A pot trial was conducted to examine the utilization of manured NH_4-N by plants as a function of different rates of organic C supplied either with separated or normal slurry and $(NH_4)_2SO_4$. The higher supply of organic C in the treatment 'normal slurry' resulted in a lower N removal compared to separated slurry (Table 2). The application of $(NH_4)_2SO_4$ led to the highest N removal and therefore, a significant greater amount of the added NH_4-N was available for plants.

After harvesting the green oat the normal slurry showed the highest fertilizer residue, probably due to a greater immobilization. The development of biomass C contents confirmed a biological fixing of nitrogen (Fig. 6). While addition of $(NH_4)_2SO_4$ led to the lowest biomass C contents, the supply of organic matter effected a strong increase of microbial activity. Table 2 showed, that in addition to NH_4-N of the normal slurry the mineralized N from soil or from organic N in slurry was partly immobilized, too. In another experiment on a more sandy soil this immobilization was markedly higher.

Discussion

Various experiments showed, that immediate incorporation of slurry considerably decreased the loss of N through volatilization (Rank *et al.,* 1987; van der Molen *et al.,* 1990). However, this precaution could not be realized in closed plant covers with exception of row cropping such as maize. But the utilization of applied NH_4-N of organic manures is highest during the growth period, probably due to a lower N leaching and N immobilization. Therefore, other modes of application must be used to minimize NH_3 losses.

Additionally to an immediate incorporation in row croppings, an injection of slurry direct into the soil reduced NH_3 losses to a negligible level. Sawyer and Hoeft (1990) reported that injection of slurry affected the maize rooting distribution due to changed soil properties, i.e. high pH, high NH_4-N and high NO_2-N. In our experiments a change of these soil properties were observed, but no alteration in rooting distribution could be demonstrated.

In growing winter wheat at shooting stage a surface band application of cattle slurry by trailing hoses caused lower NH_3 emissions of 30 and 37% compared to broadcast application of separated and normal cattle slurry, respectively. No smothering of leaves occured when slurry was applied in surface bands and therefore NH_4-N of the slurry can be retained greatest possible by cation exchange sites within the soil. The reduced NH_3 loss can also be ascribed to an absorption of NH_3 by plant leaves (Sommer *et al.,* 1992). Moreover, the closed plant cover may led to a lowered wind speed at the soil surface resulting in a smaller rate of NH_3 volatilization (Sommer *et al.*, 1991). The smaller difference in NH_3 emissions between broadcast and surface band application of separated slurry is due to a better run off from leaves onto respectively into the soil, caused by the lowered dry matter content by mechanical separation. Sommer and Olesen (1991) stated that a dry matter content higher than 12% or lower than 4% resulted in only small changes in NH_3 losses. In our experiments separation of slurry reduced the dry matter content of slurry even in the above mentioned range and therefore, NH_3 losses can be greatly influenced by a mechanical separation due to a better infiltration into the soil.

Compared to the losses through volatilization, denitrification losses are much lower. The rate of these losses were greatly influenced by the mode of application and the quantity of organic material present. Therefore, the higher rates were maintained by the injection of normal slurry into the soil. In this treatment high CO_2 emissions, stimulated by microbial respiration combined with a high O_2 consumption in a confined area, resulted in increased denitrification. In spite of a high CO_2 evolution from the injected treatment, denitrification rate was relatively low at the first date after manuring. Shortly after injection the extent of denitrification will be controlled by the NO_3-N in the soil (Comfort *et al.*, 1990). Later, when nitrification of the NH_4-N of slurry provides a large amount of NO_3-N in soil, denitrification is determined primarily by the oxidizable C in the injection zone. After 3 to 4 weeks the readily oxidizable C was metabolized and despite high NO_3-N concentrations in the soil only small denitrification losses occured. These data suggested that the potential for denitrification after injection decreases as soon as the readily oxidizable C has been removed. Immediately after injection of separated slurry emission of CO_2 was as high as for the normal slurry. But in the next dates a stronger decrease of CO_2 emissions was observed -the lower C input by separated slurry was faster metabolized- reduced N losses through denitrification were measured.

According to this results, the level of gaseous N losses can be largely minimized by plant specific application techniques. However, even an optimized application of slurry led to a lower availability of applied NH_4-N compared to ammonium sulfate, as shown in the pot trial. Slurry manuring is associated with the supply of readily oxidizable C resulting in an increased biological activity and a higher potential for immobilization of soil. The extent of this immobilization will be controlled by the quantity of supplied available C (Dosch and Gutser, 1993). Therefore, the C reduced separated slurry showed a lower N immobilization and consequently a better utilization of the applied NH_4-N already during the first vegetation period. The availability of immobilized N for plants and its effects to environment is discussed in detail by Gutser and Dosch (1994).

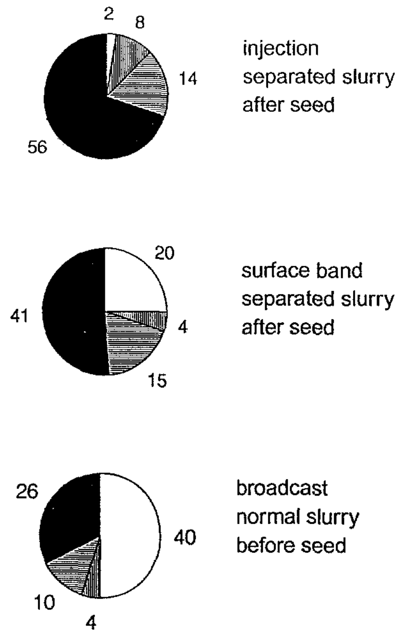

Fig. 7. Losses, immobilization and availability of slurry NH_4-N in different application systems for maize (kg NH_4-N ha^{-1}). N dose: 80 kg NH_4-N ha^{-1}.

Figure 7 represents a calculation of the amount of N available for maize in different slurry managements, estimated by results of model and especially field trials. An important criterion is the prevailing reduction of N losses and N immobilization. As the diverse N losses may vary in the tested slurry managements, the sum of all N losses is important for an ecological and economical valuation. High N losses through volatilization of NH_3 were primarily responsible for the unsatisfied N utilization after broadcast application of slurry without incorporation before seed. A distinctly reduction of NH_3 losses is obtained by a surface band application of separated slurry, e.g. by trailing hoses in growing maize. Furthermore, the losses are markedly diminished after injection of separated slurry, while N losses due to denitrification increases only slightly. Considering a lower N immobilization of applied separated slurry the potentially available nitrogen in the treatment 'injection' come to 56 kg N ha^{-1} compared to 41 respectively 22 kg N ha^{-1} after surface band application and broadcast application. The supply of C reduced slurry (separation or anaerobic fermentation (Messner and Amberger, 1988)) in combination with special application techniques (injection in row croppings, trailing hoses in closed plant covers) increases the predictability of the manurial value of slurry and in consequence an optimized nutrition of plants by combination of mineral and organic fertilizers is possible. Moreover, these practices are favourable for the environment. Further investigations are needed to evaluate the production of N_2O, thereby taking into account both denitrification and nitrification.

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