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Review

Ammonia emission from field applied manure and its reduction—invited paper

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Abstract

Emissions of ammonia to the atmosphere are considered a threat to the environment and both United Nation treaty and European Union legislation increasingly limit emissions. Livestock farming is the major source of atmospheric NH_3 in Europe and field applied manure contributes significantly to the emission of NH_3 from agriculture. This paper presents a review of studies of NH_3 emission from field-applied animal manure and of the methods available for its reduction. It is shown that there is a complex relationship between the NH_3 emission rate from slurry and the slurry composition, soil conditions and climate. It is concluded that simple empirical models cannot be used to predict ammonia emission from the wide range of circumstances found in European agriculture and that a more mechanistic approach is required. NH_3 emission from applied solid manure and poultry manure has been studied less intensively than slurry but appear to be controlled by similar mechanisms. The use of trail hoses, pre- or post-application cultivation, reduction in slurry viscosity, choice of application rate and timing and slurry injection were considered as reduction techniques. The most effective methods of reducing ammonia emissions were concluded to be incorporation of the animal slurry and farmyard manure or slurry injection. Incorporation should be as close to the application as possible, especially after slurry application, as loss rates are high in the 1st hours after application. Injection is a very efficient reduction technique, provided the slurry is applied at rates that can be contained in the furrows made by the injector tine. © 2001 Published by Elsevier Science B.V.

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1. Introduction

Farming is recognised as a major source of atmospheric ammonia (NH_3), contributing 50% of the global NH_3 emissions (Schlesinger and Hart-

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ley, 1992) and over 70% in areas with intensive livestock farming, such as Europe (Buijsman et al., 1987; Jarvis and Pain, 1990; Asman, 1992; ECETOC, 1994). Furthermore the efficiency of ammonium (NH_4^+) in surface applied animal slurry as a source of nitrogen (N) to crops can be variable, due to volatilisation of ammonia (NH_3) (Jarvis and Pain, 1990).

Ammonia is a chemically active gas and readily combines with nitrate (NO_3^-) and sulphate (SO_4^{--}) in acid cloud droplets to form particulates (Asman et al., 1998). The formation of particulates prolongs their existence in the atmosphere and therefore influences the geographic distribution of acidic depositions. The emitted NH_3 is subsequently deposited to land and water, either by dry deposition of NH_3 or by dry and wet deposition of ammonium (NH_4^+) (Asman and van Jaarsveld, 1991). The addition of available nitrogen (N) to low-nutrient ecosystems disturbs the competitive balance between plant species, and this can cause unwanted changes in the plant communities present. The N input can also be nitrified to nitric acid (HNO_3) leading to acidification of the soil (van Bremen et al., 1982; Schulze et al., 1989).

In 1999, the UN Convention on Long-range Transboundary Air Pollution to Abate Acidification, Eutrophication and Ground-level Ozone was extended by the Gothenburg Protocol to include ammonia (http://www.unece.org/env/lrtap/). This formed the starting point for the European Union (EU) National Emission Ceilings Directive (NECD), which proposes to make the limitations on the national emissions of NH_3 legally binding. The NECD has currently proposed to demand significant reductions in NH_3 emissions from a number of European countries. On top of that the implementation of the EU Habitat Directive (Directive 92/43/EEC) may demand additional reductions in ammonia emissions, particularly from farms that are near to low-nutrient ecosystems.

It has been estimated that field-applied manure contributes about 10% of the total emission of NH_3 in Europe (ECETOC, 1994). Economic analyses suggest that reductions in NH_3 losses from field-applied manure would be the most economically effective first step in the reduction of national NH_3 emissions (Klaasen, 1994). Knowledge of the emission of NH_3 from manures is also essential for the efficient utilisation of manure N for crop production. An underestimation of NH_3 losses leads to the under-fertilisation of crops whilst an overestimation can result in the over-application of plant available N, with the risk that the excess N is lost by nitrate leaching (Thomsen et al., 1993).

The objective of this paper is to review the literature on ammonia emissions from field-applied livestock manure and provide agricultural advisors with the information they require to help farmers reduce NH_3 losses from this source.

2. Background

2.1. Factors affecting NH_3 loss from animal manures

Although there has been much research on NH_3 loss from field-applied manures, manure types and climatic conditions vary so much within Europe that advisors will often have to interpret or extrapolate research results to their specific situation. For this reason, it is necessary to understand the major factors that affect NH_3 loss.

Agricultural ammonia losses occur primarily from the surface of ammoniacal solutions in water. It is usual to quote the amount of total ammoniacal N ($TAN = NH_3 + NH_4^+$) present since the techniques normally used to analyse manure measure both dissolved NH_3 and NH_4^+. Such liquid surfaces are found in association with animal slurries, urine and solid animal manures. TAN are produced through the hydrolysis of urea (from sheep, cattle, pigs, horses and similar animals) or ureic acid (poultry) (Cabrera and Chiang, 1994; Petersen et al., 1998a; Whitehead and Raistrick, 1993). The concentration of NH_3 is in a dynamic equilibrium with NH_4^+ and H^+ in the manure (Sherlock and Goh, 1984, 1985).

Ammonia emission is the function of transfer of NH_3 to the free air phase from the air-phase in immediate contact to the ammoniacal solution. The concentration of NH_3 in air close to the manure surface is in equilibrium with the dissolved NH_3 (Génermont and Cellier, 1997). As the air from the atmosphere passes over the manure surface, NH_3 from the manure surface is transported away horizontally by advection and vertically by turbulent diffusion.

The factors that in theory determine the total amount of NH_3 that is lost from the manure are shown in Fig. 1. The factors are divided according to whether they have a direct affect (first column) or indirect effect (second column). The arrows point to the factor affected and the direction of the effect (positive or negative) is shown by the + or − sign, respectively. Fig. 1 shows that the concentration of NH_3 at the liquid surface is primarily a function of the chemical and physical conditions within the manure whilst the transfer of NH_3 from the air at the surface to the atmosphere is primarily a function of the local meteorological conditions, i.e. processes of a physical nature. The area of manure exposed and the time the manure is exposed to the air are related to the management of the manure application. In the following sections, we consider whether the empirical evidence from previous investigations supports the theory.

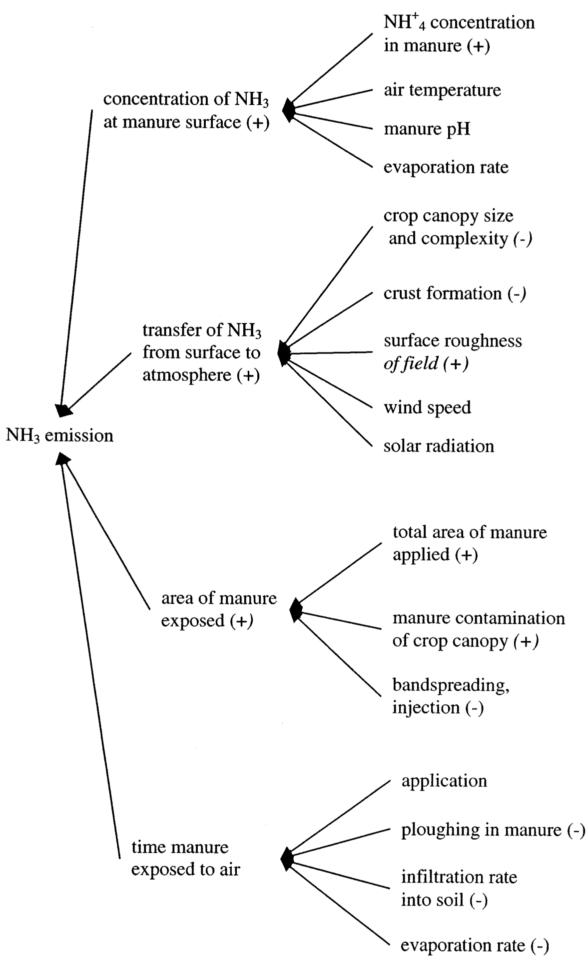

Fig. 1. Factors affecting NH_3 volatilisation from field-applied manures.

2.2. Manure types and composition

The TAN in pig, cattle or sheep manure originates mainly from the hydrolysis of the urea in urine, which traditionally will be completed before the manure is removed from the animal house (Voorburg and Kroodsma, 1992). Urine contains the surplus of feed N after N has been included in animal tissue or milk, or excreted as faeces. Excretion of N in faeces is relatively constant at increasing feeding rates, therefore, TAN content in urine reflects feeding practice. It also means, that a reduction of the N surplus in the animal feed is an effective method of reducing NH_3 emissions in animal housing, storage and after field application (see Paul et al., 1998; Misselbrook et al., 2000).

The composition of animal manure varies widely between animal species and manure types (Table 1). Animal manure from animal houses is a mixture of faeces and urine plus bedding, spilt feed, spilt drinking water and water used for washing. Slurries collected from below slatted floors have a lower dry matter content than other manures, due to addition of washing water and little use of bedding materials. In housing systems where livestock are tied, the excretion is separated into solid manure (farmyard manure; FYM), mainly containing faeces and straw, and liquid manure, which is a mixture of water, urine and dissolvable faecal components. If manure is collected as FYM, additions of bedding are much higher than in those based on slurry. Conditions in FYM in the animal housing or in storage may be favourable for composting, and this can lead to a reduction in TAN of applied manure due to substantial changes in the chemical composition and emissions of NH_3 (Karlson and Jeppson, 1995; Rom and Henriksen, 2000).

Table 1
Typical composition of animal manures

Manure	Animal	DM ($g\ kg^{-1}$)	N-tot ($g\ kg^{-1}$)	TAN ($g\ kg^{-1}$)	Ureic acid–N ($g\ kg^{-1}$)	P ($g\ kg^{-1}$)	K ($g\ kg^{-1}$)	pH
Slurry	Cattle	74.23	3.95	1.63		0.63	3.46	7.20
Slurry	Pig	34.50	9.35	3.66		0.74	3.62	6.72
Slurry	Poultry	218.00	12.00	5.93				7.23
Solid manure	Cattle	181.50	4.85	1.33		1.45	3.85	7.80
Solid manure	Pig	222.00	10.45	4.40		3.70	5.25	7.70
Solid manure	Poultry	574.60	29.60	5.49	6.0	5.98	6.53	8.50
Deep litter	Cattle	261.00	5.20	0.90		1.40	9.70	8.60
Deep litter	Pig	412.00	11.20	2.80				8.90
Deep litter	Poultry	570.00	27.10	6.48	7.54	9.25	15.50	9.1
Liquid manure	Cattle	1.68	2.60	2.05		0.03	4.33	8.70

Mean values derived from Chambers et al. (1997), Lockyer et al. (1989), Husted et al. (1991), Japenga and Harmsen (1990), Karlson and Jeppson (1995), Paul and Beauchamp (1989), Petersen and Kjellerup (1996); Petersen et al. (1998b); Rohde and Johansson (1996), Safley et al. (1986), Sommer and Christensen (1990), Sommer and Husted (1995a).

TAN in poultry manure originates mainly from decomposed ureic acid in the droppings, i.e. no urine is produced. Ureic acid is a heterocyclic nitrogen compound which slowly hydrolysis to urea, which then is hydrolysed to TAN. The concentration of TAN and ureic acid in applied manure will therefore be very variable and related to storage conditions, and prediction of NH_3 emissions from poultry manure should include transformation of ureic acid, which is influenced by water content and temperature (Koerkamp, 1994). Laying hen are often housed in battery cages, i.e. several cages with wire floors stacked one on top of another. The faeces drop through the cages to a store below the cages or onto a conveyor belt which transport the manure to an external store of dry solid manure (Koerkamp, 1994). In the housing, the droppings may be stored dry on the floor or, after addition of water, as slurry. The slurry and the dry solid manure has a higher variation in dry matter content than that of livestock solid manure, e.g. Lindhard and Kjellerup (1979) found slurry dry matter (DM) varied from 5 to 27% and in dry solid manure between 31 and 67%. The variation in dry matter content of the solid manure is probably caused by drinking water leaking to the manure (Kroodsma et al., 1988).

During storage changes in manure may occur due to the input of dirty water, precipitation and evaporation, NH_3 volatilisation and composting (Bode, 1991; Lammers et al., 1997; Petersen et al., 1998b). In most countries, livestock manure is stored for a month or more before manure application and so all the excreted urea will be hydrolysed to TAN prior to spreading. In slurry, relatively little transformation of organic N appears to occur during storage (Zhang and Day, 1996; Sørensen, 1998). In poultry manure, the hydrolysis of ureic acid is slow and is affected by storage conditions, so the concentration of TAN and ureic acid will often be more variable than for other manures (Kroodsma et al., 1988).

3. Broad-spreading

Broad-spreading with splash plate is the cheapest method of applying slurry and other liquid manures and remains the most commonly used method in Europe (Burton et al., 1996). All solid manures are applied using a broad-spreader.

3.1. Losses during application

Direct micrometeorological measurements have shown, that NH_3 losses during spreading of slurry were less than 1% of the applied ammonium with conventional spreaders, trail hose application and a cable driven irrigator (Pain et al., 1989). However, losses of up to 10% of applied TAN have been measured when using an irrigation device having a spreading length of 25–30 m (Phillips et al., 1991; Gronauer et al., 1994). Thus increasing the spreading length and decreasing the size of slurry droplets will increase the NH_3 emission because both the exposure time and the surface area exposed are increased (Boxberger and Gronauer, 1990). To our knowledge, there is no information available concerning NH_3 losses during handling and spreading of solid manure. The loss may be higher than for slurry because emission may take place during filling, transport and application, whereas for slurry, emission will only take place during spreading.

3.2. Emission after application

3.2.1. Climate

The rate of NH_3 emission from surface-applied manure is markedly affected by the current weather conditions. A number of studies have found positive relationships between the initial

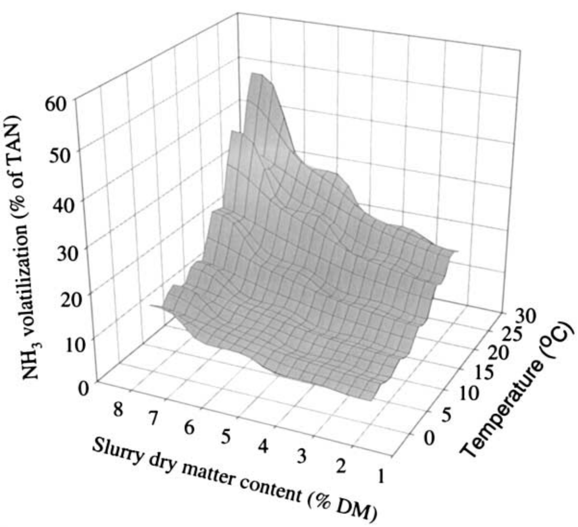

Fig. 2. Ammonia volatilisation in relation to slurry dry matter and temperature using the models from Sommer et al. (1991) and Olesen and Sommer (1993).

NH_3 emission from surface-applied manures and incident solar radiation or air temperature (Brunke et al., 1988; Sommer et al., 1991; Moal et al., 1995; Rohde and Johansson, 1996; Braschkat et al., 1997; Sommer et al., 1997). Solar radiation increases emission in three ways. Firstly, solar warming increases the turbulence in the atmosphere and this increases the transport of NH_3 away from the surface (Fig. 1). Secondly, solar radiation drives the evaporation of water and this effectively increases the concentration of TAN in the remaining manure liquid. Finally, solar radiation increases the temperature of the manure, increasing the NH_3 concentration at the manure surface. The relationship between emission and air temperature (Fig. 2) is often simply a reflection of the warming effect of solar radiation but on some occasions, a cold manure may be warmed by the air passing over it. Low but sustained emission rates, resulting in high cumulative NH_3 losses, have been observed at temperatures near freezing point (Thompson et al., 1987; Sommer et al., 1991) but this probably reflects the slow infiltration of slurry into the frozen soil.

The NH_3 at the manure surface is transported away upwards by turbulent transport, and sideways, by advection. Consequently, NH_3 emission from surface-applied slurry is related to wind speed (Sommer et al., 1997). The effect of wind speed has not been found in all studies (Beauchamp et al., 1978; Bussink et al., 1994), probably because wind speed is often high enough that factors other than the atmospheric transport limit emission.

Rainfall dilutes the TAN in manure, reducing the current NH_3 emission rate. In the absence of other affects, this reduction will only be temporary and the NH_3 emission may increase again when the water evaporates (Beauchamp et al., 1982; Gordon and Schuepp, 1994). However, the delay may be beneficial, if it allows time for incorporation of the applied manure. Usually, rainfall also increases the rate of infiltration of TAN into the soil and this will reduce the cumulative emission (Horlacher and Marschner, 1990; Klarenbeek and Bruins, 1991). There is some evidence, that NH_3 emission from solid manure may behave somewhat differently. Sommer and

Christensen (1990) found that irrigation with more than 20 mm reduced total NH_3 emission to less than half of the emission from untreated pig solid manure. However, Chambers et al. (1997) found emission increased following rain events of 13 mm about 5 days after application and 16 mm about 8 days after manure application. This may have been due to the re-wetting of dried manure or enhanced mineralisation. A similar increase in emission may occur when dried poultry manure is wetted, as the wetting increases hydrolysis of uric acid to NH_4^+ and this is then volatilised.

3.2.2. Infiltration of TAN into soil

Infiltration into the soil reduces NH_3 losses from surface applied slurry, partly because the rate of diffusion of NH_3 in the soil is relatively low and partly because the sorption of NH_4^+ to soil colloids reduces the concentration of TAN in the soil solution. The rate of infiltration and sorption of NH_4^+ should be related to soil type but few studies have quantified the effect of soil type on NH_3 emission rates. Bussink et al. (1994) found NH_3 emission was higher from peat and heavy clay soil than from sand and clay soils, when slurry was applied on grassland, whereas Döhler (1991) found lower NH_3 emission from slurry applied to a loamy soil than from the same slurry applied to a sandy soil. The effect of soil type is likely to be difficult to predict, as infiltration rate and CEC tend to be negatively correlated. Döhler (1991) found emission from cattle slurry with a higher viscosity was not significantly affected by differences in soil types, so it is possible that for such slurries, infiltration rate is determined more by the slurry DM than soil type.

DM content has been shown to affect NH_3 emission significantly (Fig. 2), thus the higher DM content has been shown to cause higher NH_3 emission from cattle than from pig slurry (Pain et al., 1990a). Little liquid from a DM-rich manure will infiltrate the soil because DM has both a high water retention capacity (Petersen and Andersen, 1996) and a high slurry viscosity (Donovan and Logan, 1983; Jarvis and Pain, 1990). The high DM content of solid manure means emission rates tend to be high (Menzi et al., 1997; Chambers et al., 1997).

A number of studies have shown that the infiltration of slurry and NH_3 emission is affected by the soil moisture status. Sommer et al. (1991) found NH_3 emission to be low when slurry was applied on a dry soil, even though the air or soil surface temperature was high. This was interpreted to be an effect of enhanced infiltration and has subsequently been confirmed in a laboratory experiment (Sommer and Jacobsen, 1999). Conversely, NH_3 losses increase if infiltration is reduced by a high soil water content (Donovan and Logan, 1983).

3.2.3. Canopy interception

Broad spreading slurry or liquid manure to crops will lead to some interception by the plant canopy. Some of the NH_3 will be absorbed by the leaves of the crop but the rate at which this occurs is likely to be small in comparison with the rate of NH_3 emission. Consequently, a number of studies have found the emissions from slurry broadspread to a well-developed crop to be greater than from a juvenile crop or bare soil (Rohde and Johansson, 1996).

3.2.4. Time course of NH_3 emission

The NH_3 loss rate is usually highest immediately after slurry application (Fig. 3a). This is partly due to the high initial concentration of total ammoniacal N (TAN) in the surface of the mixture of soil and slurry and partly due to a rise in pH in the surface of newly spread slurry (Sommer and Sherlock, 1996). NH_3 emission is relatively sensitive to pH over the range commonly found in manures—a change from 7.7 to 8 will double the emission. The factors determining the rise in pH are complex (Sommer and Husted, 1995b) and there may be little relationship between NH_3 emission and the initial pH of the manure. NH_3 emission may be more closely related to the total alkalinity of the manure (Husted et al., 1991), so that a manure with a relatively low pH may have a high total alkalinity and therefore lose substantial amounts of NH_3.

After the high initial NH_3 emission, the rate normally falls rapidly as the concentration of TAN in soil surface decreases due to emission, infiltration and nitrification (van der Molen et al.,

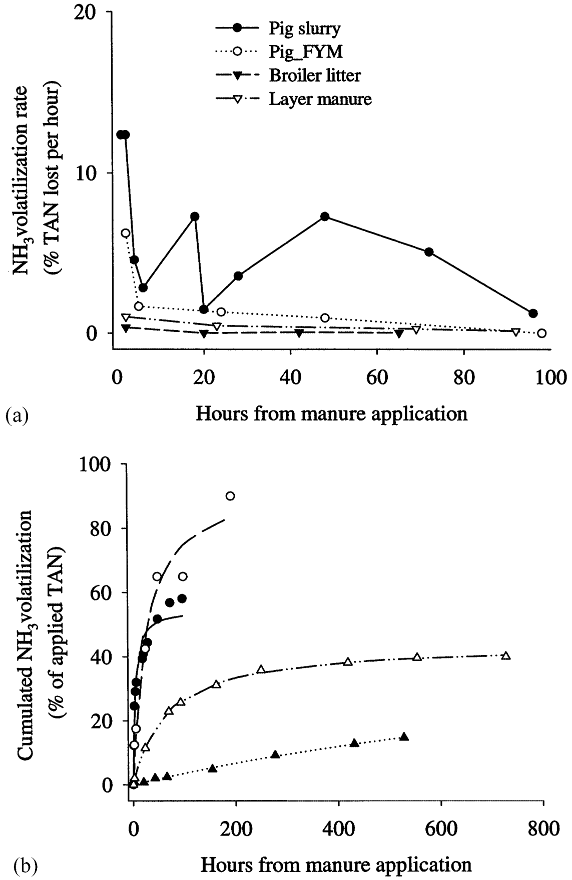

Fig. 3. NH_3 emission after surface application of manure to stubble, expressed as: (a) the mean hourly rate; or (b) the cumulative emission. Emissions are expressed as % of TAN or TAN + ureic acid applied. Pig slurry (adapted from Bless et al., 1991), pig farmyard manure, layer manure and broiler litter (adapted from Chambers et al., 1997).

1990). In a constant weather condition, the rate would decrease exponentially but in reality, the emissions are also affected by the diurnal variation in radiation input, temperature and wind speed. This means that losses are often low during the first night after application but may increase again the following day (Brunke et al., 1988; Bless et al., 1991). NH_3 emission rates from slurry are generally low after the first 2 days and the cumulative NH_3 emission will usually reach 50% of its maximum within the first 12 h after slurry application (Fig. 3b; Pain et al., 1989; Moal et al., 1995). Emissions may continue for longer periods if conditions for volatilisation are poor (e.g. low temperature, radiation and wind speed) or if the infiltration rate is low e.g. low porosity or frozen soils.

The emissions of NH_3 from applied solid manure follow a similar pattern over time as slurry but at a lower initial rate and continue for longer (Sommer and Christensen, 1990; Chambers et al., 1997). This is because the TAN will not infiltrate into the soil to the same degree as that in slurry. The few studies available indicate that about 50% of the loss occur within 24 h and that a significant amount of the TAN may be lost during 10 days.

The pattern of NH_3 emission from poultry slurry, litter and dried droppings applied to the soil may be different from that of pig or cattle slurry. The initial emission rate may be very high, as found for surface applied poultry slurry (Lockyer et al., 1989) and or nearly zero, as found for broiler litter applied to cereals (Chambers et al., 1997). This large variation is probably due to differences in content of TAN, reflecting differences in the degree to which the hydrolysis of ureic acid has progressed (Cabrera et al., 1994).

4. Reduction techniques

A range of techniques is available to reduce NH_3 emissions. The appropriate choice of technique will vary depending on the relevant national and EU legislation, climate and on the restrictions imposed by the soil, topography and farming system. The reduction techniques available in the field are presented here approximately in order of increasing cost.

4.1. Trail hoses

NH_3 losses from slurry applied to crops may be reduced by the use of trail hoses (Fig. 4), which apply the slurry onto the soil between rows of plants (Bless et al., 1991; Döhler, 1991). The NH_3 loss is reduced due to the small surface area of the slurry, reduced canopy interception, a reduced wind speed above the slurry surface and higher atmospheric NH_3 concentrations above the slurry surface (Thompson et al., 1990a,b). NH_3 emitted from the slurry on the soil is also absorbed by the leaves of the crop, which can lead to the capture of up to nearly 40% of the emitted NH_3 (Sommer et al., 1997). The reduction in cumulative NH_3 emission due to trail hose application is consequently related to the crop cover, so the technique has little effect on losses from slurry on bare soil (Fig. 4).

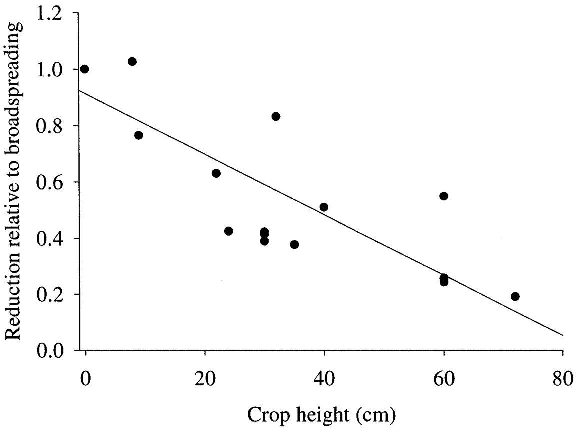

Fig. 4. Effect of crop height on the reduction in NH_3 emission from slurry after application with trail hoses. Emissions are related to NH_3 emission from slurry broadspread to soil or crops (adapted from data in Sommer et al., 1997 and Sommer and Olesen, 2000).

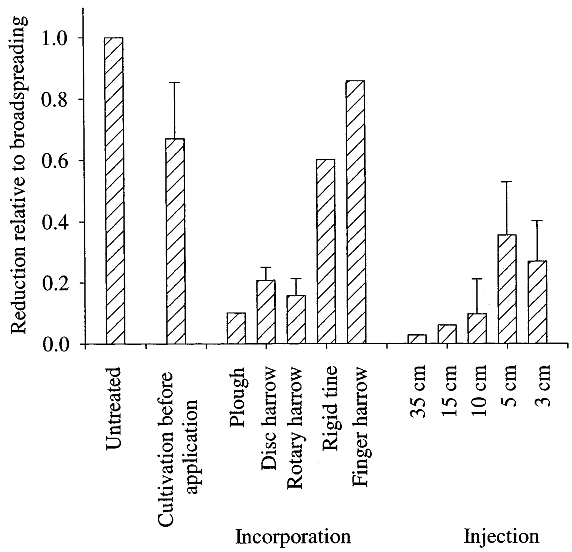

Fig. 5. Reduction in NH_3 emission due to application technique related to ammonia losses from animal slurry broadspread onto soil or a plant covered soil (from Döhler, 1991; Kowalewsky, 1990; Pain et al., 1990c; Klarenbeek and Bruins, 1991; Phillips et al., 1991; Sommer and Petersen, 1992; Larsen et al., 1992; Rubæk et al., 1996; Sommer and Ersbøll, 1994; Bless et al., 1991; Thompson et al., 1987).

4.2. Cultivation

Cultivating the soil surface before surface application of slurry can reduce NH_3 losses to about 50% of those from an uncultivated soil. The reduction is caused by higher infiltration rate of the slurry into the soil and by an increased surface roughness (Bless et al., 1991; Sommer and Ersbøll, 1994).

Incorporation of slurry by ploughing or by a rotary harrow after application reduces losses of NH_3 by burying the majority of the manure. The losses decrease with increasing depth of incorporation (Fig. 5). Given the time-course of NH_3 volatilisation (Fig. 3a), the timing of the cultivation is crucial. For example, from Fig. 3b, it can be seen that in this particular case, incorporation pig slurry 1 h after application would have reduced losses by 80% whereas if incorporation where delayed until 6 h after application, the reduction would only be 45%.

Incorporation of liquid and solid manures is an effective method of reducing losses (Tables 2–4) and the only practical method of reducing NH_3 losses from these types of manure.

4.3. Reducing viscosity

Reducing the viscosity of a slurry will often reduce NH_3 losses, although it will not be effective if the infiltration rate is limited by other factors, such as soil moisture content (Rubæk et al., 1996). The viscosity of the slurry may be reduced by dilution with water, by reducing the fibrous fraction by filtration (Gordon et al., 1988; Sommer and Olesen, 1991; Frost 1994) or by anaerobic digestion (Rubæk et al., 1996). However, the net effect of such treatments may be hard to predict; Pain et al. (1990b) and Pain et al. (1990c) found anaerobic and aerobic treatment reduced the viscosity of slurry but increased pH. As a consequence, NH_3 emission from anaerobi-

Table 2
Ammonia emission from poultry manure applied in the field

Animal	Manure	System of manure handling	NH_3 emission		Ref.
			g NH_3 per bird per year	% of total-N	
Laying hen	Slurry, 26% DM	Surface applied	0.263	45	1
Laying hen	Slurry, 18% DM	Surface applied	0.230	38	1
Laying hen	Solid manure, 61% DM	Surface applied	0.039	7	1
Broiler	Litter, 75% DM	Surface applied	0.012	7	1
Turkey	Slurry, 48% DM	Surface applied		2	2
Turkey	Slurry, 48% DM	Incorporated into the soil		0.1	2
Broiler	Litter	Surface applied		22.5–27.6	3
Broiler	Litter, diluted to 30% DM	Surface applied		4–31	4
Broiler	Litter diluted to 30% DM	Immediately mixed 20 cm into the soil		2–4	4

Source: (1) Lockyer et al. (1989); (2) Nathan and Malzer (1994); (3) Cabrera et al. (1994); (4) Schilke-Gartley and Sims (1993).

Table 3
Ammonia emission from cattle and pig slurry or liquid manure applied by different methods

Animal	Crop (height in brackets)	Emission,% of applied NH_4 (SD in brackets)			Ref.
		Broadspreading	Trail hose application	Injection to 2 cm	
Pig	Barley (10 cm)	10	5		1
Cattle	Ley (10–13 cm)	40 (10)	29 (13)	39 (15)	1
Cattle	Ley (10–13 cm)	67 (28)	31 (15)	42 (19)	1
Cattle	Ley	9 (5)			2
Pig	Ley	8			2

Sources: (1) Rohde and Johansson (1996); and (2) Morken (1992). In brackets SE of the mean.

Table 4
Ammonia emission from solid animal manure (FYM) applied to the field

Animal	Treatment	Ammonia emission, % of NH_4 applied				Ref.
		0–6 h	0–24 h	0–36 h	>6 days	
Cattle and pigs	Surface applied	22	32.5		65	1
Cattle	Surface applied			60		2
Cattle	Surface applied	11	22		37	3
Pig	Surface applied, irrigation >20 mm	6	10		19	3
Pig	Incorporated	5	8		18	3
Pig	Surface applied	9	14		44	3

Sources: (1) Chambers et al. (1997); (2) Menzi et al. (1997); (3) Sommer and Christensen (1990).

cally digested slurry was similar to that from untreated slurry, whilst emissions from aerobic treated slurry were higher.

4.4. Application rate

Ammonia emission from surface-applied slurry, expressed as a proportion of the TAN applied, decreases with increasing application rate as a greater proportion of the slurry is likely to infiltrate into the soil (Lauer et al., 1976). The effect may not be linear, as Klarenbeek and Bruins (1991) found that NH_3 emission was reduced from 57 to 36% of applied TAN, when increasing application rate from 30 to 90 m^3 ha^{-1}, whereas no effect was seen when application rates were increased from 10 to 30 m^3 ha^{-1}. In practice, manipulation of application rate is not a very useful method of reducing volatilisation. The upper limit for the application rate will normally be determined by the nutrient content of the slurry and mineral nutrient need of the crops, and low application rates would represent an inefficient use of labour, machinery and fuel.

4.5. Timing of application

Choosing to apply manure when conditions do not favour volatilisation may reduce losses of NH_3, e.g. during the coolest part of the day or when rain is expected. It has been calculated, that avoiding applications during times of the day with a high potential for NH_3 losses could reduce the total emission of NH_3 from applied slurry by half (Sommer and Olesen, 2000). How useful this technique may be in practice will depend on the farmer's flexibility in the choice of application date and time. This will in turn depend on the total amount of manure to be applied, the length of the period available for application (which may be determined by soil conditions or legislation) and other demands on labour and machinery.

4.6. Injection

Injecting the slurry into the soil is an effective method of reducing ammonia emission, the effectiveness increasing with the depth of injection (Fig. 5). However, the effect of injection can be small if the soil is moist and compacted, because the furrow may not close behind the injection tines. Harrowing a compacted soil before injection of slurry reduces losses by 60% compared to losses from slurry injected into uncultivated soil (Sommer and Ersbøll, 1994). At high application rates, the effect of shallow injection will be significantly reduced, as slurry will spill out of the injection furrow.

4.7. Acidification for the reduction of NH_3 volatilisation

A range of manure additives exist (Pain et al., 1990a) but only acidification is included here, as acid would normally be added shortly before application.

NH_3 volatilisation from slurry may be reduced by acidification of the slurry. The effect of acidifying different slurries to the same initial pH values may vary if they differ in alkalinity; if the alkalinity is high, pH may increase once again (Husted et al., 1991). For example, Bussink et al. (1994) added acid immediately prior to slurry application, giving a pH of 4.5. The pH of the applied slurry subsequently increased with 1–1.5 units after application, probably due to the dissolution of $CaCO_3$ after application. To get a significant reduction in emission, the amount of acid added has to be sufficient to reduce the alkalinity significantly e.g. by reducing pH to below 5–6 (Jarvis and Pain, 1990; Stevens et al., 1989, 1992).

5. Predicting NH_3 volatilisation

A range of empirical models of NH_3 volatilisation from slurry have been produced (Table 5). However, the underlying experiments were in each case to investigate one or two particular factors e.g. the effect of slurry DM on volatilisation and the models are used to illustrate the response to the relevant factor. Such models cannot be used for predictive purposes as part of day-to-day advice to farmers as there may be interactions between factors that are not accounted for in the models. For example, a significant interaction has been found between slurry DM and air temperature (Fig. 2). Horlacher and Marschner (1990) developed a predictive model in a form suitable for advisory use but this has not been tested against an independent data set. A limited test using data from (Sommer and Ersbøll, 1994) suggests that the model is unsuitable for general use in its present form (Fig. 6).

A re-analysis of data from a large number of earlier experiments with field-applied slurry is currently in progress (Søgaard et al., 2001). The preliminary results suggests that manure characteristics (animal species, TAN, %DM), climate (air temperature, rainfall, wind speed) and soil characteristics (soil type and wetness) all significantly affect NH_3 volatilisation from slurry. An empirical model based on multiple regression (www.alfam.dk) was able to explain a significant amount of the variance in the data but was still found to give meaningless results for realistic combinations of input data. It appears that the mechanisms controlling ammonia emissions from slurry are too complex for simple regression models to be reliable for the prediction of losses under the wide range of conditions found in European agriculture. Conversely, the cost of experimentation is likely to make the development of national or regional regression models prohibitively expensive. More complex, mechanistic models of ammonia emission from field-applied animal slurry exist (van der Molen et al., 1990; Génermont and Cellier, 1997) but demand input data that would be difficult to obtain in practice. The solution may

Table 5
Statistical models for predicting NH_3 emission from surface applied livestock slurry

Period	Equation	Definition of variables	Ref.
0–6 h	$L=13.0+0.031\exp(0.375T)$, $T<15$ °C	T is the mean air temperature (°C)	1
	$L=0.5+1.68T$, $T>15$ °C		2
6–12 h	$L=11.9+0.23T$	L is the volatilization in % of TAN remaining in slurry at start of period (Initial TAN-volatilized NH_3)	1
12–24 h	$L=-58.4+9.32\ \mathrm{pH}-0.28T_o$	T_o is the average temperature from slurry application till 24 h, pH is slurry pH before application	1
24 h–6 days	$L=23.6+1.19T$		1
0–6, 6–12, 12–24 h and 24 h–6 days	$F=L(0.38 + 0.014/[0.0086 + 1.66\exp(-0.654\mathrm{DM})]$	F is the NH_3 emission (% of TAN) in the four periods corrected for effect of variation in DM (%)	2
0–24 h	$F=5.42\times10^7 (NH_{3,G})+4.25*a+10.44*b$	$NH_{3,g}$ is calculated knowing the initial slurry pH and TAN, and average air temperature during 0–24 h, $a=1$ if the soil is a peat soil, $b=1$ if the soil is a heavy clay soil, $a=b=0$ if the soils are not peat or heavy clay soils	3
0–4 days	$F=3.61+1.58{*}^{TM}E_p{*}\ 10^7 (NH_{3,G})+12.09*a+17.87*b$	$*^{TM}E_p$ is the cumulated water evaporation during the 4 days	3
0–6 h	$F=7.347+31.466\ln(\mathrm{DM}) + 0.067Y$	Y is the mean solar radiation for the period (W m^{-2})	4
0–6 days	$\mathrm{pH}=7.87–0.52(\ln\phi)^2$	ϕ is the soil water content, l (H_2O) l^{-1}	5
0–6 h	$F_c=F*(-0.011+0.914x)$	Emission F_c from manure applied with trail hoses to a cereal crop, x is crop height (cm)	6

Sources: (1) Sommer et al. (1991); (2) Sommer and Olesen (1991); (3) Bussink et al. (1994); (4) Braschkat et al. (1997); (5) Sommer and Olesen (2000); (6) Calculated through linear regression of data from the articles of Sommer et al. (1991) and Sommer and Olesen (2000).

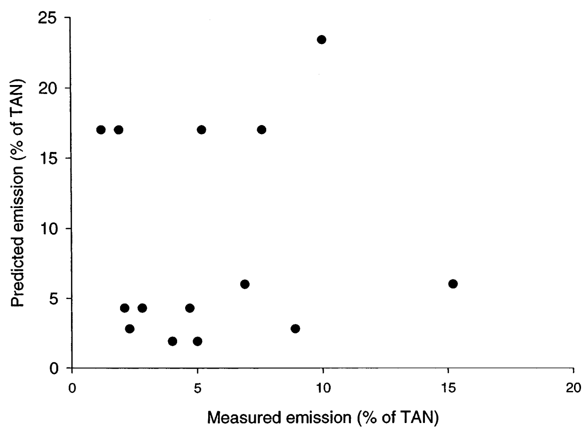

Fig. 6. NH_3 emission predicted by the model of Horlacher and Marschner (1990) versus measurements from Sommer and Ersbøll (1994).

lie in the development of hybrid models in which some representation of the underlying mechanisms is retained but in which the demand for inputs is reduced by the use of empirically derived functions.

There are too few data concerning NH_3 volatilisation from solid and liquid manures to permit the construction of a similar model for these manure types. Table 2, Table 3 and Table 4 give an indication of the magnitude of losses that can occur from such manures.

6. Conclusion

NH_3 emission is related to manure composition, soil conditions and the weather at the time of application. The factors most commonly found to affect losses are the concentration of total ammoniacal N and the manure dry matter, soil infiltration rate and meteorological variables such as air temperature, irradiation, wind speed and rainfall. The relative importance of each of these factors will vary from situation to situation. Statistical models derived from separate experiments cannot be merged to predict NH_3 emission as a function of weather and slurry composition because there are significant interactions between these factors.

Ammonia volatilisation can be reduced by incorporation of the animal slurry and farmyard manure. Incorporation should be as soon after the application as possible, especially for slurry. Application of slurry by trail hose is also an effective method to reduce emissions, provided a sufficiently well-developed crop is present. Injection is a very efficient reduction technique if the slurry is applied at a rate that can be contained in the furrows made by the injector tines.

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