

Management Factors Affecting Ammonia Volatilization from Land-Applied Cattle Slurry in the Mid-Atlantic USA

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ABSTRACT

Ammonia (NH_3) volatilization commonly causes a substantial loss of crop-available N from surface-applied cattle slurry. Field studies were conducted with small wind tunnels to assess the effect of management factors on NH_3 volatilization. Two studies compared NH_3 volatilization from grass sward and bare soil. The average total NH_3 loss was 1.5 times greater from slurry applied to grass sward. Two studies examined the effect of slurry dry matter (DM) content on NH_3 loss under hot, summer conditions in Maryland, USA. Slurry DM contents were between 54 and 134 g kg^{-1} . Dry matter content did not affect total NH_3 loss, but did influence the time course of NH_3 loss. Higher DM content slurries had relatively higher rates of NH_3 volatilization during the first 12 to 24 h, but lower rates thereafter. Under the hot conditions, the higher DM content slurries appeared to dry and crust more rapidly causing smaller rates of NH_3 volatilization after 12 to 24 h, which offset the earlier positive effects of DM content on NH_3 volatilization. Three studies compared immediate incorporation with different tillage implements. Total NH_3 loss from unincorporated slurry was 45% of applied slurry NH_4^+-N , while losses following immediate incorporation with a moldboard plow, tandem-disk harrow, or chisel plow were, respectively, 0 to 3, 2 to 8, and 8 to 12%. These ground cover and DM content data can be used to improve predictions of NH_3 loss under specific farming conditions. The immediate incorporation data demonstrate management practices that can reduce NH_3 volatilization, which can improve slurry N utilization in crop-forage production.

THE collection of dairy manure as a semi-liquid slurry of urine, feces, washing water, and bedding material is a common practice in the USA. Farm N budgets indicate that a large proportion of N consumed by intensively managed dairy cattle is contained in collected manure (Bacon et al., 1990; Meisinger and Thompson, 1996). Generally, 40 to 50% of N in cattle slurry is in the labile form of ammonium N (NH_4^+-N); the remainder is in much less labile, organic compounds (Beauchamp and Paul, 1988). Slurry NH_4^+-N represents a large pool of plant-available N that, if used effectively, could appreciably reduce mineral N fertilizer requirements for crop production.

Large and variable N loss by ammonia (NH_3) volatilization occurs following land application of cattle slurry (Pain and Thompson, 1988; Jarvis and Pain, 1990). Commonly, 30 to 70% of slurry NH_4^+-N is lost within a week of application (Pain and Thompson, 1988). These large N losses are an agronomic problem because of uncertainty as to the amount of slurry NH_4^+-N retained in soil for crop-forage production. They can also create

environmental problems by contributing to N enrichment of nearby surface waters and natural terrestrial ecosystems (van Breemen and van Dijk, 1988; Schulze et al., 1989; Fisher and Oppenheimer, 1991; Valigura et al., 1994).

Farmers, advisors, and environmental managers require information that (i) quantifies NH_3 volatilization from slurry applications, (ii) identifies major factors influencing these losses, and (iii) suggests practical methods of control. For the Mid-Atlantic region of the USA, unlike northwestern Europe (e.g., Pain and Thompson, 1988; Jarvis and Pain, 1990, 1997; Nielsen et al., 1991), there is currently very little quantitative data on NH_3 loss following slurry application under field conditions (Thompson et al., 1997).

Published research data have been obtained from either grassland or arable soils. One English study (Thompson et al., 1990a) directly compared these two surfaces and reported that losses were 50% greater from grassland. To assist with "customizing" NH_3 volatilization loss factors for extension advice, and for more accurate extrapolation of research data, data from direct comparisons of NH_3 volatilization from arable and grassland soils are needed. The dry matter (DM) content of cattle slurry positively affects NH_3 volatilization (Sommer and Olesen, 1991; Moal et al., 1995) under cool northwestern European conditions. However, it is uncertain whether DM will similarly affect NH_3 volatilization under summer Mid-Atlantic conditions, where temperatures can be much higher.

Various methods have been shown to reduce NH_3 loss following slurry application to soils (e.g., injection, banded application, subsequent irrigation, acidification; see Jarvis and Pain, 1990). However, one of the most practical methods for U.S. livestock farms, where corn (*Zea mays* L.) is commonly grown, may be incorporation into arable soil following conventional surface application. As NH_3 volatilization is most rapid immediately after slurry application (Thompson et al., 1987), incorporation must be carried out as soon as possible to minimize NH_3 loss. Information is required on the relative effectiveness of common tillage implements when used to incorporate cattle slurry immediately after surface application to arable land.

A series of field studies were conducted to assess the effect of the following factors on NH_3 volatilization following cattle slurry application: (i) grass cover compared with bare soil, (ii) slurry dry matter content, and (iii) immediate incorporation with three different cultivation implements (tandem disk-harrow, chisel plow, and moldboard plow). As surface crusting was a charac-

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Abbreviations: DM, dry matter; GC, ground cover; II, immediate incorporation.

teristic of the field soil used, the effect of surface crusting was also examined.

MATERIALS AND METHODS

Seven field studies were conducted to examine factors affecting NH_3 volatilization following land application of dairy cattle slurry (Table 1). Two of the studies examined the effect of grass cover vs. bare soil. Two other studies examined the influence of slurry dry matter content, one in combination with the effect of soil-surface crusting. Three studies examined NH_3 losses as affected by immediate incorporation with different tillage implements.

Field Site

The studies were conducted at the USDA Agricultural Research Service Beltsville Agricultural Research Center (BARC), in Beltsville, Maryland, USA. The soil on the study sites has a silty-loam surface texture and an internal drainage classification of moderately well-drained. The soil is classified as a Codorus silt loam (fine-loamy, mixed, active, mesic, Fluvaquentic Dystrudept). Some relevant properties of the soil (0–10 cm) are pH = 6.0 (1:1 in water), sand = 35%, clay = 20%, silt = 45%, total C = 11.1 g kg⁻¹, total N = 0.93 g kg⁻¹, cation exchange capacity = 14.5 cmol kg⁻¹, bulk density = 1.35 g cm⁻³, and field capacity water content = about 300 g kg⁻¹. This soil is prone to surface crusting, especially after rainfall on a recently tilled soil. The experimental site consisted of areas of bare soil and well-established grass sward.

Ammonia Volatilization Measurement

The system of small wind tunnels used for the collection of volatilized NH_3 was very similar in design and size to that described by Lockyer (1984). The system consisted of six individual wind tunnel units. Each wind tunnel unit has two parts: (i) a transparent section formed from polycarbonate sheet, flexed and pinned to the ground along each edge to form an inverted "U"-shaped canopy covering an area of 1 m² (2.0 × 0.5 m), and (ii) a steel duct of circular section of 40 cm i.d., containing an electrically powered fan blade and motor, to draw air through the canopy section. The canopy section was placed over a 1-m² (2.0 × 0.5 m) treated plot, directing all NH_3 volatilized from the plot surface to the steel duct section where a measured proportion of air flow was sampled.

The speed of the fan in the steel duct section was manually adjusted with a variable voltage controller to maintain the air velocity at a target value of 1 m s⁻¹. Air velocity within each tunnel was measured every 10 s using a TSI (St. Paul, MN) hot-wire anemometer positioned centrally in the forward part of the steel duct with output recorded on a Campbell Scientific (Logan, UT) 21X data logger. The relationship between air velocity and total air flow within the tunnels had been previously established using a balometer.

The NH_3 concentration of air entering and leaving the transparent canopy section, of each tunnel, was sampled with gas washing bottles containing 0.002 mol L⁻¹ H_3PO_4 . The air entering the canopy was sampled with 125-mL bottles containing 80 mL of the acid solution; the air leaving was sampled with 250-mL bottles containing 120 mL of acid solution. Air entering the steel duct section from the canopy was sampled with a star-shaped sampler system, with six arms of 19 cm length, located 20 cm in front of the fan blade in the steel duct. The six arms were joined at a central hub from where sampled air was drawn into the outlet acid trap. Along each arm of the sampler system were three holes, at distances of 7, 14, and 18 cm with corresponding diameters of 3.0, 4.0, and 4.4 mm. The six-arm sampler was designed to ensure an even sampling of the total air stream in the steel duct (D. Lockyer, personal communication, 1996).

Each acid trap was connected to a small pump and a flow meter. The flow meters for the inlet and outlet air were set at 4 and 5 L m⁻¹, respectively. At the end of each sampling interval, both acid traps on each tunnel were replaced with fresh bottles of acid. The exposed H_3PO_4 solutions were then made up to known volumes and stored at 3°C prior to analysis for $\text{NH}_4^+\text{-N}$ with a Lachat (Milwaukee, WI) flow injection analyzer system, using the salicylate method (Kempers and Kok, 1989).

A commercial power hookup provided electrical energy for the tunnel motors, hot-wire anemometer systems, and small pumps.

The rate of NH_3 volatilization, for each time period, for each tunnel was calculated as follows:

- (i) $\text{NH}_3\text{-N}$ concentration in the inlet (NH_3 concentration_{IN}) and outlet air (NH_3 concentration_{OUT}) = acid $\text{NH}_4^+\text{-N}$ concentration × acid volume / (acid trap air flow rate × time),
- (ii) Increase in air $\text{NH}_3\text{-N}$ concentration (ΔNH_3 concentration) = NH_3 concentration_{OUT} - NH_3 concentration_{IN},
- (iii) Total volume of air passing over treated soil (Volume_{TOTAL}) = $f_{\text{TUNNEL}} \times$ average air velocity × time, where f_{TUNNEL} is a calibration function for each tunnel,
- (iv) Rate = (ΔNH_3 concentration × Volume_{TOTAL}) / (treated area × time)

Rate of NH_3 volatilization data are generally expressed in units of kg N ha⁻¹ h⁻¹ or g N ha⁻¹ h⁻¹. In Study DM1, because of slight differences in the slurry $\text{NH}_4^+\text{-N}$ application rate between different DM content slurries, NH_3 volatilization rate data are expressed as percent applied slurry $\text{NH}_4^+\text{-N}$ lost ha⁻¹ h⁻¹. Total and cumulative loss data are expressed as percent applied slurry $\text{NH}_4^+\text{-N}$ lost, for all studies. When presented graphically, NH_3 volatilization data are presented in the mid-point of the sampling interval.

Following slurry application, the tunnels were immediately placed on the treated plots, and measurements commenced within 5 min. The cover sections remained in place for the

Table 1. For each of the seven studies, the treatments examined, the date the study commenced, and the number of days for which measurements were made.

Study	Treatments	Date commenced	Number of days measurements were made
GC1	grass cover vs. bare loose soil	9 June 1997	4
GC2	grass cover vs. bare crusted soil	26 June 1997	4
DM1	six different dry matter (DM) contents	8 July 1997	3
DM2	three different DM contents on firm and loose soil surface	16 July 1997	4
I1	immediate incorporation with different implements	31 July 1997	5
I2	immediate incorporation with different implements	7 Aug. 1997	5
I3	immediate incorporation with different implements	26 Aug. 1997	5

duration of each study. Wind barriers were placed both in front of and behind each tunnel to reduce the effect of ambient wind on air velocity within the tunnel. The barriers consisted of either sheets of plastic stretched between vertical wooden posts, or sections of plywood held upright by metal pegs.

Slurry Treatments

The cattle slurries used in the studies were obtained from housed dairy cattle at BARC. The cattle were fed a diet based on corn silage. A small amount of sawdust, which was used as bedding, would have been contained in the slurry. The slurries used in the two studies examining the effect of dry matter content (Studies DM1 and DM2) were collected 24 to 48 h prior to application. The different slurry dry matter content treatments were prepared the day before commencing the studies. For the other studies, fresh slurry was collected during the 24-h period prior to application.

Descriptions of the treatments examined in each study, the dates they began, and the study duration are given in Table 1. Relevant details of the composition of the slurries are given in Table 2. Details of the slurry, $\text{NH}_4^+\text{-N}$, and total N application rates are provided in Table 3.

For the studies examining the effects of ground cover (Studies GC1 and GC2) and dry matter content (Studies DM1 and DM2), slurry was applied using hand-held watering cans. The slurry was poured onto a flat piece of wood, held just above the ground, to increase spreading uniformity.

In Studies GC1, DM1, and DM2, 8 L of slurry was applied to plots measuring 2.0 by 0.5 m, giving an application rate equivalent to $80 \text{ m}^3 \text{ ha}^{-1}$ (Table 3). In Study GC2, 8 L of slurry was applied to a plot measuring 1.75 by 0.5 m, giving an application rate equivalent to $91 \text{ m}^3 \text{ ha}^{-1}$ (Table 3). The shorter plot was used in Study GC2 to ensure that all of the applied slurry was well within the tunnel cover when rain threatened.

For the studies examining immediate incorporation (Studies II1, II2, and II3), slurry was applied with a tractor-pulled Houle (Drummondville, QC, Canada) EL 54-3600 tanker with a low trajectory spreading bar (40 cm above ground). One nozzle was used to apply slurry in a 2.0-m-wide band. The actual application rate for each immediate incorporation study (Table 3) was determined by weighing the slurry collected in trays placed on the ground, in a position adjacent to and downwind from the experimental plots.

Ground Cover Studies

Studies GC1 and GC2 examined the effect of grass cover compared with bare soil on NH_3 loss following slurry applica-

tion. Slurry was applied to both bare soil and to a well-established tall fescue (*Festuca arundinacea* L. cv. Kentucky 31) grass sward, which was cut to a height of approximately 3 cm. In both studies, the bare soil was free of plant material, two tunnels (duplicates) were used for each treatment, and measurements were made for 4 d.

In Study GC1, the surface of the bare soil was cultivated, using a hand rake, prior to slurry application to break up a surface crust and provide a tilled soil surface. Slurry was applied at 1430 h on 9 June 1997. The acid traps were changed after 3, 6, 19, and 24 h; thereafter, they were changed two or three times per 24-h period.

In Study GC2, the crusted bare soil was not raked prior to slurry application. Slurry was applied at 0830 h on 26 June 1997. The acid traps were changed after 3, 6, 12, and 24 h; thereafter, they were changed two or three times per 24-h period.

Dry Matter Studies

Study DM1 examined the effect of slurry dry matter content on NH_3 volatilization following slurry application to bare soil that had been raked prior to slurry application. The different DM contents (Table 2) were obtained by sequentially sieving slurry through 12.7-, 1.0-, and 0.5-mm sieves, and then adding the collected solid material, in different ratios, to the sieved or raw slurry. This procedure produced slurries with a range of DM contents, but with similar $\text{NH}_4^+\text{-N}$ and total N contents (Table 2). Dry matter contents of the raw and sieved slurry were 117 and 54 g kg^{-1} . Slurry was applied at 1400 h on 8 July 1997. One tunnel was used for each of the six treatments. The acid traps were changed after 3, 6, 18, and 24 h; thereafter, they were changed two or three times per 24-h period. Measurements were made for 3 d.

Study DM2 examined the effects of slurry DM content and surface soil crusting on NH_3 volatilization following slurry application. Three slurries with different DM contents were applied to soil that had either a surface crust or a loose soil surface. The slurry DM contents were 56, 96, and 113 g kg^{-1} (Table 2); these corresponded to, respectively, sieved slurry (0.5 mm), sieved slurry with some solids addition, and raw slurry. The crusted soil had a surface crust that had formed naturally, and the loose surface soil was hand-raked immediately prior to applying the slurry treatments. Slurry was applied at 0900 h on 16 July 1997. One tunnel was used for each of the six treatments. The acid traps were changed after 2, 4,

Table 2. Nitrogen, dry matter (DM), and pH characteristics of slurries used in seven studies.

Study	DM content	$\text{NH}_4^+\text{-N}$ content	Total N content	pH
	g kg^{-1}	g N L^{-1}		
GC1	75	0.6	2.3	6.8
GC2	102	0.8	2.5	6.9
DM1	54	1.2	3.6	7.1
	74	1.2	3.5	7.1
	94	1.1	3.7	7.1
	105	1.1	3.5	7.1
	117	1.1	3.4	7.0
	134	1.1	3.6	7.0
DM2	56	1.1	4.1	6.9
	96	1.1	4.1	6.9
	113	1.1	4.1	6.8
II1	84	0.8	2.8	6.8
II2	90	0.9	2.9	7.0
II3	108	1.7	4.5	6.9

Table 3. Slurry and equivalent $\text{NH}_4^+\text{-N}$ and total N application rates in seven studies. Slurry dry matter (DM) content data included to identify slurries used in Studies DM1 and DM2.

Study	Slurry		N applied	
	DM content	Rate applied	$\text{NH}_4^+\text{-N}$	Total N
	g kg^{-1}	$\text{m}^3 \text{ ha}^{-1}$	kg N ha^{-1}	
GC1		80	48	185
GC2		91	74	232
DM1	54	80	97	292
	74	80	98	278
	94	80	90	295
	105	80	90	278
	117	80	89	275
	134	80	88	288
DM2	56	80	90	327
	96	80	90	326
	113	80	90	326
II1		32	26	89
II2		36	32	104
II3		50	86	221

6, 8, 12, and 24 h; thereafter, they were changed two or three times per day. Measurements were made for 4 d.

Immediate Incorporation Studies

Studies II1, II2, and II3 examined the effect of immediate incorporation on NH_3 volatilization. In each study, there were four treatments: surface-applied slurry that was not incorporated, and surface-applied slurry that was incorporated immediately after application with a tandem disk-harrow, a chisel plow, or a moldboard plow. The three studies commenced between 0900 and 1100 h on the dates indicated in Table 1. In each study, one incorporation treatment was randomly assigned to a new area of soil and a tunnel was randomly assigned to measure NH_3 loss. This protocol produced an immediate incorporation investigation with a completely randomized design with three replicates over time.

Slurry was applied in 5- by 2-m bands, using the tractor-pulled Houle tanker. Bands of slurry were parallel and separated laterally by 4 m, and longitudinally by 6 m. The 2- by 0.5-m canopy of each tunnel was placed across the band of slurry, 3 m from the beginning of the band. The prevailing wind direction was perpendicular to the bands and directly into the canopy openings. This arrangement of the slurry bands and tunnels ensured that the exhaust from one tunnel had minimal effect on the inlet NH_3 concentration of the other tunnels.

Immediate incorporation was achieved by having another tractor with the tillage implement follow several meters behind the slurry tanker. Immediately after each implement had incorporated the slurry, the tunnel was positioned across the band of treated soil, and measurements were begun. The sequence of slurry application, incorporation, tunnel placement, and start of measurement was completed for each treatment prior to applying slurry for another treatment. This ensured that measurements commenced within 5 min of treatment application. Once the tunnels were positioned, soil was placed along the edges of each tunnel cover and firmed to ensure a good seal between the tunnel cover and the underlying soil. Measurements were made for 5 d for each of the three studies. For the unincorporated surface-applied treatment, the slurry-treated soil to both sides of the tunnel was incorporated with a rotovator within 5 min of positioning the tunnel in order to minimize background concentrations of atmospheric NH_3 . The unincorporated treatment was always placed in the most downwind position at the beginning of the trials to minimize background NH_3 levels.

In Study II1, the acid traps were changed after 2, 4, 6, 10, 20, and 24 h; and thereafter, two or three times per day. In Study II2, they were changed after 2, 4, 6, 8, 10, 22, and 24 h; and thereafter, two or three times per day. In Study II3, they were changed after 2, 6, 10, and 24 h; and thereafter, one to three times per day.

Analysis of Slurries

The $\text{NH}_4^+\text{-N}$ content of the slurries was determined by distillation with MgO using 10 g of slurry, diluted to 250 mL with deionized water and distilled in a macro-Kjeldahl distillation unit. About 100 mL of distillate were collected in 4% boric acid and titrated with standardized sulfuric acid to determine $\text{NH}_4^+\text{-N}$. Total N was determined by Dumas combustion using a LECO (St. Joseph, MI) CHN analyzer. Slurry DM content was determined by drying 50 mL in a forced-air oven at 105°C for 48 h.

Measurement of Environmental Parameters

During each study, data on rainfall, soil and air temperature, atmospheric relative humidity (RH), and solar radiation were collected. Rainfall was sampled with a tipping bucket rain gauge, soil and air temperature with thermocouples, RH with a psychrometer, and solar radiation with a pyranometer; data was recorded on a Campbell 21X data logger. Where environmental data are presented in figures, the data are averaged for the corresponding time interval for which the rate of NH_3 volatilization was measured.

Statistical Analyses

The limited number of wind tunnels available for each study dictated the need for compromise between number of replicates and number of treatments. We chose to emphasize treatment comparisons with limited replication, that is, two replicate tunnels in Studies GC1 and GC2, and replicates in time for Studies II1–3. This approach has been commonly employed in studies using similar wind tunnel systems to examine NH_3 volatilization, using either nonreplicated comparisons (e.g., Lockyer et al., 1989; Sommer and Olesen, 1991; Sommer et al., 1991; Thompson et al., 1990b) or limited replication with duplicates or triplicates (e.g., Moal et al., 1995; Pain et al., 1989b; Sommer and Ersbøll, 1994; Thompson et al., 1990a). Statistical estimates of uncertainty, in the current studies, were calculated by pooling variances among replicated studies, or by pooling variances over time, as described below.

Methods Used to Analyze Rates of NH_3 Volatilization and Total NH_3 Loss

Treatment comparisons for the rate of NH_3 volatilization, in the GC and DM studies, used a pooled variance term obtained from the duplicated rate data for each sampling interval in Studies GC1 and GC2. Linear regression analysis of the standard deviation (SD) of NH_3 volatilization rates versus the mean rate, for each sampling interval, indicated a significant relationship ($r^2 = 0.39$) with larger SD values associated with larger means. Rates of NH_3 volatilization in Studies GC1 and GC2 were consequently separated into high-loss and low-loss groups to allow pooling of similar variance estimates (M. Kramer, personal communication, 2001). The criterion for separation was the relative concentration of NH_3 in outlet to inlet air. Data were placed in the high-loss group if the NH_3 concentration of the outlet air was at least ten times that of the inlet air. The high-loss group contained NH_3 volatilization rates of at least 100 g $\text{NH}_3\text{-N ha}^{-1} \text{ h}^{-1}$. The pooled variance for the high-loss group (23 df) yielded a SD of $\pm 105 \text{ g N ha}^{-1} \text{ h}^{-1}$, and that of the low-loss group (21 df), a SD of $\pm 15 \text{ g N ha}^{-1} \text{ h}^{-1}$. The pooled variance used to examine the rate variable percent of applied $\text{NH}_4^+\text{-N lost ha}^{-1} \text{ h}^{-1}$ in Studies DM1 and DM2 was calculated using the same approach, using data from Studies GC1 and GC2 after expressing the results on a percentage loss basis. Least significant differences (LSD) for comparing rates of NH_3 volatilization between treatments for individual sampling intervals in the GC and DM studies used the appropriate pooled variance values referred to above.

Statistical analysis of total NH_3 loss (as percent of applied slurry $\text{NH}_4^+\text{-N lost}$) was conducted by calculating a pooled variance term from those studies that had duplicates or triplicates. Specifically, the residual mean square from Studies GC1 and GC2 (each with 2 df) was pooled with the residual mean square from Studies II1, II2, and II3 (with 7 df) after confirming variance homogeneity using F tests (Snedecor and Cochran, 1980). The II1, II2, and II3 studies contributed 7 df to the pooled variance because the surface-applied treatment of

II2 was not included, due to a loose vacuum line on the outlet air sampling pump, which produced an unreliable data point. The resulting pooled variance (11 df) of 15.6 (SD of $\pm 4\%$) was used to calculate the LSD values for the treatment comparisons of total NH_3 loss (as percent of applied slurry $\text{NH}_4^+\text{-N}$) for the GC and DM studies.

Analysis of Individual Studies

Treatment comparisons in the two ground cover studies used the pooled variance terms for rate of NH_3 volatilization ($\text{g N lost ha}^{-1} \text{ h}^{-1}$) and total NH_3 loss (percent of applied slurry $\text{NH}_4^+\text{-N lost}$) described above. The corresponding LSD values for the rate of NH_3 volatilization in the high-loss group at $P \leq 0.05$ and $P \leq 0.01$ were 218 and 295 $\text{g N ha}^{-1} \text{ h}^{-1}$, respectively. The LSD values for the rate of NH_3 volatilization in the low-loss group at $P \leq 0.05$ and $P \leq 0.01$ were 32 and 43 $\text{g N ha}^{-1} \text{ h}^{-1}$, respectively. The LSD values for total NH_3 loss, over the duration of the study, at $P \leq 0.01$ and $P \leq 0.05$ were, respectively, 12.0 and 8.7% of applied slurry $\text{NH}_4^+\text{-N}$.

In the unreplicated DM1 and DM2 studies, treatment comparisons for rate of NH_3 volatilization (percent of applied $\text{NH}_4^+\text{-N lost ha}^{-1} \text{ h}^{-1}$) and total NH_3 loss (percent of applied slurry $\text{NH}_4^+\text{-N lost}$) used the appropriate pooled variance terms described previously. The LSD values for the rate of NH_3 volatilization for high-loss periods were, respectively, 0.6 and 0.8% of applied $\text{NH}_4^+\text{-N lost ha}^{-1} \text{ h}^{-1}$ at $P \leq 0.05$ and $P \leq 0.01$. In Study DM2, which had a complete factorial treatment design, the previously mentioned, 11 df pooled variance term for total $\text{NH}_3\text{-N lost}$ was used in an analysis of variance (ANOVA) to test for treatment effects. This allowed testing of the main effects of slurry DM content (three levels), soil surface condition (two levels), and the interaction of these two factors. Linear regression analyses were also used to examine the effects of slurry DM content on the rate of NH_3 volatilization and on the total loss in specific time periods. Because of the limited replication, and the field nature of these studies, a statistically significant level of probability of $P \leq 0.10$ was used for interpreting these regression analyses.

The three immediate incorporation studies were combined and analyzed as a single investigation using total loss expressed as percent of applied slurry $\text{NH}_4^+\text{-N}$, with three replicates in time. A one-way ANOVA with an arc sine transformation was used to compare the tillage treatments using the 7 df residual mean square term from the combined three immediate incorporation studies. The arc sine transformation is recommended for comparing percentage data containing values close to zero (Snedecor and Cochran, 1980). The unincorporated surface-applied treatment had only two replicates due to a loose vacuum hose as noted above.

RESULTS

Ground Cover Studies

Rates of NH_3 volatilization from slurry applied to grass sward were consistently higher than from bare soil, although the differences were relatively small (Fig. 1). In Study GC1 (Fig. 1a), differences in the rate of NH_3 volatilization were significant ($P \leq 0.05$) up to 24 h, but not significant thereafter. In Study GC2 (Fig. 1b), differences were highly significant ($P \leq 0.01$) up to 6 h, but not significant thereafter.

Consistently greater rates of NH_3 volatilization from the grass surface caused appreciable differences in cumulative loss in both studies (Fig. 2). Most of the differ-

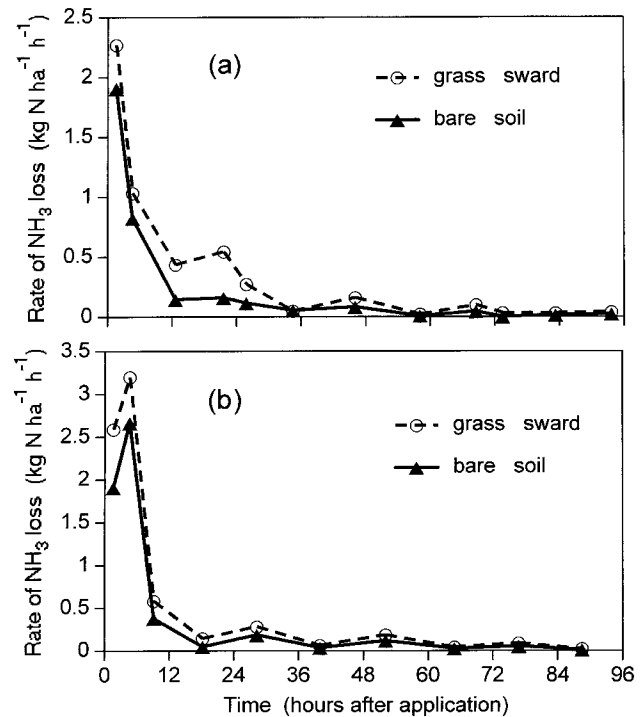


Fig. 1. (a) Study GC1 and (b) Study GC2. Rate of NH_3 volatilization from grass sward and bare soil following surface application ($80 \text{ m}^3 \text{ ha}^{-1}$) of cattle slurry.

ence in total loss between the two surfaces occurred within 24 h of slurry application (Fig. 2).

Total 4-d NH_3 volatilization loss in Study GC1 was 49% of applied slurry $\text{NH}_4^+\text{-N}$ from grass and 29% from bare soil (Fig. 2a); this difference was highly significant

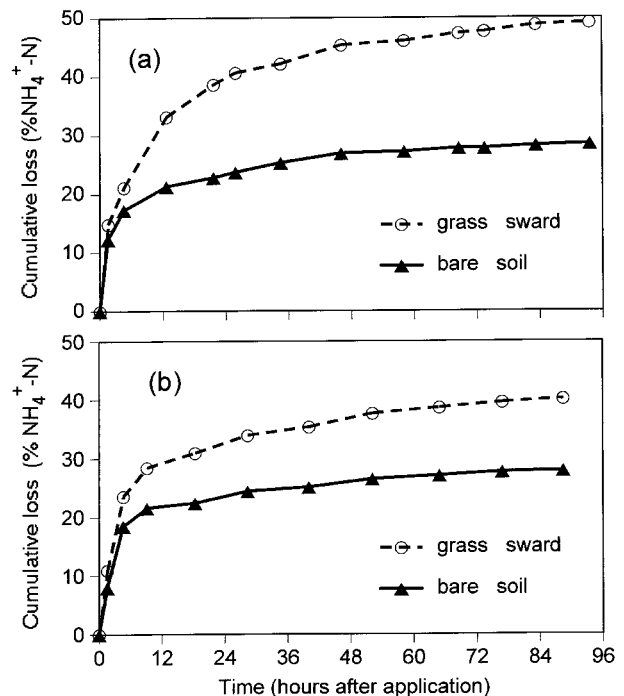


Fig. 2. (a) Study GC1 and (b) Study GC2. Cumulative loss of N by NH_3 volatilization (percent applied slurry $\text{NH}_4^+\text{-N lost}$) with time, following surface application of cattle slurry to grass sward or bare soil.

($P \leq 0.01$). Total NH_3 loss in Study GC2 was 40% of applied slurry $\text{NH}_4^+\text{-N}$ from grass and 28% from bare soil (Fig. 2b); this difference was also highly significant. The total 4-d loss from grass was 1.7 times that from loose bare soil in Study GC1, and 1.4 times that from crusted bare soil in Study GC2.

In Study GC1, air temperature during the first 6 h averaged 25°C , and thereafter was 12 to 30°C . In Study GC2, air temperature averaged 31°C during the first 6 h, and then was 15 to 30°C . These temperatures are generally typical of this time of the year.

Dry Matter Study 1

The hourly rate of NH_3 volatilization is plotted against time in Fig. 3a, for four of the six different DM content slurries. The rate is expressed as percent applied slurry $\text{NH}_4^+\text{-N}$ lost $\text{ha}^{-1} \text{h}^{-1}$ to adjust for slight differences in the rates of $\text{NH}_4^+\text{-N}$ applied with the different DM content slurries (Table 3).

The 0- to 3-h rate of NH_3 volatilization was very similar for the four slurries (Fig. 3a). Subsequently, NH_3 volatilization from the two more dilute slurries (74 and 94 g kg^{-1} DM) exhibited (i) a more rapid decline in rate during the period 3 to 18 h, (ii) appreciably higher rates during the 18- to 28-h period, and (iii) slightly higher rates throughout the remainder of the study (28-72 h) (Fig. 3a). During the first day after application, diurnal variation in the rate of NH_3 volatilization was observed from the two more dilute slurries, but not from the two higher DM content slurries (Fig. 3).

The 54 g kg^{-1} DM content slurry had a similar general pattern of NH_3 volatilization to the 74 g kg^{-1} DM content slurry but maintained lower rates throughout (data

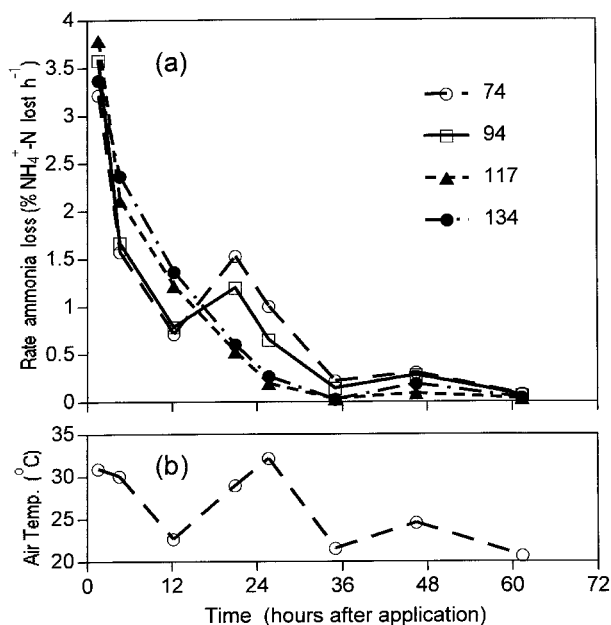


Fig. 3. Study DMI. (a) Rate of NH_3 volatilization from cattle slurries with dry matter (DM) contents of 74, 94, 117, and 134 g kg^{-1} following surface application ($80 \text{ m}^3 \text{ ha}^{-1}$), on 8 July 1997. Rate of NH_3 loss is expressed as percent of applied slurry $\text{NH}_4^+\text{-N}$ lost with time. (b) Air temperature data for the experimental period.

not presented). Ammonia volatilization from the 105 g kg^{-1} DM content slurry followed a similar pattern to the 117 g kg^{-1} DM content slurry but with consistently lower rates (data not presented).

Linear regression of rate of NH_3 volatilization by slurry DM content (Fig. 4, Table 4) indicated a positive but nonsignificant relationship ($r^2 = 0.49$, $P > 0.10$) for the 0- to 3-h interval, a highly significant positive relationship ($P \leq 0.01$) for the 3- to 6- and 6- to 18-h intervals, and a significant, negative relationship ($P \leq 0.10$) in four of the five subsequent time intervals. The effect of slurry DM content on the rate of NH_3 volatilization changed from positive to negative approximately 18 h after application.

There was a strong, positive, linear relationship (Fig. 5) between total NH_3 loss occurring in the 0- to 18-h period and DM content ($r^2 = 0.94$, $P \leq 0.01$), and a significant, negative relationship for the 18- to 72-h period ($r^2 = 0.70$, $P \leq 0.05$). The total NH_3 loss during the 72-h study was not significantly related to DM content ($r^2 = 0.09$, $P > 0.10$). Thus, the more prolonged negative effect of DM content on the rate of NH_3 volatilization during the 18- to 72-h period, when rates were relatively low, offset the positive effect during the 0- to 18-h period when rates were generally much higher.

Average air temperature during the first 6 h after

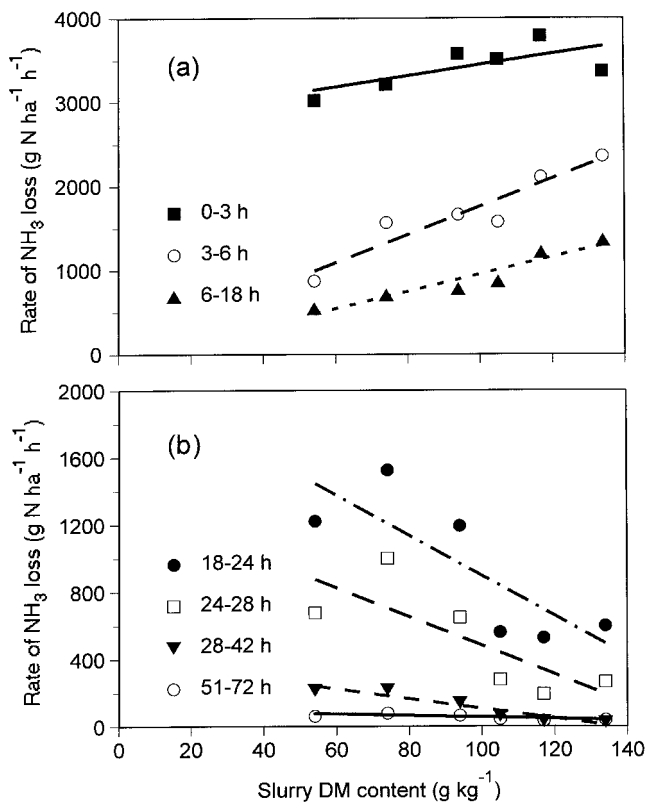


Fig. 4. Study DMI. (a) Relationships between rate of NH_3 volatilization and cattle slurry dry matter (DM) content for the 0- to 3-, 3- to 6-, and 6- to 18-h periods after slurry application, and (b) relationships between rate of NH_3 volatilization and slurry DM content for the 18- to 24-, 24- to 28-, 28- to 42-, and 51- to 72-h periods after slurry application. Regression equations and coefficients are presented in Table 4.

Table 4. Study DM1. Results of linear regression analyses examining the relationship between rate of NH₃ volatilization (percent applied slurry NH₄⁺-N lost h⁻¹) with dry matter (DM) content, for individual time intervals.

Time interval	Linear regression parameters		
	Equation	Regression coefficient (r ²)	Statistical significance
h			
0-3	rate = 0.0653DM + 2.79073	0.485	NS†
3-6	rate = 0.1666DM + 0.09424	0.887	0.01
6-18	rate = 0.1020DM - 0.06287	0.901	0.01
18-24	rate = -0.1190DM + 2.08917	0.650	0.10
24-28	rate = -0.0855DM + 1.33834	0.613	0.10
28-42	rate = -0.0291DM + 0.39887	0.896	0.01
42-51	rate = -0.0180DM + 0.38116	0.380	NS
51-72	rate = -0.0047DM + 0.10238	0.583	0.10

† Not significant.

application was 31°C, for the next 18 h it was 25°C, and for the remaining 48 h was 26° (Fig. 3b).

Dry Matter Study 2

On both the crusted and loose soil surfaces, higher total 4-d NH₃ volatilization loss was determined from the most dilute slurry (56 g kg⁻¹ DM) (Fig. 6). Linear relationships between the total loss and slurry DM content were not significant (*P* > 0.05) on either soil surface.

Rate of NH₃ volatilization can be assessed from the slopes of the cumulative loss curves (Fig. 6). In the first 12 to 24 h after application, rates of NH₃ volatilization from the most dilute slurry were initially less than, or similar to, that from other two slurries. During the 24- to 48-h period on the crusted soil surface, and the 12- to 48-h period on the loose surface, rates were consistently highest from the most dilute slurry. After 48 h, the rates were very small from all slurries, and differences were inconsistent. Linear regression analysis did not show consistent significant relationships between rate and DM content.

As in Study DM1, more of the total NH₃ loss occurred earlier from the higher DM content slurries. After 6 h on the loose soil surface, 44, 62, and 63% of the total

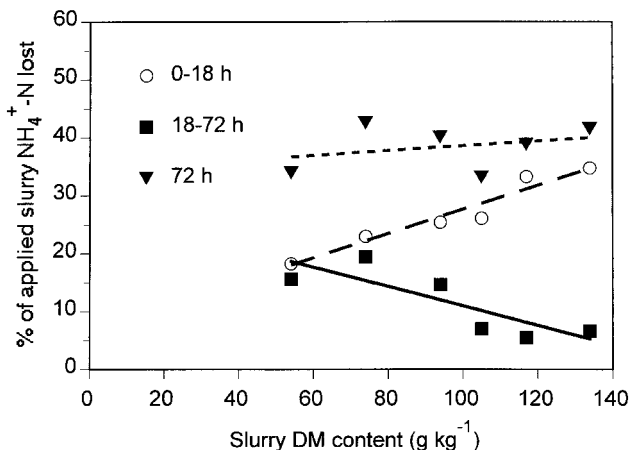


Fig. 5. Study DM1. Total NH₃ volatilization loss, expressed as percent of slurry NH₄⁺-N applied, in the 0- to 18-, 18- to 72-, and 0- to 72-h periods, after application, from cattle slurries with varying dry matter (DM) content.

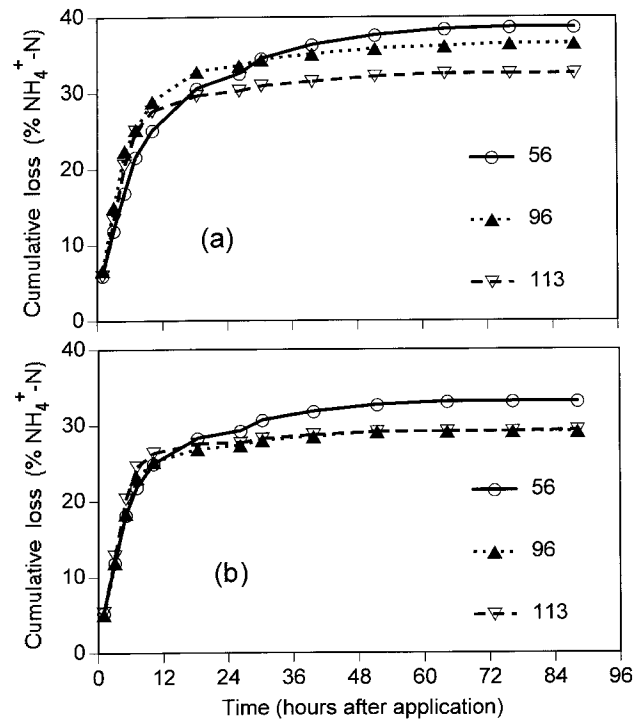


Fig. 6. Study DM2. (a) Cumulative loss (percent slurry NH₄⁺-N lost) with time for cattle slurries with dry matter (DM) contents of 56, 96, and 113 g kg⁻¹ following application to a crusted soil surface, and (b) cumulative loss (percent slurry NH₄⁺-N lost) with time for slurries with DM contents of 56, 96, and 113 g kg⁻¹ following application to a loose soil surface.

4-d loss had occurred from, respectively, the 56, 96, and 113 g kg⁻¹ DM content slurries. Corresponding values on the crusted soil surface were 55, 63, and 70%.

For each slurry DM content, the total NH₃ loss from the crusted soil surface was consistently higher than from the loose soil surface (Fig. 6). The average difference between total loss from the loose and crusted soil was 4.8% of applied slurry NH₄⁺-N, which was not statistically significant (*P* > 0.05). The effect of the interaction between slurry DM content and soil surface condition on total NH₃ loss was also not significant (*P* > 0.05).

The average loss from the three different DM content slurries on the crusted soil was significantly greater (*P* ≤ 0.05) than from the loose soil (6.3 vs. 5.3% of applied slurry NH₄⁺-N, respectively) during the first 2 h. The smaller loss on the loose soil was most likely due to greater initial infiltration on the looser soil surface. There were no consistent effects of soil surface condition after the initial 2 h.

The average air temperatures for Study DM2 during the first and second 12-h periods were 29 and 27°C. For the remaining 72 h, the average air temperature was 31°C.

Immediate Incorporation Studies

In each of the three studies, the total NH₃ loss from each of the three immediate incorporation treatments was much less than from the unincorporated slurry treat-

Table 5. Studies II1, II2, and II3. Total N loss by NH₃ volatilization over 5 d, from surface-applied cattle slurry that was not incorporated, or was immediately incorporated with a disk harrow, chisel plow, or moldboard plow.

Study	Applied slurry NH ₄ ⁺ -N lost by NH ₃ volatilization			
	Not incorporated	Disk harrow	Chisel plow	Moldboard plow
	%			
II1	38.7	5.8	7.6	0.3
II2	30.2 [†]	8.1	12.0	3.0
II3	52.4	2.2	8.1	0.8

[†] This value is regarded as an underestimate because of a loose suction line connection.

ment (Table 5). The average total loss from unincorporated surface-applied slurry, in Studies II1 and II3, was 46% of applied slurry NH₄⁺-N. The moldboard plow was the most effective implement, reducing the total NH₃ loss to negligible amounts (0.3–3.0% of applied slurry NH₄⁺-N). The total loss from the disk harrow treatment was of 2 to 8% of applied slurry NH₄⁺-N. The chisel plow was the least effective implement, with total losses of 8 to 12% of applied slurry NH₄⁺-N.

The ANOVA analysis indicated that the total loss from the moldboard plow and disk harrow treatments was significantly less than from the chisel plow treatment at the probability levels of $P \leq 0.01$ and $P \leq 0.05$, respectively. Total losses from the disk harrow and moldboard plow treatments were not significantly different ($P > 0.05$). In each of the three studies, the degree of reduction in NH₃ loss was positively related to the degree of soil inversion–mixing provided by each implement; the order being: moldboard plow > disk harrow > chisel plow.

Soil moisture data were not directly measured in these studies. However, rainfall records prior to the studies provided a qualitative indication of soil moisture status. Prior to Study II1, there was 18 mm of rain seven days before and 3 mm three days before the study. Study II2 commenced one week later, during which time there was no rain (i.e., quite dry soil conditions). Forty-six millimeters of rain fell six days before starting Study II3 (i.e., moist soil conditions). The largest losses from incorporated slurry were associated with the drier soil of Study II2, and the smallest losses with the wetter soil of Study II3. The larger NH₃ loss from the shallow-incorporated slurry in drier soil is consistent with greater gas exchange potential, between the soil air and the atmosphere, in drier soil.

DISCUSSION

The magnitude and the pattern of loss observed in these studies in the Mid-Atlantic region of the USA were generally consistent with directly measured field data for NH₃ loss from surface-applied cattle slurry in northwestern Europe (Thompson et al., 1987, 1990a,b; Pain et al., 1989a,b; Sommer and Olesen, 1991; Moal et al., 1995).

The total NH₃ loss from slurry applied to grass sward was 1.7 and 1.4 times that from bare soil in the two ground cover studies, giving an average value of 1.5.

The similarity of air temperatures following application suggests that any effect due to the different application times (1430 and 0830 h) of the two studies would be small in relation to the ground cover effect.

The results from the two ground cover studies are consistent with a 1.5-fold difference in an English study (Thompson et al., 1990a). Grass sward presumably enhances NH₃ loss by reducing the infiltration of slurry into soil, and the subsequent retention of NH₄⁺ ions on soil exchange sites. Crop residues similarly increase NH₃ loss following slurry applications (Döhler, 1991). These data demonstrate the need to consider the presence of grass sward or thick crop residues when considering NH₃ loss factors for manure management purposes. As a general guideline, it is suggested that NH₃ loss from cattle slurry surface-applied to grass sward be considered to be 1.5 times more than from bare soil.

Higher slurry dry matter content did not increase total NH₃ loss from surface-applied cattle slurry in Studies DM1 and DM2. This contrasted the positive effect of slurry DM content reported by Sommer and Olesen (1991) and Moal et al. (1995) working under more moderate temperature conditions in, respectively, Denmark and Brittany, France. In Study DM1, there was a strong positive effect of DM content on NH₃ volatilization for the first 18 h, followed by a clear negative effect during the remaining 54 h. The data from Study DM2 were generally supportive, with higher NH₃ volatilization rates from the most dilute slurry after 12 to 24 h on both loose and crusted soil surfaces.

The positive effect of slurry DM content on NH₃ volatilization during the first 12 to 24 h of the studies reported here is attributed to less infiltration into soil of the higher DM content slurries. The negative effect of slurry DM content on NH₃ volatilization after 12 to 24 h is attributed to more rapid crust formation on the slurry surface, and more rapid drying of the applied slurry. A surface crust and drier applied slurry increases physical resistance to NH₄⁺ and NH₃ transport within the slurry matrix, and to NH₃ release from the slurry surface (Thompson et al., 1990a,b). Visual observations were that the higher DM content slurries dried and produced surface crusts more quickly. The lack of diurnal increase in the rate of NH₃ volatilization from the higher DM content slurries on the day after application, and the occurrence of diurnal affects with the more dilute slurries, is consistent with this hypothesis (see Fig. 3).

It is suggested that the overall effect of increasing slurry DM content on total NH₃ volatilization loss depends on the relative influence of the contrasting effects of infiltration and surface crusting, and that prevailing weather conditions determine the balance between these two effects. Under mild climatic conditions, infiltration appears to be more influential with reduced infiltration promoting greater losses with high DM slurries (e.g., Sommer and Olesen, 1991; Moal et al., 1995). Under the hot summer conditions of the present studies, the two effects apparently balanced one another.

These data suggest that climatic conditions need to

be considered when predicting total NH_3 volatilization loss in relation to slurry DM content. This may be particularly relevant in regions of the USA where there are large seasonal changes in temperature.

Slurry DM content appreciably affected cumulative NH_3 loss in the first several hours after slurry application. Consideration of this effect of slurry DM content may improve prediction of NH_3 loss from slurry that is incorporated into soil several hours after surface application.

In the moist, loam-textured soil used, immediate incorporation with the moldboard plow, disk harrow, or chisel plow substantially reduced NH_3 loss in each of three studies. The degree of reduction was positively related to the degree of inversion. Klarenbeek and Bruins (1991) observed that NH_3 volatilization from pig slurry was directly related to the degree of soil inversion during immediate incorporation.

The results from the present studies demonstrate the potential for using immediate incorporation to substantially reduce NH_3 volatilization loss from surface slurry applications. However, for the development of extension recommendations, similar studies should be performed on a range of soil texture classes; soil moisture effects should also be considered.

The data from Study DM2 and the ground cover studies suggest that soil surface crusts do not appreciably influence total NH_3 loss. For management guidelines, it is suggested that surface soil crusts have only a small effect on NH_3 loss following slurry applications under warm climatic conditions.

CONCLUSIONS

Improving the N utilization from surface-applied slurries requires improved estimates of NH_3 volatilization. These improved estimates should be based on results from locally derived NH_3 loss data that use the soils, weather conditions, application techniques, and tillage equipment common to the region. Our late-spring and summer wind-tunnel studies, conducted in the Mid-Atlantic region of the USA, show that:

- (i) Ammonia losses were 1.7 and 1.4 times greater from slurry applied to grass sward than from slurry applied to bare soil. A factor of 1.5 is suggested when relating NH_3 loss from grassland soil to arable soil.
- (ii) In two studies conducted under hot summer conditions, slurry dry matter content did not influence total NH_3 loss.
- (iii) Immediate incorporation with a moldboard plow, disk harrow, or chisel plow, on a loam soil, reduced NH_3 loss to, respectively, 0 to 3, 5 to 8, and 8 to 12% of applied slurry $\text{NH}_4^+\text{-N}$; while unincorporated slurry lost 39 to 52% of applied slurry $\text{NH}_4^+\text{-N}$.
- (iv) A crusted soil surface did not appreciably influence NH_3 loss from surface application of cattle slurry in warm weather conditions.

ACKNOWLEDGMENTS

We thank Peter Zitter, Charlotte Schomberg, Juliette Cartron, and Jeff DeBeradinis for assistance with the field work, Richard Brown for assistance with the sample analyses, and David Hill for his work on the initial construction of the wind tunnels. The provision of, and assistance with, the Lachat analyzer from Greg McCarty is gratefully acknowledged. We thank the Soil Science department of the University of Maryland at College Park for analyzing slurry samples, and David Lockyer, formerly of IGER, United Kingdom for providing the dimensions of the sampling star system for the wind tunnels.

REFERENCES

- Bacon, S.C., L.E. Lanyon, and R.M. Schlauder, Jr. 1990. Plant nutrient flow in the managed pathways of an intensive dairy farm. *Agron. J.* 82:755-761.
- Beauchamp, E.G., and J.P. Paul. 1988. A simple model to predict manure N availability to crops in the field. p. 140-149. *In* J.H. Hansen and K. Henriksen (ed.) Nitrogen in organic wastes applied to soil. Academic Press, London.
- Döhler, H. 1991. Laboratory and field experiments for estimating ammonia loss from pig and cattle slurry following application. p. 132-140. *In* V.C. Nielsen et al. (ed.) Odour and ammonia emissions from livestock farming. Elsevier Appl. Sci., London.
- Fisher, D.C., and M. Oppenheimer. 1991. Atmospheric nitrogen deposition and the Chesapeake Bay estuary. *Ambio* 23:201-208.
- Jarvis, S.C., and B.F. Pain. 1990. Ammonia volatilization from agricultural land. *In* Proceedings no. 298. The Fertiliser Soc., London.
- Jarvis, S.C., and B.F. Pain (ed.) 1997. Gaseous nitrogen emissions from Grasslands. CAB Int., Wallingford, Oxon, UK.
- Kempers, A.J., and C.J. Kok. 1989. Re-examination of the determination of the determination of ammonium as the indophenol blue complex using salicylate. *Anal. Chim. Acta* 221:147-155.
- Klarenbeek, J.V., and M.A. Bruins. 1991. Ammonia emissions after land spreading of animal slurries. p. 107-115. *In* V.C. Nielsen et al. (ed.) Odour and ammonia emissions from livestock farming. Elsevier Appl. Sci., London.
- Lockyer, D.R. 1984. A system for the measurement in the field of losses of ammonia through volatilisation. *J. Sci. Food Agric.* 35: 837-848.
- Lockyer, D.R., B.F. Pain, and J.V. Klarenbeek. 1989. Ammonia emissions from cattle, pig and poultry waste applied to pasture. *Environ. Pollut.* 56:19-30.
- Meisinger, J.J., and R.B. Thompson. 1996. Improving nutrient cycling in animal agriculture systems. p. 92-110. *In* Proc. of the Animal Agric. and the Environ. Conf., Rochester, NY. 11-13 Dec. 1996. Northeast Regional Agric. Eng. Serv., Ithaca, NY.
- Moal, J.F., J. Martinez, F. Guiziou, and C.M. Coste. 1995. Ammonia volatilization following surface-applied pig and cattle slurry in France. *J. Agric. Sci. (Cambridge)* 125:245-252.
- Nielsen, V.C., J.H. Voorburg, and P. L'Hermite (ed.) 1991. Odour and ammonia emissions from livestock farming. Elsevier Appl. Sci., London.
- Pain, B.F., V.R. Phillips, C.R. Clarkson, and J.V. Klarenbeek. 1989a. Loss of nitrogen through ammonia volatilisation during and following the application of pig or cattle slurry to grassland. *J. Sci. Food Agric.* 47:1-12.
- Pain, B.F., and R.B. Thompson. 1988. Ammonia volatilization from livestock slurries applied to land. p. 202-210. *In* J.H. Hansen and K. Henriksen (ed.) Nitrogen in organic wastes applied to soil. Academic Press, London.
- Pain, B.F., R.B. Thompson, Y.R. Rees, and J.H. Skinner. 1989b. Reducing gaseous losses of nitrogen from cattle slurry applied to grassland by the use of additives. *J. Sci. Food Agric.* 50:141-153.
- Schulze, E.D., W. De Vries, M. Haugh, K. Rosen, L. Rasmussen, C.O. Tamm, and J. Nilsson. 1989. Critical loads for nitrogen deposition on forest ecosystems. *Water Air Soil Res.* 48:451-456.
- Snedecor, G.W., and W.G. Cochran. 1980. Statistical methods. 7th ed. Iowa State Univ. Press, Ames.
- Sommer, S.G., and A.K. Ersbøll. 1994. Soil tillage affects on ammonia

- volatilization from surface-applied or injected animal slurry. *J. Environ. Qual.* 23:493–498.
- Sommer, S.G., and J.E. Olesen. 1991. Effects of dry matter content and temperature on ammonia loss from surface-applied cattle slurry. *J. Environ. Qual.* 20:679–683.
- Sommer, S.G., J.E. Olesen, and B.T. Christensen. 1991. Effects of temperature, wind speed and air humidity on ammonia volatilization from surface applied cattle slurry. *J. Agric. Sci.* 117:91–100.
- Thompson, R.B., D. Morse, K.A. Kelling, and L.E. Lanyon. 1997. Computer programs that calculate manure application rates. *J. Prod. Agric.* 10:58–69.
- Thompson, R.B., B.F. Pain, and D.R. Lockyer. 1990a. Ammonia volatilization from cattle slurry following surface application to grassland. I. Influence of mechanical separation, changes in chemical composition during volatilization and the presence of the grass sward. *Plant Soil* 125:109–117.
- Thompson, R.B., B.F. Pain, and Y.J. Rees. 1990b. Ammonia volatilization from cattle slurry following surface application to grassland. II. Influence of application rate, wind speed and applying slurry in narrow bands. *Plant Soil* 125:119–128.
- Thompson, R.B., J.C. Ryden, and D.R. Lockyer. 1987. Fate of nitrogen in cattle slurry following surface application or injection to grassland. *J. Soil Sci.* 38:689–700.
- Valigura, R.A., J.E. Baker, J. Scudlark, and L.L. McConnell. 1994. Atmospheric deposition of nitrogen and contaminants to Chesapeake Bay and its watershed. p. 45–76. *In* S. Nelson and P. Elliott (ed.) *Perspectives on Chesapeake Bay, 1994: Advances in estuarine sciences*. Chesapeake Res. Consortium Publ. no. 147. Chesapeake Res. Consortium, Edgewater, MD.
- Van Breemen, N., and H.F.G. van Dijk. 1988. Ecosystem effects of atmospheric deposition of nitrogen in the Netherlands. *Environ. Pollut.* 54:249–274.