RESEARCH ARTICLE

Ammonia volatilization following surface application of raw and treated liquid swine manure

Martin H. Chantigny · J. Douglas MacDonald · Celine Beaupré · Philippe Rochette · Denis A. Angers · Daniel Massé · Léon-Étienne Parent

Abstract The treatment of liquid swine manure (LSM) is primarily intended to produce energy and/or decrease P concentration in the liquid fraction, but may have a simultaneous impact on its potential for N volatilization. We compared NH_3 volatilization in the field following surface application (May 2004; May 2005; September 2005) of untreated LSM and the liquid fraction of LSM (hereafter called treated LSM) that had undergone either natural decantation, filtration, anaerobic digestion, or anaerobic digestion + flocculation. Though most treatments increased pH and the proportion of total ammoniacal N (TAN) in LSM, the proportion of applied TAN lost as NH_3 was 22% lower with treated than untreated LSMs. Most likely, the increased infiltration rate of treated LSMs, associated with reduction in dry matter, compensated for increases in TAN and pH. Emissions of NH_3 on the day of application were correlated with LSM pH ($R^2 = 0.51$) and were the highest with the digested and the digested + flocculated LSMs. However, these LSMs generally emitted less NH_3 than the other LSMs on the following days. As a consequence, when the volatilization period was short (e.g., dry soil conditions), the proportion of applied N lost from the digested and the digested + flocculated LSMs was similar or higher than the filtered and decanted LSMs. In contrast, when the volatilization period was long, the digested and digested + flocculated LSMs emitted less NH_3 than the other treated LSMs. It can be concluded that LSM treatments tended to decrease NH_3 volatilization, compared to the untreated LSM; across application dates, the digested LSM most consistently reduced NH_3-N losses whereas the filtered LSM was the least efficient.

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Introduction

Interest for manure treatment and the number of treatment technologies are increasing worldwide. Benefits from manure treatment include energy production

(Massé et al. 1996) and partitioning of N and P in different fractions (Møller et al. 2000; Chantigny et al. 2008) allowing for more efficient management in the field. However, treatment affects several physical and chemical manure properties, and possible side-effects of treatments, such as increased gaseous N losses, must be assessed in the field to avoid pollution swapping.

A variety of treatments are used to separate dry matter from the liquid fraction of manure, including physical separation (Pain et al. 1978; Møller et al. 2000), chemical separation (Pain et al. 1990b, c; Powers and Flatow 2002), and biological treatments such as digestion and aeration (Massé et al. 1996; Rubæk et al. 1996; Mattila and Joki-Tokola 2003). Dry matter is reduced by as much as 80% in liquid animal manure depending on treatment type (Rubæk et al. 1996; Sommer et al. 2006; Chantigny et al. 2007, 2008). Reductions in dry matter can increase the infiltration of liquid manure into the soil, thereby decreasing the exchange of NH_3 with the atmosphere (Sommer and Olesen 1991; Braschkat et al. 1997; Mattila and Joki-Tokola 2003). However, treatments may also increase the proportion of N present as TAN by 10–50%, and the pH by as much as 0.8 units in the liquid fraction of manure (Pain et al. 1990c; Rubæk et al. 1996; Sommer and Jacobsen 1999; Sommer et al. 2006; Chantigny et al. 2007).

These contradictory effects of manure treatment on NH_3 volatilization combined with interactions with soil pH, exchange capacity (Whitehead and Raistrick 1992; Kirchmann and Lundvall 1993) and meteorological conditions (Adriano et al. 1974; Sommer and Olesen 1991; Van der Stelt et al. 2007) resulted in variable response of NH_3 losses to liquid swine manure (LSM) treatment (Pain et al. 1990b, c; Thompson et al. 1990; Sommer and Olesen 1991; Sommer et al. 2004; Chantigny et al. 2004, 2007; Balsari et al. 2008).

Assuming that NH_3-N can be preserved following application, LSM is an effective fertilizer for annual (Chantigny et al. 2008) and perennial (Chantigny et al. 2007) crops. Higher pH (Pain et al. 1990c; Rubæk et al. 1996; Sommer et al. 2006) and TAN (Sommer et al. 2003) in the liquid fraction of treated LSM, however, increase the potential to emit NH_3 once applied to the soil. In this study, we compared NH_3-N emissions from untreated LSM with those from the liquid fraction of LSM (hereafter called treated LSM) that had undergone physical separation by decantation

or filtration, or biological treatment by anaerobic digestion, with or without chemical flocculation. Volatilization losses were measured at three periods on the same soil but under varying meteorological conditions.

Materials and methods

Study site

The study was conducted at the research farm of the Institut de recherche et de développement en agro-environnement (IRDA) located near Québec City, Canada (latitude: 46° 05′, longitude: 71° 02′, altitude: 110 m). The mean annual temperature in the area of study is 4.2°C and the mean annual precipitation is 1,213 mm. The site was on a Le Bras series, silty clay loam (270 g clay kg^{-1}, 420 g silt kg^{-1}; loamy, mixed, frigid, Typic Humaquept) that had been cropped to barley (*Hordeum vulgare* L.), harvested in the fall of 2003, harrowed (0–10 cm) in spring 2004, prior to LSM application, and left fallow during the experiment to avoid possible interaction of LSM with standing crop or crop residues. Two of the trials were carried out in early spring (11 May 2004 and 9 May 2005), and the third trial was in the late summer (6 September 2005). In the month of May, average mean temperature is 11.6°C and precipitation is 106 mm; in September they are 12.5°C and 125 mm.

Manure collection, treatment, and analyses

Untreated LSM was obtained from a commercial farrow-to-finish hog operation with a slatted-floor barn, produced by animals fed a corn-soybean based diet. The LSM was collected by composite subsampling during the emptying of the transfer tank after 48 h of accumulation, and homogenized by thorough stirring. A portion of the homogenized LSM was put aside in three 1-m^3 plastic containers and stored at ~15°C for 1 month. One container was kept as is and labelled "untreated LSM", whereas the upper half of the other containers was siphoned out, combined in an empty container, and labelled "decanted LSM". One part of the homogenized LSM was transferred into an anaerobic, psychrophilic batch digester for 1 month as described by Massé and Droste (2000). Part of the digested LSM was put aside and labelled "digested LSM", whereas another part of the digested LSM was

chemically coagulated with the polymer Aquaperl (Les produits environnementaux Atlas Inc., Sherbrooke, QC, Canada) and flocculated with a copolymer of a quaternary acrylate salt and acrylamide (Chemfloc CTT 8668, CHEMCO Inc., St-Augustin-de-Desmaures, QC, Canada). The flocculated material was removed and the remaining liquid fraction was labelled "digested + flocculated LSM". Finally, some of the homogenized LSM was passed through a rotary vacuum (−66 kPa) filter made of diatomaceous earth with effective porosity of 10 μm. The filtrate was collected and labelled "filtered LSM". All LSM types were stored in 1 m^3 closed plastic containers and maintained at ambient temperature (15–20°C) until application.

All LSM types were subsampled 3–4 days before the application date to determine application rates based on total N content. During field application, a 2-l composite sample of each LSM type was taken for detailed chemical characterization. Laboratory analyses were made in triplicate for each LSM type. The LSM samples were homogenized with a Polytron (Model PT 3100, Kinematica AG, Littau-Lucerne, Switzerland) for 2 min and tested for pH by direct reading with a glass electrode. Dry matter content was determined as the weight of material remaining after drying 100 ml of LSM at 55°C for 96 h. Total C concentration was measured by injecting 50 μl of homogenized LSM into an automated combustion C analyzer (Model Formacs, Skalar Analytical, De Breda, The Netherlands). Total N and P concentrations of the homogenized LSM samples were determined by acid digestion as described by Chantigny et al. (2007). The mineral N content in LSM was determined by shaking 10 ml of LSM with 50 ml of 1 M KCl for 60 min. The extract was centrifuged (3,000g; 10 min) and passed through pre-washed (1 M KCl) filter papers (Whatman #42). The NH_4 and $NO_3 + NO_2$ concentrations were measured in the extracts and acid digests by colorimetry with an automated continuous-flow injection analyzer (Model QuickChem 8000 FIA+, Lachat Instruments, Loveland, CO).

Volatilization measurement

Containers with LSM were transported to the experimental site the day before application. The various LSMs were randomly assigned to fifteen 0.5 m × 2 m plots. During application, the slurry in the containers was continuously stirred and LSM was drawn by gravity from a spout at the base of the 1 m^3 plastic container into graduated watering cans. The slurry was then applied evenly on the bare soil of the entire plot surface to provide 150 kg total N ha^{-1}. Ammonia volatilization was measured for 10 days using wind tunnels (Lockyer 1984), consisting of a 0.5 m × 2 m Plexiglas dome placed over each plot less than 1 min after LSM application. Tunnels were attached to a steel duct housing a fan that drew air through the tunnel at a rate of 15 m^3 min^{-1}. Air entering and leaving the dome was sampled at 3 l min^{-1} and passed through a 100-ml 0.005 M phosphoric acid (H_3PO_4) trap to capture the emitted NH_3. Air flow rates were measured with a domestic gas metre and NH_4-N concentration in the traps was analyzed by colorimetry as described for LSM analysis. Air temperature and velocity under the tunnels, were measured using a hot-wire sensor (Model KM 4007, Comark Ltd., Hertfordshire, UK). The rate of ammonia volatilization (F_{NH_3}, mg N m^{-2} h^{-1}) was calculated as:

$$F_{NH_3} = \frac{f}{A}(c_o - c_i)$$

where f (l h^{-1}) is the air flow rate through the tunnel, A (m^2) is the enclosed surface area and c_i and c_o (mg NH_3-N l^{-1}) are the NH_3 concentrations of the air entering and leaving the tunnel. Ammonia traps were changed each half hour for the first 2 h, hourly for 4 h, at 6 h intervals until the 96th hour, and daily for the remaining 6 days. Tunnels were left in place during rainfalls, but equivalent quantities of distilled water were added to soil surface in the tunnels immediately after each rainfall. A new set of plots was established for each of the three trials.

Soil sampling and analyses

Fifteen separate 2 m × 2 m plots were established ∼5 m beside the wind tunnel plots. All LSM treatments described above were applied to these plots (three replicates); an unamended control treatment was included in the set up for soil sampling in May and September 2005. Soil samples were taken from all plots daily for the first 4 days after LSM application, with the exception of May 2004 in which samples were not taken on the third day after application, and every 2–3 days thereafter. Composite soil samples (eight sample points) were collected randomly using a stainless steel (3-cm diam.) probe at

0–5 and 5–10 cm in 2004. Based on visual observations of LSM infiltration during soil sampling in 2004, soils were sampled at 0–2 cm and 2–10 cm in 2005. Soil samples were transported immediately to the laboratory and analyzed for pH (2:1 soil:water ratio) and extractable mineral N (10 g field moist soil in 50 ml of 1 M KCl). Soil slurries were shaken for 1 h on a reciprocal shaker, centrifuged (3,000g; 10 min), and passed through pre-washed (1 M KCl) filter papers (Whatman #42). The extracts were stored at −20°C until analysis for NH_4 and $NO_3 + NO_2$ by colorimetry as described for LSM analysis.

Data treatment and statistical analyses

The three application dates were treated as individual experiments and analyzed separately to identify treatment effects on NH_3-N emissions. For the first 4 days of measurements, the least square means (LSMEANS) of daily NH_3 emissions were estimated using the MIXED procedure in SAS (Version 8, SAS Institute, Cary, NC), with replicate daily measurements treated as repeated measures. The daily measurements for the final 6 days were also treated as repeated measures to calculate LSMEANS of NH_3 emissions for the 5–10 days period. The LSMEANS among treatments were compared with the restricted maximum likelihood (REML) method of the MIXED procedure. Covariance structures were selected based on information criteria calculated by SAS (Wang and Goonewardene 2004). Differences among treatments were compared using Tukey's adjusted least square means.

Differences in cumulative NH_3-N loss among treatments, calculated as the proportion of applied N and the proportion of applied TAN, were tested with the MIXED procedure in SAS on each application date and on the overall average by treating application dates as a random variable. Orthogonal contrasts were carried out to evaluate if there were overall differences in N loss between treated versus untreated LSMs, as well as among treated LSMs.

Results and discussion

Liquid swine manure characteristics

Treatments modified the chemical and physical characteristics of LSM (Table 1). On average, anaerobic digestion reduced dry matter content by the least (45% reduction) and digestion + flocculation by the most (73% reduction). On average, the pH of LSM was not influenced by decantation, but was increased by 0.3, 0.5, and 0.6 unit by filtration, anaerobic digestion, and digestion + flocculation, respectively. Digestion and decantation reduced LSM total N by 11%, compared to a 34% reduction with filtration and digestion + flocculation. Digestion + flocculation, decantation and filtration reduced TAN in LSM by 15–28%, whereas digestion alone slightly increased it. The LSMs applied in 2004 and 2005 were generally similar in their chemical composition, but contained less total N present as TAN in 2004 (49–68%) than in 2005 (79–92%). The main explanation for this difference was that LSMs were stored in the 1-m³ containers about 3 weeks longer for manure collected in 2005 than in 2004, hence, manure organic N had more time to mineralize in 2005. On average, the percentage of total N as TAN was 5–7% greater in treated than untreated LSM. Inorganic C (carbonate) was slightly reduced by decantation and filtration, and increased by digestion and digestion + flocculation.

An application rate of 150 kg total N ha⁻¹ was targeted for all treatments. Actual rates varied by less than 10% in all treatments on all dates, with the exception of the decanted LSM in September 2005 that was applied at a rate 35% lower than the other treatments (Table 2). Since application rates were based on total N, TAN applied to the plots depended on the proportion of total N in the form of TAN. The TAN application rates with untreated and decanted LSM were roughly 15% lower than the highest TAN application rate with the digested + flocculated LSM.

Ammonia volatilization

Emissions and changes in soil properties shortly after application

Ammonia emission rates were the highest for the first 12 h following application of LSMs (Fig. 1). A diurnal pattern in NH_3 emission was observed for the first 3–4 days following application in May 2004 and 2005 (Fig. 1a, b), but not in September 2005 when NH_3 emission rate remained low for all LSM types 12 h after application (Fig. 1c). Soil NH_4 concentration was highest immediately following LSM application, and declined during the monitoring

Table 1 Characteristics of liquid swine manures on three application dates

| Application date	Treatment	pH	Dry matter (g l^{-1})	TAN (g l^{-1})	Total N (g l^{-1})	CO$_3$-C (g l^{-1})
May, 2004	Untreated	7.4	52	3.5	7.2	1.2
	Decanted	7.7	28	3.7	6.0	0.8
	Filtered	8.1	16	3.2	4.7	0.7
	Digested	8.0	26	3.7	5.4	2.3
	Flocculated[a]	8.3	10	2.8	4.6	3.1
May, 2005	Untreated	7.5	76	5.3	6.4	1.9
	Decanted	7.8	41	5.1	6.3	1.7
	Filtered	8.1	32	3.5	4.1	1.5
	Digested	8.3	48	4.9	6.1	3.8
	Flocculated	8.3	27	4.4	5.1	3.7
September, 2005	Untreated	8.7	50	5.4	6.8	3.0
	Decanted	8.2	12	3.4	4.1	2.9
	Filtered	8.4	13	3.5	4.3	2.7
	Digested	8.8	26	5.6	6.3	3.6
	Flocculated	9.0	12	4.7	5.1	3.1
Mean	Untreated	7.9	59	4.7	6.8	2.0
	Decanted	7.9	27	4.1	5.4	1.8
	Filtered	8.2	20	3.4	4.4	1.6
	Digested	8.4	33	4.8	5.9	3.2
	Flocculated	8.5	16	4.0	4.9	3.3

TAN, total ammoniacal N; CO$_3$-C, carbonates or inorganic C

[a] Flocculated = digested + flocculated

Table 2 Application rates of liquid swine manure at three dates

Application date	Treatment	Volume (m^3 ha^{-1})	TAN (kg ha^{-1})	Total N (kg ha^{-1})
May, 2004	Untreated	14	76	159
	Decanted	16	93	150
	Filtered	34	118	145
	Digested	16	94	134
	Flocculated[a]	25	88	150
May, 2005	Untreated	21	112	135
	Decanted	24	122	150
	Filtered	34	118	145
	Digested	23	113	139
	Flocculated	28	124	143
September, 2005	Untreated	21	114	143
	Decanted	24	82	98
	Filtered	34	118	145
	Digested	24	135	152
	Flocculated	30	141	152

TAN, total ammoniacal N

[a] Flocculated = digested + flocculated

Fig. 1 Emissions of NH$_3$-N measured after application of liquid swine manures on three application dates. *Arrows* indicate quantities and timing of precipitation. *Vertical bars* represent standard deviation of the mean
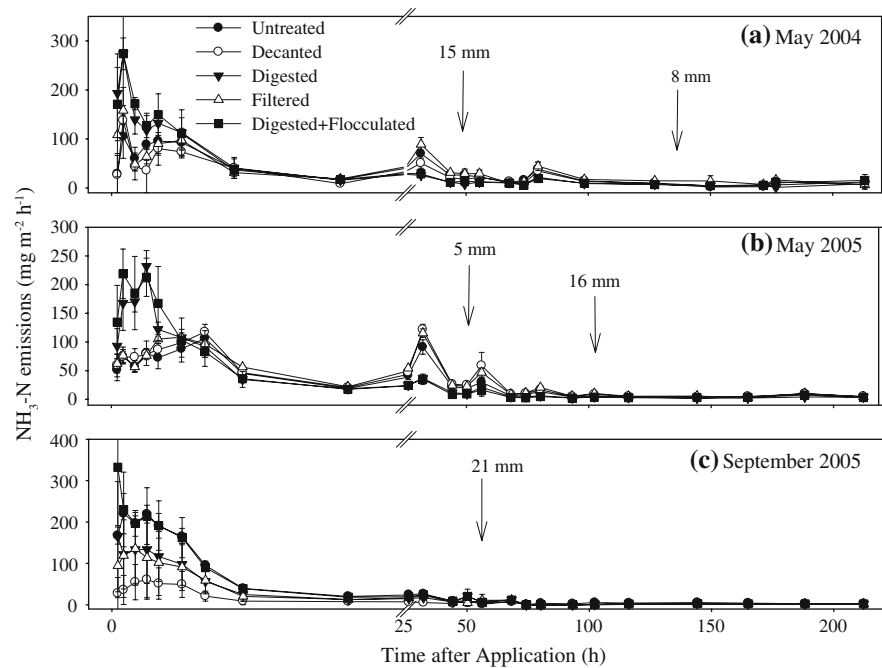
period (data not shown). Application of LSMs also increased soil pH in the upper 2–5 cm by as much as 1.4 units, followed by a gradual decline (Fig. 2). Increases in soil NH$_4$ and pH are common immediately after LSM application and are known to increase the NH$_3$ source intensity (Sommer and Hutchings 2001). This most likely explains that the NH$_3$ emission rate was highest immediately after LSM application and declined as the change in soil pH was buffered over time (Fig. 2) and NH$_4$ penetrated in deeper soil layers or was nitrified.

The slower increase in soil pH with untreated, decanted and filtered LSMs, in May 2004 (Fig. 2a), was due to a greater volume of soil collected in May 2004 (0–5 cm) than in the other dates (0–2 cm), and reflected two different processes involved in altering soil pH. The digested and the digested + flocculated LSMs contained large amounts of inorganic C (Table 1) that rapidly dissociated in our acidic soils and likely induced the increase in soil pH (Sommer and Husted 1995; Chantigny et al. 2004). With the other LSMs, initial carbonate concentration was low, and pH increase was due to the slower process of oxidation of volatile fatty acids (Sørensen 1998), which are present in high concentrations in undigested LSMs, but in very low concentrations in digested slurries (Kirchmann and Lundvall 1993; Sommer and Husted 1995).

In general, NH$_3$ emission rate from soils receiving digested and digested + flocculated LSMs were greater than emissions from the other LSMs on the day of application (Table 3). In contrast, NH$_3$ emissions from these treatments on the days following application were similar or significantly lower than from soils receiving other LSMs. The initial pH of LSM explained 51% ($P < 0.05$) of the variability observed in NH$_3$ emission rates on the day of application (Fig. 3). The pH of LSM has a strong influence on NH$_3$ volatilization, particularly when above eight, as concentrations of aqueous NH$_3$ will not be limited by the availability of OH$^-$ anions in solution (Sommer et al. 2003). Slurry separation techniques that increase slurry pH have been observed to increase volatilization rates immediately after surface application (Pain et al. 1990b; Sommer and Hutchings 2001; Chantigny et al. 2004; Möller and Stinner 2009).

Our results thus indicate that the higher pH of the digested and digested + flocculated LSMs (Table 1), and the presence of rapidly soluble carbonates in these slurries, resulted in higher NH$_3$ emissions from these treatments on the day of application. The relationship between NH$_3$ emissions and LSM pH was not significant after the first day of application possibly because other factors, such as decreased NH$_4$ concentration in the soil solution, infiltration at depth, and weather conditions became more influential to NH$_3$ emissions.
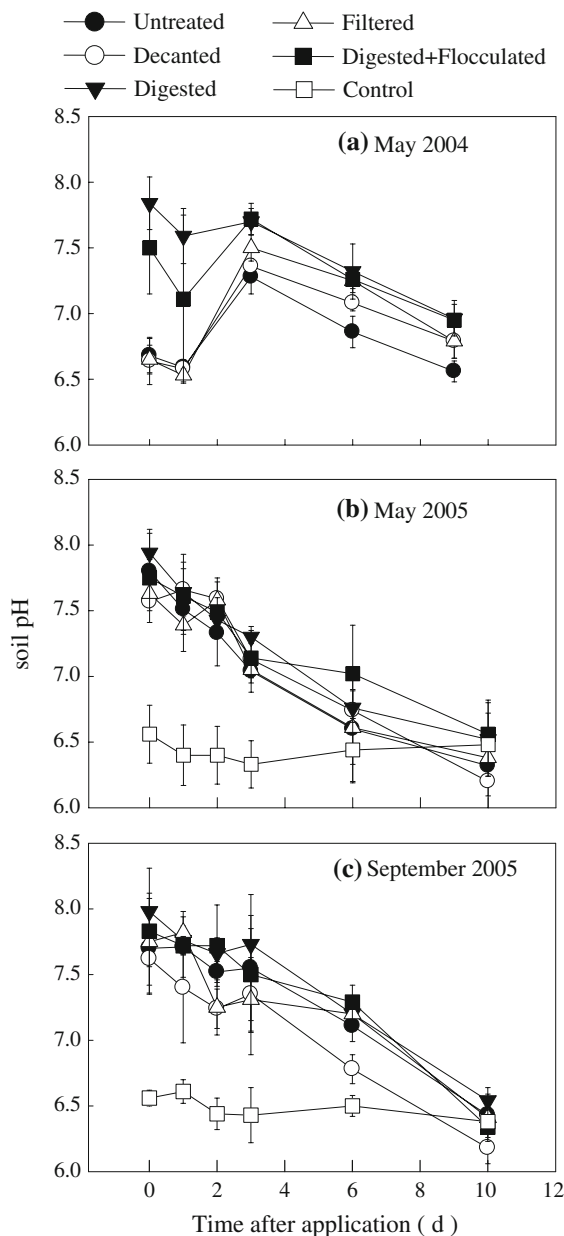
Fig. 2 Soil pH after application of liquid swine manures for three application dates. *Vertical bars* represent standard deviation of the mean

Proportions of applied N lost as NH₃-N: influence of application dates

Two of the trials were carried out in the spring when air and soil temperatures were cool with mean daily values of 16°C at the initiation of both trials (Fig. 4) and periods in which average daily temperatures

dropped below 10°C with lows below 0°C (minimums not shown). Those cool temperatures resulted in a low evaporative demand and moist soil conditions on the day of LSM application, with volumetric water content of 0.30 $m^3 m^{-3}$ in the upper 10 cm of soils for both spring applications. In contrast, in September 2005 air and soil temperatures were warm (24°C) and remained warm throughout the monitoring period (Fig. 4) with relatively dry soil conditions (0.22 $m^3 m^{-3}$). Overall, air and soil temperatures were more conducive to NH_3 volatilization in September 2005, whereas the moist soil conditions in May 2004 and 2005 were more favourable to volatilization by reducing the infiltration rate of surface applied LSMs.

The proportions of applied total N and TAN emitted as NH_3-N were lower in September 2005 than in spring applications (Table 4). In the September application, cumulative NH_3-N loss was largely driven by emissions during the day of application (Fig. 1c), since after 30 h, 60–70% of total NH_3-N volatilization had already occurred and levelled off. With dry soil conditions in September 2005, LSM infiltration was likely favoured, thereby reducing the volatilization period. Furthermore, warm soil temperatures in September 2005 stimulated nitrification of LSM TAN, as reflected by the rate of NO_3 accumulation which was about twice as rapid as in the spring applications (Fig. 5). As most nitrification occurred in the top 2–5 cm of soil (Fig. 5a–c), the NH_3 source intensity decreased more rapidly in September 2005 than in spring applications. The combination of better infiltration conditions and higher nitrification rate most likely explains that cumulative NH_3-N losses were lower in September 2005, compared to May 2004 and 2005.

Proportions of applied N lost as NH₃-N: influence of LSM treatments

In spring applications, the proportion of applied total N lost as NH_3-N was the highest in soils amended with filtered LSM, whereas losses from the other treated LSMs were generally similar to or lower than the untreated LSM (Table 4). In September 2005, the proportion of total N lost as NH_3-N was lower with all treated LSMs than with the untreated LSM. Similar trends were found when expressing NH_3-N losses as a proportion of applied TAN. Results

Table 3 Least square means of daily fluxes of NH_3-N following application of liquid swine manure at three dates

Application date	Treatment	Day 1 (g NH_3–N m^{-2})	Day 2 (g NH_3–N m^{-2})	Day 3 (g NH_3–N m^{-2})	Day 4 (g NH_3–N m^{-2})	Day 5–10 (g NH_3–N m^{-2})
May 2004	Untreated	72.6b	28.1a	19.7	21.6a	6.7b
	Decanted	62.5b	21.2b	17.3	18.9ab	7.9b
	Filtered	85.2b	31.1a	22.4	22.0a	13.2a
	Digested	144.1a	18.3b	10.3	13.5bc	6.5b
	Flocculated[a]	148.7a	19.3b	12.0	11.6c	6.6b
ANOVA	Treatment (T)	0.001	0.010	0.066	0.017	0.054
(P values)	T × Date	0.17	0.033	0.033	0.040	0.28
May 2005	Untreated	67.1b	43.6b	24.8a	9.4b	4.1ab
	Decanted	74.0b	39.4b	20.0ab	12.1a	5.5a
	Filtered	77.4b	55.0a	29.7a	13.5a	6.0a
	Digested	132.5a	23.0c	10.4c	5.2c	3.0b
	Flocculated	151.2a	23.5c	12.4bc	3.6c	3.2b
ANOVA	Treatment (T)	0.001	0.001	0.005	0.001	0.008
(P values)	T × Date	0.001	0.001	0.82	0.001	0.77
September 2005	Untreated	171.3a	23.7	7.3	3.9	4.2a
	Decanted	41.3b	6.7	4.8	2.7	0.7c
	Filtered	96.6ab	17.6	7.5	3.8	1.9b
	Digested	113.3a	15.0	11.4	4.1	1.7bc
	Flocculated	195.2a	20.8	11.9	3.9	1.9b
ANOVA	Treatment (T)	0.028	0.23	0.40	0.65	0.005
(P values)	T × Date	0.86	0.20	0.50	0.070	0.62

Different letters within the same column for a given date indicate differences at $P < 0.05$

[a] Flocculated = digested + flocculated
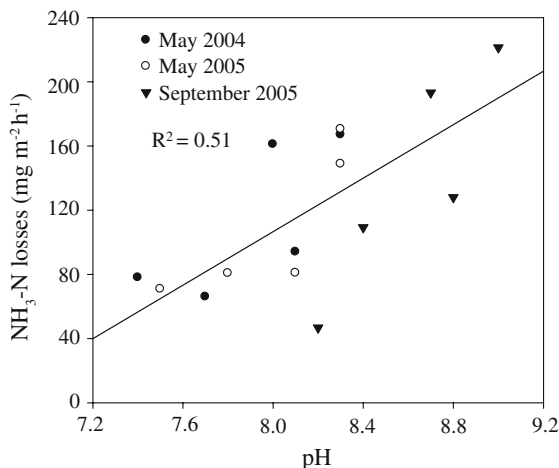
Fig. 3 Relationship between initial manure pH and NH_3-N losses on the day of manure application for three application dates

obtained with the decanted LSM were quite variable among application dates, as the proportion of N lost was larger than with the untreated LSM in May 2005,

but was the lowest among all LSMs in September 2005. The particularly low losses measured with the decanted LSM in September 2005 were likely due to the low TAN application rate with this treatment (Table 2), which decreased the NH_3 source intensity.

Averaged across application dates and treated LSMs, the proportion of total applied N lost as NH_3 was 11% lower ($P = 0.12$), and the proportion of applied TAN lost was 22% lower ($P = 0.001$) than with the untreated LSM (Table 4). Treatment of LSM generally increased its pH and the proportion of total N present as TAN (Table 1), thereby increasing the potential for NH_3 volatilization (Sommer and Hutchings 2001). Therefore, the lower emissions measured with the treated LSMs could be explained by improved infiltration as they contained 45–73% less dry matter than the untreated LSM (Table 1).

Relative to untreated LSM, Sommer et al. (2006) measured an increase of 35% in NH_3 emissions with anaerobically digested LSM, but a reduction of 50%
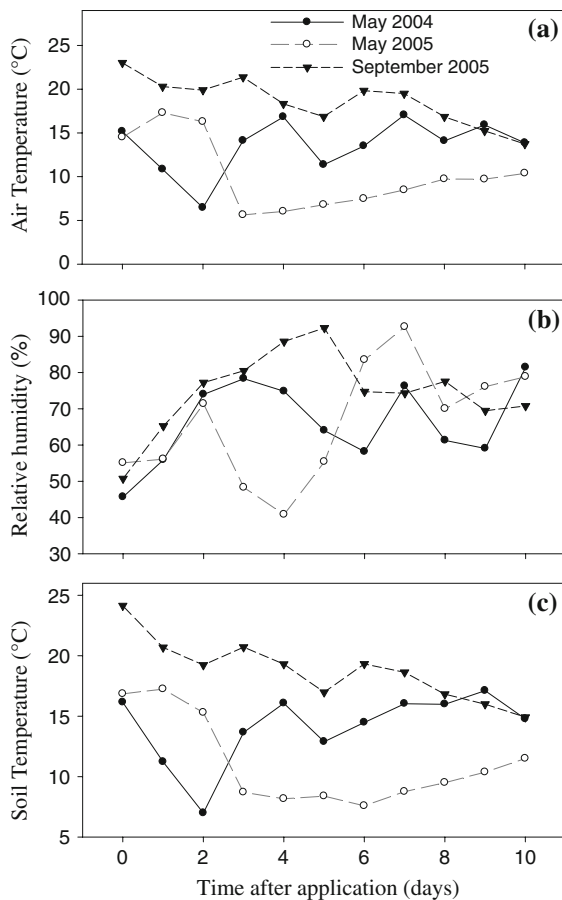
Fig. 4 Mean air temperature (**a**) and relative humidity (**b**), and soil temperature (**c**) after application of liquid swine manures for three application dates

with LSM that had undergone physical separation combined with anaerobic digestion. In that study, volatilization was measured over a short period, and increased emissions with the digested LSM were attributed to increased pH, while decreased emissions for the separated + digested LSM were attributed to increased infiltration rate in the soil. Likewise, Möller and Stinner (2009) observed increased losses with digested LSM, when emissions were measured over a 4-days period after application. Many field studies have also reported reduced emissions with the use of separated animal slurries, though the results with the same material may be variable depending on weather and soil conditions at time of application (Pain et al. 1990a; Rubæk et al. 1996; Chantigny et al. 2007). Those discrepancies on the effect of manure

treatment on field emissions of NH_3 appear to be largely dependant on the duration of emissions, which is largely driven by air temperature and soil water content at the time of application.

Across application dates, the NH_3-N losses tended ($P = 0.088$–0.092) to be lower with the digested LSMs than with the physically separated LSMs, and the filtered LSM was the least effective treatment in reducing NH_3-N loss (Table 4). The higher proportion of applied N that was lost from the filtered LSM in the spring applications was unexpected as it had similar or lower pH, dry matter content, and TAN content than the other treated LSMs (Table 1). Moreover, the result is in contrast to a previous study with similar LSMs applied to forage grasses. Chantigny et al. (2007) observed that relative to untreated LSM, filtered LSM reduced NH_3 volatilization by the most (46% abatement). It is noteworthy that filtered LSM had an average pH of 8.2 in the present study, compared to 7.7 in Chantigny et al. (2007). This increased its potential for NH_3 emission, which resulted in variable losses depending on environmental conditions. Alternatively, LSM was filtered through saw dust in Chantigny et al. (2007), and through diatomaceous earth in the present study. Observation of the dried filtered LSM revealed the presence of highly hygroscopic, gelatinous materials possibly derived from the diatomaceous earth bed. We therefore hypothesize that this material coated the soil surface, and possibly occluded soil pores, thereby maintaining volatilization for longer periods of time, relative to the other treated LSMs. This hypothesis could also explain why the digested + flocculated LSM tended to emit larger proportions of applied N as NH_3 than the digested LSM, as gelatinous materials were also present during drying of this LSM. The possibility that certain treatments may release colloidal or gelatinous materials in the liquid fraction of LSM, with possible increase in potential for NH_3 volatilization, warrants further investigations.

Conclusions

Treatments generally increased pH and/or the proportion of total N present as TAN in LSM, thereby increasing the potential for NH_3 volatilization following field application. However, improved

Table 4 Cumulative losses of NH_3-N following application of liquid swine manures on three application dates

	May 2004 (%)	May 2005 (%)	Sept. 2005 (%)	Mean (%)	Change (%)[a]
% Total N applied					
Untreated	22.7	25.0	19.3	22.3	0
Decanted	20.5	27.8	8.7	19.0	−15
Filtered	28.9	29.0	12.4	23.4	+5
Digested	22.1	19.6	12.6	18.1	−19
Flocculated[b]	22.1	19.3	17.6	19.7	−12
Summary of ANOVA (*P* values)					
Treatment (*T*)	0.15	0.007	0.049	0.50	
Date	NA	NA	NA	0.001	
Treatment × date	NA	NA	NA	0.008	
Contrasts					
Treated versus untreated	0.80	0.56	0.029	0.12	
Physical versus digestion	0.30	0.001	0.073	0.092	
Filtered versus digested	0.071	0.003	0.94	0.007	
Decanted versus flocculated	0.64	0.006	0.021	0.68	
% TAN applied					
Untreated	47.6	30.3	24.1	34.0	0
Decanted	33.1	34.3	10.3	25.9	−24
Filtered	42.6	33.8	15.2	30.5	−10
Digested	31.7	24.2	14.2	23.4	−31
Flocculated	37.7	22.2	19.0	26.3	−23
Summary of ANOVA (*P* values)					
Treatment (*T*)	0.10	0.001	0.056	0.15	
Date	NA	NA	NA	0.001	
Treatment × date	NA	NA	NA	0.047	
Contrasts					
Treated versus untreated	0.034	0.34	0.014	0.001	
Physical versus digestion	0.47	0.001	0.20	0.088	
Filtered versus digested	0.092	0.002	0.81	0.011	
Decanted versus flocculated	0.44	0.001	0.056	0.82	

[a] Increase or reduction relative to untreated LSM

[b] Flocculated = digested + flocculated

infiltration due to the removal of dry matter compensated for this increased potential and resulted in an overall reduction in N volatilization, compared to the untreated LSM.

Anaerobic digestion was globally the most effective LSM treatment in reducing NH_3 volatilization. However, NH_3 emissions on the day of application were highly correlated with slurry pH. Hence, under warm and dry soil conditions, when most volatilization occurred within 24 h of application, the digested LSMs were less efficient at reducing NH_3 losses than

under cooler and moist soil conditions when volatilization occurred over several days. Filtration of LSM did not consistently reduce NH_3-N loss, especially under cooler conditions when cumulative N loss was similar or even higher than with the untreated LSM.

On average, 22% less TAN was volatilized from surface-applied treated LSMs than from the untreated LSM. Therefore, LSM treatment to produce energy and/or improve manure N and P management should not be a concern in terms of NH_3 losses following field application of the treated effluents.

Fig. 5 Soil NO$_3$-N content at two depths after application of liquid swine manures for three applications dates. *Vertical bars* represent standard deviation of the mean
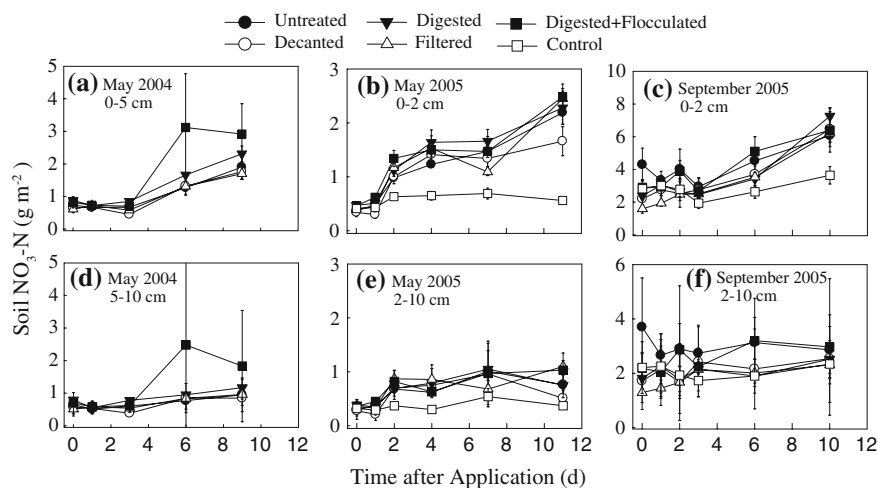
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