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Ammonia Volatilization from Dairy and Poultry Manure

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Introduction

Ammonia volatilization is a major N loss process for surface-applied manures and urea fertilizers. The lost ammonia is important for both agricultural and non-agricultural ecosystems because it: i) is a direct loss of plant available N to the farmer, ii) reduces the N:P ratio in manure, which accelerates P build-up in soils, and iii) contributes to eutrophication in aquatic and low-N input ecosystems through atmospheric transport and deposition (Asman, et al. 1994; Asman et al., 1998; Sharpley et al., 1998). Atmospheric ammonia originating from agricultural activities has been implicated in widespread damage to natural ecosystems in Europe (Asman et al. 1998; Hacker & Du, 1993). Similarly, there is growing public concern in the US that current manure management practices may be promoting ammonia enrichment of streams, estuaries, and coastal waters.

Agriculture is the major source of ammonia emissions to the atmosphere, contributing about 90% of the total in Western Europe according to recent estimates (Kirchmann et al., 1998; Stevens & Laughlin, 1997; Bussink & Oenema 1998). Most ammonia emissions are from livestock production with cattle farming, especially dairy, regarded as the largest source (Bussink

& Oenema 1998). Land application of manure contributes close to half (46%) of the ammonia emissions from livestock in the UK, animal housing about one-third, and waste storage and grazing the remaining 20% (Phillips & Pain, 1998). Smaller ammonia emissions are attributed to non-animal agricultural, such as fertilizer and crops (Sommer & Hutchings, 1995). Most efforts to reduce agricultural ammonia losses have focused on land application, the single largest source. This paper will therefore focus on land application of dairy and poultry manures, which are two major livestock enterprises in the Northeast.

Ammonia volatilization occurs because ammonium-N in manure or solution is converted to dissolved ammonia gas, by the reaction:

$$NH_4^+\text{-N} \rightleftarrows NH_{3g} + H^+ \quad \text{(Eqn. 1)}$$

The reaction produces more NH_{3g} as pH or temperature increases, and as the NH_4-N concentration increases. The rate of ammonia release to the atmosphere is a function of the difference in NH_{3g} concentration in the manure and the air (Lauer et al., 1976; Freney et al., 1983). The details of ammonia volatilization are complex, being affected by the level of dissolved vs. clay adsorbed ammonium-N, the chemical conversion of ammonium-N to dissolved ammonia gas, and the physical transport of the ammonia gas into the atmosphere. A large number of environmental and management factors influence ammonia loss under field conditions (Freney et al., 1983). The dominant factors influencing losses can be categorized as: manure composition, application method, soil factors, and environmental conditions (Meisinger & Randall, 1991; Sharpley et al. 1998).

The above economic and environmental concerns emphasize the necessity for developing improved management practices for conserving ammonia N in manures. The goals of this paper are: i) to examine the major factors affecting ammonia loss by reviewing relevant ammonia volatilization data, ii) to examine ammonia volatilization estimates used in the Northeast, and iii) to provide suggestions for improving ammonia volatilization estimates used in nutrient management planning.

General Magnitude and Pattern of Field Losses

Ammonia volatilization losses vary greatly depending on environmental conditions and management. Losses can range from close to 100% for surface application with optimal conditions for volatilization, to only a few percent when manure is injected or incorporated immediately into the soil. Ammonia losses are usually expressed as a percentage of the total ammoniacal N (TAN, ammonium-N plus ammonia-N) in the manure or slurry, because it is that portion that is immediately susceptible to loss. Typical results of studies on the application of liquid cattle manure to grassland (incorporation not possible) lie in the range of 40 to 70% loss (Stevens and Laughlin, 1997). Losses of dairy slurries applied in the spring to land tilled the previous fall in Ontario were 24 to 33% of TAN (Beauchamp et al., 1982), while losses from solid dairy manure (about 20% solids) in several New York experiments ranged from 61 to 99% (Lauer et al., 1976). Ammonia losses from surface applied poultry litter in Europe are commonly

15 to 45% of TAN plus uric acid N (Jarvis & Pain, 1990; Moss, et al., 1995; Chambers, et al., 1997). Ammonia losses from spring surface-applied poultry litter to fescue pastures in the Southeast ranged from 28 to 46% of the NH_4-N (Marshall et.al., 1998). These data illustrate that ammonia losses from poultry litter are commonly 20-45% of TAN, which is considerably less than cattle slurry losses which are frequently 35-70% of TAN. Most of the research on ammonia volatilization from manures has been conducted in Europe. While the specific circumstances or conditions may be somewhat different from those in the Northeast, the general principles and conclusions derived from these studies should be relevant to Northeastern agriculture.

The temporal pattern of slurry ammonia emissions is a very rapid loss during the first 6 to 12 hours after application, and a prominent reduction in the rate during the next few days (Fig. 1). Poultry litter, because of its drier condition, has a slower initial rate of loss than slurries, but has significant losses extending over several days or weeks (Fig. 2).

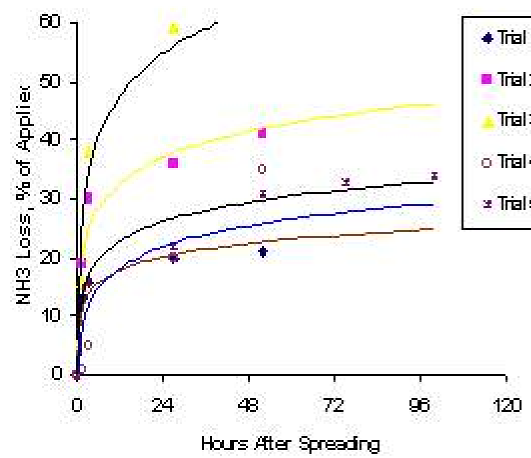

Fig. 1. Cumulative NH_3-N loss as a percent of surface-applied dairy slurry NH_4-N in five trials in Vermont during 1995-96.

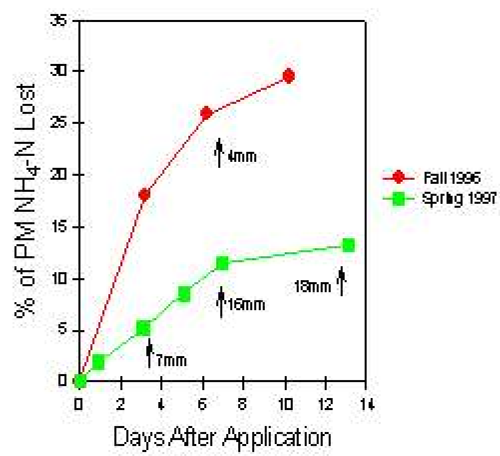

Fig. 2. Cumulative NH_3-N loss as percent of surface-applied poultry litter NH_4-N in Maryland in fall 1996 or spring 1997.

Results from a review of 10 studies with cattle slurry applied to grassland (Stevens and Laughlin, 1997) found that 30 to 70% of the total ammonia loss occurred in the first four to six hours, and 50 to 90% in the first day. One reason for the rapid losses from slurries is the slurry matrix, which is a well-mixed liquid abundantly supplied with urease. This matrix "sets the stage" for rapid ammonia losses once gas exchange is readily available. An example of a typical pattern of ammonia loss from surface broadcast dairy slurries is shown in Fig. 1 where 35 to 95% of the loss occurring in the first two to five hours. By contrast, the typical pattern of ammonia loss from surface-applied poultry litter in Maryland (Fig. 2) illustrates the high losses the first day after application, followed by continued substantial loss through day seven. Some investigators have even observed linear rates of volatilization from poultry litter for up to three weeks after application (Chambers et al., 1997). Volatilization losses from six poultry litter studies in the

Southeast (Marshall et al., 1998) show that an average of 25% of the total loss occurred on day one, 17% on day two, 15% on day 3, and 22% of the total loss over days four through seven. Thus, the time-course of ammonia loss is quite different for the liquid slurries (90-95% moisture) than for the drier poultry litters (20-40% moisture).

The pattern described above for slurries can be explained by a combination of manure and soil properties that change over time. Immediately after spreading the pH of slurry typically increases substantially, e.g., from the 7.6 to 8.4 (Sommer et al.,1991). The increased pH results from urea hydrolysis (Lauer et al. 1976) and loss of CO_2 by degassing. The initial concentration of TAN is usually high (1,000 to 2,000 mg TAN/l) and drying of the manure increases the TAN concentration further due to a decrease in the volume of water. After this initial high pH and high NH_4-N period, the length of which varies with environmental conditions, the rate of volatilization decreases dramatically due to: i) lower NH_4-N levels resulting from NH_3 losses, adsorption of NH_4-N onto soil colloids, and nitrification, ii) a lowering of the pH due to removal of the basic NH_3 molecule and release of H^+ (Eqn. 1), iii) infiltration of dissolved NH_4-N into the soil which decreases TAN at the air interface, and iv) formation of surface crusts which restrict gas exchange (Beauchamp et al., 1982; Brunke, et al., 1988; Sommer et al., 1991).

A review of ammonia volatilization literature quickly reveals that it is a highly variable process. But hidden beneath this variability are the major governing factors which affect ammonia volatilization in the field. Therefore, rather than focus on a case-by-case literature review and the variability of the process, we have chosen to emphasize the main factors affecting ammonia losses with resultant focus on techniques to improve manure N management.

Factors Affecting Ammonia Volatilization

Understanding the main factors affecting ammonia volatilization will delineate practices to reduce ammonia losses, will improve the prediction of these losses, and will aid in developing more efficient farm nutrient management plans. The factors can be categorized in four groups: i) manure characteristics (dry matter content, pH, NH_4-N content), ii) application management (incorporation, zone application, timing), iii) soil conditions (soil moisture, soil properties, plant/residue cover), and iv) environmental factors (temperature, wind speed, rainfall). The categories are ordered from the most practical factors to the least manageable factors.

Manure Characteristics

It is well known that manure is a highly variable commodity. Other papers at this workshop have focused on manure analysis; it is sufficient to state that sound manure management should begin with an analysis of the manure. Management of ammonia volatilization should include analysis of ammonium-N, total N, and dry matter (DM). Knowledge of the ammonium-N content is essential to set the upper limit on ammonia losses and gain better estimates of plant available N. Knowledge of dry matter can be useful in estimating ammonia loss rates.

The content of solids, or dry matter, in slurries has been shown to be an important factor in determining the ammonia volatilization potential in Europe (Sommer & Olesen 1991; Smith and

Chambers, 1995; Lorenz and Steffens, 1997; Pain & Misselbrook 1997). The general observation is that slurries with higher dry matter content show greater ammonia loss. For example, Sommer and Olesen (1991) showed a linear relationship between cattle slurry dry matter content and ammonia emission for slurries between 4 and 12% DM, however DM had little effect above or below those values. This relationship is due to the fact that slurries with lower solids tend to have greater fluidity and, therefore, infiltrate more readily into the soil where ammonium is protected from volatilization by adsorption onto soil colloids. Where vegetation is present, more fluid slurries make more direct contact with the soil, rather than adhering to plant material. The effect of dry matter content has been most pronounced in the short-term period immediately after application.

The 'fluidity and soil contact' concept explains why solid manures tend to volatilize a higher percentage of the TAN than dilute slurries, although solid manures lose less N the first day. For example, Menzi et al. (1997) found that, per unit of TAN applied, total emissions from solid manure were 30% higher than liquid manure in side-by-side comparisons. Researchers in Europe have used dry matter content to explain differences among manure of different species, e.g. more dilute pig slurri vs. thicker cattle slurry (Pain & Thompson, 1988; Brunke et al., 1988). The UK manure model "MANNER" employs a DM variable to predict losses by increasing NH_3 loss by about 5% of applied NH_4-N for each 1% increase in DM (Chambers et al., 1999). This principle has led to examination of dilution of manure with additional water as a management practice to reduce ammonia volatilization. A combination of solids separation and dilution to reduce dry matter content from 11.3 to 5.6% resulted in a 50% reduction in ammonia emissions (Stevens et al., 1992). Preliminary results from Vermont (Jokela et al, unpublished) are consistent with European results, showing about one-third less ammonia volatilization from liquid cattle manure diluted to reduce DM from 9 to 3%.

Dry matter content is not as dominant a factor for poultry litter, because most modern poultry units produce relatively dry litter, containing 55 to 75% DM. In fact, it is the low moisture level of poultry litter which is likely contributing to a lower potential for ammonia loss. It is often useful to think of ammonia volatilization as comparable to water evaporation. Thus, a drier poultry litter would loose less water and ammonia than a dairy slurry. Few studies have evaluated variations in potential ammonia loss among poultry manures. In a laboratory study of 18 poultry litters in Delaware, Schilke-Gartley and Sims (1993) found potential ammonia volatilization to vary from 4 to 31% of manure total N, but only weak correlations between ammonia loss and individual manure composition parameters. The multiple correlation using manure total N and pH produced an R^2 of 0.77 - if four manure samples which produced anomalous ammonia losses were omitted. Schilke-Gartley and Sims (1993) concluded that a manure test to estimate potential ammonia volatilization would be very useful, especially considering the wide range in potential ammonia loss among manures.

Measurement of manure N characteristics other than NH_4-N, total N, and DM are not in general use in the U.S. Manure pH is not regularly measured, even though a higher initial manure pH can increase the rate of ammonia volatilization (Sommer et al., 1991). However, initial manure pH has often not had a significant effect on slurry NH_3 emissions because of the rapid increase in slurry pH after application (Sommer & Hutchings, 1997; Sommer & Sherlock, 1996). Adding nitric or sulfuric acid to slurries before spreading to lower the pH to 6.5 has been effective at reducing ammonia volatilization (Stevens et al., 1992), but safety and other practical issues have limited adoption of the practice. Consideration of parameters such as pH, soluble Al, or soluble Fe may become useful if manure amendments such as alum ($AL_2(SO_4)_3$) or ferrous sulfate ($FeSO_4$) come into use. Both alum and ferrous sulfate have an acidifying effect on manures which could markedly decrease potential ammonia volatilization (Moore et al., 1995), because ammonia losses are minimal below pH 7. Consideration of the uric acid content of poultry litter may also be an important, as it is in the "MANNER" model, especially if the trend toward drier litters continues.

Application Management

Nitrogen losses during application can be grouped into losses during spreading and losses incurred after application. Unique problems and opportunities exist for reducing ammonia losses from slurries and solid manures for annual cropping systems, both tilled and non-tilled soils, and for grasslands. Management opportunities also exist for adjusting the time and rate of application.

<u>Annual Cropping Systems</u>

Volatilization losses during the spreading operation itself have generally been found to contribute little to total ammonia loss, usually less than 1% (Pain & Thompson, 1988; Phillips et al., 1990). The exception is irrigation of slurry, where ammonia losses can be much higher than conventional application methods (Phillips et al., 1990). Sharpe and Harper (1997) reported that 13% of slurry TAN was lost during irrigation in Georgia, while another 69% was volatilized from the sandy loam soil within 24 hours after application.

It is a well-known fact that soils are a good sink for ammonia, which leads to the corollary that incorporation of manure is a good method to reduce ammonia losses. There are a number of classic papers which clearly illustrate the importance of incorporation soon after application to achieve maximum agronomic response (Salter & Schollenberger 1939; Heck 1931). The rapid loss of ammonia from dairy slurries (Fig. 1) exemplifies the need to immediately incorporate these sources. In fact, even a one day delay in incorporating slurries can lead to loss of 50 to 90% to the TAN. Disking cattle manure reduced ammonia losses by 85 to 90% in a Canadian study (Brunke et al., 1988). Cultivating before slurry application can also reduce ammonia emissions because of increased infiltration into the soil (Bless, 1991; Sommer & Ersbøll, 1994). The literature is abounding with comparisons of tillage equipment to reduce ammonia loss (Amberger 1990; Klarenbeek & Bruins 1990; Dohler 1990). The general observation is that the more thorough and deep the tillage implement mixes the manure with the soil, the better it prevents ammonia losses, e.g., moldboard plows are more effective than fixed tines (Klarenbeek & Bruins, 1991). For solid manures (DM above 20%), direct tillage into the soil is the main avenue for incorporation, but slurries have many application options for conserving ammonia.

Various equipment options are available for injection or direct incorporation of liquid manure in annual row crop systems (Fig. 3).Deep injection with a knife or chisel (6 to 12 inches deep) has produced large reductions in ammonia emissions from slurries applied to corn in the US (Hoff, 1981). The reduced ammonia volatilization is generally reflected in improved N utilization and increased yields. Beauchamp (1983) obtained increased corn yields and approximately twice the N efficiency from liquid cattle manure when it was injected at either pre-plant or sidedress time compared to surface application. Klausner and Guest (1981) obtained increased corn yields from sidedressed injected dairy manure in New York. In recent years a horizontal sweep injector that operates at a shallower depth (4 to 6 inches; Fig. 3b) has become more popular because it provides more even distribution of manure, improves N availability, and requires less power (Schmitt et al., 1995).

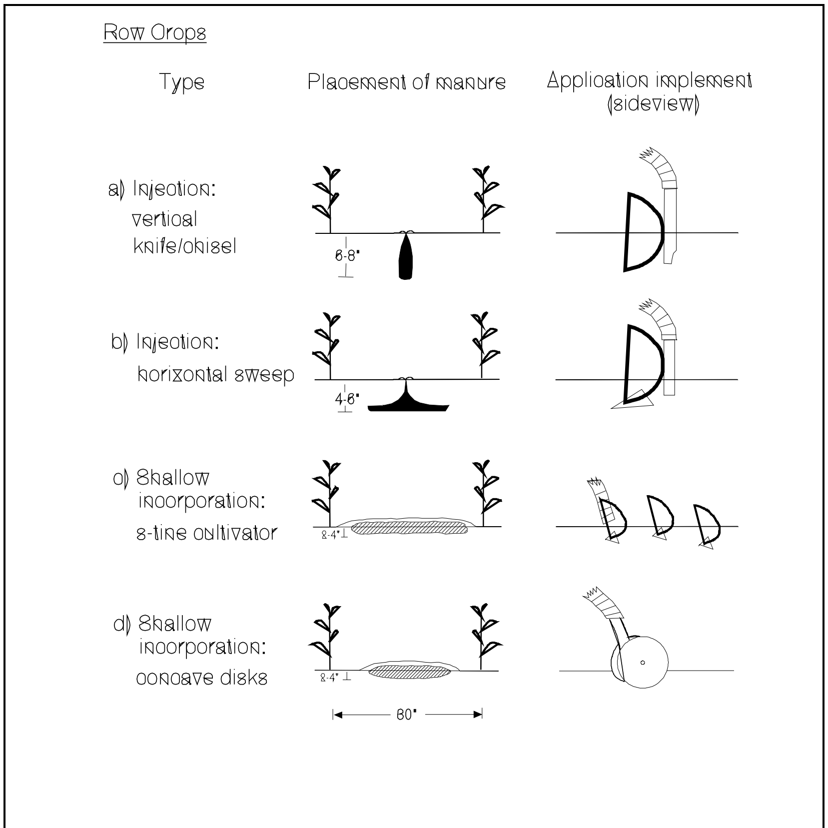

Fig. 3. Equipment options for injection or direct incorporation in row crops or on bare ground (Jokela & Côté, 1994).

A relatively new design, now available commercially from a few companies in Canada and the U.S., does not actually inject the manure but mixes and covers it with soil using either "s-tine" cultivator shanks or pairs of concave covering disks. (Figs. 3 c, d) These shallow incorporation methods require less power than injection options and can be operated at a faster ground speed and with less problem on stony soils. A long-term study with liquid swine manure as a sidedress application on corn (Côté et al., 1999) showed better utilization of N from manure applied between rows with "s-tine" incorporation than with deep injection. Results from a study in Vermont (Jokela et al., 1996) showed equal or slightly greater corn silage yields from 5000 gal/acre liquid dairy manure (68 lbs/acre NH_4-N and 135 lbs total N/acre) sidedressed with "s-tine" incorporation than from sidedressed fertilizer N at a 65 lb/acre. The above discussion shows that there are several good options to reduce ammonia losses from slurry and therefore improve N use efficiency for annual cropping systems.

Perennial Forage Systems

There are situations where injection or incorporation is not possible, e.g., manure applied to grasslands or manure applied to a no-till culture. In these situations modified application equipment is needed. Deep injection (6 to 12 inches) can effectivly reduce ammonia losses on grassland, but the practice has not been well accepted because of root damage and occasional yield reductions (Thompson et al., 1987). As a result, shallow injection systems (2-inch depth) have been developed (Fig. 4d) which still reduce ammonia emissions but produce less soil disturbance and crop damage (Pain & Misselbrook, 1997), although some yield reductions have been observed (Misselbrook et al., 1996). Ammonia volatilization has been reduced by 40 to 95% by shallow injection in various trials in the Netherlands and the UK (Frost, 1994; Misselbrook et al., 1996; Huijsmans et al., 1997). In some cases increased denitrification losses have been associated with reductions in ammonia emissions from injection, due to the localized high concentrations of carbon (which drives denitrification) and nitrogen (Thompson et al., 1987; Pain & Thompson, 1988).

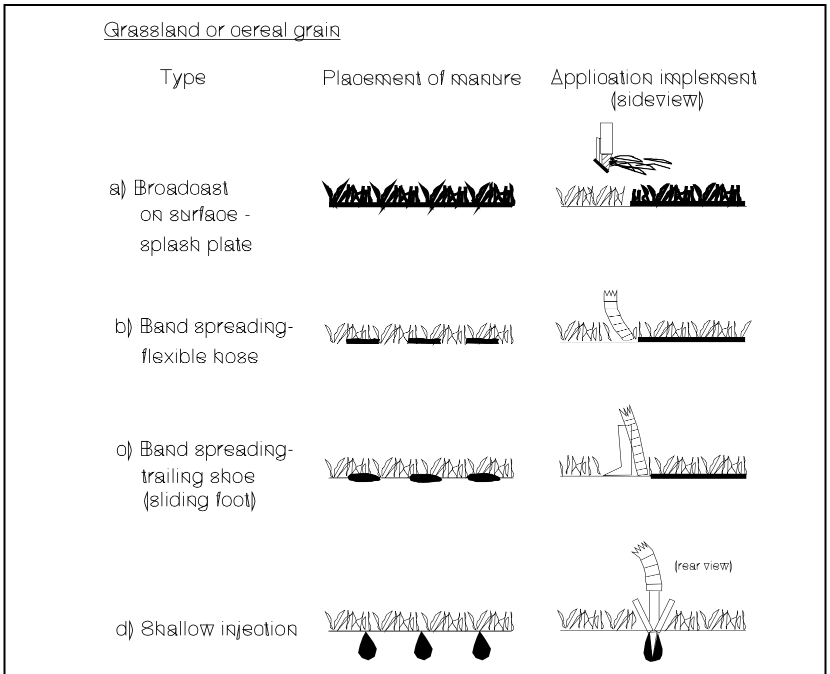

Fig.4. Equipment options for injection or direct incorporation in grassland or no-till crops (Jokela & Côté, 1994)

An approach that avoids soil disturbance entirely, while still reducing ammonia losses, is application of slurry in narrow bands either directly from the spreader hose or through a sliding shoe that rides along the soil surface (Fig. 4 b, c). The intent is to place the manure in a band close to the ground below the crop canopy, providing less surface exposure and some wind protection and preventing contamination of foliage with slurry. This equipment reduces ammonia volatilization, especially in the first few hours after application, though not as effectively as with injection. Most studies in Europe have reported volatilization reductions of 30 to 70% compared to surface application (Huijsmans et al., 1997; Frost, 1994; Pain & Misselbrook, 1997).

However, Thompson et al. (1990) reported a total reduction of only 17% over five days, a result of a slightly greater emission rates from the banded treatment during the last three days. This low effectiveness may have been because the bands were wider than in other studies and covered 35 to 40% of the ground surface.

Research with a trailing foot application system (Fig. 4c) in Vermont gave ammonia loss reductions of 30 to 90% compared to broadcast application, most of the difference occurring in the first several hours (Jokela et al., 1996). Small, but significant, yield increases of 6 to 14% resulted from band application in two of four site-years (Carter et al., 1998). A three-year study in British Columbia showed greater grass yields and N recovery from a sliding shoe system (Bittman et al., 1999), attributed to reductions in ammonia emissions although measurements were not made.

Timing

Another potential element for managing ammonia volatilization is time of application, considering either a seasonal scale (e.g. fall vs. spring) or a daily scale. If manure is immediately incorporated, timing issues center on applying the manure as close to the time of crop need as possible. If incorporation is not possible, timing should try to balance the objectives of applying close to crop need, yet avoid high ammonia loss seasons. Higher ammonia losses were reported from slurry on grassland in summer than in cooler seasons in the UK (Pain & Misselbrook, 1997) and in other Western European research (Amberger, 1990; Dohler, 1990). In other work in the UK (Smith & Chambers, 1995) ammonia losses decreased with each month's delay in application from September until January, and N efficiency was greater from spring than from fall-applied slurry. Smaller losses in cooler seasons are a result of lower temperatures, which provide less energy for volatilization, as demonstrated by the data in Fig. 2. Fall applications are not generally recommended in the Northeastern states due to the high susceptibility of loss through volatilization plus leaching. However, limited manure storage, soil trafficability issues, and time constraints have frequently contributed to significant fall-applications of manure in the region.

On a daily time scale, manure could potentially be applied in the late afternoon or evening to take advantage of the marked diurnal trend in ammonia losses, which consist of high daytime losses and lower losses at night (Beauchamp et al., 1982; Brunke, et al., 1988). However, evening applications have not always successfully reduced losses (Klarenbeek & Bruins 1991). Time and operational restraints greatly limit this approach to small operations. In any case, this short-term measure does not eliminate the need for incorporation the next day to minimize further losses.

Application Rate

Several researchers have found that total ammonia emissions were proportional to the application rate of manure TAN (Brunke, et al., 1988; Menzi et al., 1997; Svensson, 1994; Hoff, 1981). However, others (Thompson et al., 1990; Frost, 1994; Lauer et al., 1976) found a decreasing volatilization rate, per unit of slurry, as the application rate increased. The conflicting results are probably due to the competing factors of infiltration vs. volatilization. An explanation for these findings would be that a thinner layer of manure (lower rates) can lose a high percentage of its NH_4-N if adsorption or infiltration is small. In this situation higher rates increase the diffusion path length of NH_{3g} (deeper manure) and give more time for adsorption or infiltration to occur. However, if higher rates do not increase adsorption then more of the manure NH_4-N could be lost. Thus, the effect of application rates depends on the competing forces of adsorption vs. volatilization. In any event, application rates are generally governed by crop N needs and manure composition, rather than a desire to manage ammonia loss.

Soil Conditions

Soil conditions, such as moisture content, cation exchange capacity (CEC), pH, and plant or residue cover can also impact ammonia losses. The analogy between water loss and ammonia loss is useful for soil moisture because dissolved ammonia gas moves to the surface via the soil water, where it is subject of gaseous exchange with the atmosphere. A study of 32 soils showed a two- to three-fold increase in ammonia emissions from moistened soils compared to those in an air-dry condition (Kemppainen 1989), the increase ascribed to a lower absorption of the liquid fraction into the wetter soils (Kemppainen 1989; Pain et al., 1989; Sommer & Christensen, 1991).

<u>Soil Chemical Properties</u>

Soil chemical properties of pH, CEC, and texture can also impact ammonia loss. High soil pH increases ammonia losses by increasing concentrations of NH_3. For example, the percentage of TAN which is NH_3 is about 0.1, 1, 10, and 50% at pH values of 6, 7, 8 and 9, respectively (Court, et al., 1964). Ammonia volatilization from cattle slurry surface-applied to a fine-sand soil increased linearly with soil pH ($CaCl_2$) in the range of 5.4 to 6.9 (Kemppainen 1989). Factors which increase the change in pH will also increase potential ammonia loss. The buffering capacity of a soil is determined from its CEC, texture, soil minerals, and organic matter content. The CEC decreases with decreasing clay content (coarse textured sandy soils), decreasing organic matter content, and highly-weathered clay minerals (1:1 clays). A high CEC can impact ammonia loss by restricting the pH change associated with adding manures. In a study of 63 Finnish soils volatilization of NH_3 from surface-applied cattle slurry decreased with increasing CEC and, particularly, with increasing clay content (Kemppainen 1989). Thus, a low CEC sandy soil is susceptible to higher pH's and larger ammonia losses than a silt loam. Soil pH is readily managed, but since most Northeastern soils are acidic the pH factor is not a major option to control ammonia losses. The other soil properties related to CEC are not easily changed by management, so the best scenario for integrating soil properties into ammonia volatilization management is to use soil properties as a category variable to adjust estimates of ammonia loss.

Soil Cover

The presence of vegetative cover, the nature of the vegetation, and crop residues can also affect ammonia volatilization by restricting contact between manures and soil colloids. Thompson et al. (1990) reported 50% higher ammonia emissions from grassland than from a bare soil, most of the difference occurring in the first 24 hours. The explanation was that the grass served as a barrier and prevented much of the slurry from making contact with soil, and that slurry adhering to the grass created a larger surface area for volatilization. Likewise, in a French ammonia volatilization study with pig slurry there was about 30% greater losses from grassland than from wheat stubble (Moal et al. 1995).

Environmental Factors

Environmental factors can also impact ammonia losses because weather elements provide the energy and the driving force for the soil-air gas exchange. In general weather elements that increase the evaporative demand will also increase ammonia volatilization. Thus, ammonia volatilization is increased by higher temperatures and by increased wind speeds.

Temperature

The rate of ammonia volatilization increases with increasing temperature (Sommer et al. 1991; Svensson, 1994; Moal et al., 1995) with a greater effect observed in the first several hours after application (Sommer et al. 1991). Higher temperatures increase ammonia losses by decreasing the solubility of NH_3 gas in the soil solution and by increasing the proportion of TAN as NH_3 gas. Physical chemistry predicts that higher temperatures should cause ammonia losses to increase by a factor of about 3 for every 18˚F (10˚C) rise in temperature (Denmead et al., 1982). For example, a slurry containing 1500 mg NH_4-N/l at pH 7.8 would support equilibrium gaseous ammonia pressures of about 7, 23, and 69 mbars at temperatures of 50, 68, and 86˚F (10, 20, and 30˚C), respectively. The seasonal ammonia loss differences in Fig. 2 can be partially attributed to temperature because the average fall temperature was 64˚F (18˚C) while the spring temperature was 48˚F (9˚C). Thus, temperature can potentially have a considerable impact on ammonia losses. Temperature effects on ammonia loss have also been reported by others (e.g. Beauchamp et al., 1982; Harper et al., 1983; Nathan & Malzer, 1994; Sommer & Olesen, 1991; Sommer et al., 1991) but all the temperature effects have been less dominant than theory would suggest. This is because ammonia concentrations are seldom at equilibrium and because losses are also influenced by gaseous transport factors (tortuous air paths in soil, boundary layers, crusts, etc.). Ammonia losses do not stop at near-freezing temperatures. Laboratory studies with cattle manure in Vermont (Midgely & Weiser, 1937) and in New York (Steenhuis et al., 1979) reported losses of 50% of the TAN in two days at near-freezing temperatures. Losses near freezing can occur because a lower, but still substantial rate, of volatilization continues for a longer period of time (Sommer et al., 1991) and because freezing can have the same NH_4-N concentrating effect as drying (Midgely & Weiser, 1937; Lauer et al., 1976).

Temperature is not a universal driving variable, however. In a series of 11 experiments with swine slurries and solid dairy manure, Brunke et al. (1988) found that variations in ammonia flux were not well correlated with temperature. Brunke et al. (1988) attributed the results to interactions and correlations among meteorological parameters which affected the ammonia loss process. They suggested use of composite parameter, such as the hay drying index, which quantifies potential evaporation based on temperature, wind, and humidity, as a indicator of potential ammonia volatilization.

Wind speed

Higher winds contribute to higher ammonia losses by increasing the mass transfer and air exchange between the manured surface and the atmosphere. Most investigators have found a linear relation between wind speeds up to about 6 mph (2.5 m/s) and ammonia volatilization (Brunke et al., 1988; Sommer et al., 1991; Thompson et al., 1990). The greatest effect of wind speed is in the early phase of volatilization, before drying and surface depletion of NH_4-N occur. The precise impact of wind speed is difficult to assess from field data because wind increases are often confounded with changes in temperature and solar radiation.

Rainfall

Significant rainfall soon after slurry application can reduce ammonia volatilization by moving ammonium into the soil where it is held by soil colloids. The end result is an effect similar to shallow incorporation by tillage. Pain and Misselbrook (1997) reported ammonia reductions of about one-third from a 0.7 inch (18 mm) rainfall after application of cattle slurry. Significant reductions after rainfall was also reported by Beauchamp et al. (1982) in three Canadian studies with cattle slurry. Ammonia losses from urea fertilizers have suggested that only 0.3 inches (7-9 mm) of rainfall are needed to reduce ammonia losses and cause a significant yield response from grasses (Bussink & Oenema, 1996). Rainfall doesen't always stop ammonia losses, e.g., Chambers et al. (1997) noted an increase in NH_3 volatilization rate immediately following rainfall events several days after application of solid pig manure, perhaps due to re-wetting and subsequent re-drying of the solid manures. One management option to benefit from the rainfall effect is to irrigate soon after application. Work in Sweden (Malgeryd, 1998) reported a 70% reduction in ammonia losses from 1.2 inches (30 mm) of irrigation applied right after a surface broadcast application of pig slurry.

The above weather elements, of course, cannot be directly managed to control ammonia loss. Although some investigators have proposed applying manure before possible rainfall, or the use of irrigation on freshly manured fields. However, it is possible to include environmental conditions within a comprehensive ammonia management scheme. For example, ammonia emission values could be varied by categories based on average temperatures, drying conditions, or rainfall for the first day or two after manure application. Such an approach should improve ammonia loss estimates with attendant improvements in

N availability estimates.

Estimation of Ammonia Volatilization

Ammonium-N is the fraction of manure most readily available to plants, but it is also the portion most easily lost via volatilization and most affected by field management and environmental conditions. Therefore, accurate estimates of ammonia loss are critical for improving the crop recovery of manure N and for reducing environmental losses of ammonia. Every US State and Canadian Province in the Northeast incorporates some type of estimate of ammonia volatilization into their manure N recommendation process (Table 1).

Table 1. Ammonia loss estimates for spring-applied manure in various Northeastern US States or Canadian Provinces (F.J. Coale, pers. comm., 2000; Penn. St. Coop. Ext., 1999; Klausner, 1995; Jokela et al., 1998; OMAFRA, 1999).

Location	Manure Type or Weather Condition	Injected or Immed. Incorp.	First Day Losses	Losses for non-incorporated
		Ammonia Loss, % of Applied NH_4-N		
Maryland	All Manures	0	20	100
Pennsylvania	Dairy	0	35	100
	Poultry [1]	0	20	80
New York	All Manures (spring)	35	47	100
	All Manures (sidedress in summer)	0	--	--
Vermont	Dairy <5% DM	5	30	40
	Dairy 5-10% DM	5	45	60
	Dairy 5-10% DM	10	60	80
	Dairy Solid	5	40	90
	Poultry [1]	10	20	80
Ontario [2]	All, Cool, Moist	0	10	40
	All, Cool, Dry	0	15	50
	All, Warm, Moist	0	25	75
	All, Warm, Dry	0	50	90

[1] Values from Univ. of Delaware recommendations.

[2] Nonincorporated is for bare soil condition.

The concept of separating manure total N into the ammonium N and organic N fractions, and adjusting the availability of ammonium-N for time of incorporation was implemented in New York about 20 years ago (Klausner & Bouldin, 1983). This approach was based on research done earlier in New York by Lauer et al, (1976) which utilized solid manures and estimated ammonia losses by difference. The original recommendations have undergone some revision over the years, but the current New York recommendations are not greatly different (Klausner, 1995, Table 2).

Table 2. Ammonia loss and N availability estimates for manure applications in New York (Klausner, 1995).

Time of application/incorporation		% of NH_4-N Lost	% of NH_4-N Available
During growing season as sidedress injection for row crops		0	100
Spring season	Immediate incorporation	35	65
	1 day	47	53
	2 days	59	41
	3 days +	Increase number by 12 for each day incorporation is delayed.	Reduce number by 12 for each day incorporation is delayed.
All other conditions		100	0+

Other Northeastern states (PA, VT, MD, etc.) adopted this approach along with further refinements. A common feature in most ammonia loss estimates is the predicted zero loss (or close to it) for manures immediately incorporated by tillage or by significant rainfall, commonly defined as > 0.5 inches (12 mm) of rain. However, ammonia loss estimates for all other situations vary greatly among States or Provinces because of differences in the assumed ammonia-loss vs. time relationship. In addition, some States employ manure type (animal species) as classification variables, while others use manure composition variables such as manure dry matter content, to predict ammonia losses (Table 1). One Province utilizes soil and weather conditions, e.g., temperature, moisture, and soil cover, to estimate ammonia emissions.

Manure recommendations by the University of Vermont initially utilized an approach similar to New York. However, a recent revision was undertaken to incorporate dry matter content and a different N-loss vs. time relationship (Jokela et al, 1998). These changes were based on recent Vermont research (Fig. 1; Jokela et al., 1996; Carter et al., 1998) and a number of European studies discussed above in the 'manure composition' section. The research results, and resulting modifications in ammonia loss estimates, incorporate the following points: i) the rate of ammonia loss from slurries is much greater the first few hours after application than recognized in the older recommendations, but the losses declines dramatically after a day or two, ii) ammonia loss is a function of slurry dry matter content (more accurately fluidity; Svensson, 1994), with losses being lower in dilute slurries because of greater soil infiltration, iii) under most circumstances there is significant utilization of some manure NH_4-N, especially from slurries, even when manures are left on the surface, i.e. there is not 100% loss of NH_4-N from nonincorporated manure. The precise estimates of loss and availability of NH_4-N are calculated from a series of equations similar to those used in the "MANNER" model (Chambers et al., 1999; see Fig. 5a, 5b, and Table 1).

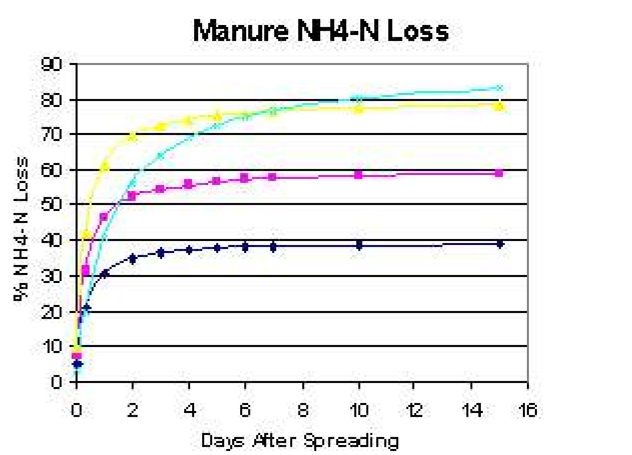

Fig. 5a. Ammonia loss as related to slurry DM content (fluidity, legend in 5b)and time after slurry application (Jokela et al., 1998).

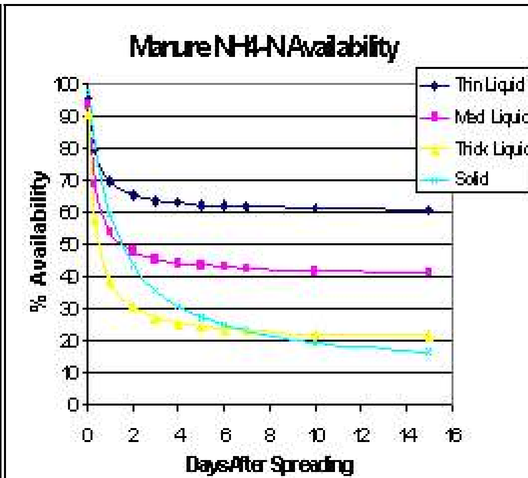

Fig. 5b. Plant availabile NH_4-N as related to slurry DM content (fluidity) and time after spreading (Jokela et al., 1998).

Manure ammonia loss estimates in Ontario employ a weather and soil related approach. These estimates are based on interpretations of Canadian and European research which utilizes several of the elements discussed above in the 'soil conditions' and 'environmental factors' sections.

Table 3. Ammonia loss estimates from spring or summer manure applications in Ontario due to different weather and soil conditions. (OMAFRA, 1999).

Days from Application to Incorporation, Soil Condition	Cool Temps.		Warm Temps.	
	Wet Cond.	Dry Cond.	Wet Cond.	Dry Cond.
	Ammonia Loss, % of Applied NH_4-N			
Not Incorpor., Bare Soil	40	50	75	90
Not Incorpor., Standing Crop	20	25	40	50
Incorp. w/in 1 day, Bare Soil	10	15	25	50
Incorp. w/in 2 days, Bare Soil	13	19	31	57
Incorp. w/in 3 days, Bare Soil	15	22	38	65
Incorp. w/in 4 days, Bare Soil	17	26	44	73
Incorp. w/in 5 days, Bare Soil	20	30	50	80

The Ontario approach utilizes soil condition classes of: bare soil, crop residues, or the presence of a standing crop; plus the environmental factors of: season of year, temperature, and evaporative demand/soil moisture level. All of these factors form a multi-class ammonia estimation scheme which allows greater site-specificity (Table 3; OMAFRA, 1999). The Ontario system forecasts high losses when days are sunny and warm and soils are drying, and lower losses under cool, cloudy, rainy conditions when soils are moist. Estimated losses are highest for bare soil conditions and lower for a standing crop where the formation of an internal layer of calm air within a crop canopy can reduce gas exchange (Harper, et al., 1983; Freney, 1982).

Overview

Ammonia volatilization is a major N loss process for surface applied manures. Ammonia volatilization losses vary greatly depending on management practices and environmental conditions. The major factors affecting manure ammonia loss were categorized and discussed, namely: i) manure characteristics (dry matter content, pH, NH_4-N content), ii) application management (incorporation, zone application, timing), iii) soil conditions (soil moisture, soil properties, plant/residue cover), and iv) environmental factors (temperature, wind speed, rainfall).

The current ammonia loss recommendations in the Northeast region illustrate both the problems and opportunities that face researchers seeking to improve the management of manure N. The problems arise from the range of manures being applied in the region, the range of application equipment, and the range of soil and weather conditions commonly encountered. The most urgent items required to resolve these problems are reliable field data on ammonia losses under the soil, climate, and application regimes of the individual state. Fortunately there are a number of simplified field methods to measure ammonia volatilization, such as: the dynamic chamber methods (Svensson, 1994), wind-tunnel methods (Lockyer, 1984; Klarenbeek & Bruins, 1991; Thompson et al., 1990), and micrometeorological methods employing either multi-level or one-point passive samplers (Denmead, 1983; Ryden & McNeill, 1984; Wilson et al., 1983). Each of these methods can contribute valuable data on field ammonia loss that is needed to revise volatilization estimates. The collection of current data, the sharing of data into common databases, and the improved understanding of the factors affecting ammonia loss should all contribute to the realization of improved estimates for ammonia volatilization for the Northeast. These improved ammonia loss estimates then need to be combined with crop yield response to obtain an estimate of the manure 'fertilizer N equivalents', which also incorporates factors such as mineralization of organic N, leaching and denitrification losses, and manure N efficiency (timing, etc). The manure 'fertilizer N equivalent' can then be compared to the crop N requirement to determine the recommended rate of manure application and possible need for supplemental fertilizer N. Improved estimates and management techniques for recovering manure ammonium N will conserve a major plant nutrient, will improve the N:P ratio in manures, and will decrease the impacts of agricultural ammonia on low-N input ecosystems.

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