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# Effect of application technique, manure characteristics, weather and field conditions on ammonia volatilization from manure applied to grassland

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## Abstract

To predict ammonia ($NH_3$) volatilization from field-applied manure, factors affecting volatilization following manure application need to be known. A database of field measurements in the Netherlands was analysed to identify factors affecting the volatilization from manure applied to grassland by various techniques, and to quantify their effects. The application techniques were broadcast surface spreading, narrow-band application, and shallow injection. External factors considered were weather conditions, manure characteristics, soil type and soil moisture content, and grass height. Narrow-band application and shallow injection significantly reduced $NH_3$ volatilization, compared with broadcast surface spreading. The mean cumulative volatilization for surface spreading was estimated to be 77% of the total ammoniacal nitrogen (TAN) applied, 20% for narrow-band application and 6% for shallow injection. The TAN content of the manure, the manure application rate and the weather conditions significantly influenced the $NH_3$ volatilization rate. The volatilization rate increased with an increase in TAN content of the manure, manure application rate, wind speed, radiation, or air temperature. It decreased with an increase in the relative humidity. The identified influencing factors and their magnitude differed with the application technique. Grass height affected $NH_3$ volatilization when manure was applied in narrow bands. The results show that external factors need to be taken into account when predicting ammonia volatilization following manure application.

*Keywords:* ammonia volatilization, application techniques, grassland, manure characteristics, weather conditions, field conditions.

## Introduction

Ammonia ($NH_3$) volatilization from animal manure is a topical environmental issue in various countries. $NH_3$ deposition can lead to the eutrophication and acidification of natural ecosystems. An increased availability of nitrogen (N) in combination with soil acidification can cause disturbed nutrient ratios in the soil and mineral deficiencies.

Since 1980, volatilization of ammoniacal N from livestock manure was responsible for more than 90% of the contamination of the environment by $NH_3$ in the Netherlands (Steenvoorden *et al.*, 1999; Anon., 2000). The annual $NH_3$ volatilization from animal manure was estimated to be more than 200 million kg in 1980 and at about 150 million kg in 1998 and 1999. The distribution of the total $NH_3$ volatilization from agriculture in the Netherlands over various sources in 1980 was estimated to be 37% from animal housing and manure storage, 56% from field application of manure and 7% from grazing cattle. In 1999, these contributions were 50, 41 and 9%, respectively (Anon., 2000). Because the contribution from manure application to farmland is large and improved application methods can be easily introduced at low costs, measures to reduce $NH_3$ volatilization following manure application were amply studied.

Injection of liquid manure into grassland was the first measure considered to reduce $NH_3$ volatilization. However, Wadman (1988) estimated that only 33% of the grassland in the Netherlands is suitable for injection. The draught force required, the crop damage along the slit on various soil types, and the remnants of tree stubs in the soil often make injection impossible. So other application techniques for grassland had to be developed to reduce $NH_3$ volatilization from field-applied manure under Dutch circumstances. With these new techniques, either a shallow slit is cut into the sward and the manure is applied into the slit (shallow injection), or the manure is applied in narrow bands onto the soil surface using a trailing-foot implement. These techniques require low draught force compared with conventional deep injectors (Huijsmans *et al.*, 1998). In the Netherlands, shallow injection and narrow-band application by the trailing-foot system considerably reduce $NH_3$ volatilization compared with broadcast surface spreading (Huijsmans *et al.*, 1997). Field studies in Germany gave similar results (Lorenz & Steffens, 1997).

The objective of these studies was primarily to quantify the relative differences in cumulative $NH_3$ volatilization between the various application techniques and to approve these techniques for application in practice. Little attention was paid to the factors that influence the magnitude of the $NH_3$ volatilization for a given application technique. Volatilization of $NH_3$ following field application of manure can be influenced by factors like application rate, weather conditions, soil type, soil condition and the presence of a crop. Knowledge of these factors can be decisive for an efficient strategy to reduce $NH_3$ volatilization. Air temperature, relative humidity and wind speed are often mentioned as the main factors. Brunke *et al.* (1988) concluded that the volatilization of $NH_3$ from field-applied manure is affected by a combination of factors that cause the manure to dry out, which results in a higher $NH_3$ concentration in the manure. Jarvis & Pain (1990) mention total ammoniacal nitrogen content (TAN, $NH_4^+ + NH_3$), pH and dry matter content of the manure as key factors in the $NH_3$ volatilization.

Until now, the literature does not provide firm quantitative conclusions on the effect of influencing factors and their interactions on $NH_3$ volatilization. Moreover, in literature only volatilization following surface spreading of manure has been addressed. Data on other application methods are lacking. Therefore, a study was initiated to unravel the complexity of the volatilization process and quantify the effect of factors that influence $NH_3$ volatilization following manure application using various application techniques. The study comprised the analysis of a large database of field records in the Netherlands. The objective was to identify factors that affect $NH_3$ volatilization from manure applied in the field using various techniques, and to quantify the effects. The external factors considered in this study were *weather conditions*, *manure characteristics*, *soil type*, *soil moisture content* and *grass height*.

## Materials and methods

### *Field data*

$NH_3$ volatilization was measured on 110 experimental grassland plots in 45 separate field experiments in the growing seasons (March–September) of 1989–1993. A summary of these experiments is given in the Appendix. The experiments included different soil types (clay, peat and sand), soil water contents, grass heights, manure characteristics and weather conditions. Both cow manure and pig manure were used. All experiments were carried out on grassland with well-established and intensively managed swards. Perennial ryegrass (*Lolium perenne* L.) was the dominant species. Per experiment, $NH_3$ volatilization was measured on up to five comparable plots. Plots differed in application technique, application rate, type of manure applied or grass height. $NH_3$ volatilization from manure applied by surface spreading, narrow-band application and shallow injection was measured on a total of 47, 29 and 34 plots, respectively.

### *Application techniques*

Commercially available application implements were used in all cases. *Surface spreading* was carried out by a tanker fitted with a splash-plate. The manure was pumped through an orifice onto a splash-plate from where it was spread onto the soil and the grass. The net working width was about 8 m. The techniques for the application of manure in narrow bands and for manure injection have been described by Huijsmans *et al.* (1998). *Narrow-band application* was carried out by trailing narrow sliding feet (also called 'shoes') over the soil surface, pushing aside the grass cover but not cutting the sward. Each foot was 0.37 m long and 0.02 m wide and was kept horizontally by a parallelogram construction. Manure was released at the back of the feet leaving narrow bands of manure onto the soil surface. The bands had a width of about 0.03 m and were spaced 0.20 m apart. Contamination of the grass with manure was negligible. A tanker was equipped with 25 trailing feet with a total working width of 5 m. *Shallow injection* (open slot) was carried out with injection coulters. Coulters and discs were used to cut vertical slots into the grass sward. Manure was released into the slots, which were left open. The slots were up to 0.05 m deep and were spaced 0.20 m apart. The total working width of the implements used was 4.0 to 5.6 m. Depending on the application rate, the slots were more or less filled with manure. Unlike the conventional deep injector, the shallow injectors used had no lateral wings and did not cut the soil horizontally underneath the sward.

*Manure*

The experiments were carried out on dairy farms. The cow manure used had been produced on these farms. Pig manure was imported from pig farms. The plots of an experiment received manure in the morning and at about the same time to reduce the effects of changes in soil and weather conditions on $NH_3$ volatilization. The manure was applied on circular plots with a radius varying from 20 to 24 m. These plots were created by applying the manure over a pre-marked area in parallel passes that varied in length (Figure 1). The amount of manure applied per plot was measured by weighing the manure tank before and after application. The average application rate was 14 $m^3$ $ha^{-1}$ for surface spreading and narrow-band application, and 22 $m^3$ $ha^{-1}$ for shallow injection. The higher application rate for shallow injection was in accordance with present-day practice. At least three manure samples were taken from each tank load. The manure was analysed for pH, dry matter and TAN content. On average, the cow manure contained 2.15 g TAN $kg^{-1}$ and 77 g dry matter per kg, and had a pH of 7. The data for the pig manure were 5.60 g TAN $kg^{-1}$, 101 g dry matter per kg, and pH 7.5.

*$NH_3$ volatilization*

The volatilization of $NH_3$ following manure application was determined per plot using the micrometeorological mass balance method (Denmead, 1983; Ryden & McNeill, 1984). Shortly after the manure had been applied to the first half of the plot – which usually was within 5 minutes after manure application had started – a mast supporting seven to eight $NH_3$ traps between 0.25 and 3.30 m above ground level was placed in the centre of each experimental plot (Figure 1). At the windward boundary of the plot another mast was placed with four to five $NH_3$ traps at heights between 0.40 and 2.30 m above ground level. At the boundary, fewer traps were used because the background concentration was low and independent of height. Each trap

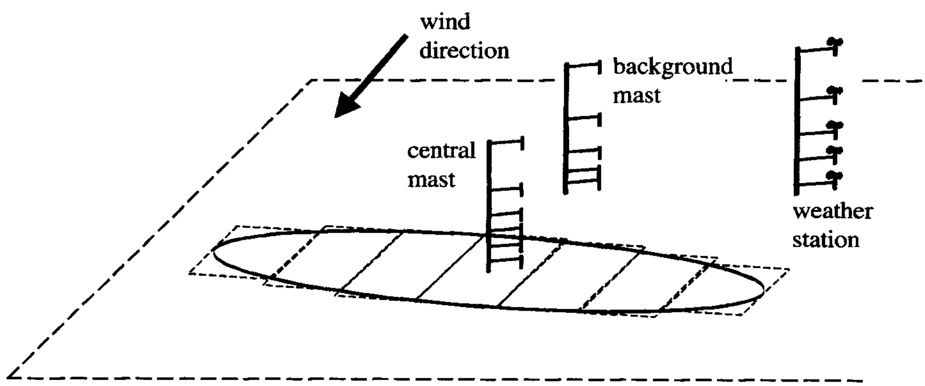



Figure 1. Lay out of circular plot (diameter about 50 m) for the measurement of $NH_3$ volatilization using the micrometeorological mass balance method, with masts supporting $NH_3$ traps at various heights in the centre of the plot and at the windward boundary of the plot.

contained 20 $cm^3$ of 0.02 M $HNO_3$ held in 100-$cm^3$ collection tubes. Air was drawn through the acid solution via a stainless steel inlet tube with a perforated Teflon cap. The volume of air was measured with flow meters. Flow rate was 2 to 4 $dm^3$ per minute. Ion-chromatography and colorimetry were used to measure the $NH_4^+$ concentration in the solutions.

Measurements continued for at least 96 hours after manure was applied. During the first 12 hours – when the rate of $NH_3$ volatilization was highest – traps were replaced four to five times. Further replacement took place every morning for the following four days. The amount of $NH_3$ volatilized during each interval was estimated from the amount of $NH_3$ trapped and from the airflow data. Bussink *et al.* (1994) showed that after 96 hours $NH_3$ volatilization from manure was negligible.

### *External factors*

At the start of each experiment the soil of each plot was sampled for the determination of the soil moisture content. Prior to manure application, the plot's grass height was determined by measuring the height of a disc resting on the grass surface, above the soil surface. Weather conditions were recorded over the total measuring period of the $NH_3$ volatilization. Wind speed was measured on a mast outside the plot, at 6 heights from 0.40 to 3.30 m. Air temperature, relative humidity and global radiation were recorded by a weather station. These climatic data were recorded every 10 minutes. The data have been averaged over the duration of each interval that $NH_3$ volatilization was measured. The various data are presented in Table 1.

### *Data analysis*

Each experimental plot yielded an $NH_3$ volatilization-time profile, expressing the volatilization measured during each interval following manure application. The volatilization from an experimental plot can be expressed as the volatilization rate in the course of time (Figure 2A) or as the cumulative amount of $NH_3$ volatilized dur-

Table 1. Ranges of measured variables in data set for different manure application techniques.

| Variable | Surface spreading | Narrow-band application | Shallow injection |
|---|---|---|---|
| TAN [1] content (g $kg^{-1}$) | 1.5 – 6.4 | 1.8 – 6.4 | 1.6 – 6.3 |
| Application rate ($m^3$ $ha^{-1}$) | 8 – 25 | 7 – 28 | 14 – 46 |
| Wind speed (m $s^{-1}$) | 0.5 – 8.0 | 0.4 – 7.2 | 0.5 – 7.3 |
| Radiation (J $cm^{-2}$ $h^{-1}$) | 0 – 318 | 0 – 300 | 0 – 375 |
| Air temperature (°C) | 3 – 32 | 3 – 32 | 4 – 32 |
| Relative humidity (%) | 16 – 100 | 34 – 100 | 40 – 100 |
| Grass height (cm) | 4 – 12 | 5 – 12 | 5 – 11 |
| Soil moisture content (%) | 14 – 67 | 24 – 67 | 24 – 61 |
| Dry matter content of manure (g $kg^{-1}$) | 46 – 119 | 56 – 113 | 52 – 113 |
| pH of manure | 6.8 – 8.0 | 6.9 – 8.0 | 6.8 – 8.0 |

[1] TAN = total ammoniacal nitrogen ($NH_4^+$ + $NH_3$).

ing consecutive measuring intervals. The cumulative volatilization is often expressed as the percentage of TAN applied with the manure (Figure 2B). The TAN applied results from multiplying the manure application rate (expressed as $m^3$ $ha^{-1}$) and the TAN content of the manure. The application rate varied for the different application techniques. Therefore, the cumulative volatilization percentage was used to compare application techniques between plots, assuming a linear relation between application rate and volatilization.

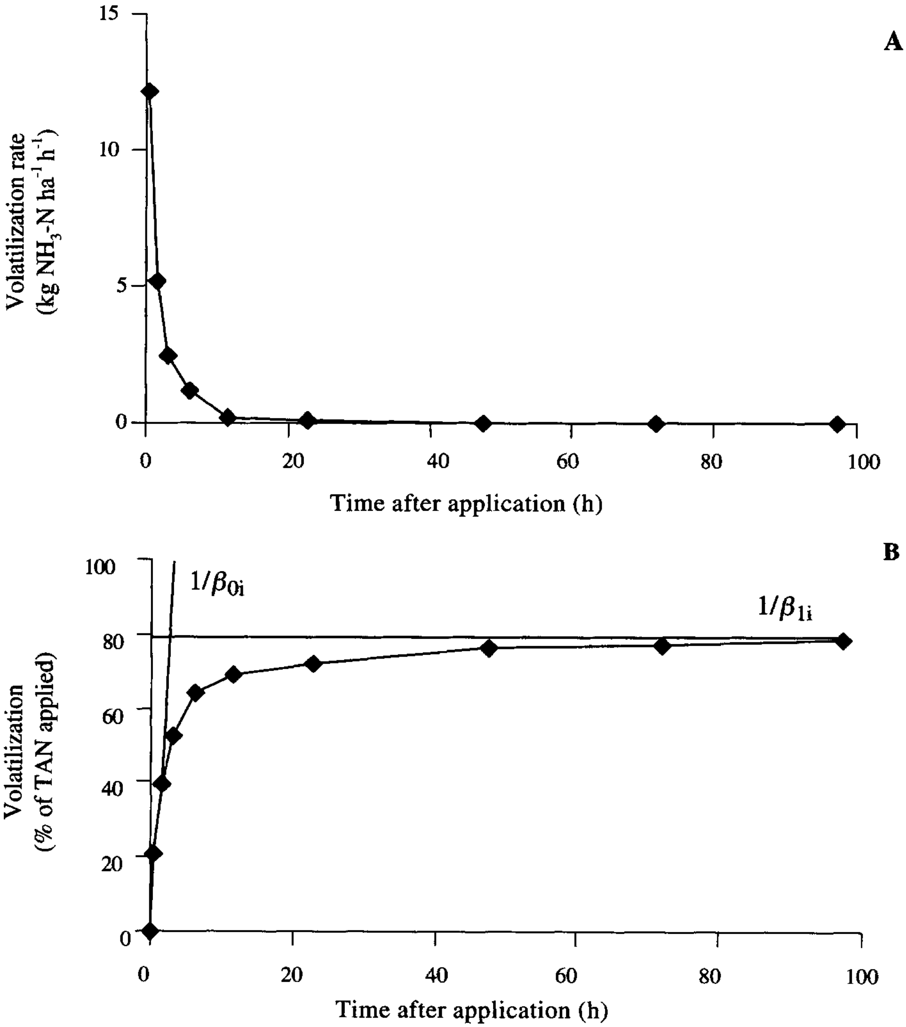



Figure 2. $NH_3$ volatilization from an experimental plot expressed as (A) the course of the volatilization rate and as (B) the calculated cumulative volatilization during the consecutive measuring intervals, with initial volatilization rate (slope, $1/\beta_{0i}$) and total cumulative volatilization (intercept on absciss, $1/\beta_{1i}$). TAN = total ammoniacal nitrogen ($NH_4^+ + NH_3$).

During the 96 hours of an experiment, the weather conditions could vary considerably. The volatilization rate varied with the time after application: after an initial peak, the rate gradually dropped (Figure 2A). Therefore, the effect of the factors that characterize the weather conditions was analysed by relating the magnitude of these factors to the $NH_3$ volatilization during each measuring interval. Each interval yielded a volatilization rate, expressed as kg $NH_3$-N $ha^{-1}$ per hour. Compared with intervals immediately after manure application, later intervals differed in length and in time of the day, and thus in weather conditions. The volatilization rate during each interval is related to the weather conditions during that interval. By using the volatilization rate instead of the percentage of TAN applied – as used in the case of cumulative volatilization – the effect of TAN content and of manure application rate can be analysed separately. Furthermore, by using the volatilization rate per interval instead of the cumulative volatilization, one cause of the interdependence of response values (expressed as cumulative volatilization) was eliminated. However, because observations were made on the same plot and resulted from depletion of the same $NH_3$ source, interdependence of response values was not completely eliminated.

Differences in total cumulative volatilization and volatilization rate during the period following the application may be due to differences between experimental conditions. The number of measurements per soil type, soil moisture content, manure type, manure characteristics, grass height and application technique differed and was limited (unbalanced number of experiments). Moreover, weather conditions varied between experiments. Therefore, the data from all experiments were pooled to analyse the effect of application technique, and of external factors for each application technique. Statistical modelling was used to quantify $NH_3$ volatilization, and to select and assess the effect of the main external factors influencing $NH_3$ volatilization.

*Application technique*

The effect of the application techniques was analysed by using the cumulative volatilization profiles with volatilization expressed as the percentage of TAN applied. When analysing cumulative volatilization, the underlying assumption is that volatilization from the source, i.e., the manure applied to the grassland, is completed at the end of the measuring period. The relation between cumulative volatilization and time can be described for each plot by asymptotic curves (Figure 2B). This type of saturation curve is usually described by the following equation:

$$\mu = t / (\beta_0 + \beta_1 t) \qquad (1)$$

where

$\mu$ = the expected value of the cumulative volatilization at time $t$,

$t$ = the time lapsed since the manure was applied,

$\beta_0$ = the inverse of the slope of the curve at the start of the experiment,

$\beta_1$ = the inverse of the intercept of the asymptote on the ordinate of the curve.

$\mu = 1/\beta_1$ when $t$ approaches infinity. The value of the parameters $\beta_0$ and $\beta_1$ depends on the manure application technique. Inclusion of the manure application technique and linearization of the equation by taking its reciprocal, results in the following equation:

$$1/\mu = \beta_{0i} / t + \beta_{1i} \quad (2)$$

where i is the index for the manure application technique.

Volatilization, and thus initial volatilization rate and total volatilization, will not only differ between techniques (i) but will also be influenced by external factors. The effect of these factors generates deviations in the values of the model parameters from estimated mean values. $\beta_{0i}$ and $\beta_{1i}$ are subject to variation between experiments (j). Within an experiment, weather conditions were considered equivalent, whereas random variation due to unknown sources was assumed to be the same for each experimental plot (k) (piece of grassland), where crop, soil and manure characteristics were the same. Therefore, Equation 2 can be extended to:

$$1/\mu = (\beta_{0i} + u_{0j} + v_{0k}) / t + (\beta_{1i} + u_{1j} + v_{1k}) \quad (3)$$

where $u_{0j}$, $u_{1j}$, $v_{0k}$ and $v_{1k}$ are the deviations of the model parameters, representing random variation due to differences between experiments ($u_{0j}$, $u_{1j}$) and between plots ($v_{0k}$ and $v_{1k}$).

A linear mixed model (LMM) was used to estimate treatment effects (parameter values for different techniques) and random effects. For the measured cumulative volatilization the following equation holds:

$$1/ y_{tijk} = (\beta_{0i} + u_{0j} + v_{0k}) / t + (\beta_{1i} + u_{1j} + v_{1k}) + e_{tijk} \quad (4)$$

where
$y_{tijk}$ = the estimated volatilization, and
$e_{tijk}$ = the residual component of the variation.

Observed cumulative volatilization values for one experimental plot are not only interdependent because they resulted from one $NH_3$ source and were measured under the same experimental conditions, but are also interdependent due to the way these data were collected. Cumulative volatilization is the sum of volatilization during the different intervals. In the analysis these correlations are taken into account by incorporating the random effects $v_{0k}$ and $v_{1k}$.

Cumulative volatilization – expressed as the percentage of the TAN applied – was analysed using the REML (Residual Maximum Likelihood) procedure of Genstat (Payne *et al.*, 1993), which estimates the treatment parameters ($\beta_{0i}$ and $\beta_{1i}$) and the random effects in a LMM. Weights were used to compensate for the fact that variance is not constant but increases with cumulative volatilization, while the random intercepts and slopes were assumed to be positively correlated.

*External factors*

The analysis of the effect of external factors on $NH_3$ volatilization at different intervals after manure application was carried out by modelling the volatilization rate during the different measuring intervals (Figure 2A). External factors included in the analyses were weather (wind speed, air temperature, relative humidity, radiation), soil type (sand, peat, clay), soil moisture content, type of manure (cow, pig), manure characteristics (TAN content, dry matter content, pH), application rate, and grass height. The interdependence of the response values owing to the observations being made in the same plot and resulting from depletion of the same $NH_3$ source, was partly overcome by explicitly incorporating the depletion of the $NH_3$ source into the model. Thus, for the volatilization rate $z_{tk}$ at time $t$ for plot k, the following equation was used:

$$\ln (z_{tk}) = \alpha_0 + \alpha_t \ln(t) + \sum \alpha_m x_{mt} + v_k \quad (5)$$

where
$x_{mt}$ = the value of external variable m at time $t$, and
$\alpha_0$ = a constant.

Random effects $v_k$ account for interdependence of observations on the same field owing to unknown (other than variables tested for) sources. The depletion of the $NH_3$ source is represented by $\alpha_t \ln(t)$, assuming that the decrease of the size of the $NH_3$-source is continuous and exponential. The effects of the weather and other external factors ($\alpha_m$) on the volatilization rate were assumed to be multiplicative, and thus additive on a logarithmic scale. Volatilization rates were analysed with REML, according to Equation 5. Wald tests (Payne *et al.*, 1993) were used for model selection to identify influencing (external) variables ($P < 0.05$).

The influence of external factors on the volatilization following manure application can depend on the application technique. Therefore, the effect of external factors on $NH_3$ volatilization was analysed for each technique separately.

## Results

### *Application technique*

The cumulative $NH_3$ volatilization from surface-applied manure as measured over all experiments, varied from 27 to 98% of the TAN applied. With narrow-band application volatilization varied from 8 to 50%, and with shallow injection from 1 to 25% of the TAN applied (see Appendix). For all application techniques, volatilization was highest during the first hours after application. In the case of surface spreading, on average about 70% of the total measured volatilization took place during the first 3 hours. For narrow-band application and shallow injection this percentage was 30 on average.

In the statistical analysis the $NH_3$ volatilization following the different application techniques – expressed as the percentage of the TAN applied – was estimated for each technique as initial volatilization (slope $1/\beta_{0i}$, Figure 2B) and total cumulative volatilization (intercept $1/\beta_{1i}$, Figure 2B). Differences between the application techniques were large, both for the intercept ($\beta_{1i}$) and the slope ($\beta_{0i}$) of the linear model (Table 2). Total mean cumulative volatilization (of the TAN applied) was estimated

Table 2. Estimated coefficients for the reciprocals of initial volatilization ($\beta_0$) and total volatilization ($\beta_1$), and estimated mean volatilization ($1/\beta_1$) for the different manure application techniques. Standard errors in parentheses.

| Model parameter | Surface spreading | Narrow-band application | Shallow injection |
|---|---|---|---|
| $\beta_0$ [1] | 0.010 (0.085) | 0.385 (0.114) | 1.227 (0.107) |
| $\beta_1$ [2] | 0.013 (0.010) | 0.051 (0.013) | 0.155 (0.012) |
| Volatilization ($1/\beta_1$) | 77 | 20 | 6 |

[1] [h.(% of TAN applied)$^{-1}$], TAN = total ammoniacal nitrogen ($NH_4^+ + NH_3$).
[2] (% of TAN applied)$^{-1}$.

to be 77% for surface spreading, 20% for narrow-band application and 6% for shallow injection. Thus, when 30 kg TAN ha$^{-1}$ is applied (TAN content 2 g per kg manure, application rate 15 m$^3$ ha$^{-1}$), 23 kg TAN ha$^{-1}$ would volatilize when manure is surface-spread and 6 kg ha$^{-1}$ when manure is applied in narrow bands. Injecting 20 m$^3$ ha$^{-1}$ would result in a volatilization of 2.4 kg TAN ha$^{-1}$.

In the statistical model about 50% of the variation of the $NH_3$ volatilization accounted for was explained by the application technique. The variation in model coefficients owing to differences among plots and differences among experiments (indexes $v$ and $u$ in Equations 3 and 4, respectively) contributed to the total variance, and could not therefore be neglected.

*External factors*

The effect of weather, field conditions and manure characteristics on $NH_3$ volatilization was statistically analysed using Equation 5. Wald tests were used for model selection to identify influencing variables per application technique. The analysis showed that volatilization of $NH_3$ was affected by the TAN content of the manure, the manure application rate and the parameters of the weather conditions (Table 3). These effects varied per application technique. Grass height affected $NH_3$ volatilization when manure was applied in narrow bands. No effect was found of the parameters soil type and soil moisture content. Type of manure, dry matter content and pH of the manure had no effect on the $NH_3$ volatilization rate either.

The following equations present the resulting models comprising the influencing external variables:

for surface spreading:

$$\ln z_t = \alpha_0 + \alpha_t \ln(t) + \alpha_1\, TAN + \alpha_2\, rate + \alpha_3\, wind + \alpha_4\, radiation \quad (6a)$$

for narrow-band application:

$$\ln z_t = \alpha_0 + \alpha_t \ln(t) + \alpha_1\, TAN + \alpha_2\, rate + \alpha_3\, wind + \alpha_5\, temp + \alpha_6\, RH + \alpha_7\, gh \quad (6b)$$

for shallow injection:

$$\ln z_t = \alpha_0 + \alpha_t \ln(t) + \alpha_1\, TAN + \alpha_2\, rate + \alpha_3\, wind + \alpha_4\, radiation + \alpha_5\, temp \quad (6c)$$

Table 3. Regression coefficients for selected model variables of Equation 6 that affect the volatilization rate for the different manure application techniques. Standard errors in parentheses.

| Variable | Model parameter | Surface spreading | Narrow-band application | Shallow injection |
|---|---|---|---|---|
| Constant | $\alpha_0$ | –1.08 (0.06) | –1.82 (0.07) | –2.42 (0.08) |
| Time | $\alpha_t$ | –1.20 (0.02) | –0.81 (0.03) | –0.66 (0.03) |
| TAN [1] content | $\alpha_1$ | 0.25 (0.05) | 0.31 (0.05) | 0.23 (0.07) |
| Application rate | $\alpha_2$ | 0.10 (0.02) | 0.07 (0.01) | 0.03 (0.01) |
| Wind speed | $\alpha_3$ | 0.25 (0.02) | 0.22 (0.04) | 0.12 (0.03) |
| Radiation | $\alpha_4$ | 0.0057 (0.0006) | n.s.[2] | 0.0041 (0.0007) |
| Air temperature | $\alpha_5$ | n.s | 0.05 (0.01) | 0.04 (0.01) |
| Relative humidity | $\alpha_6$ | n.s. | –0.018 (0.004) | n.s. |
| Grass height | $\alpha_7$ | n.s. | –0.14 (0.03) | n.s. |

[1] TAN = total ammoniacal nitrogen ($NH_4^+$ + $NH_3$).
[2] n.s. = not selected.

where
*rate* = application rate,
*wind* = wind speed,
*temp* = temperature,
*RH* = relative humidity,
*gh* = grass height.

Estimates of the (selected, statistically significant) model parameters and their standard errors are given in Table 3 for the different techniques. In the Equations 6a–c all predictors are corrected for their averages (Table 4).

The explained variation of the volatilization rate accounted for by external factors (Equations 6a, 6b and 6c) was 46, 64 and 59% for surface spreading, band application and shallow injection, respectively.

With the models 6a, 6b and 6c the effects of changes in the values of influencing factors on the volatilization can be calculated. As the models are on a logarithmic scale, the ratio of two volatilization rates – when comparing two situations – can be

Table 4. Means of the selected model variables in Equation 6 that affect the volatilization rate for the different manure application techniques.

| Variable | Surface spreading | Narrow-band application | Shallow injection |
|---|---|---|---|
| TAN [1] content (g kg$^{-1}$) | 2.7 | 2.7 | 2.4 |
| Application rate (m$^3$ ha$^{-1}$) | 13.9 | 14.2 | 22.0 |
| Wind speed (m s$^{-1}$) | 3.2 | 3.4 | 3.4 |
| Radiation (J cm$^{-2}$ h$^{-1}$) | 98.9 | 101.3 | 117.5 |
| Air temperature (°C) | 14.6 | 15.2 | 15.8 |
| Relative humidity (%) | 70.5 | 72.1 | 73.0 |
| Grass height (cm) | 7.2 | 7.4 | 7.5 |

[1] TAN = total ammoniacal nitrogen ($NH_4^+$ + $NH_3$).

calculated as the difference between the volatilization values for a single factor in the compared situations, keeping the other factors constant. The effect of differences between the values of a single factor on the relative $NH_3$ volatilization rate (expressed as the ratio of volatilization between the situations) can be derived from Figure 3. When the difference between the compared situations (value on abscissa) is 0, the ratio of the volatilization (value on ordinate) is 1.

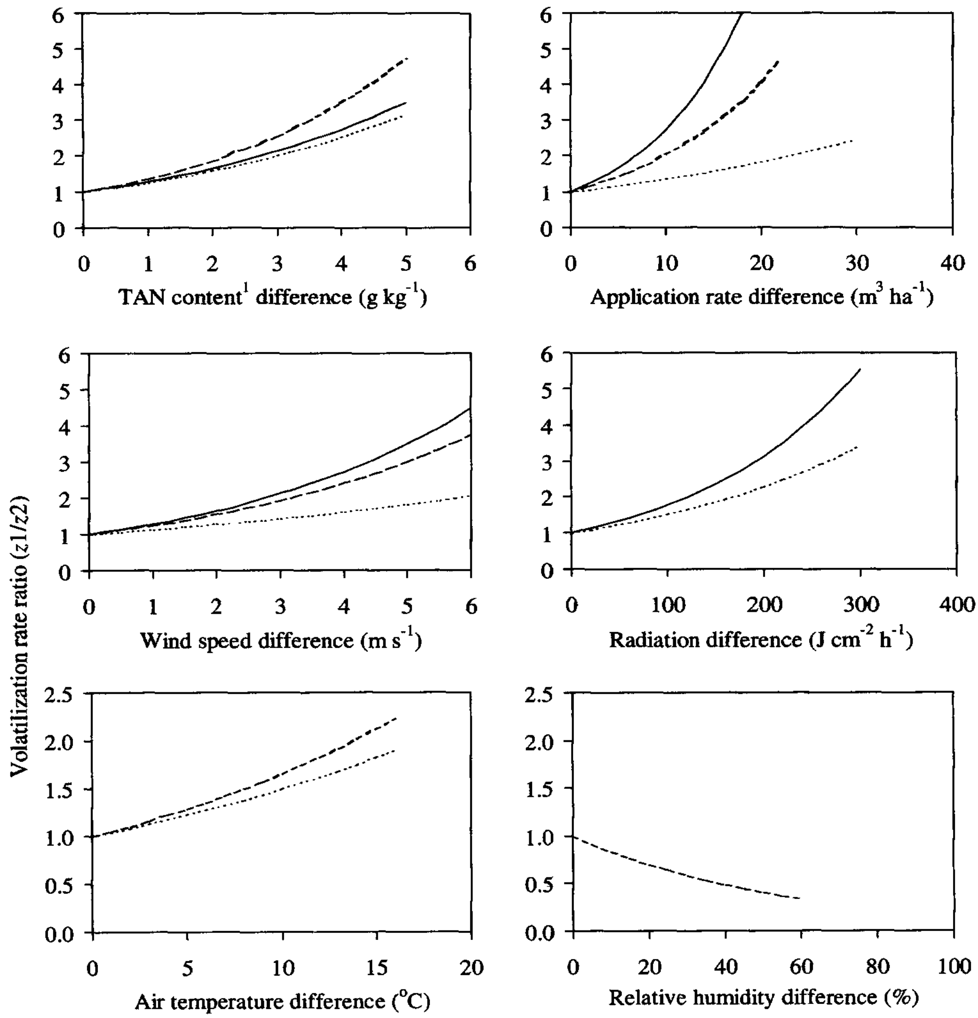
For each of the application techniques, increases in the TAN content of the manure and in the application rate led to an increase in $NH_3$ volatilization rate. In most cases the effect of the factors increased in the order: shallow injection, narrow-band application, surface spreading. Only for the effect of TAN content, volatilization rate was relatively more affected by band application than by surface spreading.

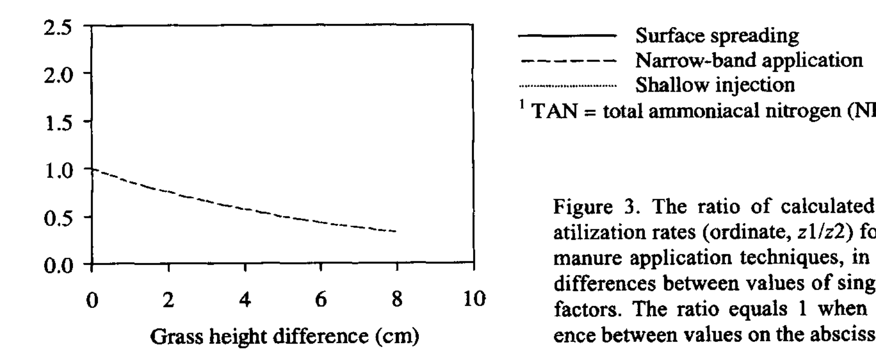
Wind speed affected the volatilization rate for all application techniques. The effect of wind speed decreased in the order: surface application, narrow band application, shallow injection. An increase in wind speed by 2 m $s^{-1}$ increased the volatilization rate with a factor 1.65, 1.55 and 1.27 for surface application, band application and shallow injection, respectively. Radiation, air temperature or relative humidity affected the volatilization rate, but the effect depended on the application technique. An increase in radiation increased the volatilization rate for surface spreading and shallow injection. With narrow-band application and shallow injection the volatilization rate increased when air temperature increased, but in the case of narrow-band application it decreased when the relative humidity increased. For surface spreading an increase in radiation by 100 J $cm^{-2}$ $h^{-1}$ resulted in the same order of increase of the volatilization rate as an increase of the wind speed by 2.25 m $s^{-1}$. With band application the effect of an increase in wind speed by 2 m $s^{-1}$ would be counterbalanced by a decrease in air temperature by 9 °C or an increase in the relative humidity by 25%. For shallow injection the corresponding temperature decrease would have to be 6 °C. An increase in the grass height led to lower $NH_3$ volatilization when manure was applied in narrow bands. With this technique a reduction of the grass height from 8 to 4 cm would be counterbalanced by a decrease in wind speed of 2.5 m $s^{-1}$ or by an increase in relative humidity of about 30%.

## Discussion and conclusions

The present study of factors affecting $NH_3$ volatilization following the application of manure benefited from a unique set of data available from field experiments in the Netherlands. The combination and the statistical analysis of these data, together with the model that was designed, yielded valuable and new information about the factors that influence $NH_3$ volatilization, and about the magnitude of their effects. By focussing on the influencing factors, the information obtained has a high potential for practical application and for deepening the insight into the mechanisms of $NH_3$ volatilization following the application of manure on grassland.

In this study, cumulative $NH_3$ volatilization from surface-applied manure varied from 27 to 98% of the TAN applied. With narrow-band application the volatilization varied from 8 to 50%, and with shallow injection from 1 to 25% of the TAN applied.




[1] TAN = total ammoniacal nitrogen ($NH_4^+ + NH_3$).

Figure 3. The ratio of calculated $NH_3$ volatilization rates (ordinate, $z1/z2$) for the three manure application techniques, in relation to differences between values of single external factors. The ratio equals 1 when the difference between values on the abscissa is 0.

With all application techniques the volatilization was highest during the first hours after application. Ammonia volatilization was significantly affected by the application technique. Compared with surface spreading, narrow-band application and shallow injection reduced $NH_3$ volatilization by 74% and 92%, respectively. A reduced contact area between the manure and the ambient air and a larger surface area for infiltration of the manure into the soil can account for this reduction. Amberger *et al.* (1987) found that volatilization is increased when manure is applied onto a stubble or onto crop residues on arable land, and explained this increase by a decreased infiltration into the soil and an increased contact area with the ambient air. In the present study, manure was surface-spread on top of the grass, which may have acted as a physical barrier against infiltration, whereas in the case of narrow-band application and shallow injection manure may have infiltrated easier due to the direct contact with the soil. Moreover, when surface-applied, manure has a relatively large contact area with the air; the manure mainly covers the grass. On the other hand, band application and shallow injection leave the manure only in contact with the air through a small band or via the opening of the injection slit, and smothering of grass leaves with manure is prevented. Shallow injection further restricts the contact of the manure with the ambient air by placing the manure into the soil.

The $NH_3$ volatilization rate from manure applied with the three techniques was affected by weather conditions. The study showed that with each of the techniques the $NH_3$ volatilization rate increased by weather conditions that favour drying, such as an increase in wind speed, air temperature or radiation, or a decrease in relative humidity. Evaporation of water from the manure is known to lead to an increase of the aqueous ammonia concentration in the manure and to an increase in $NH_3$ volatilization (Brunke *et al.*, 1988; Horlacher & Marschner, 1990; Sommer *et al.*, 1991a). In this way, the decreasing contact area with the ambient air in the order: surface spreading, narrow-band application, shallow injection, may have restricted the volatilization in the same way as evaporation was decreased by restricting the contact area with the air.

The effect of wind speed on the $NH_3$ volatilization rate with the three application techniques can also be explained by an increased diffusion rate of ammonia into the air. Volatilized ammonia is removed by the wind, and the ammonia concentration in the air above the manure stays low, stimulating further ammonia volatilization (Freney *et al.*, 1983).

A crop may act as an interface between the atmosphere and the applied manure, resulting in a lower wind speed at the manure's surface (Thompson *et al.*, 1990; Amberger, 1991; Sommer *et al.*, 1991b), and thus in less volatilization. The effect of grass height on $NH_3$ volatilization from narrow-band-applied manure may be due to a change in microclimate around the manure, leading to lower volatilization rates at higher grass heights.

With the three application techniques an increase of the TAN content and a higher application rate of the manure resulted in an increase in $NH_3$ volatilization rate due to a larger source of $NH_3$.

The study showed no effect of soil type, soil moisture content, type of manure, dry matter content or pH of the manure on the $NH_3$ volatilization rate. The variation in these variables (Table 1) could explain why no effect was found. For example, from several studies it appeared that ammonia volatilization could be decreased by lowering the pH of the manure to values below 6 (Stevens *et al.*, 1989; Frost *et al.*, 1990; Stevens *et al.*, 1992, Bussink *et al.*, 1994). In the present study the pH of the manure was never lower than 6.8 (Table 1). No effect of the type of manure (cow, pig) was found. However, the pig manure had a higher TAN content than the cow manure and an increase in TAN content as such, increased $NH_3$ volatilization.

Generally, the $NH_3$ volatilization rate from applied manure is not linear with time but peaks the first hours after spreading (Figures 2 and 4). In agreement with Bussink *et al.* (1994), in the present study, the rate of $NH_3$ volatilization at the end of the experimental period (96 hours) was virtually zero. The experimental data therefore reflect qualitative effects and may be used quantitatively. The high initial volatilization rate is expressed in the analyses by the initial slope of the cumulative volatilization ($1/\beta_{0i}$) and by the depletion of the $NH_3$ source represented by $\alpha_t\ln(t)$ in Equation 6. Quantitatively, the impact of the weather conditions on volatilization following manure application will therefore be highest during the first hours after manure application. Information on factors influencing the size of volatilization may be lost if the cumulative volatilization is considered only at a certain time after application. Therefore, including the volatilization profile into the analysis yielded more insight into the volatilization process.

The factors causing variation between the experiments in the present study were

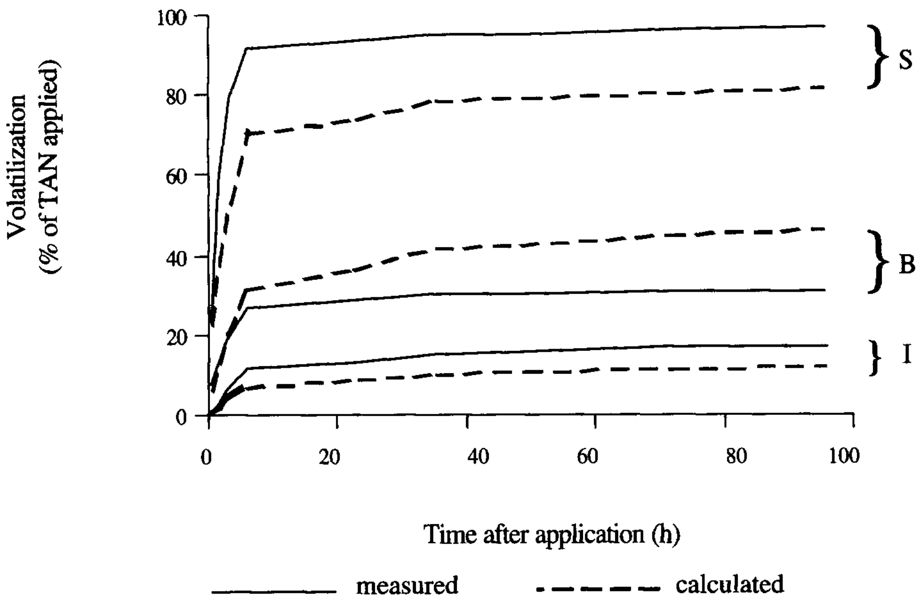



Figure 4. Measured $NH_3$ volatilization-time profiles and the calculated estimates of the $NH_3$ volatilization according to Equation 6 for an experiment in which the application techniques surface spreading (S), narrow-band application (B) and shallow injection (I) were compared. TAN = total ammoniacal nitrogen ($NH_4^+ + NH_3$).

analysed. Important external variables and the size of their effect on the $NH_3$ volatilization rate were identified. However, a relatively large part of the variation is caused by variation between experiments and between plots within experiments. Figure 4 presents the measured $NH_3$ volatilization in an experiment comparing the three application methods, together with the $NH_3$ volatilization predicted with the models, taking into account the manure characteristics, and the field and weather conditions in the experiment. Fitted values are the result of fixed and random effects. Figure 4 shows that predictions by the model show deviations from measured values. The measured $NH_3$ volatilization was 97% of the TAN applied in the case of surface spreading, 31% for narrow-band application and 17% for shallow injection. The predicted $NH_3$ volatilization for the three techniques was 82, 47 and 13% of the TAN applied, respectively. Differences between measured and predicted values are the result of random variation between plots. Further research with validation measurements could result in a model that can be used to improve the predictions of volatilization profiles, given a certain application method and known external conditions.

The study shows that $NH_3$ volatilization – field and weather conditions, and manure characteristics being equal – can be reduced considerably by the use of narrow-band application and shallow injection compared with surface spreading. Differences between conditions under which the application techniques are used can affect the overall reduction of $NH_3$ volatilization. In the Netherlands, narrow-band application and shallow injection were prescribed in the 1990s. In this period it also became forbidden to apply manure outside the growing season (autumn–winter period). Before these prescriptions, surface spreading was common and manure was also applied outside the growing season. Conditions favouring volatilization are more often met in spring and summer than in autumn and winter. Therefore, when comparing the overall national annual $NH_3$-volatilization between the 1980s and the period from 1990 onwards, not only the application methods used, but also the time of the year when manure was applied should be taken into account. When comparing the 1980s and the period since 1990, the overall reduction in $NH_3$-volatilization by the introduction of volatilization-reducing techniques may be less than predicted by the present study. However, the present study shows – provided conditions for all application methods are the same – that prescribing or convincing farmers to use volatilization-reducing techniques will help to control contamination of the environment caused by $NH_3$ volatilization from field-applied manure. From the results of this study it can be concluded that application method and external factors need to be taken into account when predicting ammonia volatilization following manure application.

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## Appendix

Summary of the experiments and the measured $NH_3$ volatilization from manure after surface spreading (S), narrow-band application (B) and shallow injection (I).

| Exp. No | Year | Week | Application technique | Soil type [1] | Soil moisture content (%) | Grass height (cm) | Manure type [2] | TAN [3] content (g kg$^{-1}$) | Application rate (m$^3$ ha$^{-1}$) | Volatilization (% of TAN [3] applied) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 89 | 13 | I | S | – | 6 | 1 | 3.3 | 26.8 | 3.6 |
| | | | S | S | – | 6 | 1 | 3.2 | 17.2 | 29.3 |
| 2 | 89 | 15 | I | S | – | 6 | 2 | 5.8 | 26.0 | 2.3 |
| | | | S | S | – | 6 | 2 | 6.0 | 10.0 | 27.3 |
| 3 | 89 | 27 | I | C | – | 6 | 1 | 2.8 | 14.0 | 10.9 |
| 4 | 89 | 28 | I | C | – | 6 | 2 | 5.3 | 15.4 | 5.7 |
| | | | S | C | – | 6 | 2 | 5.4 | 12.7 | 68.1 |
| 5 | 89 | 38 | I | P | – | – | 1 | 1.6 | 18.4 | 1.5 |
| | | | S | P | – | – | 1 | 1.6 | 15.4 | 66.1 |
| 6 | 90 | 11 | S | C | 37 | – | 1 | 3.3 | 16.3 | 43.2 |
| | | | S | C | 37 | – | 1 | 3.3 | 12.5 | 47.9 |
| 7 | 90 | 12 | B | C | 40 | 10 | 1 | 2.2 | 19.0 | 14.7 |
| | | | B | C | 45 | 10 | 1 | 2.2 | 6.6 | 12.0 |
| | | | I | C | 40 | 10 | 1 | 2.2 | 16.8 | 15.7 |
| | | | S | C | 40 | 10 | 1 | 2.2 | 19.7 | 47.7 |
| 8 | 90 | 17 | I | P | 61 | 6 | 1 | 2.2 | 17.8 | 8.9 |
| | | | S | P | 61 | 10 | 1 | 2.2 | 10.2 | 58.3 |
| 9 | 90 | 18 | S | P | 50 | 8 | 1 | 2.8 | 8.7 | 71.9 |
| 10 | 90 | 20 | B | C | 35 | 8 | 1 | 2.2 | 17.3 | 31.4 |
| | | | B | C | 40 | 8 | 1 | 2.2 | 8.4 | 14.6 |
| | | | I | C | 35 | 8 | 1 | 2.2 | 18.8 | 11.8 |
| | | | S | C | 35 | 8 | 1 | 2.2 | 16.1 | 64.3 |
| 11 | 90 | 22 | I | P | 42 | 10 | 1 | 2.3 | 18.2 | 11.3 |
| | | | S | P | 42 | 10 | 1 | 2.3 | 9.8 | 44.2 |
| 12 | 90 | 23 | B | C | 28 | 8 | 2 | 6.3 | 14.9 | 31.0[4] |
| | | | B | C | 28 | 8 | 2 | 6.3 | 7.9 | 16.1[4] |
| | | | I | C | 28 | 8 | 2 | 6.3 | 17.3 | 11.4[4] |
| | | | S | C | 28 | 8 | 2 | 6.3 | 17.5 | 67.4[4] |
| 13 | 90 | 24 | I | S | – | 8 | 1 | 2.3 | 22.2 | 3.9 |
| | | | S | S | – | 8 | 1 | 2.3 | 9.9 | 33.9 |
| 14 | 90 | 24 | B | C | 33 | 5 | 1 | 2.3 | 8.6 | 19.9 |
| | | | B | C | 33 | 5 | 2 | 6.4 | 8.8 | 32.0 |
| | | | S | C | 33 | 5 | 1 | 2.3 | 8.3 | 61.2 |
| | | | S | C | 33 | 5 | 2 | 6.4 | 8.6 | 49.5 |
| 15 | 90 | 25 | S | C | 25 | 6 | 1 | 2.4 | 8.8 | 84.5 |
| 16 | 90 | 26 | I | S | – | 8 | 1 | 2.4 | 25.0 | 9.3 |
| | | | S | S | – | 8 | 1 | 2.3 | 9.8 | 51.0 |
| 17 | 90 | 27 | S | P | 50 | 9 | 1 | 2.2 | 8.7 | 58.4 |
| 18 | 90 | 29 | S | C | 19 | 7 | 1 | 2.3 | 8.7 | 43.7 |
| 19 | 90 | 30 | S | C | 19 | 8 | 1 | 2.2 | 8.6 | 83.5 |
| 20 | 90 | 31 | S | C | 22 | 8 | 2 | 3.5 | 8.4 | 66.2 |
| 21 | 90 | 35 | S | P | 58 | 8 | 1 | 2.0 | 12.7 | 52.0 |
| 22 | 90 | 36 | I | P | 48 | 10 | 1 | 2.3 | 15.1 | 4.9 |
| | | | S | P | 48 | 10 | 1 | 2.3 | 9.6 | 49.7 |

| Exp. No | Year | Week | Application technique | Soil type [1] | Soil moisture content (%) | Grass height (cm) | Manure type [2] | TAN [3] content (g kg$^{-1}$) | Application rate (m$^3$ ha$^{-1}$) | Volatilization (% of TAN [3] applied) |
|---|---|---|---|---|---|---|---|---|---|---|
| 23 | 91 | 15 | B | C | 34 | 6 | 1 | 1.9 | 10.7 | 21.7 |
| | | | B | C | 34 | 12 | 1 | 1.9 | 10.6 | 10.6 |
| | | | S | C | 34 | 6 | 1 | 1.9 | 16.2 | 80.1 |
| | | | S | C | 34 | 12 | 1 | 1.9 | 15.3 | 64.7 |
| 24 | 91 | 16 | B | C | 24 | 6 | 2 | 5.0 | 12.0 | 14.9 |
| | | | B | C | 24 | 12 | 2 | 5.0 | 10.6 | 8.5 |
| | | | S | C | 24 | 6 | 2 | 5.0 | 16.3 | 73.7 |
| | | | S | C | 24 | 12 | 2 | 5.0 | 15.2 | 84.9 |
| 25 | 91 | 24 | B | C | 28 | 6 | 1 | 1.8 | 24.6 | 37.7 |
| | | | S | C | 28 | 7 | 1 | 1.8 | 13.0 | 97.7 |
| 26 | 91 | 29 | S | C | 21 | 6 | 1 | 1.5 | 9.8 | 96.7 |
| 27 | 91 | 30 | S | C | 24 | 7 | 1 | 1.6 | 14.0 | 70.8 |
| 28 | 91 | 36 | S | C | 14 | 9 | 1 | 2.5 | 16.4 | 67.8 |
| 29 | 92 | 11 | S | C | 39 | 7 | 1 | 2.1 | 17.3 | 86.2[4] |
| 30 | 92 | 12 | S | C | 34 | 7 | 1 | 2.2 | 17.6 | 84.8 |
| 31 | 92 | 16 | I | C | 40 | 6 | 1 | 1.8 | 19.1 | 5.2 |
| | | | I | C | 40 | 11 | 1 | 1.8 | 17.9 | 2.8 |
| | | | I | C | 40 | 6 | 1 | 1.8 | 19.2 | 3.8 |
| | | | S | C | 40 | 6 | 1 | 1.8 | 18.7 | 57.2 |
| 32 | 92 | 17 | B | P | 67 | 6 | 1 | 2.6 | 13.5 | 30.1 |
| | | | B | P | 67 | 11 | 1 | 2.6 | 14.0 | 11.9 |
| | | | S | P | 67 | 6 | 1 | 2.6 | 24.9 | 66.0 |
| 33 | 92 | 21 | S | C | 31 | 8 | 1 | 2.0 | 11.6 | 87.7 |
| 34 | 92 | 25 | I | C | 29 | 7 | 1 | 2.0 | 15.6 | 9.9 |
| | | | I | C | 29 | 7 | 1 | 2.0 | 20.6 | 15.2 |
| | | | I | C | 29 | 7 | 1 | 2.0 | 30.8 | 14.1 |
| | | | I | C | 29 | 7 | 1 | 2.0 | 31.3 | 15.8 |
| 35 | 92 | 26 | B | C | 25 | 6 | 1 | 2.1 | 28.1 | 50.3 |
| | | | B | C | 25 | 6 | 1 | 2.1 | 27.1 | 38.2 |
| | | | B | C | 25 | 6 | 1 | 2.1 | 15.0 | 42.9 |
| | | | B | C | 25 | 6 | 1 | 2.1 | 13.6 | 39.5 |
| | | | S | C | 25 | 6 | 1 | 2.1 | 13.7 | 78.1 |
| 36 | 92 | 27 | S | P | 42 | 5 | 1 | 2.3 | 13.6 | 97.5 |
| | | | B | P | 42 | 5 | 1 | 2.3 | 16.2 | 30.9 |
| | | | B | P | 42 | 7 | 1 | 2.3 | 11.5 | 28.6 |
| | | | I | P | 42 | 5 | 1 | 2.3 | 17.1 | 17.3 |
| | | | I | P | 42 | 5 | 1 | 2.3 | 18.9 | 24.5 |
| 37 | 92 | 28 | S | P | 50 | 7 | 1 | 2.3 | 14.6 | 91.2 |
| 38 | 92 | 35 | S | P | 62 | 8 | 1 | 2.0 | 15.5 | 92.0 |
| 39 | 92 | 38 | I | C | 24 | 9 | 1 | 2.0 | 25.0 | 3.4 |
| | | | I | C | 24 | 9 | 1 | 2.0 | 17.8 | 3.9 |
| | | | S | C | 24 | 9 | 1 | 2.0 | 16.3 | 87.3 |
| 40 | 93 | 10 | S | C | 38 | 4 | 1 | 2.2 | 17.9 | 71.1 |
| | | | S | C | 38 | 4 | 1 | 2.2 | 18.5 | 71.9 |
| 41 | 93 | 11 | B | C | 34 | 6 | 1 | 2.1 | 10.4 | 37.5 |
| | | | B | C | 34 | 6 | 1 | 2.1 | 10.3 | 38.1 |
| | | | B | C | 34 | 6 | 1 | 2.1 | 11.6 | 34.6 |
| | | | B | C | 34 | 6 | 1 | 2.1 | 10.0 | 37.4 |
| | | | S | C | 34 | 6 | 1 | 2.1 | 15.1 | 68.9 |
| | | | S | C | 34 | 6 | 1 | 2.1 | 15.8 | 66.7 |

| Exp. No | Year | Week | Application technique | Soil type [1] | Soil moisture content (%) | Grass height (cm) | Manure type [2] | TAN [3] content (g $kg^{-1}$) | Application rate ($m^3$ $ha^{-1}$) | Volatilization (% of TAN [3] applied) |
|---|---|---|---|---|---|---|---|---|---|---|
| 42 | 93 | 12 | S | C | 33 | 5 | 1 | 2.1 | 19.4 | 81.2 |
| | | | S | C | 41 | 7 | 1 | 2.1 | 19.0 | 95.2 |
| 43 | 93 | 18 | I | C | 29 | 7 | 1 | 1.6 | 18.5 | 7.1 |
| | | | I | C | 29 | 7 | 1 | 1.6 | 17.5 | 19.0 |
| | | | I | C | 29 | 7 | 1 | 1.6 | 17.8 | 25.1 |
| | | | I | C | 29 | 7 | 1 | 1.6 | 20.8 | 18.6 |
| 44 | 93 | 21 | I | C | 24 | 8 | 1 | 2.0 | 20.2 | 7.1 |
| | | | I | C | 24 | 8 | 1 | 2.0 | 19.5 | 8.5 |
| | | | I | C | 24 | 8 | 1 | 2.0 | 19.8 | 8.9 |
| | | | I | C | 24 | 8 | 1 | 2.0 | 32.7 | 16.6 |
| | | | I | C | 24 | 8 | 1 | 2.0 | 45.5 | 10.3 |
| | | | I | C | 24 | 8 | 1 | 2.0 | 44.2 | 8.3 |
| 45 | 93 | 22 | B | C | 28 | 9 | 1 | 2.0 | 14.4 | 17.0[4] |
| | | | B | C | 28 | 9 | 1 | 2.0 | 15.7 | 16.1[4] |
| | | | B | C | 28 | 9 | 1 | 2.0 | 14.8 | 11.1[4] |
| | | | B | C | 28 | 9 | 1 | 2.0 | 15.5 | 13.0[4] |

[1] S = sand, P = peat, C = clay.
[2] 1 = cow manure, 2 = pig manure.
[3] TAN = total ammoniacal nitrogen ($NH_4^+ + NH_3$).
[4] Measured cumulative volatilization 72 hours after manure application.