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Research Paper

Effect of reduced exposed surface area and enhanced infiltration on ammonia emission from untreated and separated cattle slurry

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Ammonia (NH_3) loss during field application of liquid manure (slurry) causes loss of nutrients for the crops and contributes to contamination of the environment. The emission can be mitigated by different low-emission application technologies and slurry treatment prior to application. It is assumed that a reduced area for air-slurry interaction will reduce the emission. The NH_3 emission mitigation potential of technologies intended to reduce manure-air contact by reducing the exposed surface area (ESA) of the slurry or enhancing slurry infiltration was investigated for cattle slurry applied on grassland. Treatments tested were: 1) removing solids by solid–liquid separation of the slurry, 2) reduced ESA by narrow band application, and 3) application with a sub-surface-deposition (SSD) slurry application (creating aeration slots). For untreated cattle slurry NH_3 emission was not reduced by reducing ESA, but application over aeration slots significantly decreased emission. However, reduced ESA by band application reduced emission from separated slurry compared to broadcast applied slurry, but no additional reduction was obtained by using the SSD technique. Lower emission was generally observed from separated slurry compared to untreated slurry for all application methods. This study shows that a reduction in NH_3 emission is not necessarily obtained solely by reducing the ESA. It is hypothesized that rapid surface drying or crust formation of the untreated slurry in the relatively warm sunny conditions of these trials mitigated NH_3 emission, thereby masking the effects of a reduced ESA.

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Nomenclature

a	Total reduction in ESA from the initial area after application until stagnation in ESA (m^2 m^{-2})
ANOVA	Analysis of variance
AY7	Acid yellow 7 fluorescent tracer
b	Parameter that describing rate of changes in ESA following slurry application (h^{-1})
c	Area of slurry at the soil surface at $t = \infty$ (m^2 m^{-2})
DM	Dry matter
ESA	Exposed surface area (m^2 m^{-2})
GLMM	Generalised linear mixed model
N	Nitrogen
NH_3	Ammonia
NH_4^+	Ammonium
SSD	Sub-surface deposition
t	Time (h)
TAN	Total ammoniacal nitrogen

1. Introduction

Valuable nutrients in liquid manure (slurry) can be utilized when it is applied as fertilizer for crops. A substantial amount of the crop-available inorganic nitrogen (N) in the slurry can be lost through ammonia (NH_3) emissions. Ammonia emissions must be mitigated to ensure maximum use of the nutrients in the slurry and reduce contamination of the environment (Aneja et al., 2009; Sommer et al., 2003).

Previous research suggest that application techniques reducing the contact area between the applied slurry and the atmosphere, as well as methods than enhance slurry infiltration into the soil, reduce NH_3 emission (Sommer & Hutchings, 2001; Webb et al., 2010). It is hypothesized that at the time slurry is applied, the total ammoniacal nitrogen (TAN) is present in a fast and a slow pool (Hafner et al., 2019). Total ammoniacal nitrogen from the fast pool is directly exposed to the atmosphere, and is thereby available for emission. The slow pool represents TAN that has less exposure to the atmosphere as a result of incorporation or infiltration into the soil, distance from the air-manure interface or due to a barrier such as a dry surface layer or crust (Chantigny et al., 2004; Rodhe et al., 2004; Sommer et al, 2003, 2004; Webb et al., 2013). The slow pool can be protected by infiltration and incorporation whereas these processes are too slow for the fast pool.

Efficient NH_3 emission reduction can be achieved by rapid and complete incorporation of the slurry into the soil (Hansen et al., 2003; Holly et al., 2017). Hansen et al. (2003) found, that the emission reduction from cattle slurry applied on grassland was correlated with the depth and volume of injection furrows. The higher reductions also correlated with higher energy and labour demands and carbon dioxide emissions, making the application more expensive than surface broadcast application (Hansen et al., 2003; Huijsmans et al., 2004). Injection has also been found to reduce yields on grass fields (Rees et al., 1993; Rodhe & Halling, 2015). Therefore, efficient methods for abatement that does not reduce yields are needed, for example methods that reduce the contact area between slurry and atmosphere without soil- or crop damage. Slurry application in bands by either trailing hoses or trailing shoes reduce the exposed surface area (ESA) compared to broadcasting with a splash-plate type applicator. Band application of cattle slurry on grass fields has been found to give a range of reductions in NH_3 emission (26–51%) compared to broadcast application from studies with a broad variety of slurry and soil parameters and crop canopy (Bittman et al., 2005; Häni et al., 2016; Misselbrook et al., 2002; Smith et al., 2000). Even though banding on average reduce the NH_3 emission, the technique has under some conditions been found not to reduce the emission (Bhandral et al., 2009; Bittman et al., 2005; Häni et al., 2016), such as on saturated soils or where there is rapid drying and where there is limited canopy to intercept the slurry before it contacts the soil or to shelter the slurry from air flow.

Sub-surface deposition (SSD), applying slurry in bands over aeration slots made by rolling tines, has been proposed as a NH_3 mitigation strategy (Bittman et al., 2005; Chen et al., 2001) as it assists infiltration (Ai et al., 2012) and consequently is expected to lower the emission. The application technique has been tested in two studies (Bhandral et al., 2009; Bittman et al., 2005), where it showed great promise as a low-emission application technology.

Several studies have found that the dry matter (DM) of the slurry is one of the most important parameters affecting NH_3 emission after field application of slurry. A lower DM content of the slurry has been found to lower NH_3 emission (de Jonge et al., 2004; Häni et al., 2016; Misselbrook et al., 2005; Smith et al., 2000; Sommer & Olesen, 1991). This effect is assigned to higher infiltration of the slurry and thereby less fast-pool slurry left exposed to the atmosphere. This effect requires that the soil is not saturated and is reasonably permeable.

Removal of solids by solid–liquid separation of slurry lowers the DM content, and has been observed to reduce the NH_3 emission from field-application of the liquid fraction (Hjorth et al., 2010; Webb et al., 2013). While there are many techniques for mechanically removing solids, a simple method for removing a portion of heavier particles from the slurry is to let it settle in a tank and subsequently decanting the thinner liquid fraction from the top. Separation generates a thick solid-rich- and a thin liquid fraction, the former having a higher phosphor:N ratio than the latter. Separation often gives a higher nutrient utilization of field applied slurry with reduced phosphor loading and hence a higher flexibility in slurry management and storage capacity (Hjorth et al., 2010). Bittman et al. (2012) have proposed the solid fraction or sludge left at the bottom of the tank or in the first stage of a two stage lagoon system can be used as a phosphor source for maize.

An aim of this study was to further investigate the potential of SSD, both alone and in combination with separation of the slurry, and to determine if the potentially reduced emission can be explained by differences in ESA of the slurry after application. The overall objectives of this study were (i) to assess the effect of ESA of slurry on NH_3 emission, and investigate if it can be used as a predictor for emission from cattle slurry applied in late spring climate conditions and (ii) to evaluate solid–liquid separation, SSD and the combined effect of these as mitigation strategies for NH_3 emission.

2. Materials and methods

Four experiments were conducted; each experiment (A, B, C, and D) had four treatments (Table 1). The treatment with narrow banded untreated slurry was present as a reference in all experiments.

Ammonia emission was measured with 16 wind tunnels (4 treatments x 4 replicates). The ESA was measured using a new technique, based on imaging, for detecting the area of slurry doped with a fluorescence dye (Pedersen et al., 2020). The ESA of the slurry was determine in 12 dark chambers (4 treatments x 3 replicates) to preserve the effect of the dye. The NH_3 measurements spanned approximately 94 h and the ESA measurements spanned 8 h since no additional changes were observed subsequently.

2.1. *Site*

The experiments were performed at the Agassiz Research and Development Centre, Agriculture and AgriFood Canada, in south coastal British Columbia, Canada (49°24′ N, 121°76′ W) from 27th of May to 29th of July 2019. The soil was a silty loam with a 10 year old stand of mostly Kentucky bluegrass and some white clover and broadleaf weeds (<10%). Care was taken to standardise the placements of the wind tunnels and dark chambers on areas in the field with uniform soil and crop. The plots in each trial were kept as close as possible in each trial to minimise soil and crop variation. A fresh area within a few meters was used for each experiment. The grass was trimmed at about 0.1 m with a sickle bar mower in the experimental area the day before each experiment. For experiment A and C, a block design was used for the tunnels. For experiment B and D, a block design was not possible in order to accommodate the experimental rolling tine implement (SSD). After plots were chosen for aeration and no aeration, the treatments where distributed as randomly and independently as possible. This could be done since the field is very flat and any variation in the field or stand is assumed to be random.

2.2. *Slurry and slurry application*

The slurry was collected in late fall from a slurry tank on a typical Canadian commercial high producing dairy farm using saw-dust bedding. The slurry was stored for three months in two adjacent in-ground 2.5 m deep concrete storage tanks. The tanks were uncovered but had a roof to keep out rainwater, which is typical of many farms in the area. The raw slurry was thoroughly mixed before pumping for use in each experiment (hereafter called untreated). The separated slurry was decanted from the top one-third of the second tank. The untreated and separated slurries were analysed for TAN by steam distillation (Kjeltec™ 2400, Foss, Hillerød, Denmark) followed by titration (Rutherford et al., 2008) and for total N by Kjeldahl method (Rutherford et al., 2008). Dry matter was determined after oven drying at 105 °C for 24 h (American Public Health Association, 1999). Slurry properties and application rates for each experiment can be found in Table 2.

For application with a rolling tine, the AerWay™ SSD™ slurry applicator (Holland Canada, Norwich, ON) was used to make the intermittent vertical injection pockets (Bittman et al., 2005). The distance between the rows of rolling tines was 0.2 m and the distance between the centres of the aeration slots in a row was 0.4 m. The average length and depth of each aeration slot was 151 ± 23 mm and 123 ± 14 mm, respectively. The SSD was passed over the appropriate field plots with machine before the wind tunnel frames were installed. The frames were carefully positioned so that each frame had two rows of five aeration slots along the length of the frame, giving 10 slots per m^2. The dark chambers covered an area of 0.14 m^2, and were positioned so that each chamber encompassed two complete aeration slots.

A slurry application rate of 6 kg m^{-2} was used for all treatments, resulting in 6 l per tunnel and 0.87 l per dark chamber. This is a typical application rate used by farmers in the area. As it was the goal to investigate the effect of ESA, the same volume of untreated and separated slurry were applied. All the slurry was applied by hand with a watering can. The tunnel covers were placed over the frames and measurements begun so that less than 10 min elapsed between slurry spreading and the start of NH_3 collection. To broadcast the manure, the watering can was fitted with a wooden plate (150 × 100 mm) that deflected and spread the slurry. For band application and application by SSD the watering can without the wooden plate was used slurry application. For SSD the bands were applied on top of the SSD injection pockets made by machine beforehand. For all experiments, slurry was applied in the morning between 9 and 11AM, starting with all the dark chambers followed by all the tunnels.

The slurry spread in the dark chambers was doped with AY7 dye (Acid Yellow 7/Brilliant Sulfaflavine, 404.37 M, 100% +/− 3% MP Biomedics, USA). The dye was first diluted into 1 l sample of the slurry, which was then mixed thoroughly with

Table 1 – Overview of experiments and treatments. Narrow banded: as trailing hose application, wide banded: banded in 0.2 m wide line, SSD: narrow band applied over subsurface deposition aeration slots.

Experiment	Treatments
A & C	Untreated narrow banded, untreated wide banded, untreated broadcast, separated broadcast
B & D	Untreated narrow banded, untreated SSD, separated narrow banded, separated SSD

Table 2 – Slurry properties. Standard deviations are displayed in parenthesis (*n* = 2).

Experiment	Slurry	Application rate [g NH_4–N m^{-2}]	DM [%]	Total N [g kg^{-1}]	TAN [g kg^{-1}]	pH
A	Untreated	10.52 (0.59)	7.5	2.90 (0.08)	1.75 (0.10)	6.8
B		10.76 (0.09)	7.9	3.03 (0.03)	1.79 (0.01)	6.8
C		10.86 (0.03)	7.2	3.04 (0.01)	1.81 (<0.01)	7.0
D		10.62 (0.16)	6.7	3.07 (0.03)	1.77 (0.03)	7.5
A	Separated	7.48 (0.144)	4.4	2.22 (0.01)	1.25 (0.02)	6.9
B		4.61 (<0.01)	1.8	1.23 (0.01)	0.77 (<0.01)	7.2
C		4.76 (0.12)	1.5	1.21 (0.02)	0.79 (0.02)	7.2
D		4.48 (0.05)	1.5	1.15 (0.07)	0.75 (0.01)	7.6

the rest of the slurry giving a final concentration of 25 mmol AY7 l^{-1}.

2.3. *Conditions during the trials*

At the beginning of each experiment three soil cores of 495 × 10^3 mm^3 were taken across the experimental site to gravimetrically determine the soil-water content and dry bulk density to a depth of 65 mm. An additional sample was taken for soil pH. The dry bulk density over the four trials was 1080 (20) g mm^{-3} (n = 12) and the soil pH (1:1 water pH) was 5.3 (0.2) (n = 4). Sorptivity and water infiltration at steady state was measured with a Cornell Sprinkle Infiltrometer (Cornell University, Department of Crop and Soil Sciences, NY, USA) (van Es & Schindelbeck, 2006, pp. 1–8). Soil properties can be found in Supplementary materials Table S1.

Ambient air temperature and relative humidity was logged each hour by a weather station located next to the field. Soil temperature was measured at 50 mm depth. Soil data was not logged for experiment A. Average temperature data for each shift and the total period can be found in Supplementary materials Table S2.

2.4. *Exposed surface area*

2.4.1. *Dark chambers and data treatment*

Exposed surface area of the slurry for 8 h after application was quantified with a method developed by Pedersen et al. (2020). The method quantifies the slurry area by the light emitted from a fluorescent compound (AY7) added to the slurry immediately prior to application.

To exclude light, cylinders painted matte black on the inside (diameter of 560 mm and height of 800 mm) were placed over the plots to serve as dark chambers. A round plywood sheet (680 mm diameter) with 370 × 370 mm opening was sealed to the bottom of the barrels to exclude light from the sides. The dark chambers were positioned immediately after application of the doped slurry to avoid photodecomposition of the dye. The fluorescing slurry was activated with ultra violet light and photographed through a long pass filter at 0, 2, 4, 6, and 8 h after slurry application to detect changes in ESA. A reference photo of a pink fluorescence cardboard (Tutein & Koch ApS, Denmark) was taken to correct for light intensity differences in the images (Aeby et al., 2001; Rosenbom et al., 2008).

To test for unintended photodecomposition of the dye during the experiments, black beakers (13 mm in diameter) with the dyed slurry were positioned in the chamber prior to photographing and used as reference samples with a constant area.

The images were first corrected for non-uniform lighting using the reference photo (Aeby et al., 2001; Rosenbom et al., 2008). A mask was created with the picture taken right after slurry application (0 h) by manually drawing around the slurry in the picture. Everything outside the mask was set to an RBG value of 0, to avoid influence from the crops. The colour images were converted to a greyscale and a threshold of 0.7 was used to convert the greyscale images to two tone black and white images. The number of white pixels (pixels with slurry) was counted.

For the standardization beakers (reference samples), the area detected with the imaging method was compared with the area of the beaker (data not shown).

The grass crop inside the mask of the image was to some extend analysed as slurry. Even though only the area with slurry was used for calculations of ESA, it was impossible to exclude all of the fluorescent grass in the images; hence the slurry area was slightly overestimated for all treatments and times. As the grass canopy structure was uneven, any slurry adhering to the sides of vertically oriented grass was not seen from above. This could lead to a small underestimation of ESA. While it was not possible to quantify these sources of error, it was assumed that they tended to balance out and therefore negligible.

2.4.2. *Statistical analysis*

For each dark chamber the white pixel values were fitted to a generalised linear mixed model (GLMM) (see Breslow & Clayton, 1993; McCulloch & Searle, 2002) using a logarithmic link function, the Gaussian distribution, a fixed effect regression explanatory variable representing the elapsed time, and two Gaussian random components representing the barrel and the experiment nested on the barrel. Those random components were designed to account for the dependence between the observations taken from the same barrel and the same barrel at each experiment. This regression model implements the following exponential decay of the ESA as a function of the elapsed time,

$$\mathrm{ESA} = a\, e^{(-b\ t)} + c \qquad (1)$$

Here ESA is the fraction of soil area covered by slurry (m^2 m^{-2}), a (m^2 m^{-2}) is the total reduction in ESA from the initial area after application until stagnation in ESA, b (h^{-1}) is a parameter that describes the rate of change of ESA following slurry application, t is time (h), and c is the area of slurry at the soil surface at $t = \infty$ (m^2 m^{-2}). The GLMM referred was adjusted using the function glmer implemented in the package "lme4" of the software R (R Core Team, 2018) using a grid of shifts in the response variable and adjusted by profile likelihood techniques for estimating the parameter c in Eq. (1). Wald confidence intervals were used for the parameters a and b, and profile likelihood-based confidence intervals for the parameter c. The untreated observations were modelled using a GLMM similar to the models described above but with a constant fixed effect. The hypothesis test for comparing the ESA at time zero for the untreated observations and the ESA at equilibrium (i.e., the corresponding parameter c) were made by parametric bootstrap (with 200 bootstrap replicates).

2.5. *Ammonia emission*

2.5.1. *Wind tunnels*

The wind tunnels used to measure NH_3 volatilization were based on the design of Lockyer (1984). For a detailed description of the tunnels, see Bhandral et al. (2009). Each tunnels consisted of a 2 × 0.5 m frame which was inserted into the soil to a depth of about 50 mm prior to the experiment. A flexible transparent polycarbonate sheet was attached to the long sides of a frame to form a 0.45 m high tunnel with a semicircular cross section. A blower attached to the outlet end of the tunnel drew air form the opened end giving an air velocity inside the chamber of 1 m s^{-1}. Air was drawn through a round orifice (0.15 m in diameter) situated at the centre of a concave cone shaped funnel and fitted with a rotating anemometer continuously monitored with a data logger (CR10 data logger, Campbell Scientific Inc., Logan, UT). Air flow was also measured periodically in the tunnel with a portable hot wire anemometer to ensure consistency in real time.

Air samples from both the inlet and the outlet of the tunnels were drawn continuously at 2 l min^{-1} throughout the trials through PTFE coated tubing into an impinger assembly. The impinger assembly consisted of a glass cylinder containing 100 ml phosphoric acid (0.01 mol l^{-1}) to trap NH_3, and a glass impinger with a porous bottom to ensure that the sample air was distributed in the acid solution as small bubbles. The cumulative volume of air passed through each impinger was recorded at each shift changes with a volumetric gas meter (Gallus 2000; Norgas Controls, Inc., Burlington, KY) which were tested before and after the trials. For the tunnel outlet air samples, two 100-ml bubbler units was arranged in series in order to ensure that all NH_3 was trapped, although very little NH_3 was found in the second bubbler. The acid solutions were collected and changed at 2 and 4 h after slurry application, and thereafter each morning (8:30AM) and afternoon (3PM) until a total of nine shifts had been sampled. At each change the glass cylinder and impinger were thoroughly rinsed with demineralized water, and the water used for rinsing was added to the acid solution. The data from the flowmeters was recorded for each shift. After collection, the acid samples were sealed and stored for a few days at 5 °C. Before analysis, the volumes were increased to exactly 150 ml with distilled water. The 150-ml samples were frozen and later analysed with a spectrophotometricer autoanalyser (ADVIA 1800; Siemens, Germany).

Ammonia emissions were calculated from the difference of outlet and inlet concentrations, the air flow through the tunnel and the flow rate of the sample air (Bhandral et al., 2009).

2.5.2. *Statistical analysis*

A GLMM defined with Gamma distribution was used to describe and compare the emission of the treatments together. All measurements from all four experiments were modelled together. The GLMM used was defined with the logarithm link function and contained two independent Gaussian random components, representing the experiment and the tunnel nested in each experiment, respectively, in this way taking into consideration the dependence between observations induced by the experimental design. See the details of the model in Supplementary materials Section S3. The GLMM was adjusted using the package "lmer4" of the software R (R Core Team, 2018) and the post-hoc analyses were performed using the package "postHoc" (Labouriau, 2020) adjusting the p-values for multiple comparisons using the method of controlled false discovery rates (Benjamini & Yekutieli, 2001).

3. Results

3.1. *Ammonia emission*

Emissions were highest in the first 4 h after slurry application for all treatments in all four experiments (Fig. 1). The flux quickly decreased, and after 25 h, only minor fluxes were measured. The cumulative emission ranged from 7.8% (4.55–13.21%) to 35% (20.36–59.02%) (Fig. 2 and Table 3) of applied TAN. Numerically, the highest emissions were observed from wide band-applied untreated slurry and the lowest from SSD-applied separated slurry. For the untreated slurry, there was no difference between broadcast, narrow banded or wide banded but the SSD resulted in lower emissions (Fig. 2 and Table 3). Untreated SSD was similar to separated broadcast. Emission from separated broadcast were significantly higher than separated narrow banded and separated SSD (Fig. 2 and Table 3).

3.2. *Exposed surface area*

A large decrease (23–81%, average 42 ± 14%) in ESA of untreated slurry was measured during all four experiments (data not shown). This decrease is extremely high compared to previous observations by Pedersen et al. (2020), of 10 and 16%, for untreated cattle slurry. The unprocessed images showed that the untreated slurry in this study did not show enough fluorescence for detection after the slurry surface dried out. Using more dye may have produced better results as in the previous study. The assumption that the decrease in area observed for untreated slurry was incorrect is supported by the reference sample with a constant area. For separated slurry, the measured areas were above 95% of the true area of the beakers of the reference sample, whereas the area calculated for the untreated slurry decreased very rapidly after application, and in some cases dropped below 10%. Therefore, for untreated cattle slurry, only the ESA images taken right after application

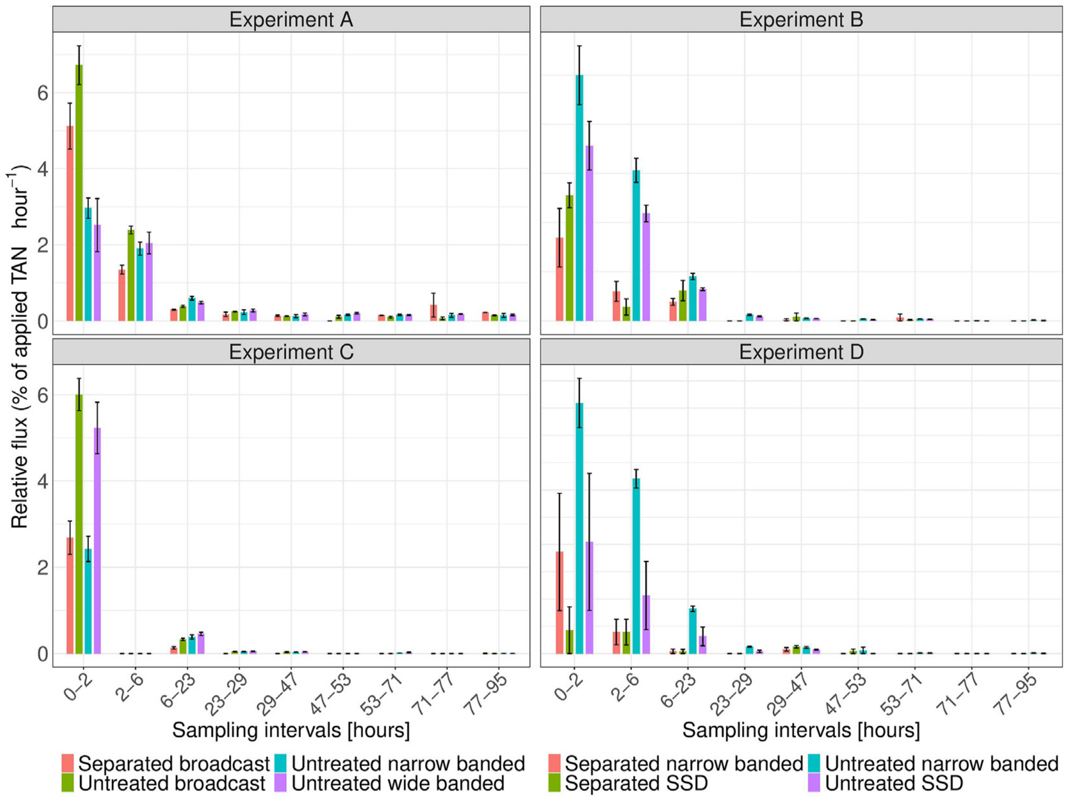

Fig. 1 – Ammonia flux after application of 60 metric ton ha^{-1} untreated and separated cattle slurry to bluegrass with different application techniques. Narrow banded: as trailing hose application, wide banded: banded in 0.2 m wide line, SSD: narrow band applied over sub-surface deposition aeration slots. Standard errors are displayed as vertical error bars ($n = 4$).

were used. Manual inspection of the unprocessed ESA pictures and manual estimations of the ESA with a ruler at the end of the experiments supported that no or only minor changes in ESA occurred for all application methods of untreated slurry. New experiments performed after the present study with sufficient fluorescence dye added to untreated cattle slurry with similar DM contents as the slurry in the present study, has confirmed that when applied on grass ESA is constant over time (+8 h of measurements) (J. Pedersen, unpublished data).

The change in ESA from separated slurry showed a similar pattern for all application techniques ($b = 0.36$–$0.46\ h^{-1}$, Table 3). The change in area of separated slurry over time (a) and final area (c) were almost identical for SSD and narrow banded slurry. The change in area over time was two times as high and the final area was almost six times as high for separated broadcast slurry compared to separated narrow banded and SSD applied slurry. Untreated broadcast slurry had twice the area of untreated narrow banded and untreated SSD applied slurry (Fig. 3 and Table 3).

4. Discussion

4.1. *General considerations*

The NH_3 flux pattern with high initial emission and a fast decrease (Fig. 1) is in agreement with other slurry application studies (Bhandral et al., 2009; Misselbrook et al., 2002; Smith et al., 2000). The cumulative emission reported from field application of cattle slurry with characteristics similar to the untreated and separated slurry used in this study, varies from 10% to 150% of applied TAN after application with broadcast, trailing hoses or band application over aeration slots (Hafner et al., 2018). The focus in the discussion will be on the relative differences in total emissions and ESA observed in the present study in comparison with differences observed by others. The results from all four experiments will be discussed together. The differences in soil water content (Table S1), slurry properties (Table 3), and ambient air temperature (Table S2) between the experiments will cause higher variation when the data is analysed together, but we believe that a more general analysis of the results allows for a more comprehensive analysis and therefore broader application of these.

The separated slurry used in experiment A had unfortunately not been separated as efficiently as the separated slurry used for the other three experiments, resulting differences in slurry properties (Table 3). Regardless of these differences, it was chosen to regard it as separated slurry in the analysis, as the trends of both NH_3 emission and ESA are similar to what is seen in the other experiments for separated slurry (Table 3 and Fig. 1), indicating that the effect of the separation is still present. This however, also causes higher variation in both the NH_3 emission and ESA results of separated broadcast slurry (Table 3 and Fig. 1).

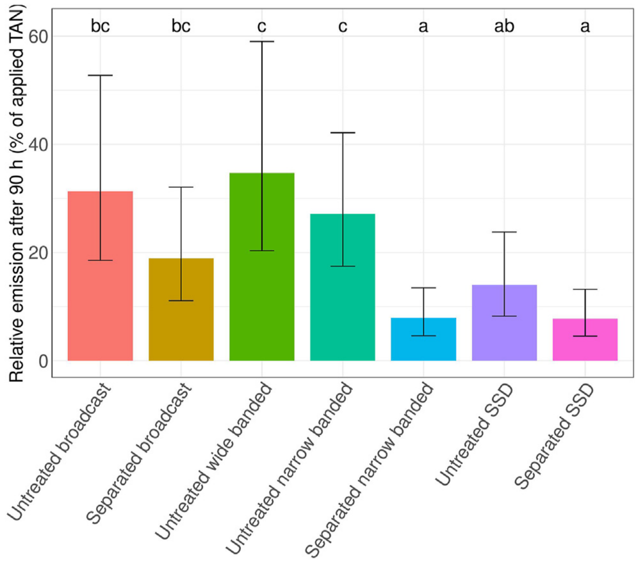

Fig. 2 – Cumulative (94 h) NH_3 emission as percent of applied TAN from untreated and separated cattle slurry applied with different application techniques to bluegrass. Narrow banded: as trailing hose application, wide banded: banded in 0.2 m wide line, SSD: narrow band applied over sub-surface deposition aeration slots. Confidence intervals with 95% coverage are displayed as error bars; treatments with the same letter in the top of chart do not statistically differ at a 5% significance level. The means and confidence intervals can be found in Table 3.

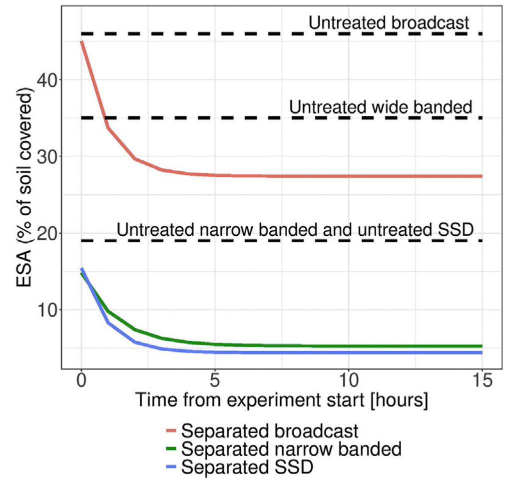

Fig. 3 – Exposed surface area after field application of 60 metric ton ha^{-1} separated and untreated cattle slurry to bluegrass with different application techniques. Narrow banded: as trailing hose application, wide banded: banded in 0.2 m wide line, SSD: narrow band applied over sub-surface deposition aeration slots. Area for untreated slurry is estimated to be constant over time (dashed lines).

4.2. *Effect of exposed surface area*

No significant differences in NH_3 emission from untreated slurry applied by broadcast, wide bands or narrow bands were observed (Fig. 2 and Table 3). This was despite significant differences in initial ESA (Table 3), which ranged from 19% for narrow banded slurry to 44% for broadcast slurry (Fig. 3 and Table 3). This is in contrast to the general assumption that a lower area of slurry–air interaction will lower the emission (Sommer & Hutchings, 2001; Webb et al., 2010). It is only in the first shift (0–2 h after application), that the flux is higher from untreated broadcast compared to untreated wide banded and untreated narrow banded (Fig. 1). Similar results were obtained by Smith et al. (2000), who generally found a reduction by band-applying slurry compared to broadcast, except form slurry with a similar DM to the one in the present study, where no differences were observed. Misselbrook et al. (2002) also found that band application of cattle slurry on grass reduced NH_3 emissions compared to broadcast, but the DM of the slurry in these experiments was approximately half of the DM content of the untreated slurry in the present study. Furthermore, the ambient air temperature was lower. We speculate that the lack of differences in emission between untreated slurry applied by broadcast, wide bands or narrow bands in the present study is caused by fast drying out of the slurry creating a dry layer which appears like surface crust,

Table 3 – NH_3 emission (Post hoc analysis results) and ESA parameters (from Eq. (1)) after field application of 60 metric ton ha^{-1} untreated and separated cattle slurry to bluegrass with different application techniques. Values followed by the same letter are not significantly different at a 5% significance level. In parenthesis a confidence interval with 95% coverage. Parameters for ESA: *a* (m m^{-2}) is the total reduction in ESA from the initial area after application until stagnation in ESA, *b* (h^{-1}) is a parameter that describes the rate of change of ESA following slurry application, and *c* (m m^{-2}) is the area of slurry at the soil surface when ESA stagnates. As ESA was assumed to be constant for untreated slurry (ESA = c at t = 0 - ∞) only parameter *c* is provided.

Treatment	NH_3 mean and confidence interval	Parameters from ESA fit		
		a [m^2 m^{-2}]	*b* [h^{-1}]	*c* [m^2 m^{-2}]
Separated broadcast	18.89 (11.11–32.1) bc	0.18 (0.15–0.2) b	0.36 (0.24–0.54) a	0.27 (0.26–0.29) c
Separated SSD	7.75 (4.55–13.21) a	0.10 (0.08–0.13) a	0.37 (0.30–0.46) a	0.04 (0.038–0.05) a
Separated narrow banded	7.89 (4.61–13.51) a	0.09 (0.07–0.12) a	0.46 (0.36–0.6) b	0.05 (0.04–0.06) a
Untreated broadcast	31.29 (18.56–52.74) bc			0.44 (0.40–0.48) e
Untreated wide banded	34.67 (20.36–59.02) c			0.36 (0.33–0.39) d
Untreated narrow banded	27.13 (17.46–42.15) c			0.20 (0.18–0.22) b
Untreated SSD	14.01 (8.24–23.82) ab			0.19 (0.17–0.22) b

which forms a physical barrier that reduce diffusion of NH_3 to the soil surface. Crust formation and its possible mitigating effect on NH_3 emission has also been discussed in other studies (Hafner et al., 2018; Misselbrook et al., 2005; Salazar et al., 2014; Sommer et al., 1991; Vandré et al., 1997). As the broadcast applied slurry was applied in a thin layer and the air temperature (Table S2) was high along with bright sunshine, it dried fast. In contrast, lower temperatures in Misselbrook et al. (2002) and lower DM in Smith et al. (2000) probably slowed surface drying or prevented crust formation of the broadcast applied slurry, allowing high emission rates to persist.

Another study by Bittman et al. (2005) with similar temperatures, DM content of slurry, and application rate as the current study obtained a 40% emission reduction after surface banding of untreated slurry compared to broadcast applied slurry, and assigned this to a lower observed ESA. The slurry used in the study by Bittman et al. (2005) had a pH that was 0.5 higher on average than the slurry used in the present study and the grass canopy was thinner (S. Bittman, unpublished). Everything else being equal, an increase in surface pH of 0.5 should approximately give a threefold increase in emission. As the flux is generally highest immediately after application, the higher pH might have given higher emission in this period, which in turn gave higher differences between broadcast and band applied slurry.

For separated slurry the emission from narrow banded slurry was significantly lower than broadcast slurry (Fig. 2 and Table 3). This corresponds with findings by Bell et al. (2015) who found a 40% reduction after band application of cattle slurry with comparable DM content as the separated slurry in the present study, compared to broadcast slurry. The low emission from narrow banded slurry can be assigned to a combination of low final ESA of only 5% (Fig. 3 and Table 3), to fast infiltration resulting from a dry soil with relatively low bulk density (Table S1) and to the low DM content of the slurry.

Reducing the area has been hypothesized to reduce emission, but these results suggest that under certain conditions such as warm temperature and sunlight, the effect of rapid drying and crust formation on high DM slurries might have a greater effect than reducing the emitting area. Our results, taken with other studies, highlights the importance of considering DM of the slurry, temperature, sunlight, slurry pH, and crop canopy, as other studies have shown great emission reductions with narrow band application compared to broadcast application under other experimental conditions and slurry characteristics (Bittman et al., 2005; Misselbrook et al., 2002; Smith et al., 2000; Webb et al., 2010).

4.3. *Effect of slurry type*

Separated slurry had lower NH_3 emission than untreated slurry (with all application methods: broadcast, narrow banded, and SSD) (Fig. 2 and Table 3), but the difference was only significant for narrow-banded untreated slurry compared to narrow-banded separated slurry. Our results are consistent with a previous study by Amon et al. (2006), who also found substantially lower NH_3 emission after band application of separated slurry. The SSD produced a similar reduction of NH_3 from untreated and separated slurry (Fig. 2 and Table 3). The SSD did not lower the emission from separated slurry, which was already very low. This is in contrast to results from Bhandral et al. (2009) who observed higher emissions from separated SSD applied slurry compared to untreated SSD applied slurry. This is probably due to higher application volumes for separated slurry in the previous study due to use of equal TAN application rates rather than manure volumes. The soil-water content and application rate of slurry in the study by Bhandral et al. (2009) were higher than the present study. Higher soil-water content has been identified to reduce infiltration rate (Sommer et al., 1997; Sommer & Jacobsen, 1999), which consequently will increase the emission (de Jonge et al., 2004). In the present study not all slurry could be contained in the aeration slots, hence higher application rates and shallower injection slots would cause lager amounts of slurry at the soil surface. However, the liquid fraction of slurries quickly infiltrated because the soil was dry and only the solids remained on the surface, thus, emissions persisted for <90 h. These factors combined might have caused the differences in emission reduction by the SSD.

The emission from separated broadcast slurry was lower than from untreated broadcast slurry, but the difference were not significant (Fig. 2 and Table 3). The initial ESA was approximately the same for the two slurries (44% for untreated broadcast and 45% for separated broadcast) (Fig. 3 and Table 3), but ESA of separated broadcast slurry quickly decreased to 27%, which assumably was due to infiltration, which is expected to lower emission. In the study by Bhandral et al. (2009) separated and untreated broadcast slurry was also compared. They found that the emission from separated broadcast slurry was higher than untreated broadcast slurry and assigned this to a rapid crust formation of the untreated slurry. This has been discussed in the preceding section as an explanatory factor for the relatively low emissions from untreated broadcast slurry in the present study.

Several studies have assigned DM content as an important factor in relation to NH_3 emission (de Jonge et al., 2004; Häni et al., 2016; Sommer et al., 2003; Sommer & Olesen, 1991). The explanation is commonly that a higher DM content makes the slurry more viscous (Thygesen et al., 2012) which reduces infiltration and thereby increase emission. The results in the present study supports the hypothesis made by Bhandral et al. (2009) and Misselbrook et al. (2005) that surface crusting might have an important influence on emission in the opposite direction. Higher DM could potentially under warm conditions result in lower emission if a crust is formed relatively rapidly. More research linking the interaction between crust formation, DM content, and temperature to NH_3 emission is needed in order to make further conclusions on the significance. In order to do this, a method for measuring the rate of crust formation and the crust thickness after field application of slurry should be developed. Future emission models will be better if they can include these factors.

4.4. *Effect of sub-surface deposition slurry applicator*

The SSD did not reduce emission from separated slurry (Fig. 2 and Table 3). As the separated slurry had a low DM ESA quickly decreases from 14% to 4% for SSD applied slurry and from 14% to 5% for narrow banded slurry (Table 3 and Fig. 3). Hence, there was no difference in ESA between the two treatments. Likewise, it is hypothesized that there was no difference in infiltration, as this was presumably already very rapid for the separated slurry under the conditions of dry soil and high permeability of the present study.

For untreated slurry, SSD reduced the emission significantly compared to band application (Fig. 2 and Table 3). This is in agreement with findings by Bittman et al. (2005) who also compared SSD and narrow banded slurry under similar conditions and with similar DM contents. Exposed surface area of untreated slurry applied with SSD and narrow banded were 19% and 20%, respectively (Table 3 and Fig. 3), but it is assumed that some of the liquid part of the SSD applied slurry infiltrated more quickly due to the aeration slots. Note that the aeration tool has a twist that causes some fracturing of friable soils, which further enhances infiltration.

5. Conclusion

The results from this study underlines the importance of the interactions between slurry and soil characteristics, application technique, and ambient weather conditions on NH_3 emission of field applied slurry. Reducing the contact area between slurry and air can be insufficient to reduce NH_3 emission under warm temperatures with high DM slurries applied to grass land, whereas a reduced emission was obtained with reduced ESA from separated slurry. The combination of band application and separation can significantly reduce the emission due to reduction of ESA and increased infiltration. An emission reduction can potentially be obtained with band application over aeration slots compared with band application. The aeration slots are hypothesized to enhance infiltration of the liquid part of the slurry. This study hypothesize that the curst formation under warm conditions possibly counteracts expected emission increases at higher temperatures, but further investigation is needed in order to make conclusions.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biosystemseng.2021.09.003.

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