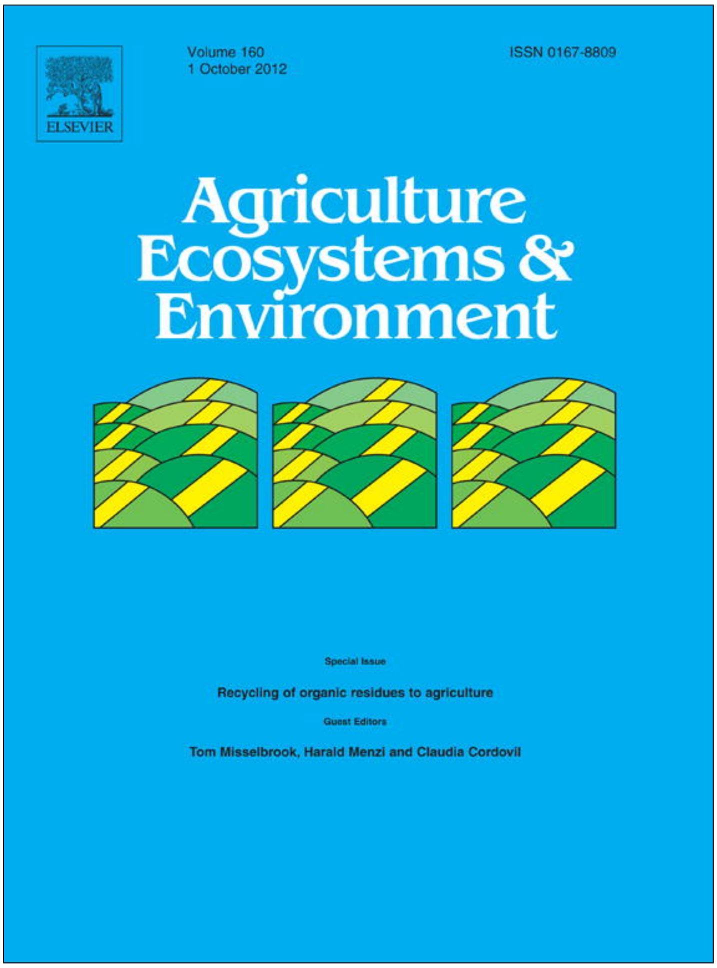
ELSEVIER
Volume 160
1 October 2012
ISSN 0167-8809
Agriculture Ecosystems & Environment
Special Issue
Recycling of organic residues to agriculture
Guest Editors
Tom Misselbrook, Harald Menzi and Claudia Cordovil

Agriculture, Ecosystems and Environment 160 (2012) 75–81

Contents lists available at SciVerse ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Ammonia volatilisation and crop yield following land application of solid–liquid separated, anaerobically digested, and soil injected animal slurry to winter wheat

T. Nyord[a,*], M.N. Hansen[b], T.S. Birkmose[b]

[a] Aarhus University, Faculty of Science and Technology, Department of Engineering, Blichers Allé 20, P.O. Box 50, DK-8830 Tjele, Denmark
[b] AgroTech, Institute of Agro Technology and Food Innovation, Agro Food Park 15, DK-8200 Aarhus N, Denmark

ARTICLE INFO

Article history:
Received 10 December 2010
Received in revised form
13 December 2011
Accepted 5 January 2012
Available online 10 February 2012

Keywords:
Ammonia
Anaerobically digestion
Separation
Injection
Animal slurry

ABSTRACT

To provide better advice to farmers and authorities on the most efficient way to reduce ammonia volatilisation from slurry applied to fields with standing crops, various treatments and injection methods were tested in field trials. In six separate experiments conducted at Research Centre Foulum, Denmark from 2007 to 2009, pig slurry was applied to winter wheat (*Triticum aestivum* L.) to determine how anaerobically digestion, solid–liquid separation of slurry and different soil injection techniques influence crop yield and ammonia emissions (NH_3). The NH_3 emission was measured by either a wind-tunnel method or by a micro-meteorological mass balance method. Both injection and solid–liquid separation were found to reduce NH_3 emission. The emission from the separated slurry did not include the emission from the solid fraction. Most effective injection techniques were found to be a winged tine or a combination of discs and a tine, which reduced NH_3 emission from approximately 20% (surface band spreading) to approximately 5% of applied Total Ammoniacal Nitrogen (TAN). The NH_3 emission from surface-applied anaerobically digested slurry was found to be almost twice that from surface-applied untreated slurry.

Injection did not affect yields significantly compared with surface application in any of the experiments, but did result in a significantly increased protein content in grains compared to band application, which increased the nitrogen utilisation of slurry nitrogen. Of the techniques tested, soil injection and solid–liquid separation reduced NH_3 emissions most effectively.

1. Introduction

Livestock manure is a major source of atmospheric NH_3. It has been estimated that more than 80% of the NH_3 emission in Western Europe originates from livestock husbandry (Buijsman and Erisman, 1988; ECETOC, 1994; Hutchings et al., 2001), with land application being one of the major sources (Misselbrook et al., 2002; Sommer and Hutchings, 2001). To reduce the NH_3 emissions following land application, farmers can make use of different application and slurry treatment technologies.

Solid–liquid separation and anaerobically digestion of animal slurry reduce the dry matter content of the applied liquid fraction. This increases the rate of slurry infiltration into the soil, shortening the potential emission period at the soil surface (Chantigny et al., 2004; Sommer and Jacobsen, 1999; Hansen et al., 2006). However, as anaerobically digestion also increases the pH of the slurry, mainly due to the reduction of volatile fatty acids, this may instead increase the potential NH_3 volatilisation (Hjorth et al., 2009; Moeller and Stinner, 2009).

Application techniques also affect the NH_3 emission. Soil injection has been shown to significantly reduce NH_3 emission compared to surface application (Misselbrook et al., 2002; Maguire et al., 2011). However, soil injection in growing cereal crops has been found to reduce crop yield due to the crop damage caused by the injection system (Pullen et al., 2004; Sorensen and Birkmose, 2007). Sorensen et al. (2003) injected pig and cattle slurry into a growing winter wheat crop using a disc coulter injector system. Compared to surface application, this method resulted in a reduction in grain yield of 200–300 kg ha^{-1} due to the crop damage caused by the injection, despite the lower ammonia loss from injected slurry. However, the reduction in grain yield may have been caused by the extra passes with the tractor and the slurry tanker and not by the injector tool itself. Pullen et al. (2004) have shown that if the slurry injection takes place early in the growing season, winter wheat yield is not affected by the slight crop damage caused by the injector tool. The same experiment also compared mineral fertilizer application with soil injection of slurry and showed that the reduced crop yields were a consequence of the

* Corresponding author. Tel.: +45 89991947; fax: +45 89991619.
E-mail address: tavs.nyord@agrsci.dk (T. Nyord).

0167-8809/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.agee.2012.01.002

Table 1
Overview of the field operations. Control treatments are highlighted in bold. Letters in brackets refers to application techniques shown in Fig. 1. Numbers in brackets represents replicates within a block.

Year of growth season	Designation	Date	Average crop height (cm)	Application method	Slurry type	Depth of application (cm)	Number of replication
				Trail hose		Surface	1 (3)
2007	Emission 2007	22 May	28	Simple tine injector (A)	Untreated	10–12	1 (3)
				Injection winged tine (B)		6–7	1 (3)
					Untreated		1 (3)
2008	Emission 2008	15 April	23	Trail Hose	Digested	Surface	1 (3)
					Separated		1 (3)
				Trail hose		Surface	1
2009	Emission 2009	9 Sept.	0	Disc injector (D)	Untreated	5–6	1
				Discs and a tine injector (D)		5–6	1
				Trail hose		Surface	4 (5)
2007	Yield 2007	20 April	10	Single disc injection (C)	Untreated	4–6	4 (5)
				Simple tine injector (A)		7–8	4 (5)
				Trail hose		Surface	5 (4)
2008	Yield 2008	7 April	10	Discs and a tine injector (D)	Untreated	4–5	5 (4)
				Simple tine injector (A)		7–8	5 (4)
				Trail hose		Surface	4 (4)
2009	Yield 2009	15 April	10	Discs and a tine injector (D)	Untreated	4–5	4 (4)
				Simple tine injector (A)		7–8	4 (4)

extra traffic with tractor and slurry tanker. The extra passings are needed because the injector machines have a narrower working width than trail hose spreaders. The reduced working width is a consequence of the extra power requirements for injector equipment compared to surface spreaders, so if soil injection of slurry is to become an economically feasible alternative to surface application, less energy-demanding injector tools are needed.

Nyord et al. (2010) investigated the power requirement needed for operating different injector tools. They found that the vertical force requirements of existing injection tools were too high if the injectors were mounted on an injector boom with a working width similar to trail hose applicators. They therefore designed a new injector tool. The agronomic performance of this and other injectors is evaluated in this paper.

The aim of this paper is thus to evaluate and compare how different soil injection tools affect NH_3 emission compared to the surface application of anaerobically digested and solid–liquid-separated slurry. The effect on crop yield of soil injection versus trail hose application is also compared.

2. Materials and methods

The investigations were divided into an emission study and a yield study. Details of both studies are given in Table 1.

2.1. Application techniques

An slurry spreader designed for experimental purposes was used for slurry application in all experiments. The spreader was equipped with a 3-m wide injection boom onto which it was possible to mount all types of injectors. When slurry was surface-applied, the boom was lifted approximately 5 cm off the ground, and the slurry was placed in bands between the crop rows similar to a regular trailing hose applicator. Distance between injection tines was 0.30 m. In all experiments, the injection depth was adjusted to the amount of slurry being applied. Consequently, none or only a negligible amount of slurry was left on the soil surface in the experimental plots after treatments. As shown in Fig. 1, the simple tine (A) and the winged tine (B) were identical except for the addition of metal wings for the winged tine. The width of the wings was 50 mm. The slurry was injected 7–12 cm below soil surface with the simple tine (A) and at approximately 7 cm with the winged tine (B). In the yield experiment, the single disc injector (C) and the combined disc and tine injector (D) were used. The single disc injector (C), which is a commercially available drilling implement, consists of a 400-mm diameter disc angled 3° off vertical with 25 mm deep cuts at the edge. The disc cut to 5–7 cm below the soil surface. The combined disc and tine injector (D) was an experimental tool made at Research Centre Foulum, DK 8830 Tjele, Denmark. Each injector tool consists of two angled 400-mm (diameter) sharpened discs with a discharged tine; for detailed information see Nyord et al. (2010). The discs operated 2–3 cm below and the tine 4–6 cm below soil surface.

2.2. Emission experiments

All of the NH_3 emission experiments were carried out from 2007 to 2009 in fields cropped with winter wheat (*Triticum aestivum* L.). Average crop height is shown in Table 1. In 2007 and 2008, the fields were located close to Research Centre Bygholm, DK-8700 Horsens, Denmark, and in 2009 near Research Centre Foulum. Soil properties are shown in Table 2. In 2007, NH_3 emission was measured following application of slurry with different application techniques: (1) surface application performed by trailing hose application, (2) shallow injection performed by an un-winged tine (A, Fig. 1), and (3) shallow injection performed by a winged tine (B, Fig. 1). In 2008, the effects of slurry type were examined using three different slurry types originating from the same batch of pig slurry: (1) untreated, (2) anaerobically digested slurry, and (3) separated slurry. All three slurry types were surface-applied by band spreading. In 2009, the emission experiment included the following three different application techniques: (1) surface application performed by trailing hose application, (2) injection performed by angled double discs (the double disc which is the front part of D (Fig. 1)), and (3) injection performed by a combination of discs and a tine (D, Fig. 1). The discs used in (2) and (3) were identical. Slurry was applied in doses as shown in Table 4.

2.3. Yield experiment

In each of the three years, the yield experiments were repeated at four or five locations in the eastern part of Jutland, Denmark. All experiments were located on commercial farms, which were representative of general Danish farming practices.

A split-plot design was used in the experiment. Therefore, at each location the experiment was divided into four blocks where

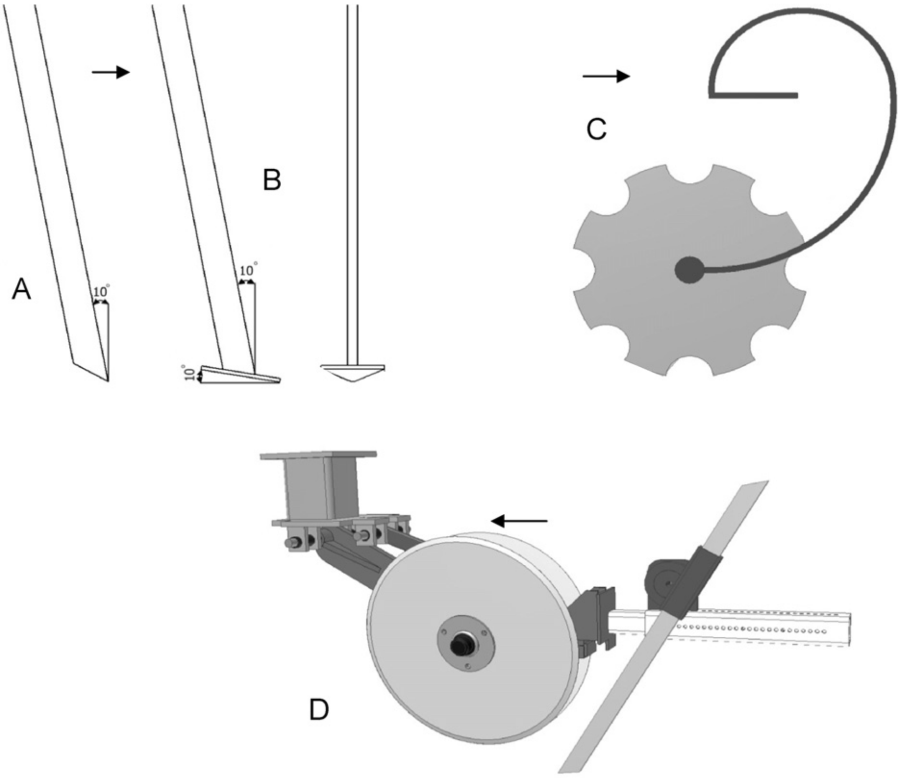

Fig. 1. Sketches of soil injection tines used in the study. (A) A profile of the simple tine with a rake-angle of 10° compared to travel direction; (B) a profile of the winged tine with a rake-angle of the wing of 80° compared to travel direction and the winged tine seen from behind; (C) single disc injector; (D) combination of discs and a tine injector. Arrows indicate travel direction. For all tines the shank is 10 mm wide. Slurry is placed by a discharged pipe in the injection slit after the soil failure following injection with all 4 types of injection tool.

each treatment was represented, giving a total of 16–20 repetitions of each treatment per experiment. The treated gross area measured 45 m^2 (3 m × 15 m) and the harvested plot 20 m^2 (2 m × 10 m). The crop was harvested with a plot combine (Haldrup C-85, Inotec GmbH, DK 9670 Løgstør), which made it possible to take grain samples from individually harvested plots. Grain samples were dried to 15% moisture content, weighed and analysed for protein content.

The winter wheat plots were fertilized in the spring at approximately crop development stage 30 at the BBHD scale (Lancashire et al., 1991) either with animal slurry or with granular mineral fertilizers, containing nitrogen (N), phosphorus, potassium and sulphur (ammonium-nitrate based fertilizers) to evaluate the yield potential at the experimental sites. The rate of N application in mineral fertilizer was equal to the rate of TAN in slurry.

2.4. Soil and weather conditions

All experiments were carried out in the eastern and central parts of Jutland, Denmark. These regions are dominated by sandy to loamy soils. The soil properties are shown in Table 2. Texture classification follows the USDA soil classification system.

All experiments were carried out under sunny conditions with no precipitation during the first 24 h after slurry application. Weather conditions for each emission experiment are given in Table 3. The weather data were obtained from official met office stations situated close to the experimental sites.

2.5. Slurry

The properties of the pig slurry used in the experiments are given in Table 4. Only slurry from fattening pigs (30–100 kg) was used in the experiments. Each year, slurry was collected directly from the pig houses on commercial pig farms, and the same batch was used for all treatments in the different experiments. The slurry was therefore relatively fresh when it was land-applied, anaerobically digested or solid–liquid separated.

The slurry was anaerobically digested in the experimental biogas unit at Research Centre Foulum. The digestion took place in a 30-m^3 experimental reactor at a temperature of approximately 52 °C and a retention time of 16 days.

The solid–liquid separation of the untreated slurry was performed by an experimental belt separator (Hjorth et al., 2009) with

Table 2
Overview of the soil properties of the soils used in the experiments. Texture classification follows the USDA scale.

Experiment	Soil texture	Soil density (g/cm^3)	Water filled pore space (%)	pH	Organic matter (%)
Emission 2007	Loamy sand	1.3	41	5.6	3.1
Emission 2008	Loamy sand	1.4	47	5.5	3.1
Emission 2009	Loamy sand	1.4	57	6.3	5.3
Yield 2007[a]	Sand, loamy sand, sandy loam	–	–	6.4–7.2	2.0–2.2
Yield 2008[a]	Sand, loamy sand, loam	–	–	6.8–7.4	2.6–3.2
Yield 2009[a]	Loamy sand, Loam	–	–	6.9–7.3	2.3–3.2

[a] The yield experiments were each year carried out at four or five sites and therefore the physic chemical soil properties vary.

Table 3
Weather conditions for each experiment. Numbers represent a mean for the period after application of animal slurry. Precipitation is cumulated rain after the application of slurry in the measuring period.

Experiment	Temperature day 1 (°C)	Temperature day 0–5 (°C)	Precipitation day 1 (mm)	Precipitation day 0–5 (mm)	Wind speed day 1 ($m\,s^{-1}$)
Emission 2007	11.9	12.8	0	0.3	2.9
Emission 2008	5.3	6.2	0	0.7	2.4
Emission 2009	16.9	14.3	0	0.1	3.2

Table 4
Overview of the properties of the pig slurry used in the experiments.

Experiment	Type of slurry	Dry matter (%)	pH	Total N ($g\,l^{-1}$)	Ammoniacal N ($g\,l^{-1}$)	Application rate ($kg\,NH_4$-$N\,ha^{-1}$)
Emission 2007	Untreated slurry	3.8	7.9	5.4	4.7	139
Emission 2008	Untreated slurry	4.7	8.0	4.5	2.9	132
	Anaerobically digested slurry	2.5	8.6	4.3	3.0	127
	Solid–liquid separated slurry	1.9	7.9	3.6	2.7	126
Emission 2009	Untreated slurry	3.9	7.7	4.8	3.6	105
Yield 2007	Untreated slurry	3.5	7.7	4.9	4.0	97
Yield 2008	Untreated slurry	1.8	7.8	3.4	2.8	101
Yield 2009	Untreated slurry	2.9	7.5	2.8	2.5	103

a mesh size of 1.2 mm and the addition of the polyacrylamide Optifloc c2364 (Kemira Water, DK-6705 Esbjerg Ø) as a polymer to increase the separation efficiency.

2.6. Ammonia emission

The ammonia emissions in 2007 and 2008 were measured by a wind tunnel technique, which is described in detail by Misselbrook et al. (2005). The emission was quantified by three separate wind tunnels per experimental plot. Each tunnel covered an area of 0.85 m^2 and air was exchanged 23 times per minute. There was one experimental plot per treatment established in a cereal crop. Each plot was 3 m wide and 10 m long. The wind tunnels were orientated across the driving direction of the application machine so that the edges of the tunnels went straight to the edge of the emission plot. The NH_3 concentration in the air entering and leaving each tunnel was determined by drawing a subsample of the air through an NH_3 absorber (gas-washing bottle containing 100 ml 0.02 M H_3BO_3) at a rate of 2 $l\,min^{-1}$ (controlled by a critical orifice). By using two serially connected absorbers, we could check that all NH_3 had been collected in the first absorber. The NH_3 emission was determined in six time intervals up to 120 h after application.

For each measuring period, background NH_3 concentration at the inlet of the wind tunnels was determined and subtracted from the amount of NH_3 leaving the tunnels. Emissions of NH_3 were quantified using

$$A = \sum_{j=1}^{n} (C_{outj} - C_{inj}) \times V_j \qquad (1)$$

where A is the total NH_3 emission in mg, j is the interval number, n is the total number of intervals, V is the volume of air flow in m^3, and C_{out} and C_{in} are the concentrations of gas in the outlet and inlet air in $mg\,m^{-3}$ air, respectively. This emission was then related to the known area covered by the wind tunnels (0.85 m^2).

The rate of NH_3 emission in the 2009 experiment was determined by the micrometeorological mass balance technique (Leuning et al., 1985; Wilson and Shum, 1992). The technique was slightly modified in that the experimental plots were square (36 m × 36 m) due to practical reasons as described in Nyord et al. (2008a). To avoid contamination between plots these were situated at least 100 m apart, but were still in the same field. Care was taken that soil and topographic conditions of the different plots were as even as possible. Slurry was applied with over as short an interval as practically possible (within 2 h), to ensure that weather conditions were as similar as possible at the application time. The six sampling intervals were equal to those employed in the wind tunnels experiment (Figs. 2 and 3).

2.7. Statistics

The cumulated NH_3 emissions were statistically modelled by a Michaelis–Menten-type equation presented by Sommer and Ersbøll (1994):

$$N(t) = \frac{N_{max} \times t}{K_m + t} \qquad (2)$$

The model (Eq. (2)) describes the relative cumulative ammonia volatilisation $N(t)$ over time t (s) after application of slurry. $N(t)$ expresses the ammonia lost as a fraction of the applied TAN. The fitted data was used to parameterise the model parameters: N_{max} which is the total loss of NH_3 as time approaches infinity, and K_m which is the time after land spreading of slurry at which $N(t)$ is equal to half of N_{max}. The parameters of models were estimated by maximum likelihood using the procedure NLMIXED of the statistical package SAS (SAS, 2010).

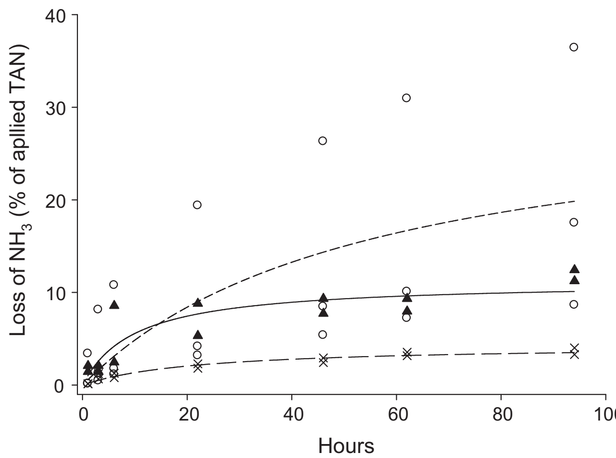

Fig. 2. Ammonia emissions 2007. Cumulative percentage loss of total applied TAN through emission over 96 h after application of pig slurry. Regression lines and symbols represent cumulative losses of NH_3 emission from each measuring period; ---- and ○: trailing hose application; — and ▲: soil injection simple tine; — —: soil injection winged tine.

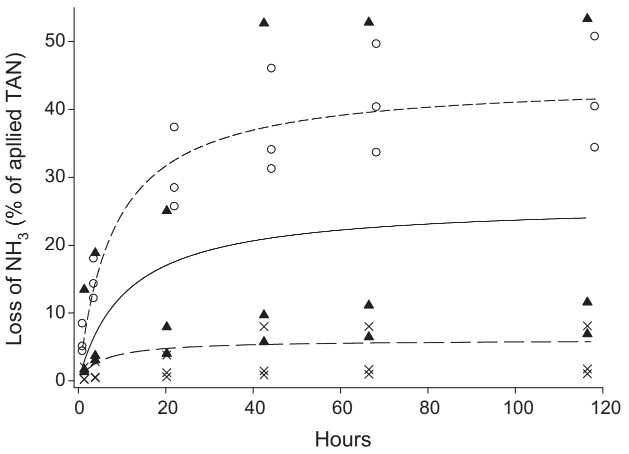

Fig. 3. Ammonia emissions 2008. Cumulative percentage loss of total applied TAN through emission over 116 h after application of pig slurry by trailing hoses. Regression lines and symbols represent cumulative losses of NH_3 emission from each measuring period; ---- and ○: digested slurry; — and ▲: untreated slurry; — — and ×: separated slurry.

The results from the yield experiments were also analysed by a mixed model. A complete block design was adopted, using four blocks on each site. Since the study was conducted over three years using slightly different technologies each year, the analysis was done separately for each year. The statistical analysis was conducted with site × block effect and random factors, and Gaussian error. Standard model control was conducted for all tests. The experimental treatments were tested against the reference treatment for both yield and protein. The yield was measured in each plot, whereas the protein was measured on the pooled sample from all four plots at each site. The data was therefore analysed at plot level and site level respectively. The *P*-values are not corrected for multiple tests.

3. Results and discussion

3.1. Ammonia emission

The cumulative NH_3 emission following land spreading of animal slurry in the 2007 emission experiment seems to depend on type of application technique, as shown in Fig. 2 and Table 5. For that year, surface application using trailing hoses resulted in the highest N_{max} value, which was approximately 20% of applied TAN. The measured NH_3 loss was high compared to the figure of 15% generally used in Denmark for trailing-hose-applied pig slurry at this time of the year (Sogaard et al., 2002). One reason could be that wind tunnels may overestimate the NH_3 emission from land-applied slurry (Misselbrook et al., 2005).

Compared to surface application, soil injection seems to reduce the NH_3 emission, although no significant difference was found between these two application techniques (Table 5). However, injection performed with the simple tine led to a cumulative loss of NH_3 of approximately 10% of applied TAN, which was about three times higher than the cumulative loss when using the winged tine. An explanation for the different N_{max} values for the injection tines could be that when using the simple tine the slurry is placed in a very concentrated string after injection. This can lead to a high concentration gradient and thereby a higher emission potential. Injection with the winged tine results in increased lateral distribution of the slurry in the soil (Chen and Ren, 2002; Warner and Godwin, 1988). The slurry was therefore less concentrated in the soil, which may reduce the volatilisation gradient (Izaurralde et al., 1990; Nyord et al., 2008b). Another important fact could be that the simple tine produced slits of smaller volume, even though the slits after injection were deeper than after the winged tine. A lower cavity of the slits means that a higher proportion of the slurry is placed closer to the soil surface, which reduces the distance that NH_3 needs to diffuse before emission into the atmospheric air.

In the 2008 emission experiment, surface application of untreated slurry also resulted in approximately 20% loss of applied TAN, even though the air temperature in 2008 was lower than in 2007. This is probably caused by the higher dry-matter content of the slurry applied in 2008 compared to 2007. Normally this would reduce the infiltration of the slurry into the soil and hence extend the period where emission can take place. The anaerobically digestion of slurry increases the pH and the TAN content of the slurry and in turn the potential for NH_3 emission (Sogaard et al., 2002). A higher NH_3 emission from land-applied anaerobically digested slurry was observed in the 2008 experiment where it was almost twice as high as the average emission from untreated slurry (Fig. 3 and Table 5). The higher NH_3 emission is likely due to the higher pH (Table 4). This is supported by the very small K_m value for the emission following land spreading of this slurry (Table 5). A small K_m value indicates a rapid emission pattern, which is characteristic for high pH solutions (Sommer et al., 2003). In our study, the possible effect of a lower dry matter content and higher viscosity of anaerobically digested slurry (deJonge et al., 2004) seems to be less important than its higher pH. The same conclusion was reached by Moeller and Stinner (2009) in their review paper. However, a reduction of NH_3 emission as a consequence of anaerobically digestion and resulting decrease in dry matter content has previously been reported (Hansen et al., 2006).

The pH of the separated slurry was 0.7 units lower than the pH of the digested slurry, and both the TAN and the dry matter content of the separated slurry were lower than in the untreated and the anaerobically digested slurry types, see Table 4. These are likely to be the main reasons for the lower N_{max} value following land spreading of separated slurry. Approximately 5% of applied TAN volatilised as NH_3 when the slurry was separated, in contrast to application of the anaerobically digested slurry where approximately 40% was emitted. Compared to untreated slurry, the emission was reduced to about one fourth by separation (Fig. 3). The NH_3 emission effect of separation in this study was significantly higher than found in other similar studies (Balsari et al., 2008; Hansen et al., 2006).

It could be concluded that slurry separation can reduce NH_3 volatilisation significantly. However, it has to be remembered that there is also an ammonia loss from the solid fraction. Other authors have found that a major part of total NH_3 emissions is related to the handling of the solid fraction of the separated slurry (Dinuccio et al., 2010). This must be taken into account when assessing the ammonia reduction potential of solid–liquid separation (Fig. 4).

Although one must be careful not to compare two experiments in which different measuring techniques are used, it seems to be evident from both the 2007 and the 2009 emission experiments that ammonia volatilisation is reduced by injection. Air temperatures were higher in 2009 than in the emission test in 2007, which may explain the higher emission rate during the first hours after application. Part of the explanation may also be that the injected slurry in the 2007 experiment was covered with soil immediately after placement in the injection slits. This was not the case in 2009. The reducing effect on the emission rate of covering the soil within the first few hours of slurry application was also found in Nyord et al. (2008b). As explained by Nyord et al. (2010), one of the main reasons for combining discs and a tine is to utilise the porous injection slit which is made by the tine. This porous injection slit increases the infiltration rate of the slurry into the soil, and thereby shortens the emission period (Petersen et al., 2003). The effect of the porous slit should be compared to an injection slit created by a pair of double discs or an angled single disc where the zones in

Table 5
Fitted N_{max} and K_m values for the emission measurements.

Experiment	Treatments	N_{max} (% of applied TAN)	K_m (h)
Emission 2007	Trail hose	22.3	27.1
	Injection simple tine	10.6	6.3
	Injection winged tine	3.5	18.7
Emission 2008	Untreated	24.5	13.2
	Digested	42.3	4.5
	Separated	6.4	7.4

Table 6
Results of the three yield experiments. Mineral fertilizer is an ammonium-nitrate based fertilizer. Numbers highlighted in bold indicate significant difference.

	Yield (tonnes ha^{-1})	*P*-value	Protein in grain (%)	*P*-value
2007				
Trailing hoses	7.64	–	10.0	–
Single disc injector (C)	+0.04	0.7273	+0.6	**0.0269**
Simple tine (A)	+0.01	0.9242	+0.8	**0.0080**
2008[a]				
Trailing hoses	8.72	–	8.9	–
Combination of discs and tine (D)	−0.15	0.2691	+0.4	0.0800
Simple tine (A)	+0.08	0.5513	+0.5	**0.0399**
2009				
Trailing hoses	9.38	–	9.0	–
Combination of discs and tine (D)	+0.01	0.9624	+0.6	**0.006**
Simple tine (A)	−0.03	0.8168	+0.5	**0.013**

[a] A different sowing method was used.

the soil around the slit are compacted. The soil compaction around the injection slit is significantly different for discs and tines due to the difference in soil failure. When soil failure is created by a single disc or double discs, the soil has to "move around" the disc(s). This is opposite to soil failure created by a tine where the soil is lifted up and placed on top of the soil surface. This creates a soil without any compacted layers and eases infiltration of the liquid into the soil (Godwin, 2007). As a result, a distinct difference in the total loss of ammonia could be confirmed between the disc injector and the combined discs and tine injector, with values of approximately 14% and 5% of applied TAN, respectively.

3.2. Yield

As shown in Table 6, no significant difference in yield of grain could be measured in the yield experiments. But in contrast there was a consistently significant increased protein content as a result of slurry injection.

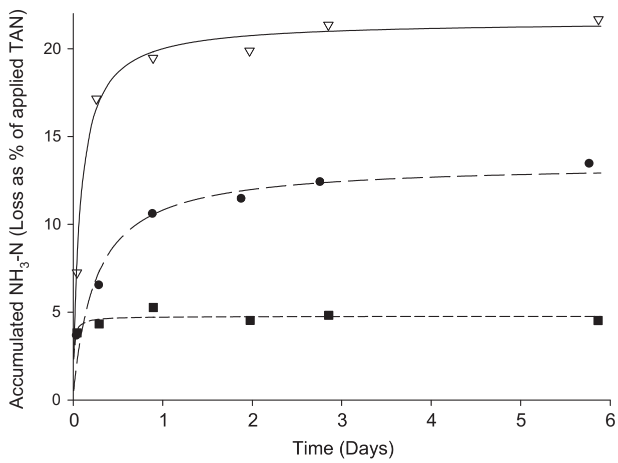

Fig. 4. Ammonia emissions 2009. Cumulative loss of NH_3-N through 6 days after application of pig slurry. Lines represent regression of the measured values (symbols); — and ▼: surface application; — — and ●: disc injector. - - - - and ■: disc and tine injector. Measured values is average emission collected by the ammonia traps per plot (n = 2).

The increased protein content is probably due to the reduced NH_3 volatilisation, which means that more TAN is available for plant uptake. The increased protein content combined with the stable crop yield shows a better N-utilisation as a result of soil injection of slurry compared to surface band spreading. This raises the question: why did the increased plant-available TAN content not increase the grain yield when the animal slurry was injected into the soil compared to when it was surface applied? The most plausible explanation is that the damage to crop roots and leaves caused by the soil injection tines reduced the crop yield potential. In an earlier Danish investigation, soil injection without injecting the slurry reduced the grain yield by approximately 200 Kg ha^{-1} due to the crop damage caused by the injector tines (Olesen, 1974). Similar results have been found by Sorensen and Birkmose (2007) and Sorensen et al. (2003). These studies did not take into account the difference in working width of a slurry injector and a trail hose applicator and that more passes of the field with the heavy slurry tanker are therefore needed for soil injection than for trail hose application, potentially reducing yield through soil compaction effects. However, it should be mentioned that the (D) injector will be mounted on a commercial 16 m wide injector, boom which under Danish soil conditions can be pulled by a standard 230 kW tractor. The working width of this injector is therefore not much smaller than trail hose systems.

There were no significant differences in yield between the injection techniques. However, it is hypothesised that the discs cause less root damage due to reduced soil disturbance in the soil surface. This has been found to minimize crop damage in a previous experiment (Nyord et al., 2010). The reason for no effect of (D) could be due to an experimental error in 2008. The injection by the (D) injector took place in a winter wheat plot that was sown in a different way compared to the plots where the other treatments took place. The distance between every third crop rows was doubled and therefore the injection by the (D) injection system took place in the extra wide band between the crop rows which obviously decreased crop damage. It is therefore difficult to evaluate the yield effect of the (D) injector in the 2008 experiment. Neither was an effect of injector (D) compared to (A) found in 2009, which leads to the conclusion that the combination of discs and a tine in this setup does not decrease crop damage.

4. Conclusion

Soil injection was found to reduce NH_3 emissions from land-applied pig slurry compared to surface-applied slurry. Crop yield was unaffected and N utilisation increased as a consequence of soil injection of slurry. N utilisation increased because protein content increased when slurry was injected due to reduced ammonia emission. Anaerobically digestion of slurry was found to increase the NH_3 emission following band-spreading of animal slurry, whereas solid–liquid separation reduced the NH_3 emission. Only emission from the liquid fraction of the separated slurry was measured and the potential loss from the solid fraction was not taken into account. Of the techniques tested in this paper, soil injection and solid–liquid separation reduced NH_3 emissions most effectively.

References

Balsari, P., Dinuccio, E., Gioelli, F., Santoro, E., 2008. 11 June 8 A.D. Ramiran Network. Albena, Bulgaria.

Buijsman, E., Erisman, J.W., 1988. Wet deposition of ammonium in Europe. Journal of Atmospheric Chemistry 6, 265–280.

Chantigny, M.H., Rochette, P., Angers, D.A., Masse, D., Cote, D., 2004. Ammonia volatilization and selected soil characteristics following application of anaerobically digested pig slurry. Soil Science Society of America Journal 68, 306–312.

Chen, Y., Ren, X., 2002. High performance tool for liquid manure injection. Soil and Tillage Research 67, 75–83.

deJonge, L.W., Sommer, S.G., Jacobsen, O.H., Djurhuus, J., 2004. Infiltration of slurry liquid and ammonia volatilization from pig and cattle slurry applied to harrowed and stubble soils. Soil Science 169, 729–736.

Dinuccio, E., Berg, W., Balsari, P., 2010. Effects of mechanical separation on GHG and ammonia emissions from cattle slurry under winter conditions. Animal Feed Science and Technology 166, 532–538.

ECETOC, 1994. Ammonia Emissions to Air in Western Europe. Rep. 62. European Centre for Ecotoxicology and Toxicology of Chemicals, Brussels.

Godwin, R.J., 2007. A review of the effect of implement geometry on soil failure and implement forces. Soil and Tillage Research 97, 331–340.

Hansen, M.N., Kai, P., Moller, H.B., 2006. Effects of anaerobic digestion and separation of pig slurry on odor emission. Applied Engineering in Agriculture 22, 135–139.

Hjorth, M., Nielsen, A., Nyord, T., Nissen, M.N., Hansen, P., Sommer, S.G., 2009. Nutrient value, odour emission and energy production of manure as influenced by anaerobic digestion and separation. Agronomy for Sustainable Development 29, 329–338.

Hutchings, N.J., Sommer, S.G., Andersen, J.M., Asman, W.A.H., 2001. A detailed ammonia emission inventory for Denmark. Atmospheric Environment 35, 1959–1968.

Izaurralde, R.C., Kissel, D.E., Cabrera, M.L., 1990. Simulation-model of banded ammonia in soils. Soil Science Society of America Journal 54, 917–922.

Lancashire, P.D., Bleiholder, H., Vandenboom, T., Langeluddeke, P., Stauss, R., Weber, E., Witzenberger, A., 1991. A uniform decimal code for growth-stages of crops and weeds. Annals of Applied Biology 119, 561–601.

Leuning, R., Freny, J.R., Denmead, O.T., Simpson, J.R., 1985. A sampler for measuring atmospheric ammonia flux. Atmospheric Environment 19, 1117–1124.

Maguire, R.O., Kleinman, P.J.A., Dell, C.J., Beegle, D.B., Brandt, R.C., McGrath, J.M., Ketterings, Q.M., 2011. Manure application technology in reduced tillage and forage systems: a review. Journal of Environmental Quality 40, 292–301.

Misselbrook, T.H., Nicholson, F.A., Chambers, B.J., Johnson, R.A., 2005. Measuring ammonia emissions from land applied manure: an intercomparison of commonly used samplers and techniques. Environmental Pollution 135, 389–397.

Misselbrook, T.H., Smith, K.A., Johnson, R.A., Pain, B.F., 2002. Slurry application techniques to reduce ammonia emissions: results of some UK field-scale experiments. Biosystems Engineering 81, 313–321.

Moeller, K., Stinner, W., 2009. Effects of different manuring systems with and without biogas digestion on soil mineral nitrogen content and on gaseous nitrogen losses (ammonia, nitrous oxides). European Journal of Agronomy 30, 1–16.

Nyord, T., Schelde, K.M., Sogaard, H.T., Jensen, L.S., Sommer, S.G., 2008b. A simple model for assessing ammonia emission from ammoniacal fertilisers as affected by pH and injection into soil. Atmospheric Environment 42, 4656–4664.

Nyord, T., Sogaard, H.T., Hansen, M.N., Jensen, L.S., 2008a. Injection methods to reduce ammonia emission from volatile liquid fertilisers applied to growing crops. Biosystems Engineering 100, 235–244.

Nyord, T., Kristensen, E.F., Munkholm, L.J., Jørgensen, M.H., 2010. Design of a slurry injector for use in a growing cereal crop. Soil and Tillage Research 107, 26–35.

Olesen, J., 1974. Oversigt, over forsøg og undersøgelser i landbo- og husmandsforeningerne (Review of field trials done by the farmers union). Landsudvaglet for Planteavl, DK-8200 Skejby, Denmark, In Danish.

Petersen, S.O., Nissen, H.H., Lund, I., Ambus, P., 2003. Redistribution of slurry components as influenced by injection method, soil, and slurry properties. Journal of Environmental Quality 32, 2399–2409.

Pullen, D.W.M., Godwin, R.J., Grundon, P., Moseley, P.J., 2004. Injecting bio solids into grass and arable crops. Part I: design and evaluation of a shallow injector. Biosystems Engineering 87, 285–297.

SAS System, 2010. Version 10, Cary, NC.

Sogaard, H.T., Sommer, S.G., Hutchings, N.J., Huijsmans, J.F.M., Bussink, D.W., Nicholson, F., 2002. Ammonia volatilization from field-applied animal slurry – the ALFAM model. Atmospheric Environment 36, 3309–3319.

Sommer, S.G., Ersbøll, A.K., 1994. Soil tillage effects on ammonia volatilization. Journal of Environmental Quality 23, 493–498.

Sommer, S.G., Géneremont, S., Cellier, P., Hutchings, N.J., Olesen, J.E., Morvan, T., 2003. Processes controlling ammonia emission from livestock slurry in the field. European Journal of Soil Science 19, 465–486.

Sommer, S.G., Hutchings, N.J., 2001. Ammonia emission from field applied manure and its reduction – invited paper. European Journal of Agronomy 15, 1–15.

Sommer, S.G., Jacobsen, O.H., 1999. Infiltration of slurry liquid and volatilization of ammonia from surface applied pig slurry as affected by soil water content. Journal of Agricultural Science 132, 297–303.

Sorensen, P., Birkmose, T., 2007. Gyllenedfældning i hvede – betydning for afgrødeudvikling, kvælstofdynamik og høstudbytte (Slurryinjection in winter-wheat – influence on crop development, nitrogen dynamic and yield). National Advisory Services. Planteavlsorientering, DK-8200 Skejby, Denmark, In Danish.

Sorensen, P., Vinter, F.P., Petersen, S.O., Petersen, J., Lund, I., 2003. Høj udnyttelse af gyllens kvælstofved direkte nedfældning (Increased utilization of nitrogen in slurry following soil injection of animal slurry). Aarhus University, Faculty of Agricultural Sciences, Grøn Viden 281, DK-8830 Tjele, In Danish.

Warner, N.L., Godwin, R.J., 1988. An experimental investigation into factors influencing the soil injection of sewage sludge. Journal of Agricultural Engineering Research 39, 287–300.

Wilson, J.D., Shum, W.K.N., 1992. A re-examination of the integrated horizontal flux method for estimating volatilisation from circular plots. Agricultural and Forest Meteorology 57, 281–295.