Reduction of Ammonia Emission by Shallow Slurry Injection: Injection Efficiency and Additional Energy Demand

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ABSTRACT

Ammonia (NH_3) emission from livestock production causes undesirable environmental effects and a loss of plant-available nitrogen. Much atmospheric NH_3 is lost from livestock manure applied in the field. The NH_3 emission may be reduced by slurry injection, but slurry injection in general, and especially on grassland, increases the energy demand and places heavy demands on the slurry injection techniques used. The reduction in NH_3 emission, injection efficiency, and energy demand of six different shallow slurry-injection techniques was examined. The NH_3 emission from cattle slurry applied to grassland was reduced by all the injectors tested in the study, but there were major differences in the NH_3 reduction potential of the different types of injectors. Compared with the trailing hose spreading technique, the NH_3 loss was reduced by 75% when cattle slurry was injected using the most efficient slurry injection technique, and by 20% when incorporated by the least efficient injection technique. The reduction in NH_3 emission was correlated with injection depth and the volume of the slot created. The additional energy demand for reducing ammonia emissions by slurry injection was approximately 13 000 kJ ha^{-1} for a 20% reduction and 34 000 kJ ha^{-1} for a 75% reduction. The additional energy demand corresponds to additional emissions of, respectively, 5.6 and 14.5 kg CO_2 per ha injected.

CONSIDERABLE NITROGEN (N) is lost from livestock production as ammonia (NH_3) (European Centre for Ecotoxicology and Toxicology of Chemicals, 1994). The loss of NH_3 to the atmosphere causes a loss of nitrogen and significant deleterious effects on forests, lakes, and natural resorts (Bak et al., 1999). It has been estimated that livestock production in Denmark contributes approximately 99% of the total Danish NH_3 emissions and that approximately 25% of this NH_3 emission is derived from the spreading of livestock manure (Hutchings et al., 2001). Therefore, there is increasing interest in technology that will reduce NH_3 emissions arising from field applications of livestock manure.

In Denmark, a steadily increasing amount of livestock manure is applied directly to growing crops to increase the utilization rate of the nutrient content of the manure and also because of regulations designed to protect the environment. However, slurry application to growing crops may increase NH_3 emissions (Nathan and Malzer, 1994; Sommer et al., 1997), due to the impossibility of incorporation into growing crops and the climatic conditions in the growing season. Ammonia emission from slurry application can be reduced by trailing-hose spreading (Morken, 1991; Sommer et al., 1997; Smith et al., 2000), trailing-feet techniques (Huijsmans et al., 1997; Smith et al., 2000), and even more so by slurry injection techniques (Thompson et al., 1987; Rubæk et al., 1996; Huijsmans et al., 1997; Smith et al., 2000).

The first slurry injectors to be produced injected slurry 15 to 20 cm below the soil surface (Thompson et al., 1987). This type of injection was efficient in reducing NH_3 emission, but is no longer used due to its restricted application capacity and the damage caused to grass crops (Prins and Snijders, 1987; Long and Gracey, 1990). A new generation of shallow slurry injectors has been developed to meet the demand for a slurry application technique to reduce NH_3 emissions with minimal damage to growing crops and with a high capacity. Several of these have been developed to permit shallow injection of slurry into grassland (grasslands injectors).

A grassland injector makes open slots into the grass sward into which the slurry is placed. The potential for ammonia loss from applied slurry then depends on the contact surface area between the applied slurry and the atmosphere, which will be at its lowest when all the slurry applied can be held in the slots. However, as soil can be very resistant to penetration in the growing season, slurry injection increases the demand for energy and puts heavy demands on the design of the injection unit. A high clay content, and especially drought, will increase the penetration resistance of the soil, and efficient slurry injection may therefore not be possible in some areas and periods.

Shallow slurry injectors are equipped with injection systems of different designs. The design of the injection system will influence the efficiency of injection and therefore the potential for reducing the NH_3 emission. Shallow slurry injection should reduce NH_3 losses with minimal energy input. A research initiative was therefore made to investigate the NH_3 reduction potentials for different types of slurry injection techniques and the additional demand for energy needed for efficient slurry injection. Injection depth, slot volume (i.e., injection efficiency), and energy demand of the injection device were measured.

MATERIALS AND METHODS

Study Site

Ammonia emission experiments were conducted in June 1999 and June 2000 at the Research Centre Bygholm, Horsens, Denmark (55°90′ N, 10°10′ E). The study site was a pasture in rotation consisting of a mixture of annual ryegrass (*Lolium*

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Table 1. Description of the six shallow injection machines included in the study.

Type	Description	Width of injection bar	Distance between injectors	System for pressing devices into soil
		m	cm	
1	A disk opening system of two angled disk coulters. The angled disks have a diameter of 305 mm and a width of 5 mm, and are placed at an angle of 7° with respect to each other. The coulters almost touch each other at the point where the cutting of the sward begins.	6.0	25	hydraulic
2	Thin disk coulters followed by vertical injector coulters. The disk coulters create thin slots with a width of 5 mm, which are widened to 24 mm by the vertical injection coulters.	6.5	25	hydraulic
3	Vibrating disk coulters, which simultaneously cut and widen slots.	9.0	30	springs
4	Three disk coulters combined in a thick disk coulter system that creates a V-shaped slot into which the slurry is applied.	8.0	25	hydraulic
5	Thick disk coulter system. The thick disks cut and create V-shaped slots into which the slurry is applied.	6.0	20	hydraulic
6	Thin disk coulters followed by vertical tines and rubber wheels. The thin disk coulters cut thin slots in the grass, which are enlarged by the vertical tines that apply the slurry into the bottom of the slot. The slots are closed by the rubber wheels after the slurry is applied.	6.0	25	hydraulic

multiflorum L.) and white clover (*Trifolium repens* L.). In both years slurry was applied to a second-year grass field immediately after the first mowing at the beginning of June. The study site soil was a sandy loam (13.1% clay, 81.7% sand, and 2.2% organic matter in 1999, and 10.3% clay, 87.7% sand, and 2.0% organic matter in 2000) (Rasmussen et al., 1995). Soil water content of the upper 5 cm of the topsoil, estimated from five soil samples per plot, was 11.2% in 1999 and 13.9% in 2000.

After the grass crop had been cut and removed, unreplicated experimental plots (four in 1999 and five in 2000) of 36 × 36 m^2 were positioned in the field, 100 m apart. Care was taken that soil parameters of the different plots were as even as possible. This was done by using previously performed field maps of soil characterization (Rasmussen et al., 1995). The slurry application machines were adjusted to apply 30 Mg ha^{-1} of cattle slurry, corresponding to about 3900 kg of slurry to each plot. Each experimental plot received one load of slurry by one of the different types of application system, and care was taken that application to the different plots took place as simultaneously as possible to minimize changes in climatic conditions. The amount of slurry applied was determined by weighing the application machines before and after application, showing that the actual application rate was in the range 29.5 to 42.3 Mg ha^{-1}. One slurry sample per load in 1999 and two samples per load in 2000 were taken for analysis of slurry composition. Each sample consisted of four subsamples. Composition of the cattle slurries was analyzed with standard techniques, dry matter (DM) was determined after drying at 100°C, total N was determined by the Dumas procedure (CNS 2000; LECO Corporation, St. Joseph, MI), total ammoniacal nitrogen (TAN) was measured with an Autoanalyzer 3 (Bran+Luebbe, Norderstedt, Germany), and pH was determined with a standard electrode (Model 2001; San-Tron, Ipswich, MA). Hourly data for wind speed, temperature, incident solar radiation, atmospheric humidity, and precipitation were taken from the meteorological station at Research Center Bygholm, situated less than 1 km from the experiment site. The resistance to penetration of the soil was estimated by 12 random measurements per plot with a handheld penetration meter.

Draft experiments were conducted in June 1999 simultaneously with the ammonia experiments and in the same field. To minimize differences in soil conditions, the draft experiments of the different types of injection devices were performed as close to each other as possible. Statistical analyses were performed on slurry composition and climatic conditions. All statistical analyses were performed as paired *t* tests.

Application Techniques

The shallow slurry injectors included in the study were chosen following a preliminary survey of the types of shallow slurry injectors used in Denmark. The aim of the preliminary survey was to obtain an overview of the different types of grasslands injectors currently in use. On the basis of this survey, six different types were selected for further testing. Three different types of slurry injectors (Types 1, 2, and 3) were used in the 1999 experiment, and four different types (Types 1, 4, 5, and 6) were used in the 2000 experiment. The characteristics of the various types of slurry injectors are summarized in Table 1. The various injection systems were positioned on frameworks mounted on the different types of spreaders and were forced into the soil to cut slots either hydraulically or by springs. In both years a trailing hose–application spreader equipped with 40 trailing hoses mounted 30 cm apart was included in the study for comparison.

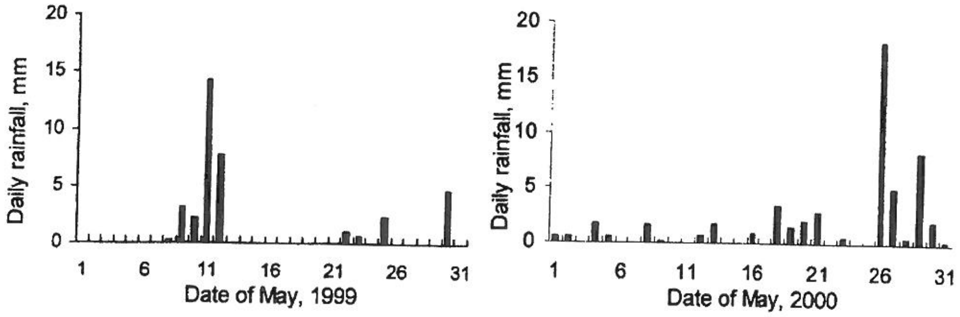

Fig. 1. Daily rainfall in the month before the slurry application in 1999 and 2000. The slurry application took place on 1 June 1999 and 30 May 2000.

Table 2. Climatic conditions during and after the slurry application in 1999 and 2000.

Period	Year	Rainfall	Soil temperature	Soil water	Air temperature	Wind speed	Air humidity
		mm	°C	%	°C	m s^{-1}	%
During application	1999	0	12.4	11.2 (1.7)a†	10.6	3.2	71.3
	2000	0	10.0	13.9 (3.7)a	12.5	7.7	66.0
The following 6 d	1999	22.0	12.8 (0.5)a	–	12.5 (3.2)a	3.9 (1.9)a	83.8 (11.5)a
	2000	8.9	11.0 (0.8)b	–	10.6 (3.3)b	3.6 (1.8)a	77.9 (7.9)a

† Values in parentheses are standard deviations. Values followed by different letters are significantly different at $P < 0.05$.

Ammonia Emission Measurements

The rate of NH_3 emission was estimated for each of the plots with the micrometeorological mass balance technique (Leuning et al., 1985; Sherlock et al., 1989), which involves a measuring mast situated centrally in each plot and a background measuring mast located outside the plot for measurement of the background NH_3 levels. In 1999, the centrally located masts and the background mast were fitted with five measuring units (passive flux samplers) mounted 30, 50, 95, 110, and 200 cm above the soil surface. In 2000 the Zinst modification of the micrometeorological mass balance technique was used (Wilson et al., 1982, 1983), where the centrally located masts and the background mast were fitted with two measuring units mounted 88 cm above the soil surface. The flux density of NH_3 was measured continuously over 6 d after slurry application in 1999 and 12 d in 2000. The length of the consecutive measuring periods was 1.5, 4, 19, 24, 24, 24, and 48 h in both years. In 2000, emission was also measured over two additional periods of 72 h. Due to the field size requirement for the measuring technique, no replication of results was performed.

Injection Efficiency

The injection efficiency for each injection device was defined as the mean injection depth and the mean volume of the slots made by the device. The mean injection depth was determined from 20 random measurements of the slot depth by means of a vertical rod-plate measurement method. The mean volume of the slots was determined by filling liquid plaster into 20 random slots per plot. After hardening, the plaster casts were removed, and the shape of the casts was drawn onto paper. The area of the drawn plaster cast was thereafter estimated by weighing the paper.

Additional Energy Demand

The additional energy requirement needed for injection was estimated in a separate study for the slurry injectors studied in 1999. The net draft requirement needed for injection was estimated by pulling the tractor and slurry injector both with and without the injector devices, creating slots over a distance of 100 m. The force required to pull the tractor and injector was measured in newtons (N) with a portable measuring unit (T20 tension cell; Nordisk Transducer Teknik, Hadsund, Denmark). The data were stored in a computer and subsequently divided by the number of injection units per slurry injector. The procedure was repeated for different driving speeds (4, 7, and 10 km h^{-1}).

The additional draft requirement (energy required to pull the working injectors minus that required to pull the tractor and equipment only) was converted into joules per hectare, which was then converted into the additional need for fuel, taking into account a 20% utilization ratio of fuel energy of tractors (Guul-Simonsen et al., 1999). The additional demand for fuel was then converted into additional emission of carbon dioxide (CO_2) per hectare injected with slurry, assuming that the consumption of 1 L of diesel produces 3.09 kg CO_2 (Danish Energy Agency, 2001).

RESULTS AND DISCUSSION

Manure, Soil, and Climate

In 1999 and 2000 the rainfall before slurry injection was close to the average for May (49 mm of rainfall), with 36 mm of rain in May 1999 and 53 mm of rain in May 2000 (Fig. 1). Therefore, the soil conditions in both years were considered to be near normal. The climatic conditions during and after the slurry application were approximately similar for the two measuring periods (Table 2), although air temperature and wind speed were higher and air humidity lower during the application in 2000 than in 1999. In both years, recently stirred cattle slurry was applied, but in 2000 the dry matter, ammonium, and total nitrogen content of the applied slurry was higher than in 1999 (Table 3).

Ammonia Loss

The higher air temperature and wind speed and the lower air humidity during slurry application in 2000 may have increased the potential for NH_3 emission (Bussink et al., 1994; Sommer et al., 1997). This may have been enhanced by the higher dry matter and ammonium content in 2000 (Braschkat et al., 1997). In consequence, the total NH_3 emission from the trail hose–applied slurry was 43% of total ammoniacal N applied in 2000, which was more than double the emission in 1999 (Fig. 2). Similar results have been found by Rubæk et al. (1996), who found that total NH_3 loss made up 47% of total ammoniacal N applied to grassland by trail hoses. In previous Danish studies, the accumulated emission of NH_3 from slurry applied by trail hoses to the soil under a wheat (*Triticum aestivum* L.) canopy has been between 4 and 26% (Sommer et al., 1997). The higher emission observed from grassland may have been caused by the fact that cut grass, unlike wheat, does not reduce wind speed or provide shade for trail hose–applied slurry.

In both years the NH_3 emission was lower from the injected slurry than from the trail hose–applied slurry (Fig. 2). Compared with trail hose–applied slurry the most efficient slurry injection technique used in 1999

Table 3. Composition of the slurry applied in 1999 and 2000.

Year	Observations	Dry matter	pH	Total N	Ammonium N
		%		g kg^{-1} slurry	
1999	4	3.6 (0.5)a†	7.7 (0.06)a	2.13 (0.10)a	1.33 (0.05)a
2000	10	8.5 (0.2)b	7.0 (0.02)b	3.24 (0.14)b	1.58 (0.06)b

† Values in parentheses are standard deviations. Values followed by different letters are significantly different at $P < 0.05$.

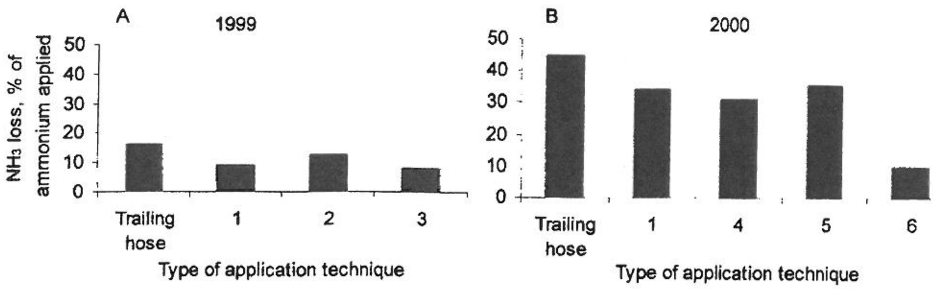

Fig. 2. Ammonia loss in percentage of applied total ammonium nitrogen (TAN) after slurry application to grass by the use of different application techniques in 1999 (*A*) and 2000 (*B*). Numbers 1 through 6 represent the different types of slurry injection technique. No replication of results was performed.

reduced the NH_3 emissions by 50% (Fig. 2a), while the least efficient injection type reduced the NH_3 emission by 20%. The most efficient type of slurry injection used in 2000 reduced the NH_3 emission by 75% relative to trail-hose application, while the least efficient injection type reduced the NH_3 emission by 20% (Fig. 2b).

Thus, in the years of this study, injection of slurry reduced the emission of NH_3 by between 20 and 75%, compared with trail-hose application (Fig. 3). A similar reduction of the NH_3 emission by means of injection has been found in previous studies (Rubæk et al., 1996; Smith et al., 2000). Compared with trail-hose application, Rubæk et al. (1996) found that the NH_3 emission was lowered by between 47 and 72% when slurry was injected into 5-cm slots. Smith et al. (2000) found that slurry injection into approximately 5-cm-deep slots reduced the NH_3 emission by 32%, while Misselbrook et al. (1996) found that slurry injection into 6-cm-deep slots reduced the NH_3 emission by between 40 and 79%, compared with broadcast application.

Injection Efficiency

The NH_3 reduction potential of slurry injection was related to the volume of the slots created by the injection units (Fig. 3). Increasing the volume of the slots will reduce the surface area of the slurry exposed to the atmosphere after application, and the interface between slurry and atmosphere will be lowest when all the slurry is contained in the slot. Thus, the greater the volume of the slots, the lower the relative NH_3 emission. In consequence, NH_3 volatilization was related to the effectiveness of the injections. A positive correlation was seen between the volume of the injection slots created by the different slurry injection techniques and the potential for reducing the NH_3 emission, with the fitted regression line accounting for 88% of the variation (Fig. 3). This indicates that creations of adequate volume of slots by slurry injections may be a more important factor for efficient ammonia reduction than the shape of the slots created.

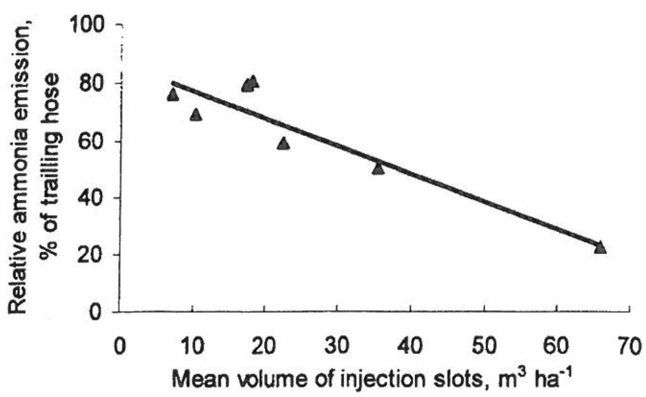

Fig. 3. The relation between the ammonia emission reductions obtained and the volume of the injection slots produced by the different slurry injection techniques.

Despite the similarity of soil conditions, the mean depth of injection and the mean volume of the slots created by the injection varied considerably for the shallow injectors used in this investigation (Table 4). The variation was caused by the differences in the shape of the slots and in particular the differences in the depth of injection. Despite major differences between designs of the different types of slurry injection units, injection depth was the most important factor in creating spacious slots that allowed a full injection of the slurry applied (Fig. 4). The fitted line of the regression $f(x) = 1.41x^{1.95}$, where $f(x)$ is the volume of the slots in m^3 ha^{-1} and x is the mean depth of injection (cm), accounted for 95% of the variation. The equation can be used to estimate the depth of injection needed to ensure a full injection of a given application rate of slurry. Accordingly, an injection depth > 5 cm is needed to ensure a full injection of, for instance, 30 m^3 of slurry per hectare.

Depth of injection will depend on the design of the injection unit, but is also influenced by the adjustment of the injector. To illustrate this, the Type 1 slurry injector was used in the investigation in both years. Despite the fact that the soil conditions in 2000 determined the efficiency of injection to be at least as good as in 1999, the depth of injection was much lower in 2000. This illustrates that efficiency of slurry injection, and thereby the potential for reduction of the NH_3 emission, is considerably influenced by the adjustment of the shallow injector used.

Energy Demand

The draft force, and therefore the need for fossil resources, will be higher when slurry is injected than when it is surface-applied. Huijsmans et al. (1998) demonstrated that the draft force needed for slurry injection depends on the design of the injection unit, the soil conditions, and the depth of injection. In the study of

Table 4. Injection efficiency of the various slurry injection systems included in the study.

Year	Type	Depth of injection	Volume of slots	Slurry applied	Part of applied slurry injected
		cm	m^3 ha^{-1}	Mg ha^{-1}	%
1999	2	3.9 (1.8)†	18 (10)	38.8	46
	1	4.3 (1.1)	22 (8)	37.7	61
	3	5.4 (1.1)	35 (12)	31.2	100
2000	4	2.5 (1.5)	10.4 (9.6)	42.3	25
	1	2.6 (1.5)	7.2 (5.2)	33.6	21
	6	6.9 (1.2)	66 (72)	29.5	100
	5	3.2 (1.7)	17.3 (12)	32.4	53

† Values in parentheses are standard deviations.

Huijsmans et al. (1998), the mean draft force needed for injection into a sandy loam using four different types of shallow slurry injectors was correlated with depth according to the following equation: $df(x) = \exp(5.32) \times \exp(0.19x)$, where df is the draft force (N) and x is the mean depth of injection (cm).

Net draft force needed per injection unit for injection into grassland on sandy loam was estimated in the present study for three different types of slurry injectors and correlated with the mean injection depth at three different working speeds. Despite major differences in the design of the different types of injection system, the estimated draft force was close to the calculated mean of the net draft force of different types of injectors estimated by Huijsmans et al. (1998; see Fig. 5). The correlation between injection depth and draft force and the correlation between injection depth and NH_3 volatilization allows a simultaneous calculation of the additional demand for fossil energy needed for a given reduction in NH_3 volatilization.

Additional Release of Carbon Dioxide

A rough estimation of the additional energy needed for efficient and less efficient reduction of ammonia emission by shallow slurry injection was calculated on basis of the knowledge of the correlation between ammonia reduction potential and injection efficiency of shallow slurry injection and of the correlation between injection efficiency and additional energy demand.

Using slurry injection to obtain a reduction of the ammonia emission by 20%, compared with trail hose–applied slurry, will require a mean volume of slots of 7 m^3 ha^{-1} (Fig. 3). This can be obtained by a mean injection depth of 2.3 cm (Fig. 4), which will require an additional draft requirement of 318 N per injection unit (Fig. 5). Given a distance of 25 cm between injection units, 40 000 injection unit meters are required to cover 1 ha, which means an additional energy requirement of 12 720 000 Nm ha^{-1}, equivalent to 12 720 kJ ha^{-1}. As diesel fuel has an energy content of 35 590 kJ L^{-1}, the additional energy demand can be met by an additional 0.36 L diesel ha^{-1}. However, on average, tractors convert only approximately 20% of the energy content of diesel to draft (Guul-Simonsen et al., 1999). Therefore, the additional demand for diesel for injection will be 1.8 L ha^{-1}. As combustion of diesel results in the emission of 3.1 kg CO_2 L^{-1} (Fenger, 2000), the demand for an additional 1.8 L of diesel to obtain a reduction in the ammonia emission by 20% will therefore result in an additional emission of 5.6 kg CO_2 ha^{-1}. A reduction of the ammonia emission by 75% by use of shallow slurry injection will increase the energy requirement to 33 509 kJ ha^{-1}. The additional demand for diesel will be 4.7 L ha^{-1}, equivalent to an additional emission of 14.5 kg CO_2 ha^{-1}.

In Denmark, 20 million Mg of slurry is applied each year (Petersen, 1996), which at standard application rate (30 Mg ha^{-1}) requires a field area of 700 000 ha. If all the slurry produced in Denmark is to be applied by injection, this will be followed by an increase in the CO_2 emission by between approximately 4000 and 10 000 Mg yr^{-1}, corresponding to an increase of between 0.3 and 0.7% of the total Danish CO_2 emission resulting from agricultural field work (1.4 million Mg yr^{-1}) (Danish Energy Agency, 2001; Danish Farmer's Union, 2001).

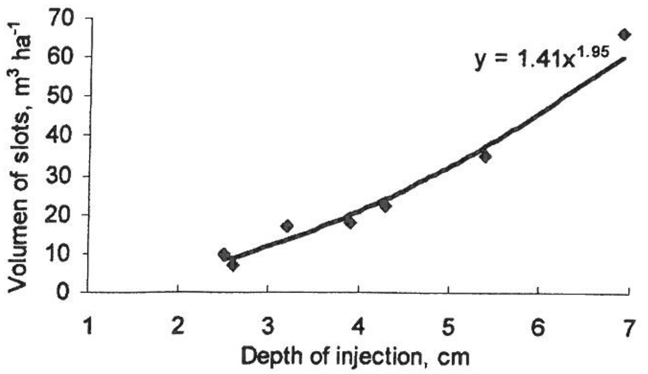

Fig. 4. Correlation between depth of injection slots and volume of the slots created by the different types of injectors. The solid line represent the fitted regression line given by the equation $f(x) = 1.41x^{1.95}$, where x is the depth of injection (cm).

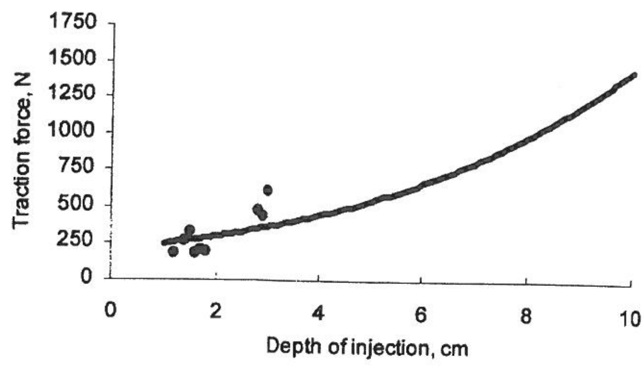

Fig. 5. Correlation between depth of injection slots and measured and estimated net draft force needed for slurry injection per injection unit. Points represent net draft force measured for slurry injectors taking part in the present investigation. The solid line represents the calculated mean of the estimated net draft force required for injection of different types of shallow slurry injectors (calculated from Huijsmans et al., 1998).

CONCLUSION

The ammonia reduction potential of various types of techniques for shallow slurry injection was investigated by unreplicated field plot experiments. According the results obtained, shallow slurry injection into grassland is capable of reducing NH_3 emissions by between 20 and 75%, compared with trailing-hose application. A high variation in ammonia reduction potential was seen between various types of slurry injection techniques. The ammonia reduction potential of different types of injection systems is linearly related to the volume of the slots created by the injection device. Energy demand for injecting slurry increases significantly with the volume of the slot created by the injector. Therefore, reducing ammonia emissions by means of a slurry injection is associated with increased greenhouse gas emissions.

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