Manure application and ammonia volatilization

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ABSTRACT

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Livestock manure applied on farmland is an important source of ammonia (NH_3) volatilization, and NH_3 is a major atmospheric pollutant. The need arose for more quantitative knowledge about NH_3 volatilization and for practical tools to reduce the NH_3 volatilization from manure.

A database of field measurements was analysed to identify factors that effect the volatilization of NH_3 from manure applied by various techniques on grassland and arable land. The analyses showed that NH_3 volatilization is substantially reduced by application techniques like narrow band application and shallow injection, and by effective manure incorporation techniques. Also the manure composition, the application rate and the weather conditions substantially influenced the NH_3 volatilization rate. Draught force required for different application techniques on grassland varied considerably. The design of the shallow injection element, the working depth and soil circumstances had a substantial influence on the required draught force. For the trailing foot a lower draught force was required than for shallow injection. On arable land the time-lag between application and incorporation of the manure substantially affected the total NH_3 volatilization. The costs of application techniques designed to reduce NH_3 volatilization were assessed across a range of farm characteristics, and compared with the conventional technique of broadcast spreading.

The results of the study supply sound and workable guidelines for the application and incorporation of manure to farmers and policy makers.

CONTENTS

Parts of this thesis have been published in or submitted to scientific journals. Chapter 2 was published as *Netherlands Journal of Agricultural Science* 49 (2001): 323-342. Chapter 3 was published as *Atmospheric Environment* 37 (2003): 3669-3680. Chapter 4 was published as *Journal of Agricultural Engineering* 71 (1998): 347-356. Chapter 5 was published as *Journal of Agricultural Engineering Research* 74 (1999): 73-82. Chapter 6 has been submitted for publication.
For this thesis, the text of the published articles and of the submitted manuscript was integrally adopted. Editorial changes were made for reasons of uniformity of presentation in this thesis. Reference should be made to the original article(s).

1

General introduction

Introduction

Manure application on farmland is an important source of ammonia (NH_3) volatilization. Ammonia volatilization has in various ways a negative impact on the environment. In the 1980s air contamination by ammonia urged a need for a proper quantification of ammonia volatilization from field-applied manure and a search started for tools to reduce the NH_3 volatilization. In this chapter the processes underlying ammonia volatilization and factors that influence ammonia volatilization are presented, and the objectives and approach of this thesis are described.

1.1 Manure and the environment

For centuries, livestock manure has been utilised on farms as an important, if not the only, source of mineral nutrients for the growing of crops. The storage, handling and use of these manures are associated with the volatilization of ammonia. Gaseous ammonia contributes importantly to the problem of environmental acidification (Van Breemen *et al*., 1982). The deposition of the nitrogenous nutrient ammonia also contributes to the eutrophication of forests and other natural ecosystems. An increased availability of nitrogen, in combination with soil acidification, may cause a disturbed nutrient balance and nutrient deficiencies. In the Netherlands, loss of ammonia from livestock manure is by far the most important source of contamination of the environment by ammonia (Buijsman *et al*., 1987; Heij & Schneider, 1995). The annual ammonia volatilization from animal manure was estimated to be more than 200 million kg in 1980 and at about 150 million kg in 1998 and 1999. In 1980 the distribution of the total ammonia volatilization from agriculture over various sources was 37% from animal housing and manure storage, 56% from field application of manure and 7% from grazing cattle. In 1999, these contributions were 50, 41 and 9%, respectively (Anon., 2000).

In the 1980s and early 1990s, the environmental problems associated with the use of livestock manure became a major issue of the Dutch government's environmental policy (Anon., 1984, Anon., 1993). The need arose for an efficient recycling of nutrients to create a sustainable agricultural use of manure. Legislation was introduced to reduce the leaching of nutrients into the environment and to reduce the volatilization of ammonia. To prevent overfertilisation of crops, limits per hectare per year were set to the amount of manure to be applied on grassland and on arable land. To increase nutrient uptake by the crops and decrease leaching, the periods, during which manure was allowed to be applied, were tuned to the growing season of the crop. Manure application in autumn and winter became forbidden. Ammonia volatilization from agriculture had to be reduced by 70% in the period 2000-2005 compared with the total ammonia volatilization in 1980 (Anon., 1993). The reduction of ammonia volatilization after manure application to farmland got much attention. The contribution from this source was the largest, and measures to reduce ammonia volatilization after manure application seemed to be easy to introduce at relatively low costs. Furthermore, the effects of measures to reduce ammonia volatilization in animal housing and during storage would be relatively small, if no measures to reduce volatilization after field application were taken. Ammonia saved in housing or storage would volatilize after all, when applying the manure to farmland without volatilization-reducing measures. Injection of liquid manure into grassland and incorporation of manure into arable land were the first measures considered to reduce ammonia volatilization. However, Wadman (1988) estimated that only 33% of the grassland in the Netherlands is suitable for injection. Unsuitability for injection is caused by the required draught force and crop damage along the slit on various soil types, and the remains of wood trunks in the soil. Therefore, new application techniques for grassland had to be developed. The effect of new techniques on ammonia volatilization and the suitability of new techniques on different soil types under varying soil conditions had to be evaluated. On arable land, the effect of the choice of implement to incorporate the manure was not known and the effectiveness of the speed of incorporation needed to be assessed, because ammonia volatilization peaks directly after surface spreading.

The Dutch ministry of agriculture, farmers organisations, research institutes and manufacturers jointly worked on solutions to reduce ammonia volatilization. In other countries, ammonia volatilization attracted similar attention in recent years, partly due to the IPPC-act constituted by the EU (IPPC, 1996). Thus, the need emerged for knowledge of the volatilization of ammonia, and for practical measures to reduce ammonia volatilization from manure applied to farmland. In the Netherlands research was initiated for liquid manures (slurry) from dairy and pigs, as the main manures applied to farmland.

1.2 Ammonia volatilization

To control ammonia losses by volatilization, it is important to know the processes that are involved, when ammonia volatilizes from manure, applied to grassland or arable land.

Ammonia volatilization from manure is proportional to the difference between the ammonia concentration at the surface of the manure, and the concentration in the air above the surface (Chardon *et al.*, 1991):

$$E = k\,(c_m - c_a) \tag{1.1}$$

in which E is the volatilization rate of ammonia (g m^{-2} s^{-1}), k the diffusion coefficient for ammonia in air (m s^{-1}), c_m the ammonia concentration at the manure surface (g m^{-3}), c_a the ammonia concentration in the atmosphere above the manure surface (g m^{-3}).

The concentration at the surface of the manure (c_m) depends on the chemical equilibrium between aqueous ammonium ($NH^{+}_{4,aq,m}$) and aqueous ammonia ($NH_{3,aq,m}$) in the manure (Freney *et al.*, 1983):

$$NH^{+}_{4,aq,m} \longleftrightarrow NH_{3,aq,m} + H^{+} \tag{1.2}$$

The formation of gaseous ammonia in the manure depends on the equilibrium between aqueous ammonia ($NH_{3,aq,m}$) and gaseous ammonia ($NH_{3,g,m}$) in the manure (Freney *et al.*, 1983):

$$NH_{3,aq,m} \longleftrightarrow NH_{3,g,m} \tag{1.3}$$

Bussink *et al.* (1994) showed that the concentration of gaseous ammonia ($NH_{3,g,m}$) increases with an increase of the concentration of aqueous ammonium ($NH^{+}_{4,aq,m}$), the pH and the temperature of the manure.

The volatilization of ammonia from manure ($NH_{3,g,m}$) into the air ($NH_{3,g,a}$) can be described by:

$$NH_{3,g,m} \rightarrow NH_{3,g,a} \tag{1.4}$$

Equation (1.1) can thus be transformed into:

$$E = k[(NH_{3,g,m}) - (NH_{3,g,a})] \tag{1.5}$$

The factors that affect volatilization of ammonia from manure and the emission of ammonia into the atmosphere can be grouped into five main categories:

1 chemical and physical properties of manure;
2 meteorological factors;
3 interaction between manure and the soil and crop, on which it is applied;
4 application technique and incorporation technique.

Interactions between the above four categories may affect the overall volatilization.

1.2.1 Chemical and physical properties of manure

At a high ammonium ($NH^{+}_{4,aq,m}$) concentration in the manure, *e.g.* due to a low water content, the potential volatilization is increased. Dilution of the manure directly decreases the ammonium concentration in the manure and may improve infiltration of the manure into the soil. By dilution at different rates, volatilization was reduced 25 to 50%, compared with undiluted manure (Döhler, 1991; Stevens *et al.*, 1992). However, when applying diluted manure, the manure volume applied will be higher than for undiluted manure, if the same nitrogen application rate is required. In this case, the higher volume of the diluted manure may slow down the infiltration into the soil, and may therefore counteract the effect of dilution on the reduction of ammonia volatilization.

A high dry matter content of the manure decreases infiltration into the soil, and results in an increased chance of volatilization (Amberger *et al.*, 1987; Sommer & Christensen, 1989; Amberger, 1991; Sommer, 1991; Stevens *et al.*, 1992). Especially, on soils with a poor infiltration rate, the dry matter content of manure may be of importance (Jarvis & Pain, 1990).

The concentration of ammonia ($NH_{3,aq,m}$) in the aqueous fraction of the manure is affected by the pH of the manure (Eq. 1.2). At a temperature of 10 to 30^{o}C and at pH 7, less than 1% of the total ammoniacal nitrogen ($NH^{+}_{4,aq,m}$ + $NH_{3,aq,m}$) is present as ammonia ($NH_{3,aq,m}$). This proportion exceeds 50% at pH 10 (ECETOC, 1994). Acidification decreases the ammonia concentration ($NH_{3,aq,m}$) in the manure (Freney *et al.*, 1983; Bussink *et al.*, 1994). In small scale experiments, ammonia volatilization could be decreased with 30 to 98% by lowering the pH of the manure from 7.0 to a range of 5.0 to 6.5 (Döhler & Aldag, 1986; Stevens *et al.*, 1989; Frost *et al.*, 1990; Pain *et al.*, 1991; Stevens *et al.*, 1992). On grassland a reduction of ammonia volatilization of 55 to 85% was achieved with acidified manure, at pH 6.0 to 4.5, respectively, compared to non-acidified manure of pH 7 (Bussink *et al.*, 1994). Acidification of manure, just before application, reduced ammonia volatilization depending on the degree of acidification and the application technique (Huijsmans *et al.*, 1994). Lenehan *et al.* (1994) described a system to acidify manure on the manure spreader.

Manure composition and the potential volatilization of ammonia may also depend on the species and breed of farm animals, the housing system and the diet composition (Monteny *et al.*, 2002).

1.2.2 Meteorological factors

Studies lack similarity in their conclusions about the influence of weather conditions on the height of ammonia volatilization. Temperature, relative humidity and wind speed are often mentioned as the main factors. Brunke *et al.* (1988) reported that the volatilization is stimulated by a combination of factors that dry the manure and thereby lead to higher ammonia concentrations.

A high temperature of the manure increases the formation of aqueous ammonia ($NH_{3,aq,m}$), in the manure, due to an increase of the dissociation constant of Equation 1.2. A high temperature of the manure also increases the formation of gaseous ammonia ($NH_{3,g,m}$ in Eq. 1.3), and decreases the solvability of ammonia in water (Vlek & Stumpe, 1978; Freney *et al.*, 1983; Bussink *et al.,* 1994). Therefore, the ambient temperature affects the potential ammonia volatilization.

Evaporation of water from the manure increases the aqueous ammonia ($NH_{3,aq,m}$) concentration in the manure (c_m in Eq. 1.1). In case the ammonia concentration in the air ($NH_{3,g,a}$; c_a) is lower than the concentration in the manure ($NH_{3,g,m}$; c_m), evaporation stimulates ammonia volatilization. The evaporation is affected by ambient temperature, air humidity and solar radiation. Drying conditions, therefore, increase ammonia volatilization (Brunke *et al.*, 1988; Horlacher & Marschner, 1990; Sommer *et al.*, 1991a). On the other hand, manure may get dried to such an extent that a crust is formed at the outer layer of the manure. This crust may act as a barrier against diffusion of ammonia from the manure (Thompson *et al.*, 1990b; Voorburg & De Bode, 1991).

The diffusion of ammonia into the air increases with wind speed. Volatilized ammonia is removed by the wind, and the ammonia concentration in the air above the manure ($NH_{3,g,a}$; c_a in Eq. 1.1) stays low, stimulating further ammonia volatilization (Freney *et al.*, 1983). High wind speeds dry the upper layer of the soil, and possibly create improved infiltration, resulting in decreased ammonia volatilization. In this case an inverse relation exists between wind speed and volatilization (Bouwmeester *et al.*, 1985; Brunke *et al.*, 1988).

Rainfall before manure application affects the soil moisture content and may dilute the manure or decrease infiltration of the manure into the soil. Rainfall directly after manure application improves infiltration into the soil, and decreases ammonia volatilization (Beauchamp, 1983; Freney *et al.*, 1983; Horlacher & Marschner, 1990). Rainfall also decreases evaporation and in that way indirectly decreases volatilization. Irrigation after manure application may, similar to rainfall, improve infiltration and dilute the manure (Mulder & Huijsmans, 1994).

1.2.3 Interactions between manure, soil and crop

Soil characteristics such as CEC (Cation Exchange Capacity) and pH affect the ammonia volatilization. A higher CEC (improved “binding” of aqueous ammonium, $NH^+_{4,aq,m}$), and a lower pH decrease ammonia volatilization (Freney *et al.*, 1983). In a dry soil, manure may infiltrate deeper through the small pores (Van Der Molen *et al.*, 1989), and ammonia volatilization decreases. Ismail *et al.* (1991) showed that ammonia volatilization was highest on dry and on very wet soils, due to poor infiltration into the soil. Soil tillage also affects ammonia volatilization. Ammonia volatilization was higher from manure applied to a compacted soil than from manure applied to a well-cultivated soil (Hoff *et al.*, 1981; Amberger, 1991). Soil tillage before manure application may improve infiltration.

When manure is applied on top of the crop (grassland), the presence of a crop acts as a physical barrier against infiltration and increases the contact area of the manure with the ambient air. Both infiltration rate and contact area affect volatilization (Thompson *et al.*, 1990a; Amberger, 1991). Volatilization is increased when applying manure on a stubble or on straw residues on arable land (Amberger *et al.*, 1987), due to decreased infiltration and an increased contact area. On the other hand, the crop acts as an interface between the atmosphere and the applied manure, causing a lower wind speed at the manure surface (Amberger, 1991; Thompson *et al.*, 1990a; Sommer *et al.*, 1991b), and thus a reduction of volatilization.

1.2.4 Application technique

Ammonia volatilization is affected by the contact area between manure and the atmosphere. The diffusion of ammonia decreases with decreasing contact area (Eqns 1.1 and 1.5). In this case also evaporation decreases. The contact area of the manure with the atmosphere can be reduced by improving infiltration of manure into the soil. Furthermore, infiltration or an increased contact of the manure with the soil may lead to improved binding of aqueous ammonium in the soil. An improved infiltration of the manure can be achieved by dilution of the manure, soil tillage before manure application, rain or irrigation during and after manure application, and by the way manure is applied or incorporated. Application of manure in bands reduces ammonia volatilization compared with broadcast spreading (Thompson *et al.,* 1990b; Svensson, 1993; Huijsmans *et al*., 1997). The reduction of volatilization is relatively smaller than the decrease of the contact area with the air (Thompson *et al.*, 1990b). Injection and direct incorporation of the manure are effective measures to reduce ammonia volatilization (Hoff *et al.*, 1981; Brunke *et al.*, 1988; Horlacher & Marschner, 1990; Amberger, 1991; Döhler, 1991; Huijsmans, 1991; Ismail *et al.*, 1991).

1.2.5 Interactions

In Table 1.1 the main factors and their influence on ammonia volatilization are summarised. Not all factors can be grouped precisely, because ammonia volatilization is often caused by a combination of factors and by interactions between these factors.

The rate of ammonia volatilization decreases with time, when the ammonia source (the manure) becomes exhausted. Ammonia fluxes sometimes show a day and night cycle. Due to a low wind speed, low temperature and high relative humidity, ammonia volatilization may decrease during the night, and may rise again in the daytime due to an increase of wind speed and temperature, and a decreasing relative humidity. However, on the long term, the ammonia source becomes exhausted, the ammonia volatilization rate decreases to the background level, and the effect of weather conditions disappears.

A higher application rate increases the volatilization rate (Horlacher & Marschner, 1990; Thompson *et al.*, 1990b) due to a larger source of ammonia. The higher application rate also slows down the infiltration of manure into the soil. However, ammonia volatilization, expressed as percentage of the total ammoniacal nitrogen ($NH^+_{4,aq,m}$ + $NH_{3,aq,m}$) applied to the field, may vary between high and low application rates (Pain & Klarenbeek, 1988; Thompson *et al.*, 1990b; Horlacher & Marschner, 1990). The volatilization percentage may be even higher at low application rates, because a thin layer of manure may dry faster, causing an increase of the total ammoniacal nitrogen concentration in the manure (Brunke *et al.*, 1988). Crust formation, however, may hamper the diffusion of gaseous ammonia from the manure ($NH_{3,g,m}$) into the air ($NH_{3,g,a}$) (Thompson *et al.*, 1990b). Jarvis & Pain (1990) mention the concentration of ammoniacal nitrogen, pH and dry matter content as the main manure characteristics that determine ammonia volatilization. Volatilization that occurs after field application of the manure will be

Table 1.1. Main factors affecting the volatilization of ammonia from manure.

Factor		Direction of change
Manure properties	pH	+
	TAN [a] content	+
	Water content	-
	Dry matter content	+
	Crustation [b]	-
Meteorological factors	Air temperature	+
	Solar radiation	+
	Wind speed	+
	Rainfall	-
	Relative humidity	-
Crop and soil properties	Presence of crop residues [b]	+
	Soil moisture content	+/-
	Infiltration rate	-
	CEC	-
	Soil pH	+
Application technique	Band application [b]	-
	Injection [b]	-
	Direct incorporation [b]	-

\+ denotes that an increase of the magnitude of the factor increases ammonia volatilization.

\- denotes that an increase of the magnitude of the factor decreases ammonia volatilization.

[a] TAN, total ammoniacal nitrogen ($NH_4^+ + NH_3$).

[b] The factors marked with a ([b]) are either present or absent; the effect of the presence of the indicated factor is denoted as + or -, when the presence of the factor increases or decreases ammonia volatilization, respectively.

influenced by factors like weather conditions, soil type and soil condition, presence of a crop, and application rate. Furthermore, the application technique, dilution of the manure, or supply of additives to the manure may affect ammonia volatilization. Interactions between these factors may be complex. Brunke *et al.* (1988) suggested that ammonia volatilization is more influenced by the manure composition and application technique, than by other factors.

1.3 Reduction of ammonia volatilization from field-applied manure

The control of the process of volatilization after manure application to farmland interferes with the mechanisms, which underlie this process (Eq. 1.5). Three main strategies can be defined to reduce ammonia volatilization when applying manure: (1) lower the ammonium ($NH^{+}_{4,aq,m}$) concentration in the manure, (2) reduce the formation of gaseous ammonia ($NH_{3,g,m}$) by lowering the pH and (3) decrease the diffusion of gaseous ammonia ($NH_{3,g,m}$) by decreasing the contact area between the manure and the atmosphere.

Lowering the ammonia concentration in the manure can be achieved by selection of diet composition, and by dilution of the manure. Lowering the pH of the manure can be achieved by adding acid to the manure, either in the store, or just before application on the field, or during application. Decreasing the exchange contact area of the manure can be achieved by the application technique or by improving the infiltration of the applied manure into the soil.

In the Netherlands, all three strategies to reduce ammonia volatilization were considered. Dilution of the manure and acidification were less feasible, because these measures were difficult to check in practice by supervising authorities. Much effort was put into the improvement and development of techniques for the application and incorporation of manure. The search for new techniques was mainly based on decreasing the contact area between the manure and the atmosphere.

The approach for manure application on grassland was different from that on arable land. Injection of manure into the soil seemed to be a good application technique on grassland. However, injection requires a high draught force, and may reduce herbage yield due to sward damage by the tines and crop die-back along the injection slots. Moreover, an imperfect closure of the injection slot was observed under dry grassland conditions (Warner *et al.*, 1991). Also, injection on permanent grassland is not possible on all soil types (Wadman, 1988). Therefore, new techniques for manure application, with low ammonia volatilization, needed to be developed for grassland and the required draught force had to be assessed to judge the suitability of new application techniques on different soil types. The presence of a crop hampers the incorporation of surface-applied manure on grassland.

On arable land, however, incorporation of surface-applied manure is a readily available technique. Various incorporation techniques are commonly available on farms. Incorporation of manure may be combined with soil tillage. Manure could also be injected into arable land, but the small working width of the injector may cause unwanted soil compaction. The effectiveness of different incorporation techniques to reduce ammonia volatilization had to be improved. In the case of incorporation after manure application, the effect of a time-delay between manure spreading and incorporation needed to be assessed, because ammonia volatilization from surface-applied manure peaks the first hours after spreading.

In view of these practical possibilities and restrictions, different techniques to control ammonia volatilization after manure application were designed for grassland and arable land. In the framework of this thesis, the research was extended to the efficiency of different application and incorporation techniques in relation to ammonia volatilization, the required draught force of the application techniques for grassland and the effect of the work organization on ammonia volatilization, when incorporating manure on arable land. Finally, techniques for the application and incorporation of manure, which can be readily adopted by farmers, were subjected to an economic evaluation.

1.4 Objective and approach of the research

This thesis deals with the development and evaluation of techniques for the application and incorporation of manure on farmland in relation to the reduction of ammonia volatilization. The objectives of this thesis are:

1. to quantify the effect of techniques for application and incorporation of manure on ammonia volatilization;
2. to assess the factors that affect ammonia volatilization after application and incorporation of manure;
3. to assess the feasibility of application techniques on grassland;
4. to assess the effect of work organization on ammonia volatilization, when

applying and incorporating manure on arable land;

5 to assess the economical aspects of volatilization-reducing application techniques.

1.5 Outline of this thesis

Ammonia volatilization is affected by the techniques of application and incorporation of manure, and by various other factors (Table 1.1). A differentiation can be made between manure application techniques for grassland and incorporation techniques for arable land. First, the effect of application technique and other factors on ammonia volatilization from manure applied to grassland is described (Chapter 2). Similarly, the effect of incorporation technique and other factors on ammonia volatilization from manure applied to arable land is described (Chapter 3). Chapters 2 and 3 deal with field experiments, in which ammonia volatilization, from manure applied or incorporated by different techniques, was measured. Experiments were carried out in different periods of the year and on different fields, to cover a large range of soil and weather conditions. The effectiveness of different techniques of application and incorporation was quantified by comparing the volatilization of ammonia with the volatilization of ammonia from broadcast surface-spread manure. Statistical analysis and modeling were used to assess the effect of factors, such as weather conditions, manure properties and field conditions, on ammonia volatilization.

Not only the potential reduction of ammonia volatilization achievable by various techniques for application and incorporation, as measured in field experiments, is of importance to reduce ammonia volatilization. Also, the implications of the required draught force for application techniques on various soil types on grassland needs to be known, to assess the suitability of the techniques under various conditions in practice. On arable land, next to the incorporation technique, the work organization for the incorporation is of importance, to optimise reduction of ammonia volatilization. Therefore, Chapters 4 and 5 deal with the practical suitability of various new application techniques for grassland and incorporation techniques for arable land. For grassland the draught force required for various new application techniques was measured, and factors that affect the draught force were analysed (Chapter 4). Subsequently, a model to assess the volatilization of ammonia after surface application and subsequent incorporation of manure on arable land is presented (Chapter 5). The effects of work organization and of the chosen techniques of application and incorporation on ammonia volatilization are also described in Chapter 5.

Application and incorporation of manure coinciding with reduced ammonia volatilization require new application techniques or a different work organization, respectively. Both aspects will affect the costs of manure application. The costs of different techniques of application were assessed for manure application on grassland and on arable land (Chapter 6).

Finally, an integrated approach of the current techniques to reduce ammonia volatilization from field-applied manure and a discussion of the feasibility of new application and incorporation techniques is presented in Chapter 7. In this chapter the implications of the findings for the present Dutch environmental policy are discussed.

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2

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

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Abstract

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

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

2.1 Introduction

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

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

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

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

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

2.2 Materials and methods

2.2.1 Field data

NH_3 volatilization was measured on 110 experimental grassland plots in 45 separate field experiments in the growing seasons (March-September) of 1989-1993. A summary of these experiments is given in Appendix 2.1. The experiments included different soil types (clay, peat and sand), soil water contents, grass heights, manure characteristics and weather conditions. Both cow manure and pig manure were used. All experiments were carried out on grassland with well-established and intensively managed swards. Perennial ryegrass (*Lolium perenne* L.) was the dominant species. Per experiment, NH_3 volatilization was measured on up to five comparable plots. Plots differed in application technique, application rate, type of manure applied or grass height. NH_3 volatilization from manure applied by surface spreading, narrow-band application and shallow injection was measured on a total of 47, 29 and 34 plots, respectively.

2.2.2 Application techniques

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

2.2.3 Manure

The experiments were carried out on dairy farms. The cow manure used had been produced on these farms. Pig manure was imported from pig farms. The plots of an experiment received manure in the morning and at about the same time to reduce the effects of changes in soil and weather conditions on NH_3 volatilization. The manure was applied on circular plots with a radius varying from 20 to 24 m. These plots were created by applying the manure over a pre-marked area in parallel passes that varied in length (Figure 2.1). The amount of manure applied per plot was measured by weighing the manure tank before and after application. The average application rate was 14 m^3 ha^{-1} for surface spreading and narrow-band application, and 22 m^3 ha^{-1} for shallow injection. The higher application rate for shallow injection was in accordance with present-day practice.

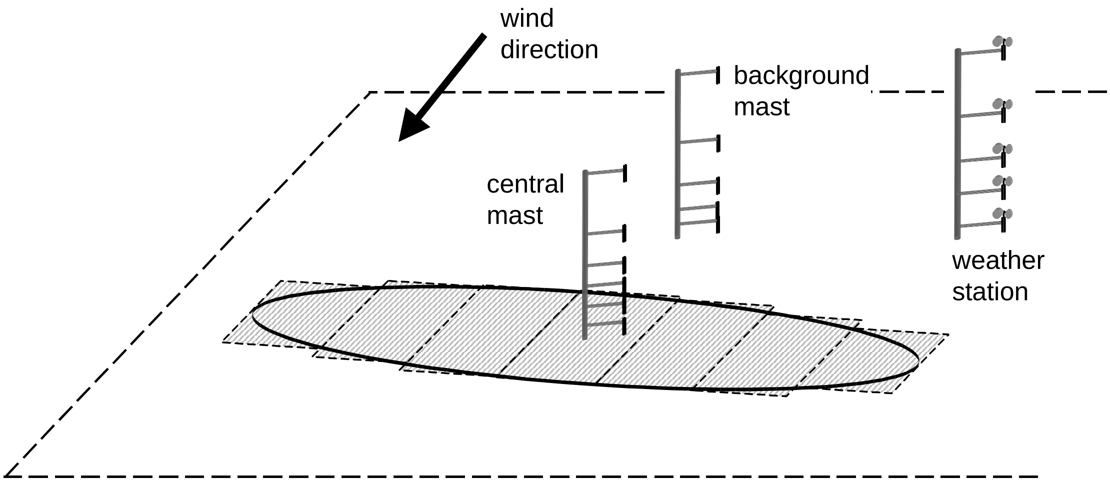


Figure 2.1. Lay out of circular plot (diameter about 50 m) for the measurement of NH_3 volatilization using the micrometeorological mass balance method, with masts supporting NH_3 traps at various heights in the centre of the plot and at the windward boundary of the plot.

At least three manure samples were taken from each tank load. The manure was analysed for pH, dry matter and TAN content. On average, the cow manure contained 2.15 g TAN kg^{-1} and 77 g dry matter per kg, and had a pH of 7. The data for the pig manure were 5.60 g TAN kg^{-1}, 101 g dry matter per kg, and pH 7.5.

2.2.4 NH_3 volatilization

The volatilization of NH_3 following manure application was determined per plot using the micrometeorological mass balance method (Denmead, 1983; Ryden & McNeill, 1984). Shortly after the manure had been applied to the first half of the plot - which usually was within 5 minutes after manure application had started - a mast supporting seven to eight NH_3 traps between 0.25 and 3.30 m above ground level was placed in the centre of each experimental plot (Figure 2.1). At the windward boundary of the plot another mast was placed with four to five NH_3 traps at heights between 0.40 and 2.30 m above ground level. At the boundary, fewer traps were used because the background concentration was low and independent of height. Each trap contained 20 cm^3 of 0.02 M HNO_3 held in 100-cm^3 collection tubes. Air was drawn through the acid solution *via* a stainless steel inlet tube with a perforated Teflon cap. The volume of air was measured with flow meters. Flow rate was 2 to 4 dm^3 per minute. Ion-chromatography and colorimetry were used to measure the NH_4^+ concentration in the solutions.

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

2.2.5 External factors

At the start of each experiment the soil of each plot was sampled for the determination of the soil moisture content. Prior to manure application, the plot's grass height was determined by measuring the height of a disc resting on the grass surface, above the soil surface. Weather conditions were recorded over the total measuring period of the NH_3 volatilization. Wind speed was measured on a mast outside the plot, at 6 heights from 0.40 to 3.30 m. Air temperature, relative humidity and global radiation were recorded by a weather station. These climatic data were recorded every 10 minutes. The data have been averaged over the duration of each interval that NH_3 volatilization was measured. The various data are presented in Table 2.1.

Table 2.1. Ranges of measured variables in data set for different manure application techniques.

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

[a] TAN, total ammoniacal nitrogen ($NH_4^+ + NH_3$).

2.2.6 Data analysis

Each experimental plot yielded an NH_3 volatilization-time profile, expressing the volatilization measured during each interval following manure application. The volatilization from an experimental plot can be expressed as the volatilization rate in the course of time (Figure 2.2A) or as the cumulative amount of NH_3 volatilized during consecutive measuring intervals. The cumulative volatilization is often expressed as the percentage of TAN applied with the manure (Figure 2.2B). The TAN applied results from multiplying the manure application rate (expressed as m^3 ha^{-1}) and the TAN content of the manure. The application rate varied for the

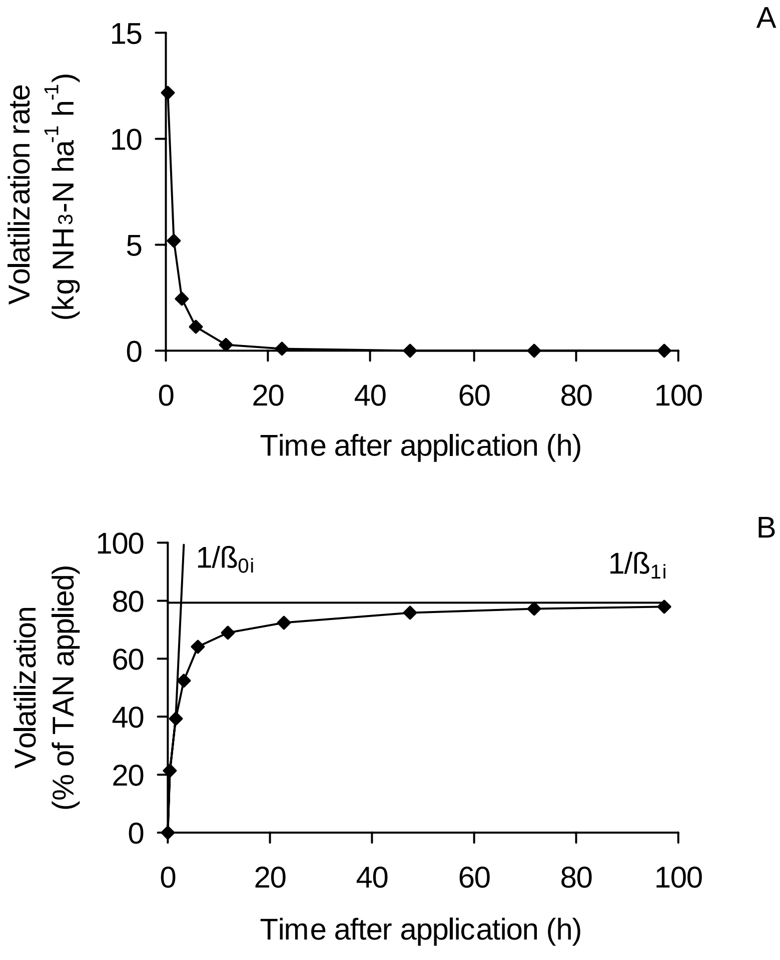


Figure 2.2. NH_3 volatilization from an experimental plot expressed as (A) the course of the volatilization rate and as (B) the calculated cumulative volatilization during the consecutive measuring intervals, with initial volatilization rate (slope, $1/\beta_{0i}$) and total cumulative volatilization (intercept on abscissa, $1/\beta_{1i}$). TAN, total ammoniacal nitrogen (NH_4^+ + NH_3).

different application techniques. Therefore, the cumulative volatilization percentage was used to compare application techniques between plots, assuming a linear relation between application rate and volatilization.

During the 96 hours of an experiment, the weather conditions could vary considerably. The volatilization rate varied with the time after application: after an initial peak, the rate gradually dropped (Figure 2.2A). Therefore, the effect of the factors that characterize the weather conditions was analysed by relating the magnitude of these factors to the NH_3 volatilization during each measuring interval. Each interval yielded a volatilization rate, expressed as kg NH_3-N ha^{-1} per hour. Compared with intervals immediately after manure application, later intervals differed in length and in time of the day, and thus in weather conditions. The volatilization rate during each interval is related to the weather conditions during that interval. By using the volatilization rate instead of the percentage of TAN applied - as used in the case of cumulative volatilization - the effect of TAN content and of manure application rate can be analysed separately. Furthermore, by using the volatilization rate per interval instead of the cumulative volatilization, one cause of the interdependence of response values (expressed as cumulative volatilization) was eliminated. However, because observations were made on the same plot and resulted from depletion of the same NH_3 source, interdependence of response values was not completely eliminated.

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

2.2.6.1 Application technique

The effect of the application techniques was analysed by using the cumulative volatilization profiles with volatilization expressed as the percentage of TAN applied. When analysing cumulative volatilization, the underlying assumption is that volatilization from the source, *i.e.*, the manure applied to the grassland, is completed at the end of the measuring period. The relation between cumulative volatilization and time can be described for each plot by asymptotic curves (Figure 2.2B). This type of saturation curve is usually described by the following equation:

$$\mu = t / (\beta_0 + \beta_1 t) \tag{2.1}$$

where μ is the expected value of the cumulative volatilization at time t, t the time lapsed since the manure was applied, β_0 the inverse of the slope of the curve at the start of the experiment, β_1 the inverse of the intercept of the asymptote on the ordinate of the curve.

$\mu = 1/\beta_1$ when t approaches infinity. The value of the parameters β_0 and β_1 depends on the manure application technique. Inclusion of the manure application technique and linearization of the equation by taking its reciprocal, results in the following equation:

$$1/\mu = \beta_{0i} / t + \beta_{1i} \tag{2.2}$$

where i is the index for the manure application technique.

Volatilization, and thus initial volatilization rate and total volatilization, will not only differ between techniques (i) but will also be influenced by external factors. The effect of these factors generates deviations in the values of the model parameters from estimated mean values. β_{0i} and β_{1i} are subject to variation between experiments (j). Within an experiment, weather conditions were considered equivalent, whereas random variation due to unknown sources was assumed to be the same for each experimental plot (k) (piece of grassland), where crop, soil and manure characteristics were the same. Therefore, Equation 2.2 can be extended to:

$$1/\mu = (\beta_{0i} + u_{0j} + v_{0k}) / t + (\beta_{1i} + u_{1j} + v_{1k}) \tag{2.3}$$

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

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

$$1/ y_{tijk} = (\beta_{0i} + u_{0j} + v_{0k}) / t + (\beta_{1i} + u_{1j} + v_{1k}) + e_{tijk} \tag{2.4}$$

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

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

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

2.2.6.2 External factors

The analysis of the effect of external factors on NH_3 volatilization at different intervals after manure application was carried out by modelling the volatilization rate during the different measuring intervals (Figure 2.2A). External factors included in the analyses were weather (wind speed, air temperature, relative humidity, radiation), soil type (sand, peat, clay), soil moisture content, type of manure (cow, pig), manure characteristics (TAN content, dry matter content, pH), application rate, and grass height. The interdependence of the response values owing to the observations being made in the same plot and resulting from depletion of the same NH_3 source, was partly overcome by explicitly incorporating the depletion of the NH_3 source into the model. Thus, for the volatilization rate z_{tk} at time t for plot k, the following equation was used:

$$\ln (z_{tk}) = \alpha_0 + \alpha_t \ln(t) + \sum \alpha_m x_{mt} + v_k \tag{2.5}$$

where x_{mt} is the value of external variable m at time t, and α_0 is a constant.

Random effects v_k account for interdependence of observations on the same field owing to unknown (other than variables tested for) sources. The depletion of the NH_3 source is represented by $\alpha_t \ln(t)$, assuming that the decrease of the size of the NH_3-source is continuous and exponential. The effects of the weather and other external factors (α_m) on the volatilization rate were assumed to be multiplicative, and thus additive on a logarithmic scale. Volatilization rates were analysed with REML, according to Equation 2.5. Wald tests (Payne *et al.*, 1993) were used for model selection to identify influencing (external) variables ($P <$ 0.05).

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

2.3 Results

2.3.1 Application technique

The cumulative NH_3 volatilization from surface-applied manure as measured over all experiments, varied from 27 to 98% of the TAN applied. With narrow-band application volatilization varied from 8 to 50%, and with shallow injection from 1 to 25% of the TAN applied (see Appendix 2.1). For all application techniques, volatilization was highest during the first hours after application. In the case of surface spreading, on average about 70% of the total measured volatilization took place during the first 3 hours. For narrow-band application and shallow injection this percentage was 30 on average.

In the statistical analysis the NH_3 volatilization following the different application techniques - expressed as the percentage of the TAN applied - was estimated for each technique as initial volatilization (slope $1/\beta_{0i}$, Figure 2.2B) and total cumulative volatilization (intercept $1/\beta_{1i}$, Figure 2.2B). Differences between the application techniques were large, both for the intercept (β_{1i}) and the slope (β_{0i}) of the linear model (Table 2.2). Total mean cumulative volatilization (of the TAN applied) was estimated to be 77% for surface spreading, 20% for narrow-band application and 6% for shallow injection. Thus, when 30 kg TAN ha^{-1} is applied (TAN content 2 g per kg manure, application rate 15 m^3 ha^{-1}), 23 kg TAN ha^{-1} would volatilize when manure is surface-spread and 6 kg ha^{-1} when manure is applied in narrow bands. Injecting 20 m^3 ha^{-1} would result in a volatilization of 2.4 kg TAN ha^{-1}.

In the statistical model about 50% of the variation of the NH_3 volatilization accounted for was explained by the application technique. The variation in model coefficients owing to differences among plots and differences among experiments (indexes *v* and *u* in Equations 2.3 and 2.4, respectively) contributed to the total variance, and could not therefore be neglected.

2.3.2 External factors

The effect of weather, field conditions and manure characteristics on NH_3 volatilization was statistically analysed using Equation 2.5. Wald tests were used

Table 2.2. Estimated coefficients for the reciprocals of initial volatilization (β_0) and total volatilization (β_1), and estimated mean volatilization ($1/\beta_1$) for the different manure application techniques.

Model parameter	Surface spreading	Narrow-band application	Shallow injection
β_0 [a]	0.010 (0.085)	0.385 (0.114)	1.227 (0.107)
β_1 [b]	0.013 (0.010)	0.051 (0.013)	0.155 (0.012)
Volatilization ($1/\beta_1$)	77	20	6

Standard errors in parentheses.

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

[b] (% of TAN applied)$^{-1}$.

for model selection to identify influencing variables per application technique. The analysis showed that volatilization of NH_3 was affected by the TAN content of the manure, the manure application rate and the parameters of the weather conditions (Table 2.3). These effects varied per application technique. Grass height affected NH_3 volatilization when manure was applied in narrow bands. No effect was found of the parameters soil type and soil moisture content. Type of manure, dry matter content and pH of the manure had no effect on the NH_3 volatilization rate either.

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

for surface spreading:

$$\ln z_t = \alpha_0 + \alpha_t \ln(t) + \alpha_1\, TAN + \alpha_2\, rate + \alpha_3\, wind + \alpha_4\, radiation \qquad (2.6a)$$

for narrow-band application:

$$\ln z_t = \alpha_0 + \alpha_t \ln(t) + \alpha_1\, TAN + \alpha_2\, rate + \alpha_3\, wind + \alpha_5\, temp + \alpha_6\, RH + \alpha_7\, gh \qquad (2.6b)$$

for shallow injection:

$$\ln z_t = \alpha_0 + \alpha_t \ln(t) + \alpha_1\, TAN + \alpha_2\, rate + \alpha_3\, wind + \alpha_4\, radiation + \alpha_5\, temp \qquad (2.6c)$$

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

Estimates of the (selected, statistically significant) model parameters and their standard errors are given in Table 2.3 for the different techniques. In the Equations 2.6a-c all predictors are corrected for their averages (Table 2.4).

The explained variation of the volatilization rate accounted for by external factors (Eqns 2.6a, 2.6b and 2.6c) was 46, 64 and 59% for surface spreading, band application and shallow injection, respectively.

With the models 2.6a, 2.6b and 2.6c the effects of changes in the values of influencing factors on the volatilization can be calculated. As the models are on a logarithmic scale, the ratio of two volatilization rates - when comparing two situations - can be calculated as the difference between the volatilization values for a single factor in the compared situations, keeping the other factors constant. The effect of differences between the values of a single factor on the relative NH_3 volatilization rate (expressed as the ratio of volatilization between the situations) can be derived from Figure 2.3. When the difference between the compared situations (value on abscissa) is 0, the ratio of the volatilization (value on ordinate) is 1.

Table 2.3. Regression coefficients for selected model variables of Equation 2.6 that affect the volatilization rate for the different manure application techniques.

Variable	Model parameter	Surface spreading		Narrow-band application		Shallow injection	
Constant	α_0	-1.08	(0.06)	-1.82	(0.07)	-2.42	(0.08)
Time	α_t	-1.20	(0.02)	-0.81	(0.03)	-0.66	(0.03)
TAN [a] content	α_1	0.25	(0.05)	0.31	(0.05)	0.23	(0.07)
Application rate	α_2	0.10	(0.02)	0.07	(0.01)	0.03	(0.01)
Wind speed	α_3	0.25	(0.02)	0.22	(0.04)	0.12	(0.03)
Radiation	α_4	0.0057	(0.0006)	n.s. [b]		0.0041	(0.0007)
Air temperature	α_5	n.s.		0.05	(0.01)	0.04	(0.01)
Relative humidity	α_6	n.s.		-0.018	(0.004)	n.s.	
Grass height	α_7	n.s.		-0.14	(0.03)	n.s.	

Standard errors in parentheses.

[a] TAN, total ammoniacal nitrogen ($NH_4^+ + NH_3$).

[b] n.s., not selected.

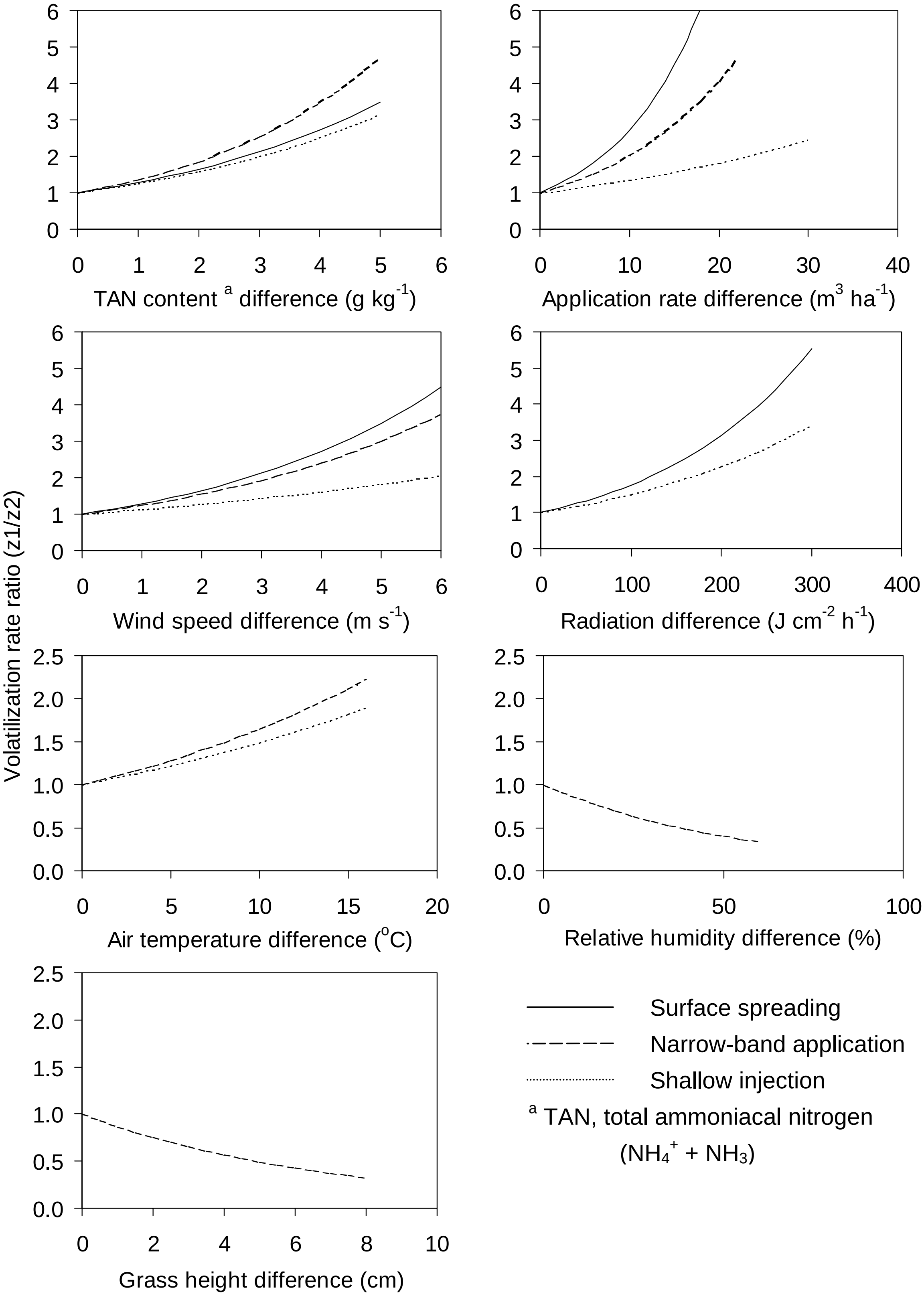
Table 2.4. Means of the selected model variables in Equation 2.6 that affect the volatilization rate for the different manure application techniques.

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

[a] TAN, total ammoniacal nitrogen (NH_4^+ + NH_3).

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

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



[a] TAN, total ammoniacal nitrogen ($NH_4^+ + NH_3$)

Figure 2.3. The ratio of calculated NH_3 volatilization rates (ordinate, z1/z2) for the three manure application techniques, in relation to differences between values of single external factors. The ratio equals 1 when the difference between values on the abscissa is 0.

An increase in the grass height led to lower NH_3 volatilization when manure was applied in narrow bands. With this technique a reduction of the grass height from 8 to 4 cm would be counterbalanced by a decrease in wind speed of 2.5 $m\ s^{-1}$ or by an increase in relative humidity of about 30%.

2.4 Discussion and conclusions

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

In this study, cumulative NH_3 volatilization from surface-applied manure varied from 27 to 98% of the TAN applied. With narrow-band application the volatilization varied from 8 to 50%, and with shallow injection from 1 to 25% of the TAN applied. With all application techniques the volatilization was highest during the first hours after application. Ammonia volatilization was significantly affected by the application technique. Compared with surface spreading, narrow-band application and shallow injection reduced NH_3 volatilization by 74% and 92%, respectively. A reduced contact area between the manure and the ambient air and a larger surface area for infiltration of the manure into the soil can account for this reduction. Amberger *et al.* (1987) found that volatilization is increased when manure is applied onto a stubble or onto crop residues on arable land, and explained this increase by a decreased infiltration into the soil and an increased contact area with the ambient air. In the present study, manure was surface-spread on top of the grass, which may have acted as a physical barrier against infiltration, whereas in the case of narrow-band application and shallow injection manure may have infiltrated easier due to the direct contact with the soil. Moreover, when surface-applied, manure has a relatively large contact area with the air; the manure mainly covers the grass. On the other hand, band application and shallow injection leave the manure only in contact with the air through a small band or *via* the opening of the injection slit, and smothering of grass leaves with manure is prevented. Shallow injection further restricts the contact of the manure with the ambient air by placing the manure into the soil.

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

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

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

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

The study showed no effect of soil type, soil moisture content, type of manure, dry matter content or pH of the manure on the NH_3 volatilization rate. The variation in these variables (Table 2.1) could explain why no effect was found. For example, from several studies it appeared that ammonia volatilization could be decreased by lowering the pH of the manure to values below 6 (Stevens *et al.*, 1989; Frost *et al.*, 1990; Stevens *et al.*, 1992; Bussink *et al.*, 1994). In the present study the pH of the manure was never lower than 6.8 (Table 2.1). No effect of the type of manure (cow, pig) was found. However, the pig manure had a higher TAN content than the cow manure and an increase in TAN content as such, increased NH_3 volatilization.

Generally, the NH_3 volatilization rate from applied manure is not linear with time but peaks the first hours after spreading (Figures 2.2 and 2.4). In agreement with Bussink *et al.* (1994), in the present study, the rate of NH_3 volatilization at the end of the experimental period (96 hours) was virtually zero. The experimental data therefore reflect qualitative effects and may be used quantitatively. The high initial volatilization rate is expressed in the analyses by the initial slope of the cumulative volatilization ($1/\beta_{0i}$) and by the depletion of the NH_3 source represented by $\alpha_i \ln(t)$ in Equation 2.6. Quantitatively, the impact of the weather conditions on volatilization following manure application will therefore be highest during the first hours after manure application. Information on factors influencing the size of volatilization may be lost if the cumulative volatilization is considered only at a certain time after application. Therefore, including the volatilization profile into the analysis yielded more insight into the volatilization process.

The factors causing variation between the experiments in the present study were analysed. Important external variables and the size of their effect on the NH_3 volatilization rate were identified. However, a relatively large part of the variation is caused by variation between experiments and between plots within experiments. Figure 2.4 presents the measured NH_3 volatilization in an experiment comparing the three application methods, together with the NH_3 volatilization predicted with the models, taking into account the manure characteristics, and the field and weather conditions in the experiment. Fitted values are the result of fixed and random effects. Figure 2.4 shows that predictions by the model show deviations

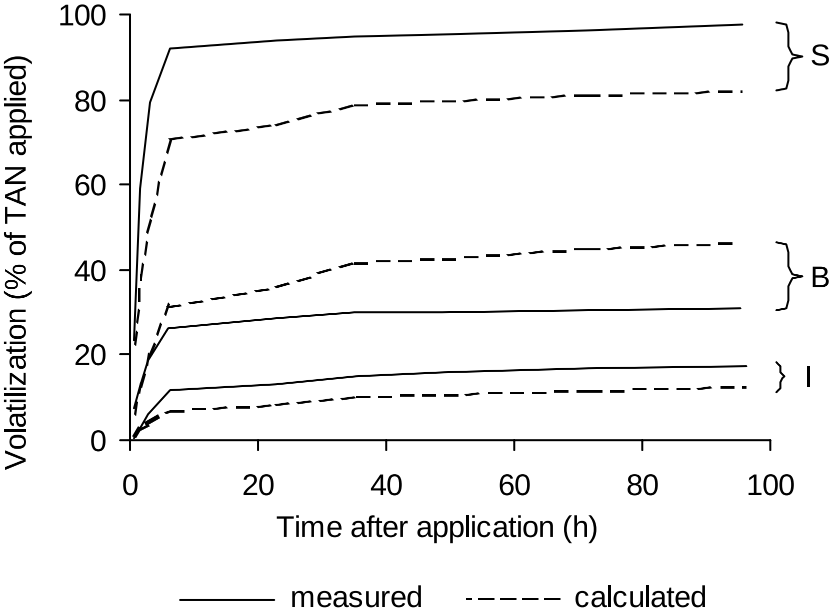


Figure 2.4. Measured NH_3 volatilization-time profiles and the calculated estimates of the NH_3 volatilization according to Equation 2.6 for an experiment in which the application techniques surface spreading (S), narrow-band application (B) and shallow injection (I) were compared. TAN, total ammoniacal nitrogen ($NH_4^+ + NH_3$).

from measured values. The measured NH_3 volatilization was 97% of the TAN applied in the case of surface spreading, 31% for narrow-band application and 17% for shallow injection. The predicted NH_3 volatilization for the three techniques was 82, 47 and 13% of the TAN applied, respectively. Differences between measured and predicted values are the result of random variation between plots. Further research with validation measurements could result in a model that can be used to improve the predictions of volatilization profiles, given a certain application method and known external conditions.

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

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Appendix 2.1

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

Exp. No	Year	Week	Application technique	Soil type [a]	Soil moisture content (%)	Grass height (cm)	Manure type [b]	TAN [c] content (g kg^{-1})	Application rate (m^3 ha^{-1})	Volatilization (% of TAN [c] applied)
1	89	13	I	S	-	6	1	3.3	26.8	3.6
			S	S	-	6	1	3.2	17.2	29.3
2	89	15	I	S	-	6	2	5.8	26.0	2.3
			S	S	-	6	2	6.0	10.0	27.3
3	89	27	I	C	-	6	1	2.8	14.0	10.9
4	89	28	I	C	-	6	2	5.3	15.4	5.7
			S	C	-	6	2	5.4	12.7	68.1
5	89	38	I	P	-	-	1	1.6	18.4	1.5
			S	P	-	-	1	1.6	15.4	66.1
6	90	11	S	C	37	-	1	3.3	16.3	43.2
			S	C	37	-	1	3.3	12.5	47.9
7	90	12	B	C	40	10	1	2.2	19.0	14.7
			B	C	45	10	1	2.2	6.6	12.0
			I	C	40	10	1	2.2	16.8	15.7
			S	C	40	10	1	2.2	19.7	47.7
8	90	17	I	P	61	6	1	2.2	17.8	8.9
			S	P	61	10	1	2.2	10.2	58.3
9	90	18	S	P	50	8	1	2.8	8.7	71.9
10	90	20	B	C	35	8	1	2.2	17.3	31.4
			B	C	40	8	1	2.2	8.4	14.6
			I	C	35	8	1	2.2	18.8	11.8
			S	C	35	8	1	2.2	16.1	64.3
11	90	22	I	P	42	10	1	2.3	18.2	11.3
			S	P	42	10	1	2.3	9.8	44.2
12	90	23	B	C	28	8	2	6.3	14.9	31.0 [d]
			B	C	28	8	2	6.3	7.9	16.1 [d]
			I	C	28	8	2	6.3	17.3	11.4 [d]
			S	C	28	8	2	6.3	17.5	67.4 [d]
13	90	24	I	S	-	8	1	2.3	22.2	3.9
			S	S	-	8	1	2.3	9.9	33.9
14	90	24	B	C	33	5	1	2.3	8.6	19.9
			B	C	33	5	2	6.4	8.8	32.0

Appendix 2.1 (continued)

Exp. No	Year	Week	Application technique	Soil type [a]	Soil moisture content (%)	Grass height (cm)	Manure type [b]	TAN [c] content (g kg^{-1})	Application rate (m^3 ha^{-1})	Volatilization (% of TAN [c] applied)
			S	C	33	5	1	2.3	8.3	61.2
			S	C	33	5	2	6.4	8.6	49.5
15	90	25	S	C	25	6	1	2.4	8.8	84.5
16	90	26	I	S	-	8	1	2.4	25.0	9.3
			S	S	-	8	1	2.3	9.8	51.0
17	90	27	S	P	50	9	1	2.2	8.7	58.4
18	90	29	S	C	19	7	1	2.3	8.7	43.7
19	90	30	S	C	19	8	1	2.2	8.6	83.5
20	90	31	S	C	22	8	2	3.5	8.4	66.2
21	90	35	S	P	58	8	1	2.0	12.7	52.0
22	90	36	I	P	48	10	1	2.3	15.1	4.9
			S	P	48	10	1	2.3	9.6	49.7
23	91	15	B	C	34	6	1	1.9	10.7	21.7
			B	C	34	12	1	1.9	10.6	10.6
			S	C	34	6	1	1.9	16.2	80.1
			S	C	34	12	1	1.9	15.3	64.7
24	91	16	B	C	24	6	2	5.0	12.0	14.9
			B	C	24	12	2	5.0	10.6	8.5
			S	C	24	6	2	5.0	16.3	73.7
			S	C	24	12	2	5.0	15.2	84.9
25	91	24	B	C	28	6	1	1.8	24.6	37.7
			S	C	28	7	1	1.8	13.0	97.7
26	91	29	S	C	21	6	1	1.5	9.8	96.7
27	91	30	S	C	24	7	1	1.6	14.0	70.8
28	91	36	S	C	14	9	1	2.5	16.4	67.8
29	92	11	S	C	39	7	1	2.1	17.3	86.2 [d]
30	92	12	S	C	34	7	1	2.2	17.6	84.8
31	92	16	I	C	40	6	1	1.8	19.1	5.2
			I	C	40	11	1	1.8	17.9	2.8
			I	C	40	6	1	1.8	19.2	3.8
			S	C	40	6	1	1.8	18.7	57.2
32	92	17	B	P	67	6	1	2.6	13.5	30.1
			B	P	67	11	1	2.6	14.0	11.9
			S	P	67	6	1	2.6	24.9	66.0
33	92	21	S	C	31	8	1	2.0	11.6	87.7
34	92	25	I	C	29	7	1	2.0	15.6	9.9
			I	C	29	7	1	2.0	20.6	15.2

Appendix 2.1 (continued)

Exp. No	Year	Week	Application technique	Soil type [a]	Soil moisture content (%)	Grass height (cm)	Manure type [b]	TAN [c] content (g kg^{-1})	Application rate (m^3 ha^{-1})	Volatilization (% of TAN [c] applied)
			I	C	29	7	1	2.0	30.8	14.1
			I	C	29	7	1	2.0	31.3	15.8
35	92	26	B	C	25	6	1	2.1	28.1	50.3
			B	C	25	6	1	2.1	27.1	38.2
			B	C	25	6	1	2.1	15.0	42.9
			B	C	25	6	1	2.1	13.6	39.5
			S	C	25	6	1	2.1	13.7	78.1
36	92	27	S	P	42	5	1	2.3	13.6	97.5
			B	P	42	5	1	2.3	16.2	30.9
			B	P	42	7	1	2.3	11.5	28.6
			I	P	42	5	1	2.3	17.1	17.3
			I	P	42	5	1	2.3	18.9	24.5
37	92	28	S	P	50	7	1	2.3	14.6	91.2
38	92	35	S	P	62	8	1	2.0	15.5	92.0
39	92	38	I	C	24	9	1	2.0	25.0	3.4
			I	C	24	9	1	2.0	17.8	3.9
			S	C	24	9	1	2.0	16.3	87.3
40	93	10	S	C	38	4	1	2.2	17.9	71.1
			S	C	38	4	1	2.2	18.5	71.9
41	93	11	B	C	34	6	1	2.1	10.4	37.5
			B	C	34	6	1	2.1	10.3	38.1
			B	C	34	6	1	2.1	11.6	34.6
			B	C	34	6	1	2.1	10.0	37.4
			S	C	34	6	1	2.1	15.1	68.9
			S	C	34	6	1	2.1	15.8	66.7
42	93	12	S	C	33	5	1	2.1	19.4	81.2
			S	C	41	7	1	2.1	19.0	95.2
43	93	18	I	C	29	7	1	1.6	18.5	7.1
			I	C	29	7	1	1.6	17.5	19.0
			I	C	29	7	1	1.6	17.8	25.1
			I	C	29	7	1	1.6	20.8	18.6
44	93	21	I	C	24	8	1	2.0	20.2	7.1
			I	C	24	8	1	2.0	19.5	8.5
			I	C	24	8	1	2.0	19.8	8.9
			I	C	24	8	1	2.0	32.7	16.6
			I	C	24	8	1	2.0	45.5	10.3
			I	C	24	8	1	2.0	44.2	8.3

Appendix 2.1 (continued)

Exp. No	Year	Week	Application technique	Soil type [a]	Soil moisture content (%)	Grass height (cm)	Manure type [b]	TAN [c] content (g kg^{-1})	Application rate (m^3 ha^{-1})	Volatilization (% of TAN [c] applied)
45	93	22	B	C	28	9	1	2.0	14.4	17.0 [d]
			B	C	28	9	1	2.0	15.7	16.1 [d]
			B	C	28	9	1	2.0	14.8	11.1 [d]
			B	C	28	9	1	2.0	15.5	13.0 [d]

[a] S, sand; P, peat; C, clay.

[b] 1, cattle manure; 2, pig manure.

[c] TAN, total ammoniacal nitrogen (NH_4^+ + NH_3).

[d] Measured cumulative volatilization 72 hours after manure application.

3

Effect of application method, manure characteristics, weather and field conditions on ammonia volatilization from manure applied to arable land

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Abstract

To predict ammonia (NH_3) volatilization from field-applied manure, factors affecting volatilization following manure application need to be known. A database of field measurements in the Netherlands was analysed to identify these factors and to quantify their effects on the volatilization of NH_3 from liquid pig manure applied and incorporated on arable land. The combination and the statistical analysis of these data, together with the models that were designed, yielded valuable information about the factors that influence NH_3 volatilization, and about the magnitude of their effects when applying and incorporating manure on arable land. Factors analysed were application method, characteristics of the manure, weather and field conditions.

The mean total volatilization, expressed as % of the total ammoniacal nitrogen (TAN) applied, was 68% for surface spreading, 17% for surface incorporation and 2% for deep placement. The volatilization rate increased with an increase in TAN content of the manure, manure application rate and air temperature. Wind speed had a substantial effect on the volatilization rate, only when manure was surface applied or surface incorporated.

The results show that useful prediction of ammonia volatilization following manure application on arable land in the Netherlands is feasible on the basis of information about application method, characteristics of the manure and weather conditions.

Keywords: ammonia volatilization, model, application technique, incorporation technique, arable land, manure characteristics, weather conditions, field conditions

3.1 Introduction

The reduction of ammonia (NH_3) volatilization is a major issue in many countries to prevent environmental pollution by ammonia deposition (ECETOC, 1994; IPPC, 1996). Especially, the reduction of NH_3 volatilization from field-applied manure draws attention, because this source contributes largely to the overall NH_3 volatilization from livestock production. Furthermore, NH_3 volatilization from field-applied manure is a direct loss of nitrogen fertilizer and by technical measures reduction of NH_3 volatilization after manure application seems easily attainable at relatively low costs.

The application technique for liquid manure on grassland substantially affects the NH_3 volatilization (Huijsmans *et al*., 1997 and 2001; Lorenz & Steffens, 1997). Manure application by a shallow injector or band spreader considerably reduces NH_3 losses compared to broadcast surface spreading.

On arable land, incorporation of broadcast-applied manure or injection of the manure into the soil are effective measures to reduce ammonia volatilization (Hoff *et al*., 1981; Brunke *et al*., 1988; Horlacher & Marschner, 1990; Van Der Molen *et al*., 1990; Amberger, 1991; Huijsmans, 1991; Ismail *et al*., 1991; Søgaard *et al*., 2002).

NH_3 volatilization from field-applied manure may be affected by weather conditions, manure characteristics, soil conditions and crop cover (Brunke *et al*., 1988; Sommer *et al*., 1991; Bussink *et al*., 1994; Braschkat *et al*., 1997; Huijsmans *et al*., 2001; Søgaard *et al*., 2002). However, relatively little attention has been paid to these factors in combination with the application method of manure on arable land.

Knowledge of the effect of these factors in combination with the application method can be decisive for an efficient strategy to reduce NH_3 volatilization. Therefore, a study was initiated with the objective to quantify the effect of factors that influence NH_3 volatilization following liquid manure application on arable land, and to assess the volatilization for various circumstances. The present study comprises the analysis of a complete database of field records in the Netherlands. Factors considered are *application method, weather conditions*, *manure characteristics*, *soil type*, *soil moisture content* and *stubble height*.

3.2 Materials and methods

NH_3 volatilization records in the Netherlands were available from 25 field experiments on various locations with a total of 58 experimental plots on arable land (see Appendix 3.1). Per experiment, NH_3 volatilization was measured on up to five comparable plots. Different application methods were compared in 15 experiments (48 plots). In 10 experiments only the reference technique (surface spreading) was used (10 plots). The reference technique was included in all experiments. The experiments were conducted in the period March-September of 1990-1998, assuming that experimental circumstances in this period were representative for the Netherlands. The experiments included various application techniques, incorporation techniques, soil types (sand, sandy loam and clay), soil water contents, stubble heights, manure characteristics and weather conditions.

3.2.1 Techniques of application

Ten different application techniques or incorporation techniques were used in the experiments. The number of volatilization records per technique (Table 3.1) was insufficient to allow analysis of the effect of each technique. However, the techniques could be suitably grouped into three application methods, based on their positioning of the manure on or into the soil:

- surface spreading
- surface incorporation
- deep placement

3.2.1.1 Surface spreading

Surface spreading was carried out with a tanker fitted with a splash-plate. The manure was pumped through an orifice onto a splash-plate from where it was spread onto the soil. The net working width was about 8 m.

3.2.1.2 Surface incorporation

Surface incorporation was defined as the treatment by which manure was surface spread and, subsequently, incorporated into the soil. Conventional tillage implements (cultivators with rigid tines, spring tines, discs, or harrows) were used to incorporate the surface-applied manure into the topsoil directly following the surface spreading.

Table 3.1. Number of observations for the various application techniques and incorporation techniques on different soil types.

Method	Principle used	Number of observations			
		Sand	Sandy loam	Clay	Total
Surface spreading	Splash plate	*5*	*10*	*11*	*26*
Surface incorporation	Rigid tine cultivator	1	1	2	4
	Disc harrow (medium duty)		2		2
	Spring tine cultivator + roller		3	1	4
	Spring tine cultivator + clodbreaker		2	2	4
	Disc harrow + rigid tine cultivator (medium duty)	3	2	2	7
	Dyna-drive	1	1		2
	Driven rotary harrow	1		1	2
	Subtotal	*6*	*11*	*8*	*25*
Deep placement	Mouldboard plough	2		1	3
	Injector		2	2	4
	Subtotal	*2*	*2*	*3*	*7*
Total		13	23	22	**58**

3.2.1.3 Deep placement

Deep placement was defined as the treatment by which the manure was buried in the soil, either directly by an injector or indirectly by ploughing with a mouldbourd plough directly after surface spreading. The arable land injector was equipped with spring tines, which placed the manure directly underneath the soil surface at a depth of 15 to 20 cm. At the same time the injector carried out a tilling operation by covering the manure with soil.

3.2.2 Characteristics of the manure, the weather conditions and the field

In all experiments liquid pig manure was applied on bare arable land or arable land with a wheat stubble. Pig manure was imported from pig farms. The amount of manure applied per plot was measured by weighing the manure tank before and after application. Manure samples were taken from each tank load to determine the content of dry matter and of total ammoniacal nitrogen (TAN) of the manure (Table 3.2). On average, the application rate was 24 m^3 ha^{-1} and the manure contained 4.5 g TAN kg^{-1} and 85 g dry matter per kg. At the start of each experiment the top soil (upper 5 cm) of each plot was sampled for the determination of the soil moisture content. Prior to manure application, the plot's stubble height was determined by measuring the height above the soil surface of a disc resting on the stubble. Weather conditions were recorded over the total measuring period of an experiment. Wind speed was measured on a mast outside the plot, at 6 heights from 0.40 to 3.30 m. Air temperature, relative humidity and global radiation were recorded by a weather station. These climatic data were recorded every 10 minutes. The data have been averaged over the duration of each interval that NH_3 volatilization was measured. The means and range of the various data are presented in Table 3.2.

Table 3.2. Means and ranges (in parentheses) of various characteristics of the conditions during the experiments.

Variable	Surface spreading	Surface incorporation	Deep placement
TAN [a] content (g kg^{-1})	4.4 (2.4 - 6.1)	4.6 (2.8 - 6.1)	4.9 (2.8 - 6.1)
Application rate (m^3 ha^{-1})	22 (14 - 39)	25 (12 - 43)	27 (19 - 38)
Wind speed (m s^{-1})	4.1 (0.5 - 8.6)	3.9 (0.5 - 8.7)	3.5 (0.5 - 7.6)
Radiation (J cm^{-2} h^{-1})	194 (5 - 649)	165 (0 - 524)	125 (6 - 349)
Air temperature (°C)	14 (0 - 34)	14 (5 - 25)	13 (7 - 26)
Relative humidity (%)	78 (22 - 100)	81 (55 - 100)	82 (58 - 98)
Stubble height (cm)	5 (0 - 16)	7 (0 - 16)	6 (0 - 12)
Soil moisture content (%)	8 (9 - 26)	18 (9 - 29)	15 (10 - 21)
Dry matter content of manure (g kg^{-1})	86 (55 - 153)	83 (55 - 136)	89 (64 - 107)

[a] TAN, total ammoniacal nitrogen (NH_4^+ + NH_3) at time of application.

3.2.3 Set-up of the experiments

The volatilization of NH_3 following manure application was determined per plot using the micrometeorological mass balance method (Denmead, 1983; Ryden & McNeill, 1984) as applied by Huijsmans *et al*. (2001). The plots of an experiment received manure in the morning and at about the same time to reduce the effects of changes in soil and weather conditions on NH_3 volatilization in the course of the day. The manure was applied on circular plots with a radius varying from 20 to 24 m. Shortly after the manure had been applied (and incorporated) on the first half of the plot – which usually was within 5 minutes after manure application or incorporation had started – a mast supporting 7 to 8 NH_3 traps between 0.25 and 3.30 m above ground level was placed in the centre of each experimental plot. At the windward boundary of the plot another mast was placed with 4 to 5 NH_3 traps at heights between 0.40 and 2.30 m above ground level. At the boundary of the plot, fewer traps were used because the background concentration was low and independent of height. Each trap contained 20 cm^3 of 0.02 M HNO_3 held in 100-cm^3 collection tubes. Air was drawn through the acid solution *via* a stainless steel inlet tube with a perforated Teflon cap. The volume of air was measured with flow meters. Flow rate was 2 to 4 dm^3 per minute. Ion-chromatography and colorimetry were used to measure the NH_4^+ concentration in the solutions.

Measurements continued for 96 h after manure was applied. During the first 12 h – when the rate of NH_3 volatilization was highest – traps were replaced 4 to 5 times. Further replacement took place every morning for the following 4 days. The amount of NH_3 volatilized during each interval was calculated from the amount of NH_3 trapped and the airflow data.

3.2.4 Data analysis

Two approaches were followed for analysis of the data. The first approach concentrated on statistical modelling of the cumulative volatilization by means of asymptotic curves to describe the NH_3 volatilization in the period following application (Figure 3.1A). The second approach focussed on modelling of the volatilization rate at a certain time after application (Figure 3.1B).

The first approach was used to analyse the effect of the method of application on total volatilization (expressed as % of TAN applied with the manure). Because some influential factors, such as the weather conditions, varied considerably during the 96 h of the experiment, the first approach was less suitable for analysis of the effect of these factors on the volatilization.

The second approach allowed for utilizing the measured characteristics of the weather conditions per measuring interval as explanatory variables in a statistical

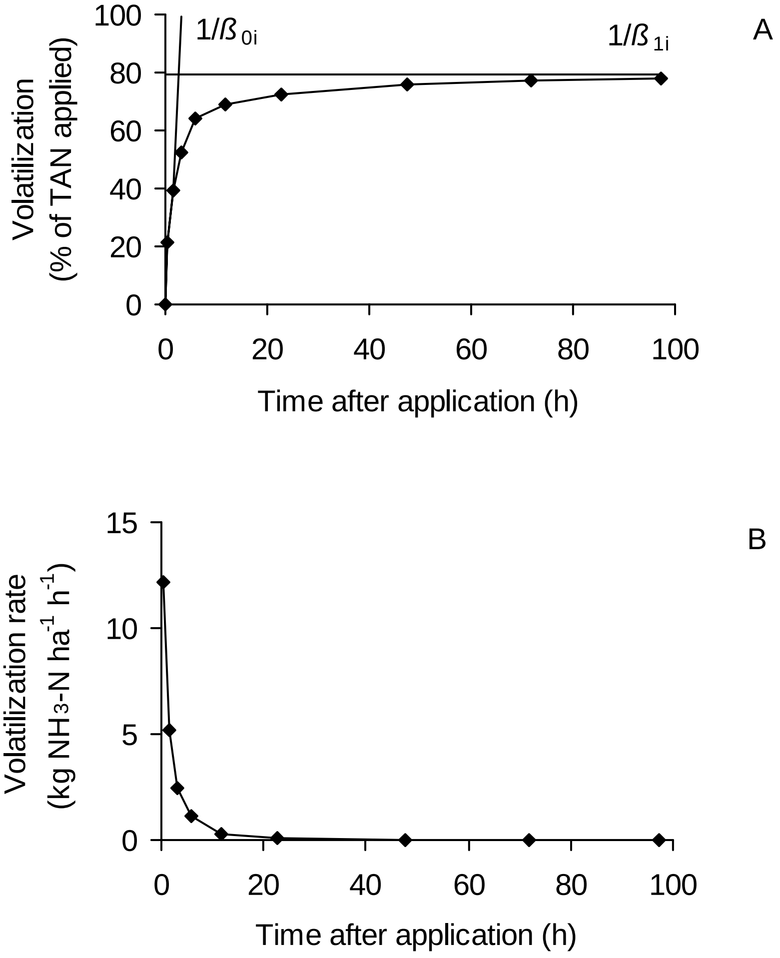

Figure 3.1. The NH_3 volatilization from an experimental plot expressed as (A) the calculated cumulative volatilization during the consecutive measuring intervals with the initial volatilization (slope $1/\beta_{0i}$) and the total cumulative volatilization (intercept, $1/\beta_{1i}$,), and as (B) the time-course of the volatilization rate.

model for the volatilization rate (expressed as kg NH_3-N ha^{-1} h^{-1}). The second approach also allowed for inclusion into the model of the change in characteristics of soil and manure in the period after application, that may be related to the observed decline in volatilization with time. As the change in TAN content of the manure (depletion of the source due to volatilization) could be calculated from the data, the adjusted total ammoniacal nitrogen content (ATAN) was used in the analysis. Other data on changes in characteristics of the manure or the soil, such as TAN lost from the available pool by infiltration, adsorption or biochemical changes, were not available.

In both approaches, due to the unbalanced nature of the dataset, the residual maximum likelihood (REML) procedure of Genstat (Payne *et al*., 1993), specifically intended to better deal with unbalanced experimental designs, was used for statistical analysis.

3.2.4.1 Statistical analysis of the cumulative NH_3 volatilization

Statistical analysis of the cumulative NH_3 volatilization was used to assess the effect of application techniques and incorporation techniques. The analysis was carried out on all experiments that included at least two different application techniques or incorporation techniques. Thus in total 48 cumulative volatilization profiles were analysed. Experiments with only the reference technique were excluded, because these experiments did not provide information about the comparison of techniques. The basis for modelling is a saturation curve, described by the following equation (Huijsmans *et al*., 2001):

$$\mu_i(t) = t / (\beta_{0i} + \beta_{1i}t) \qquad (3.1)$$

where $\mu_i(t)$ is the expected value of the cumulative volatilization at time t for treatment i, t the time lapsed since the manure was applied, β_{0i} the inverse of the slope of the curve for treatment i at the start of the experiment, β_{1i} the inverse of the intercept of the asymptote on the ordinate of the curve for treatment i.

Linearization of the equation, by taking its reciprocal, results in:

$$1/\mu_i(t) = \beta_{0i} / t + \beta_{1i} \qquad (3.2)$$

The REML procedure, with $1/t$ and treatment factor as fixed terms was used to estimate the treatment parameters (β_{0i} and β_{1i}) and the random effects (with ‘experiment’ as random term in both slope and intercept) in a linear mixed model (LMM). Weights (square of cumulative volatilization) were used to compensate for the fact that variance is not constant but increases with cumulative volatilization; the random intercepts and slopes were assumed to be positively correlated (high initial volatilization coinciding with high total volatilization).

The total cumulative volatilization of treatment i, when t approaches infinity, was calculated as $\mu_i = 1/\beta_{1i}$.

3.2.4.2 Statistical analysis of the NH_3 volatilization rate

Statistical analysis of the NH_3 volatilization rate during the various measuring intervals after application and incorporation of the manure was used to reveal the effects of application method, characteristics of the manure, characteristics of the weather conditions and characteristics of the field. The mean volatilization rate in a measuring interval was assumed to be the actual value at time *t*, being the time at the middle of the interval. The analysis was carried out on all experiments (58 plots and 503 measuring intervals).

The basic equation used to describe the logarithm of the volatilization rate of application method *k* $z_k(t)$ at time *t* after application is (cf. Huijsmans *et al.*, 2001):

$$\ln z_k(t) = \alpha_0 + F_k + \alpha_t \ln(t) + \Sigma\, \alpha_m x_{mt} \qquad (3.3)$$

where α_0 is a constant, F_k the model factor for application method, *t* the time lapsed since the manure was applied, α_t the coefficient for the term ln(*t*), α_m the coefficient for the term x_{mt}, x_{mt} the model term for explanatory variable m at time *t*.

The effect of application technique or incorporation technique on volatilization turned out to be strong, and was therefore included into the model. The logarithm of time after manure application was included in the model because the decline of the volatilization rate with time could not be fully explained from the change in NH_3 content (ATAN). Other factors considered for inclusion into the equation were weather conditions (wind speed, air temperature, relative humidity, radiation), soil type (sand, sandy loam, clay), soil moisture content, manure characteristics (ATAN content, dry matter content), application rate, and stubble height.

The REML procedure, with factors and terms as described in Eq. (3.3), and ‘experiment’ as random term, was used to estimate the constant and the coefficients of models with various explanatory variables. Wald tests (Payne *et al.*, 1993) were used for model selection to identify influencing variables that contribute significantly to the explanation of the experimentally-found volatilization rates ($P < 0.05$).

3.3 Results

3.3.1 Cumulative NH_3 volatilization

The cumulative NH_3 volatilization from surface-applied, surface-incorporated and deep-placed manure as measured over all experiments, varied considerably (see Appendix 3.1). Nevertheless, statistical analysis revealed that the application method had a very significant effect on the shape of the cumulative NH_3

volatilization curve. Both the intercept (β_{1i}) and the slope (β_{0i}) in the linear model for $1/\mu$ for surface incorporation and deep placement differed significantly ($P < 0.01$) from the parameters in the model for surface spreading (Table 3.3). Therefore, also major differences in initial volatilization rate ($1/\beta_{0i}$) and in total cumulative volatilization ($1/\beta_{1i}$) existed. The weighed mean of the total cumulative volatilization was estimated to be 68% for surface spreading, 17% for surface incorporation and 2% for deep placement (Table 3.3). For one experiment 99% of the variance in volatilization could be explained by differences in application method. For all the experiments 81% of the variance could be explained by differences in application method, indicating that the random effect of ‘experiment’ cannot be neglected.

3.3.2 NH_3 volatilization rate

Statistical analysis of the effect of the various factors that could explain the observed volatilization rates, using Eq. (3.3), revealed that the volatilization rate was significantly affected by the method of application and incorporation, the ATAN content of the manure, the manure application rate, the wind speed and the ambient temperature (Table 3.4). An interaction effect was found for wind speed and application method. The selected equation, in which only the significant factors were included, was:

$$\begin{aligned} \mathrm{E}\,(\ln z_k(t)) = {} & \alpha_0 + F_k + \alpha_t\, ln(t) + \alpha_1\, ATAN + \alpha_2\, rate \\ & + \alpha_3\, wind + \alpha_4\, temp + F_{kw}\, wind \end{aligned} \tag{3.4}$$

Descriptions, estimates and standard errors of the model parameters are presented in Table 3.4. The model used could explain 83% of the variance in the volatilization rate, excluding the variance in the ‘experiment’ *stratum*. When including the ‘experiment’ *stratum*, 92% of the variance could be explained, indicating that their is still some source of variation which cannot be explained by the factors included in the model.

Compared with the volatilization rate following surface spreading, the volatilization rate was lower for surface incorporation and much lower for deep placement of the manure. Both increases in the TAN content (initial ATAN) and in the application rate of the manure led to increases in the NH_3 volatilization rate. A higher temperature resulted in an increase of the volatilization rate. An increase in wind speed led to a substantial increase in volatilization rate, but only for surface spreading and surface incorporation. Wind speed had no significant effect for the deep placement method.

Table 3.3. Estimated coefficients for the reciprocals of initial volatilization (β_0), total volatilization (β_1) and estimated mean volatilization ($1/\beta_l$) for the different manure application techniques.

Model parameter	Surface spreading	Surface incorporation	Deep placement
β_0 [a]	0.064 (0.080)	0.319 (0.067)	1.464 (0.199)
β_1 [b]	0.015 (0.011)	0.057 (0.009)	0.546 (0.037)
Volatilization ($1/\beta_1$)	68	17	2

Standard errors in parentheses.

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

[b] (% of TAN applied)$^{-1}$.

The statistical model for the volatilization rate was used to calculate the effect on total NH_3 volatilization of the method of application and of incorporation, the effect of a change in wind speed from 2 to 5 m s^{-1}, of an increasing ambient air temperature from 10 to 20°C, of an increasing TAN content of the manure from 3 to 6 g kg^{-1}, and of an increase of the application rate from 15 to 30 m^3 ha^{-1}. Cumulative volatilization was calculated for 96 h, in 96 time steps, following the application or incorporation of the manure, starting with steps of 10 minutes and ending with a step of 6 h. In the calculations, sinusoid day-night fluctuations of wind speed and of air temperature were estimated as a function of their 24 h-average values, from the data recorded during the first 24 h after manure application. These estimated day-night fluctuations were further assumed to occur in the next 72 h of the experimental period.

The results of the calculations of the effect of wind speed and air temperature on the volatilization (Table 3.5) show that surface incorporation and deep placement reduced the total NH_3 volatilization by on average 71 and 99%, respectively, compared with surface spreading. Increasing the mean wind speed from 2 to 5 m s^{-1} resulted on average in an 65% increase in total volatilization for surface spreading and 74% for surface incorporation, and in 5% decrease in total volatilization for deep placement. Likewise, increasing the mean ambient temperature from 10 to 20^{o}C resulted in increases in total volatilization of on average 54, 73 and 84% for surface spreading, surface incorporation and deep placement, respectively.

Table 3.4. Means and regression coefficients for the model parameters of Equation 3.4, that affect the volatilization rate $z_k(t)$ (kg ha^{-1} h^{-1}).

Parameter [a]	Description	Estimate or mean	Coefficient	Coefficient estimate
α_0	Constant	0.53 (0.16)		
F_k	Factor for application method:			
	Surface spreading	0.00 (0.00)		
	Surface incorporation	-1.53 (0.23)		
	Deep placement	-5.07 (0.35)		
ln(*t*)	Term for ln (time since application)	1.90	α_t	-0.71(0.03)
ATAN	Term for ATAN [b] (g kg^{-1})	3.55	α_1	0.33(0.06)
rate	Term for application rate (m^3 ha^{-1})	23.6	α_2	0.05(0.01)
wind	Term for wind speed (m s^{-1})	3.95	α_3	0.24(0.04)
temp	Term for air temperature (°C)	13.62	α_4	0.06(0.01)
F_{kw}	Interaction term for wind speed and method:			
	Surface spreading	0.00 (0.00)		
	Surface incorporation	-0.03 (0.05)		
	Deep placement	-0.26 (0.08)		

Standard errors of estimated values in parentheses.

[a] Terms and factors in the model represent the actual value minus their mean value.

[b] Actual total ammoniacal nitrogen (NH_4^+ + NH_3) at time *t*.

Calculations of the effect of the TAN content of the manure and of the application rate (Table 3.6) showed that surface incorporation and deep placement reduced the total NH_3 volatilization by on average 69 and 99%, respectively, compared with surface spreading. The increase in TAN content and application rate did not lead to significant increases of the volatilization, expressed as % of the TAN applied. However, the volatilization in kg ha^{-1} was increased with an increase of the TAN content and of the application rate.

Table 3.5. Predicted cumulative emission (% of TAN applied) after 96 h and its 95% approximate confidence interval [a] (in parentheses) for 3 application methods, for average temperatures of 10 and 20°C and average wind speeds of 2 and 5 m s^{-1}.

Atmospheric conditions [b]		Application method		
Temper-ature (°C)	Wind speed (m s^{-1})	Surface spreading	Surface incorporation	Deep placement
10	2	35.3 (26.5 - 44.3)	9.7 (6.8 - 12.6)	0.47 (0.32 - 0.63)
10	5	60.3 (47.5 - 74.3)	17.1 (12.2 - 22.1)	0.45 (0.30 - 0.59)
20	2	56.2 (43.9 - 69.7)	17.0 (12.0 - 22.0)	0.87 (0.58 - 1.15)
20	5	89.9 (74.0 - 109.2)	29.3 (21.4 - 37.4)	0.82 (0.55 - 1.09)

Predictions refer to a TAN content of 4 g kg^{-1} and an application rate of 20 m^3 ha^{-1}.

[a] The approximate confidence interval refers to a single measurement of the cumulative emissions on a random location and at a random time of measurement.

[b] Predictions include typical day-night fluctuations of temperature and wind speed.

3.4 Discussion and conclusions

The present study of factors affecting NH_3 volatilization following the application or incorporation of manure benefited from a unique set of data available from field experiments in the Netherlands. The combination and the statistical analysis of these data, together with the models that were designed, yielded valuable information about the factors that influence NH_3 volatilization, and about the magnitude of their effects when applying and incorporating manure on arable land. By focussing on the influencing factors, the information obtained has a high potential for practical application and for deepening the insight into the actual NH_3 volatilization following the application and incorporation of manure on arable land.

The cumulative NH_3 volatilization from surface-applied manure as measured over all experiments, varied from 34 to 100% of the TAN applied. With surface incorporation, volatilization varied from 3 to 49%, and with deep placement from 0 to 5% of the TAN applied (see Appendix 3.1). The effect of the method of application and incorporation on the volatilization was statistically analysed by using cumulative volatilization in Eq. (3.1) and by using volatilization rate in Eq. (3.3). Both analyses showed that the method of application and incorporation significantly affected the volatilization. Surface incorporation and deep placement reduced NH_3 volatilization by 75% and at least 95%, respectively, compared with surface spreading (Table 3.3). Calculation of the cumulative volatilization on the basis of Eq. (3.4) (Tables 3.5 and 3.6) showed comparable results *i.e.* mean reductions of *ca* 73 and 98% for surface incorporation and deep placement, respectively, compared with surface spreading.

NH_3 volatilization was significantly affected by the method of application or incorporation. A reduced contact area between the manure and the ambient air and a larger surface area for infiltration of the manure into the soil can account for the observed effect of surface incorporation and deep placement. Amberger *et al*. (1987) found that volatilization is increased when manure is surface-applied onto a stubble or onto crop residues on arable land, and explained this increase by a decreased infiltration into the soil and an increased contact area with the ambient air. The presence of a stubble had no effect in the present study; other (significant) factors were of more importance (Table 3.4). The contact area between the manure and the ambient air is more reduced by deep placement than by surface incorporation, and may therefore account for the lower volatilization compared to surface incorporation.

Table 3.6. Predicted cumulative emission (% of TAN applied) after 96 h and its 95% approximate confidence interval [a] (in parentheses) for 3 application methods, for a TAN content of the manure of 3 and 6 g kg^{-1}, and an application rate of 15 and 30 m^3 ha^{-1}.

Manure characteristics of application		Application method		
TAN (g kg^{-1})	Application rate (m^3 ha^{-1})	Surface spreading	Surface incorporation	Deep placement
3	15	56.5 (43.0 - 70.8)	15.6 (10.9 - 20.3)	0.6 (0.4 - 0.8)
3	30	62.1 (47.6 - 77.4)	17.5 (12.3 - 22.7)	0.7 (0.5 - 0.9)
6	15	55.8 (45.6 - 68.0)	18.6 (13.5 - 23.8)	0.8 (0.5 - 1.1)
6	30	60.1 (49.6 - 72.9)	20.6 (15.1 - 26.2)	0.9 (0.6 - 1.2)

Predictions refer to a wind speed of 3 m s^{-1} and a temperature of 15°C, on average [b].

[a] The approximate confidence interval refers to a single measurement of the cumulative emissions on a random location and at a random time of measurement.

[b] Predictions include typical day-night fluctuations of temperature and wind speed.

The NH_3 volatilization rate was affected by weather conditions. The study showed that with each of the techniques the NH_3 volatilization rate increased by weather conditions that favour drying, such as an increase in wind speed and in air temperature. Evaporation of water from the manure is known to lead to an increase of the aqueous NH_3 concentration in the manure and to an increase in NH_3 volatilization (Brunke *et al*., 1988; Horlacher & Marschner, 1990; Sommer *et al*., 1991). In this way, the decreasing contact area with the ambient air in the order: surface spreading, surface incorporation, deep placement may have restricted the volatilization in the same way as evaporation was decreased by restricting the contact area with the air. Therefore, wind speed had no effect for the deep placement method.

The increase of the NH_3 volatilization rate with increasing wind speed can be explained by an increase of the diffusion of NH_3. Volatilized NH_3 is removed by the wind, lowering NH_3 concentration in the air above the manure, stimulating further NH_3 volatilization (Freney *et al*., 1983).

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

The study showed no effect of soil type, soil moisture content and dry matter content of the manure on the NH_3 volatilization rate.

The NH_3 volatilization rate from applied manure decreased with time. In the model for the cumulative volatilization (Equation 3.1), the high initial volatilization rate is expressed by the initial slope of the cumulative volatilization curve ($1/\beta_{0i}$). In the model for the volatilization rate (Equation 3.4) the initial volatilization rate is high due to a relatively small negative value of the term $\alpha_t.\ln(t)$ (t is small) and a relatively high positive value of the term α_1.ATAN (low depletion of the NH_3 source). The terms for wind speed and temperature in Eq. (3.4) are independent of time. Therefore, transformed to the z_t scale, these factors have a constant relative effect on z_t. Thus, when z_t is highest, just after application, the effect of wind speed and temperature on volatilization is also high. Likewise, when z_t has become low at some time after application, the effect on volatilization is low. In conclusion, the impact of the atmospheric conditions on total volatilization is highest during the first few hours after application. Such information, on factors influencing the magnitude of volatilization during a certain period of the process cannot be utilized when expressing the cumulative volatilization as a function of time after application or incorporation only, like in Eq. (3.1). Therefore, analysis of the volatilization profile on the basis of the temporal volatilization rate is better suited for studies intended to gain insight into the volatilization process.

The present study shows that reduction of NH_3 volatilization can be achieved by incorporation of the manure into the soil and that the degree of reduction depends on the method of incorporation. Direct burying with a mouldboard plough (deep placement) yielded more reduction of NH_3 volatilization than incorporation by a rigid tine cultivator (surface incorporation). The present study does not account for the effect of a time-lag between surface spreading and incorporation on the NH_3 volatilization. On the experimental plots the manure was directly incorporated and the time-lag was minimal. However, in practice on whole field scale, direct incorporation is not always achievable. There will always be some time between surface spreading and incorporation and during this time volatilization of NH_3 from the surface-applied manure takes place. Huijsmans & De Mol (1999) showed in a model study that incorporation by a mouldboard plough does not always result in lower NH_3 volatilization than incorporation by a rigid tine cultivator. The model study of Huijsmans & De Mol (1999) showed that the time-lag between spreading and incorporation should be considered when assessing NH_3 volatilization from manure applied and incorporated on arable land. In case of deep placement by injection the time-lag is zero and low volatilization rates can be achieved, as shown in the present study.

The factors causing variation between the experiments in the present study and variation in volatilization rate within the period after application were analysed. Important factors were identified and their effect on the NH_3 volatilization rate was estimated (Table 3.4). Uncertainty remains about the predictions and subsequent calculations made with Eq. (3.4). This uncertainty is reflected by the relatively large confidence intervals of predictions of the total volatilization for a certain application method at a random location and a random point in time (Tables 3.5 and 3.6).

Further research, including the measurement of other factors that could better explain the volatilization process, could result in improved models, giving more precise predictions of volatilization profiles, given a certain application method and known conditions. Factors that came forward during this study as being possibly responsible for variation in cumulative emission results are differences between techniques in the positioning of the manure relative to the soil (within one method) and the soil structure (loose or compacted) at the moment of manure application and incorporation.

The NH_3 volatilization rate, $z(t)$, was analysed using a linear model for $\ln(z(t))$ with an assumed normal distribution of the residuals (Equation 3.4). Cumulative volatilization was estimated by calculating $z(t)$ the predicted values of $\ln(z(t))$, subsequent calculation of the volatilization per time interval, and summation of the values per time interval. The calculation of 95% confidence limits for new predictions of the cumulative volatilization was hampered by factors, such as dependency of the chosen time step increments and unrealistic upper boundary values for the cumulative volatilization. Some of these problems could be resolved by assuming that z(*t*) had normally-distributed residuals with a standard error approximately equal to z(*t*) times the standard error of ln(z(*t*)). It is recommended, however, to further study ways to estimate the variability of ln(z(*t*)), z(*t*) and the cumulative volatilization in a more precise way.

The study shows that NH_3 volatilization – field and weather conditions, and manure characteristics being equal – can be reduced considerably by incorporation (surface or deep) of the manure compared with surface spreading. Differences between conditions under which the application techniques are used can affect the overall reduction of NH_3 volatilization. In the Netherlands, incorporation of surface-applied manure was prescribed in the 1990s. In this period it also became forbidden to apply manure outside the growing season (autumn-winter period) on sandy soils. Before these prescriptions, surface spreading was common and manure was also applied outside the growing season. Conditions favouring volatilization are more often met in spring and summer than in autumn and winter. Therefore, when comparing the overall national annual NH_3 volatilization between the 1980s and the period from 1990 onwards, not only the application methods and incorporation methods used, but also the time of the year when manure was applied should be taken into account. Incorporation techniques reduce the volatilization compared to surface spreading, but since the 1990s more manure was applied under volatilization-favouring conditions. However, the present study shows, provided conditions for all application methods are the same, that prescribing or convincing farmers to inject or incorporate manure will help to control contamination of the environment following NH_3 volatilization from field-applied manure.

From the results of this study it can be concluded that application method or incorporation method, and external factors need to be taken into account when predicting NH_3 volatilization following manure application on arable land.

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Appendix 3.1

Overview of the experiments and the measured NH_3 volatilization after application and incorporation of manure.

Year	Week	Application technique[a]	Soil type[b]	Top soil moisture content (%)	Crop residue length (cm)	Manure TAN[c] content (g kg^{-1})	Manure dry matter content (g kg^{-1})	Application rate (m^3 ha^{-1})	Volatilization (% of TAN[c] applied)
1990	15	1	SL	*	0	2.8	6.40	29.2	37.6
		4	SL	*	0	2.8	6.40	31.7	20.2
		10	SL	*	0	2.8	6.40	37.8	1.9
1990	35	1	C	13	9	5.5	10.10	38.6	68.7
		5	C	13	9	5.5	10.10	42.8	19.6
		10	C	13	10	5.5	10.10	38.1	0.0
1990	37	1	C	18	10	6.1	8.60	21.4	46.9
		10	C	18	10	6.1	8.60	26.5	0.8
		5	C	18	10	6.1	8.60	21.5	13.8
		2	C	18	10	6.1	8.60	21.4	14.0
1990	38	1	S	12	8	5.5	8.82	17.9	80.4[d]
		2	S	11	8	5.5	8.82	18.3	31.3[d]
		8	S	13	8	5.5	8.82	17.8	9.1[e]
		9	S	10	9	5.5	8.82	19.2	4.6[e]
		1	C	17	10	5.3	8.20	22.0	95.4[e]
		2	C	17	9	5.3	8.20	24.5	48.5[d]
		8	C	16	11	5.3	8.20	22.6	22.9[d]
		9	C	16	12	5.3	8.20	22.9	1.7[e]
1990	39	1	S	*	10	4.9	9.71	20.4	68.0[e]
		1	C	*	0	5.0	8.65	22.6	66.3[e]
1991	13	1	C	16	0	4.1	7.60	18.2	54.2
		4	C	18	0	4.1	7.60	16.4	21.6
1991	14	1	C	26	0	3.9	7.80	14.4	56.9[d]
1991	18	1	C	15	0	4.1	9.36	13.6	78.2[e]
1991	36	1	C	18	0	2.4	6.03	18.8	41.1[d]
1991	37	1	SL	9	0	4.5	8.36	14.6	72.8
		5	SL	14	0	4.5	8.36	15.3	3.3
		6	SL	14	0	4.5	8.36	15.1	7.8
		2	SL	9	0	4.5	8.36	25.7	31.8
1991	38	1	SL	15	0	4.2	7.12	15.9	66.3
1992	10	1	S	14	0	4.5	9.78	19.0	62.1
		9	S	14	0	4.5	9.78	19.6	1.1

Appendix 3.1 (continued)

Year	Week	Application technique [a]	Soil type [b]	Top soil moisture content (%)	Crop residue length (cm)	Manure TAN [c] content (g kg^{-1})	Manure dry matter content (g kg^{-1})	Application rate (m^3 ha^{-1})	Volatilization (% of TAN [c] applied)
1992	14	1	SL	20	0	4.4	10.70	29.5	81.4
		6	SL	16	0	4.4	10.70	25.9	26.6
		7	SL	21	0	4.4	10.70	25.2	21.2
		5	SL	16	0	4.4	10.70	28.0	29.7
		10	SL	21	0	4.4	10.70	26.3	1.5
1992	19	1	SL	22	0	4.0	9.77	16.4	82.2
1992	20	1	SL	19	0	3.9	6.64	17.4	75.0
1992	24	1	SL	15	0	4.4	7.75	15.3	92.7
1992	37	1	SL	21	13	3.8	6.07	29.1	86.2
		3	SL	21	13	3.8	6.07	28.3	23.7
		3	SL	21	13	3.8	6.07	29.2	25.9
1992	38	1	S	19	13	3.9	5.58	28.7	93.2
		7	S	19	13	3.9	5.58	29.8	30.3
		6	S	19	13	3.9	5.58	29.3	21.2
1992	39	1	S	22	14	3.8	5.50	28.9	100
		6	S	22	14	3.8	5.50	30.2	33.5
		6	S	22	14	3.8	5.50	30.9	23.8
1993	15	1	SL	19	0	4.4	13.60	28.9	63.4
		1	SL	22	0	4.4	13.60	27.3	69.7
		4	SL	15	0	4.4	13.60	28.0	29.5
		4	SL	18	0	4.4	13.60	12.1	13.3
1993	17	1	C	19	0	4.6	15.30	15.7	33.9
1998	39	1	C	26	16	4.8	7.44	21.5	58.2
		6	C	25	16	4.8	7.25	22.0	20.8
1998	40	1	C	26	16	4.7	6.23	20.8	61.0
		6	C	29	16	4.7	6.22	19.8	34.0

[a] 1, Surface spreading splash plate; 2, Rigid tine cultivator; 3, Disc harrow (medium duty); 4, Spring tine cultivator + roller; 5, Spring tine cultivator + clodbreaker; 6, Disc harrow + rigid tine cultivator (medium duty); 7, Dyna-drive; 8, Driven rotary harrow; 9 Mouldboard plough; 10, Injector.

[b] S, sand; SL, sandy loam; C, clay.

[c] TAN, total ammoniacal nitrogen ($NH_4^+ + NH_3$).

[d] Measured cumulative volatilization 58 h after application.

[e] Measured cumulative volatilization 72 h after application.

4

Draught requirement of trailing-foot and shallow injection equipment for applying slurry to grassland

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Abstract

Surface spreading of slurry leads to the inevitable emission of ammonia into the environment. Injection of slurry on grassland reduces these emissions. However, injection of slurry by deep working injector tines with goose foot chisels (wings) requires high draught forces. This type of injection has the risk of the crop dying back under dry soil conditions and is not possible on all soil types. In recent years, new slurry application techniques for grassland have been developed that achieve a large reduction in emissions of ammonia, but require less draught force. These techniques include cutting a shallow slit in the sward, into which slurry is applied, and application of the slurry in bands on the soil surface using a trailing foot implement. In a series of experiments on sandy loam, clay and peat soils, the draught force requirement of single elements of five new slurry application techniques was investigated. The application techniques were a trailed sliding foot element and four shallow injection elements: angled-disc coulters (double-disc opener), thick-disc coulter, flat disc coulter followed by a vertical injection coulter and knife coulter followed by a vertical injection coulter. The application technique, working depth and soil conditions had a significant influence on the draught force. For a working depth of 5 cm, the required draught forces per shallow injector element, measured in this experiment, were in the range of 202-706 N for a double-disc opener, 284-991 N for a thick-disc coulter, 361-1260 N for a flat-disc coulter plus injector and 389-1358 N for a knife coulter plus injector. The lowest draught forces occurred on peat soil and the highest forces on dry clay. The trailing foot required an average draught force of 39 N. The draught force of the trailing foot did not relate to the soil conditions, but an effect of the grass sward condition was suggested.

4.1 Introduction

Surface spreading of slurry leads to the inevitable emission of ammonia into the environment. Injection of slurry on grassland reduces these emissions (Thompson *et al*., 1987). In addition, slurry injection on grassland has advantages compared with conventional surface spreading. The runoff from plots after application is less polluting when slurry is injected (Ross *et al*., 1979). Fodder quality improves with injection (Kemppainen, 1986) and, on pastures, the grazing behaviour of dairy cows after injection is normal (Pain & Broom, 1978). In comparison with surface-spreading, injection of slurry may improve nitrogen utilization due to reduced ammonia volatilization (Van Der Meer *et al*., 1987), reduces ammonia losses (Huijsmans *et al*., 1997) and reduces odour emissions (Philips *et al*., 1990).

These promising results were obtained by so-called deep injection. Deep injectors for grassland consist of hollow, rigid tines, equipped with lateral wings, with a tine spacing of usually 0.5 m. The wings lead to a better distribution of the slurry under the surface at a depth of 15 cm or more. Although efforts were made to improve the injection technique by tine design (Bosma *et al*., 1977; Godwin *et al*., 1989), some problems remained. Araya (1994) found an optimal chisel length of 25 cm for injectors and obtained draught force reduction by air injection. Larsen (1986) and Rees *et al*. (1992) recorded a reduction in herbage yield due to sward damage by the tines. Crop die-back along the injection slots and the imperfect closure of the injection slot were observed under dry grassland conditions (Warner *et al*., 1991) Furthermore, injection on permanent grassland is not possible on all soil types. Wadman (1988) estimated that only 33% of the grassland in the Netherlands is suitable for injection. Unsuitability was caused by the draught force requirement and crop damage along the slit on different soil types and the remains of wood trunks in the soils.

The increasing importance of reducing ammonia emissions and hence the restrictive ammonia policy of the Dutch government led to new band-spreading and injector designs, that avoid the disadvantages of deep injection but guarantee a slurry application with a minimum of ammonia volatilization. Compared with surface spreaders, these new techniques give a significantly lower ammonia volatilization (Huijsmans *et al*., 1997). Compared with the conventional deep injector, the new designs work less deeply and the soil underneath the sward is not cut horizontally owing to the absence of lateral wings mounted on the tines.

The new designs place the slurry into vertical shallow slits in the soil by an injector or apply the slurry in bands on the soil surface between the grass by a trailing foot. Compared with deep injection, the new techniques give less soil disturbance and hence draught requirement is expected to be lower.

The draught force requirement of the various types of new application techniques is not known. In this study, the draught force of five of these new application techniques was evaluated.

4.2 Experiments

4.2.1 Background

The forces acting on an injector tine are mainly cutting forces and frictional forces (Walter, 1994). Different injector designs and soil conditions lead to different cutting and frictional forces and, thus, to different draught forces. Bosma *et al*. (1977) measured draught forces of deep injection tines. Although the shallowest working depth was 10 cm and the element design was completely different from the techniques used in this study, the main factor of influence on draught force requirement was working depth, and draught depended on injector design and soil type. Warner & Godwin (1988) found a similar correlation between draught and working depth or injector design, respectively. The shallowest working depth in their study was 8 cm.

The new shallow injection designs differ in the way they cut and widen the narrow slit. The coulter design will affect the draught force. Little information is available on how draught force is affected by the coulter design when used on grassland. It is expected that rotating disc coulters will help to reduce draught requirement. Further, the draught force will be affected by the soil type (clay and organic matter content) and soil moisture content. A higher soil moisture content will result in a lower draught force requirement. This can be explained by the increasing plasticity of the soil when soil moisture content increases. Working depth of the injectors will affect the draught force. The draught force of the trailing foot design is expected to be independent of the soil type and moisture content since no slit is cut. In this study, the effect of five application techniques on the draught force requirement, under various soil conditions was evaluated.

4.2.2 Materials and methods

4.2.2.1 Application techniques

The various application techniques examined are shown in Figure 4.1; the four injectors (Figure 4.1a-d) cut a slit in the sward into which the slurry is applied and the trailed sliding foot (Figure 4.1e) applies the slurry in narrow bands on the soil surface between the grass.

Angled-disc coulters-double-disc opener (Figure 4.1a): The angled discs have a diameter of 410 mm, a width of 5 mm and are placed at an angle of 7^{o} with respect to each other. The coulters almost touch each other at the point where the

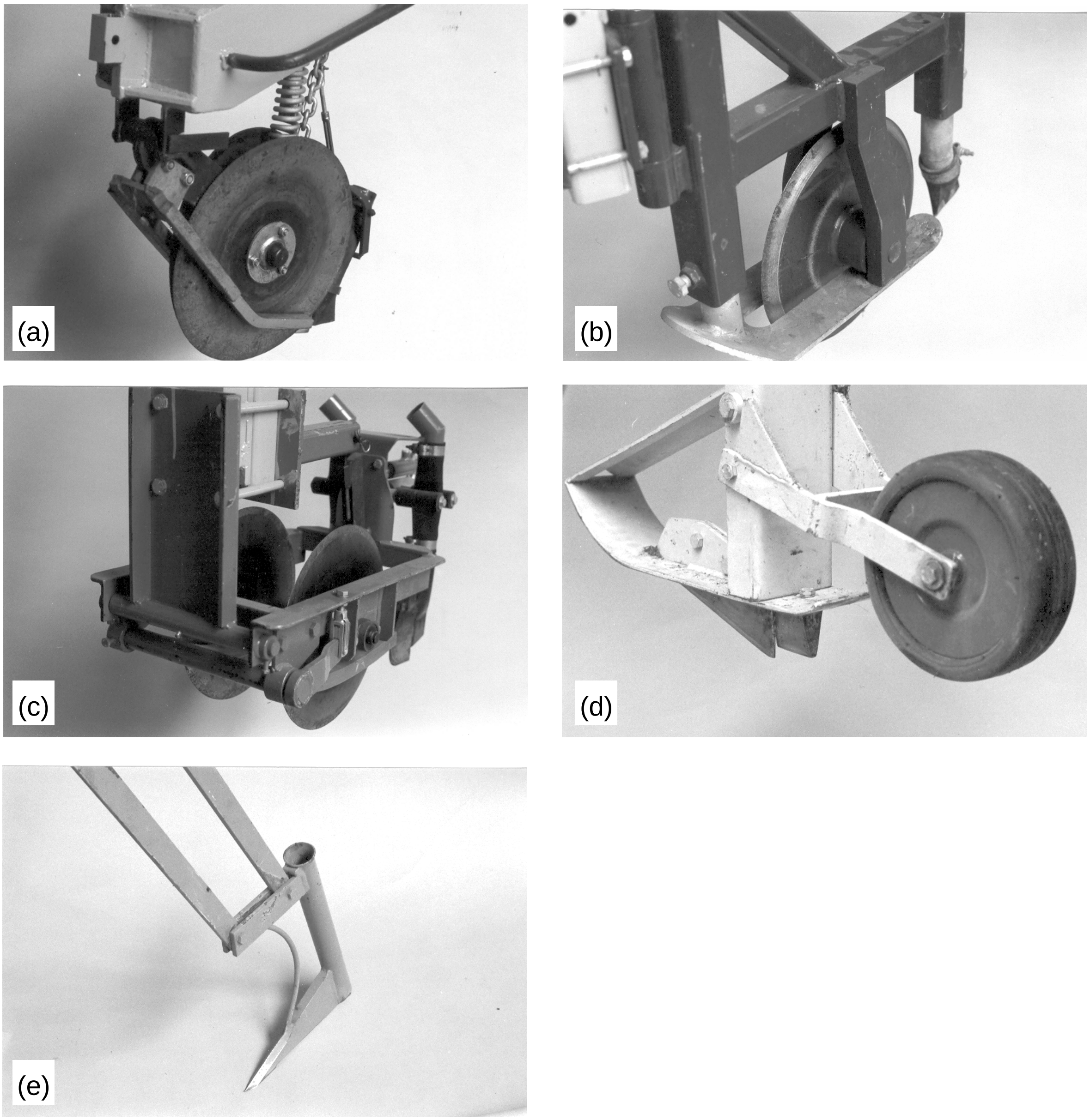

Figure 4.1. Application techniques: (a) Angled disc coulters (double-disc opener); (b) Thick-disc coulter; (c) Disc coulter followed by a vertical injection coulter; (d) Knife coulter followed by a vertical injection coulter; (e) Trailed sliding foot.

cutting of the sward begins. Due to this angle, the coulters leave a V-shaped slit into which the slurry is applied.

Thick-disc coulter (Figure 4.1b): The thick-disc coulter has a diameter of 340 mm. The thickness of the disc is 21 mm, tapering off at the periphery at an included cutting-edge angle of 49^o. The thick-disc coulter produces a 21 mm wide slit in one pass.

Disc coulter followed by a vertical injection coulter (Figure 4.1c): The disc coulter followed by a vertical injection coulter consists of a disc with a diameter of 400 mm and a width of 5 mm, and a coulter with a width of 24 mm. The disc cuts the sward and the coulter widens the slit to 24 mm. The working depth of the coulter is adjusted to approximately 5 mm less than that of the disc. In Figure 4.1c two elements are shown.

Knife coulter followed by a vertical injection coulter (Figure 4.1d): The knife coulter followed by a vertical injection coulter has no rotating parts. The sward is cut by a knife (length 200 mm, width 5 mm) with its cutting edge at a rake angle of 164^o. Attached to the knife is a flat plate, sliding over the grass sward, regulating the maximum working depth. The knife is followed by an injection coulter, which also widens the slit to 20 mm.

Trailed sliding foot (Figure 4.1e): The trailed sliding foot (also called sliding shoe) applies the slurry in bands on the soil surface. The rigid foot (length 370 mm, width 20 mm) slides on top of the soil surface, pushing the grass aside. At the back a hollow pipe is fitted vertically to the shoe and the slurry is released through this pipe. In this way, narrow bands of slurry with a width of about 30 mm are applied without covering the grass with slurry. The distance between the bands is 200 mm. The foot is kept in a horizontal position by a parallelogram construction.

4.2.2.2 Soil conditions

Measurements were carried out on three grassland sites with topsoils classified as sandy loam soil, heavy clay soil (Soil Survey Staff, 1975) and peat. The experiments were conducted during spring and summer, the periods in which slurry is applied in the Netherlands. Measurements were conducted on each soil type at three dates during the growing season, with the intention to meet the typical range of soil moisture conditions for slurry application. On each date, soil samples of the upper 10 cm soil layer were taken and dried (24 h, 105^oC) to determine the gravimetric soil moisture content.

On the sandy loam soil, the soil moisture content appeared to be 21% (mass/mass; dry base) at all three occasions, which is about at field capacity (pF2). Therefore, the data of the three dates were combined to one data set, representing one soil condition, here referred to as moist sandy loam. This soil condition may be regarded as typical for slurry application on sandy loam, but drier conditions may also occur in practise.

On the clay soil, the soil moisture content appeared to be 36% (mass/mass; dry base) on two dates and 20% on one of the dates. Therefore, the draught force data of the clay soil were arranged in two data sets representing two soil conditions, here referred to as moist clay (about at field capacity) and dry clay, respectively. These conditions may be regarded as typical in the range for slurry application, but wetter conditions may also occur in practise.

On the peat soil, the soil moisture content appeared to be 55% (mass/mass; dry base) at two occasions. This is very low compared with the (equilibrium) soil moisture content at pF2 (field capacity), which is about 100% for this soil. This feature was attributed to the fact that the previous winter was very dry. Because of the very slow water uptake of peat in a dry condition, the moisture content of the peat soil must have been far from equilibrium. In an attempt to realize more typical conditions for peat just after the winter, one plot was irrigated during three weeks preceding the draught measurements. The moisture content on this irrigated plot was 62% (mass/mass; dry base), which is still lower than usual. The draught force data of the peat soil were arranged in two data sets representing two soil conditions, here referred to as long-dry peat and irrigated long-dry peat, respectively. Wetter conditions may occur in practise. Analytical data of the soil, soil moisture content and the number of measurement runs per application technique for each soil condition are presented in Table 4.1.

Table 4.1. Analytical data of the soil, soil moisture content, number of measurement runs per injector and the range of working depths obtained for various soil conditions.

Soil conditions	Clay content (% m/m)	Organic matter content (% m/m)	Soil moisture content (% m/m; d.b.)	Number of runs	Working depth range (cm)
Moist sandy loam	12	4.5	21	37	2 - 11
Moist clay	44	7	36	5	4 - 8
Dry clay	44	7	20	15	1 - 7
Irrigated long-dry peat	25	55	62	8	5 - 10
Long-dry peat	25	55	55	17	2 - 9

4.2.2.3 Draught measurements

In the experiments, separate single elements were mounted on a measuring frame linked to a tractor. Horizontal draught force was measured with a frame with a parallelogram construction in which the element was mounted (Figure 4.2). A rigid measuring device with a load cell equipped with strain gauges connected the parallelogram to the front part of the frame, keeping the parallelogram in the vertical position. Horizontal draught force of the element was measured by the strain gauges and the analogue readings were recorded by a penwriter. During a measuring run draught force was continuously recorded over a length of 40 m.

The signal was sampled afterwards at 1 m intervals over the total run length. The working depth was measured with a sample interval of 2 m along the total run length, directly after each run. The working depth was determined by sticking a thin rod vertically through a steel plate, which was placed on the sward surface, until it reached the bottom of the slit. The working depth corresponded with the rod sinkage. The draught force and working depth per measuring run were calculated as the average of the measured values per run. All measuring runs were completely randomized over the experimental plot. Four to six measuring runs were carried out per element to realize a range of working depths. Implement support wheels were readjusted and weight was added or removed from the implement to achieve a range of working depths. The range of working depths obtained for each soil condition is presented in Table 4.1.

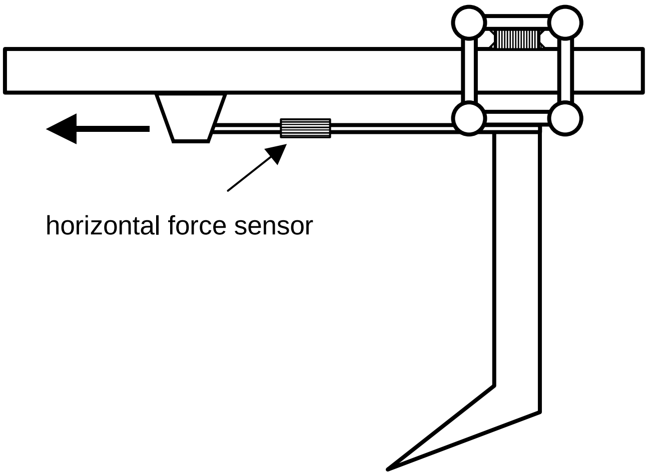

Figure 4.2. Draught force measuring frame.

4.3 Results

Four out of the five application techniques investigated concern injector type applicators that produce a slit in the grass sward. The working depth effects the required draught force of these injector type applicators. Because the working depth of the trailing foot system is zero by definition, the working depth plays no role for this applicator. Therefore, the draught force results of the injector type applicators and the trailing foot applicators were analysed separately.

4.3.1 Injector type applicators

The draught force and working depth results per measuring run are presented in Figures 4.3 - 4.5, for sandy loam, clay and peat soil respectively, each data point representing the result of one measuring run. Each figure shows the results of the four injection type applicators.

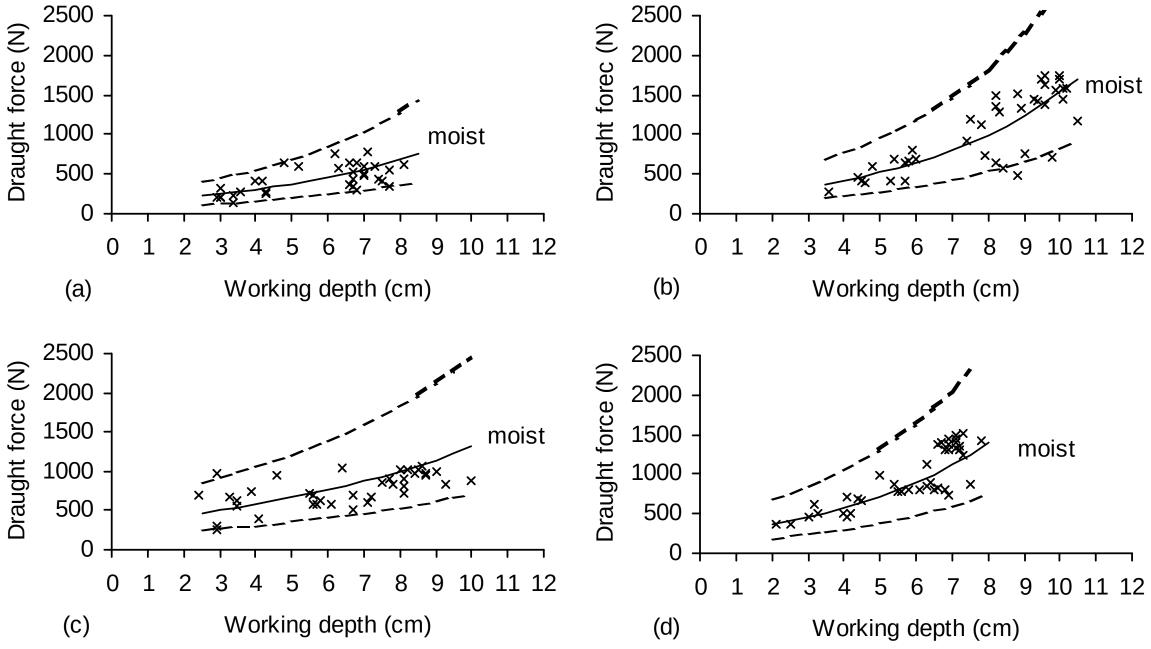

Figure 4.3. Measured and estimated draught forces per shallow injection technique for the sandy loam soil, with the lower and upper limits (dashed lines) of the confidence interval of the estimations (95%). x = moist soil; (a) Sandy loam, double disc opener; (b) Sandy loam, thick disc coulter; (c) Sandy loam, disc coulter followed by injection coulter; (d) Sandy loam, knife coulter followed by injection coulter.

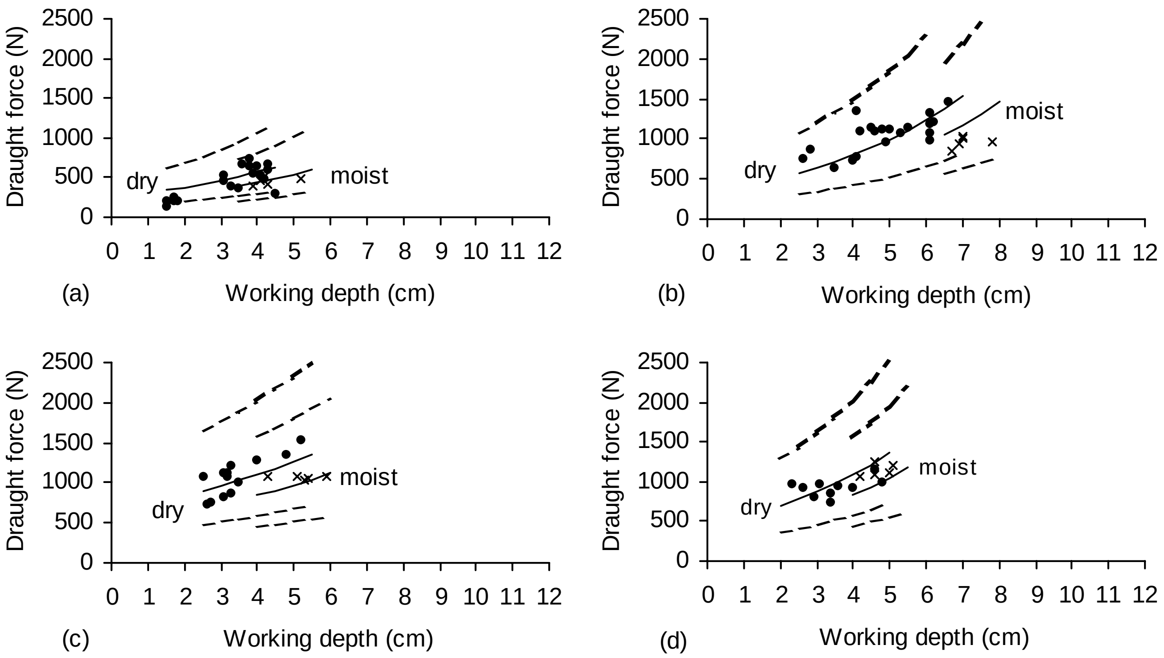

Figure 4.4. Measured and estimated draught forces per shallow injection technique for the clay soil, with the lower and upper limits (dashed lines) of the confidence interval of the estimations (95%). • = dry soil; x = moist soil; (a) Clay, double disc opener; (b) Clay, thick disc coulter; (c) Clay, disc coulter followed by injection coulter; (d) Clay, knife coulter followed by injection coulter.

The data on the injector type applicators were statistically analysed to investigate the effects of injector type, working depth and soil conditions on the required draught force. The analysis was performed by multiple linear regression on a logarithmic scale, using the following generalized linear model to fit the data:

$$E\, ln(F) = C + f_{soil} + f_{inj} + a\, D + f_{inj.depth}\, D \tag{4.1}$$

where $E\, ln(F)$ is the expected value of the logarithm of the draught force with draught force in N, C a constant, D the working depth in cm, a the coefficient of working depth and f_{soil}, f_{inj}, $f_{inj.depth}$ are factors (constants) for the effects of soil conditions and injector type and the interaction effect of injector type and working depth, respectively. The estimation of the model parameters and their confidence limits was performed by the maximum likelihood procedure with a gamma distribution for the response variate. Calculations were performed with the GLM

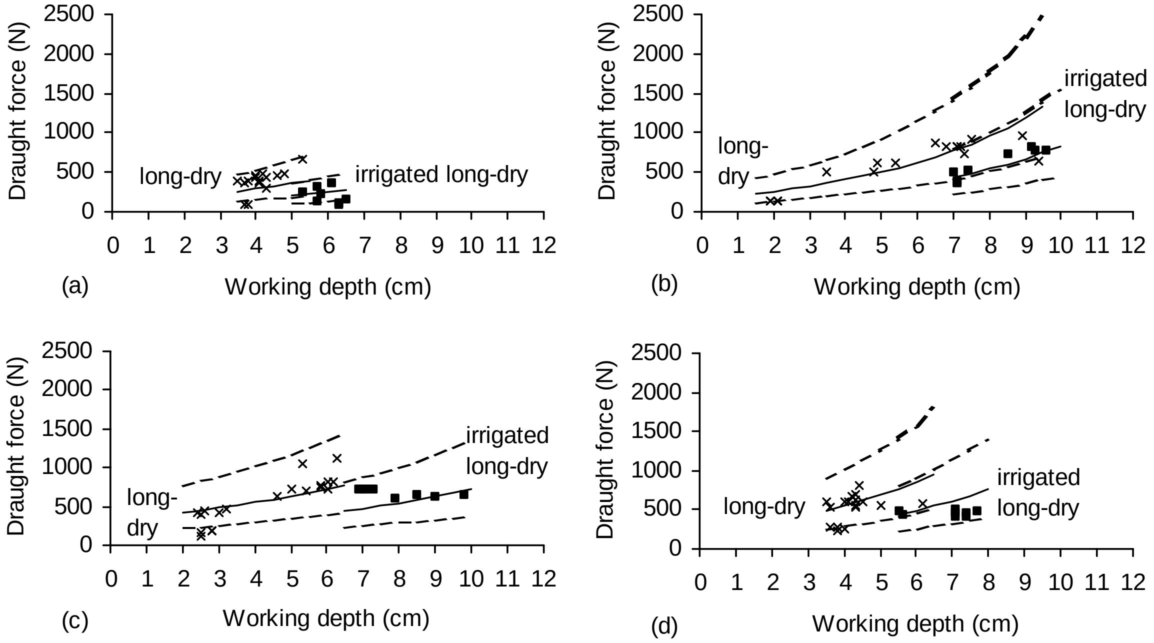

Figure 4.5. Measured and estimated draught forces per shallow injection technique for the peat soil, with the lower and upper limits (dashed lines) of the confidence interval of the estimations (95%). x = long-dry soil; ■ = irrigated long-dry soil; (a) Peat, double disc opener; (b) Peat, thick disc coulter; (c) Peat, disc coulter followed by injection coulter; (d) Peat, knife coulter followed by injection coulter.

procedure written in the statistical programming language Genstat 5 (1993).

For each of the soil conditions and injector types, model 4.1 can be reduced to the following general relationship between draught force and working depth:

$$E(F) = e^{C' + a' D} \tag{4.2}$$

Where *E(F)* is the expected value of the draught force, *C'* a constant, depending on soil conditions and injector type and *a'* a constant, depending on the injector type. The estimated values of the parameters of model 4.2 are presented in Table 4.2. Model 4.2 was used to estimate the draught force - working depth relationships that fitted best through the data for the different soil circumstances and injector types. These relationships, including the lower and upper limits of the 95% confidence interval for the estimates are also presented in Figures 4.3 – 4.5 (dashed lines).

From the statistical analysis of the data, it was concluded that injector type,

Table 4.2. Estimated values of the parameters C' and a' in model 4.2 for each injector type and the various soil conditions.

Model parameter	Soil conditions	Double-disc opener	Thick-disc coulter	Flat-disc coulter + injector	Knife coulter + injector
a'	all types/conditions	0.2088	0.2158	0.1376	0.2235
C'	moist sandy loam	4.87	5.17	5.80	5.45
	moist clay	5.25	5.56	6.19	5.83
	dry clay	5.52	5.82	6.45	6.10
	irrigated long-dry peat	4.26	4.57	5.20	4.85
	long-dry peat	4.83	5.14	5.77	5.41

working depth, the interaction of working depth and injector type and soil circumstances all had a significant effect ($P < 0.05$) on the draught force. The effect of the injection techniques on the draught force differed significantly ($P < 0.05$) from each other. The designs with rotating coulters (double-disc opener and thick-disc coulter), required a lower draught force. In all cases, the draught force increased with increasing working depth. The interaction effect of working depth and injector type was significant in one case: the increase of the draught force with increasing working depth was less for the disc followed by a coulter than for the other injection techniques.

The results also show that, in general, a higher draught force is required on the clay soil than on the peat and sand soils. Statistical tests on pairwise differences between the effects of soil conditions on the relation between draught force and working depth showed that these effects are all significantly different from each other, with exception of moist sandy loam and long-dry peat, which show similar draught force - working depth relationships. Pairwise comparison of the different soil moisture conditions revealed that a higher soil moisture content led to a significantly lower draught force requirement, both on clay and on peat soil.

For a proper comparison, the estimated injector draught force requirements including their standard errors for the different soil types/conditions and a working depth of 5 cm, which was included in the measured range of all injector types, are presented in Table 4.3. The data in Table 4.3 show a higher draught force requirement on clay than on peat and sandy loam. A higher soil moisture content

Table 4.3. Estimated mean draught force requirements and their standard errors (se) of the injector type applicators at a working depth of 5 cm for the various soil conditions.

Soil conditions	Double-disc opener		Thick-disc coulter		Flat-disc coulter + injector		Knife coulter + injector	
	draught force (N)	*se*	draught force (N)	*se*	draught force (N)	*se*	draught force (N)	*se*
Moist sandy loam	370	15	519	27	660	28	711	29
Moist clay	543	41	762	61	970	73	1045	78
Dry clay	706	38	991	51	1260	67	1358	75
Irrigated long-dry peat	202	13	284	21	361	24	389	25
Long-dry peat	357	18	501	26	637	30	686	34

led to a lower draught force requirement. The designs with rotating coulters (double-disc opener and concave disc) required lower draught force. The draught force of the disc followed by a coulter reacted differently with the working depth than the other injection techniques.

4.3.2 Trailing foot applicator

The draught force requirement of the trailing foot applicator on the various soil types/conditions is presented in Table 4.4. The trailing foot system required a low draught force compared with the injector type applicators on all soil types. The mean draught force for all soil types/conditions was 39 N (*sd* 21 N). Draught force varied from 10 N on the moist clay soil to 66 N on the long-dry peat soil.

4.4 Discussion

Parallel with this study, Walter (1994) evaluated the draught force requirement of four comparable injection techniques (of Figure 4.1) on a loam soil in Germany. Although the sizes of the injection implements were a little different from those used in this study, the results were comparable. Walter also found that the application technique, working depth and soil moisture had a significant influence on the draught force. An increasing working depth resulted in a higher draught

Table 4.4. Mean draught force of the trailing foot applicator on the various soil types/conditions.

Soil conditions	Draught force (N)	*se*
Moist sandy loam	42	5
Moist clay	10	7
Dry clay	41	7
Irrigated long-dry peat	38	6
Long-dry peat	66	8

force and drier soil conditions caused higher draught forces. In his study, the draught force requirement of the concave disc and the disc followed by a coulter was similar. The draught force requirement of the double-disc opener was lowest and that of the two coulters was highest. Forward speed did not affect the draught force. Walter found draught forces of *ca* 430, 650, 880 and 1340 N for the comparable injection techniques namely the double-disc opener, concave disc, disc followed by a coulter and two coulters, respectively, at 5 cm working depth on a loam soil. Although circumstances and application techniques were different from those in this study, the resulting draught forces were very similar to the results of Table 4.4.

In Figure 4.6, the predicted draught force of the four application techniques on the sandy soil are compared. The double-disc opener required the lowest draught forces over the range of working depths; draught force increased fivefold when the working depth increased from 1.5 to 9.5 cm. At a larger working depth than *ca* 4 cm the highest draught force was required by the injection technique with the two coulters. At the smaller working depth, the disc followed by a coulter required the highest draught force. The draught force of the disc followed by a coulter reacted differently to changes in the working depth than the other injection techniques, as shown by the shape of the curve. In the model, the factor $f_{technique,depth}$ of the disc followed by a coulter was significantly different from that factor of the other techniques.

The draught forces acting on a trailing foot are caused by friction between the foot and the grass sward. Thus, draught force requirement is likely to depend on density and condition of the grass sward and the vertically acting force on the trailing foot. The lower draught force required on the moist clay soil might be explained by a less well established, more open grass sward on the experimental site.

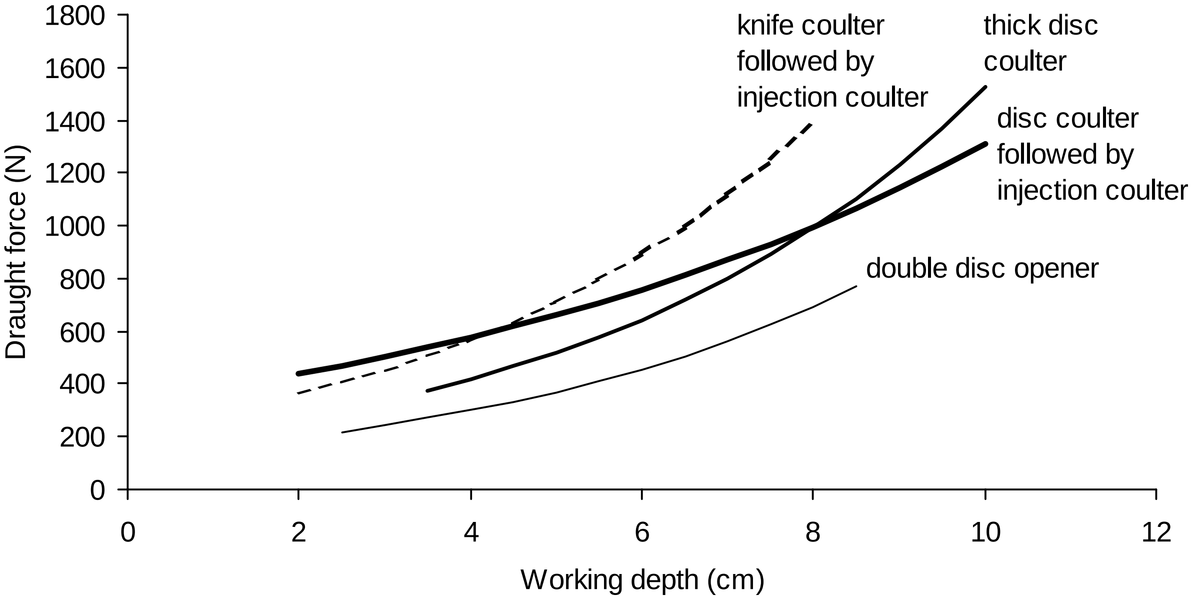

Figure 4.6. Estimated draught force of the four shallow injection techniques at various working depths on the sandy loam soil.

The results suggest that slurry injection under wet soil conditions is a practical way to reduce draught force requirement relative to dry soil conditions. However, under these conditions the rolling resistance of the implement tyres increases and the traction potential of drive wheels decreases rapidly, both causing an increased risk of sward damage (Vermeulen *et al*., 1993). Furthermore, on the clay soil, the walls of the injection slits might be smeared under wet soil conditions, leading to a poorer infiltration of the slurry into the soil. Also the smeared slit walls might become hard when dry, and the slits may remain open for a long period. On the other hand, the application of slurry under very dry soil conditions may lead to an insufficient working depth and to sward damage due to the fact that grass sods are torn out easily under dry conditions. When applying the slurry an optimum should be chosen in the soil moisture condition, avoiding sward damage but at low draught requirements.

4.5 Conclusion

The application technique, working depth and soil conditions had a significant influence on the draught force. For a working depth of 5 cm, the required draught forces per shallow injector element, measured in this experiment, were in the range of 202-706 N for a double-disc opener, 284-991 N for a thick-disc coulter, 361-1260 N for a flat-disc coulter plus injector and 389-1358 N for a knife coulter plus injector. The lowest draught forces occurred on peat soil and the highest forces on dry clay. The double-disc opener required the lowest draught force. The trailing foot required an average draught force of 39 N. The draught force of the trailing foot did not relate to the soil conditions, but an effect of the grass sward condition was suggested.

With increasing soil moisture content the draught force requirement decreased. Draught force requirement increased with increasing working depth; the increase depended on the injector design.

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5

A model for ammonia volatilization after surface application and subsequent incorporation of manure on arable land

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Abstract

When applying manure to arable land by surface spreading, volatilization of ammonia takes place. Reduction of ammonia volatilization can be achieved by incorporation of the manure into the soil. The degree of reduction depends on the method of incorporation and the time-lag between application and incorporation. In general, direct incorporation with a mouldboard plough yields more reduction than incorporation by a fixed tine cultivator. Direct incorporation is not always achievable. In practice, there will always be some time between the spreading and incorporation and during this time volatilization of ammonia from the surface-applied manure takes place. Previous studies do not account for the effect of the time-lag between spreading and incorporation on the ammonia losses. To assess the ammonia volatilization after spreading and incorporation of manure, the time-lag between these two operations was modelled *via* computer simulation. The model developed includes plot size, work capacity of the spreader, work organization, incorporation method, capacity of the incorporator, volatilization rate of surface applied manure, potential volatilization reduction by the incorporator and application rate. The simulation results are only valid for a specific set of input parameters. Time-consuming simulation runs are required to draw general conclusions. Therefore, a generalized model was also developed to approximate in a simplified way the influence of capacities of the spreader and incorporator on the volatilization reduction without simulating the whole process of spreading and incorporating. In a case study, the effect of the capacity of an incorporator and spreader on the reduction of volatilization was calculated. The case study showed that incorporation by a mouldboard plough does not always result in lower ammonia volatilization than incorporation by a fixed tine cultivator. The lower capacity of the plough results in a larger overall time-lag between spreading and incorporation and therefore the eventual volatilization reduction is lower than that with the fixed tine cultivator, despite the higher potential volatilization reduction of the mouldboard plough. The model showed that the time-lag between spreading and incorporation should be considered when assessing ammonia losses from manure applied and incorporated on arable land. The model could be used as a comprehensive instrument to evaluate the effect of different management strategies for manure spreading and incorporation on ammonia volatilization when applying and incorporating manure on a plot scale.

5.1 Introduction

In different countries in Europe, the reduction of ammonia losses is a major issue to control environmental pollution. When applying manure to arable land by surface spreading, volatilization of ammonia takes place. One of the policies to reduce ammonia losses is incorporation of surface-applied manure into the soil. The degree of reduction depends on the method of incorporation. The manure can be directly injected into the soil or, after surface spreading, be incorporated by various tillage implements.

The ammonia volatilization rate from surface-applied manure is not linear with time but peaks during the first hours after spreading. When manure is spread and incorporated on farm field scale, the time between spreading and incorporation thus affects the overall ammonia volatilization. The time to carry out field operations such as manure spreading and a tillage operation depends on the circumstances (such as dimensions of the plot, working speed and width of the implements) and the work organization (Hunt, 1986; Witney, 1995). To assess the ammonia volatilization from manure applied and incorporated in two sequential operations, the time-lag between spreading and incorporation needs to be known. Combining this time-lag with a volatilization curve of surface-applied manure and the potential volatilization reduction by a particular tillage implement is necessary to predict the actual volatilization of a manured field. In previous studies, different tilling techniques to reduce volatilization have been investigated (Van Der Molen *et al*., 1990; Huijsmans, 1991; Mulder & Huijsmans, 1994; Huijsmans & Hol, 1995). With these studies the ammonia losses cannot be assessed on farm field scale, because all measurements of ammonia losses after manure application and incorporation are derived from trials in which incorporation took place directly or at a set time following the spreading on a small field plot. In practice, on farm field scale, some time will always elapse between spreading and incorporation, and this period is not precisely controlled.

Furthermore, the volatilization rate also depends on the method of incorporation (Van Der Molen *et al*., 1990; Huijsmans, 1991; Mulder & Huijsmans, 1994; Huijsmans & Hol, 1995). Burying of the manure by the mouldboard plough gave 90% reduction compared to surface spreading. Depending on the intensity of mixing of the manure with the soil, and the soil condition, other tillage implements achieved a reduction of the volatilization from 40 to more than 90%. Applying slurry with an arable land injector equipped with spring tines, placing the manure directly underneath the soil surface, and at the same time carrying out a tilling operation by burying the manure with soil, almost completely prevented ammonia volatilization (Huijsmans, 1991). Experiments in which the incorporation was delayed by 3 and 6 hours showed a higher volatilization compared with direct incorporation (Huijsmans & Hol, 1995).

The present Dutch legislation prescribes that manure should be injected or incorporated on arable land. The method of incorporation is not prescribed, but surface-applied manure should be incorporated within a certain time limit. Farmers and contractors choose the implements and work organization that fit best in their labour plan, fulfil the soil requirements and cost little. Both the legislator and the farmer have an interest in the extent of ammonia losses when spreading and incorporating manure. Assessing the ammonia losses for the present practice is necessary to evaluate the legislative regulations and to provide farmers better information on the available nutrients (nitrogen budget) after applying and incorporating manure on their land. To investigate the effectiveness of incorporation of surface-applied manure, a computer model was developed to simulate the spreading and incorporating operations and to calculate their effect on ammonia volatilization. In the present study, the factors that affect the time-lag between spreading and incorporation are analysed and their effects on the reduction of ammonia volatilization are assessed.

5.2 Materials and methods

A simulation model was developed to calculate the relation between the time-lag between spreading and incorporation, and ammonia volatilization for each point of an arable plot. The time-lag depends on the circumstances (dimensions of plot, working speed and width of the machines, distance to manure storage, *etc.*) and the work organization: spreading and incorporation simultaneously (two-man system) or spreading and incorporation consecutively (one-man system). The time-lag is calculated by simulation of the activities on the plot. Given the time-lag, the volatilization is determined by a volatilization function, derived from a measurement as shown in Figure 5.1, and the reduction of the volatilization by the incorporation implement. A combination of the time-lag and the volatilization gives the average volatilization and the reduction of the volatilization for the whole plot. Furthermore, the model gives the average time delay and a division of the time spent over the activities spreading and incorporation.

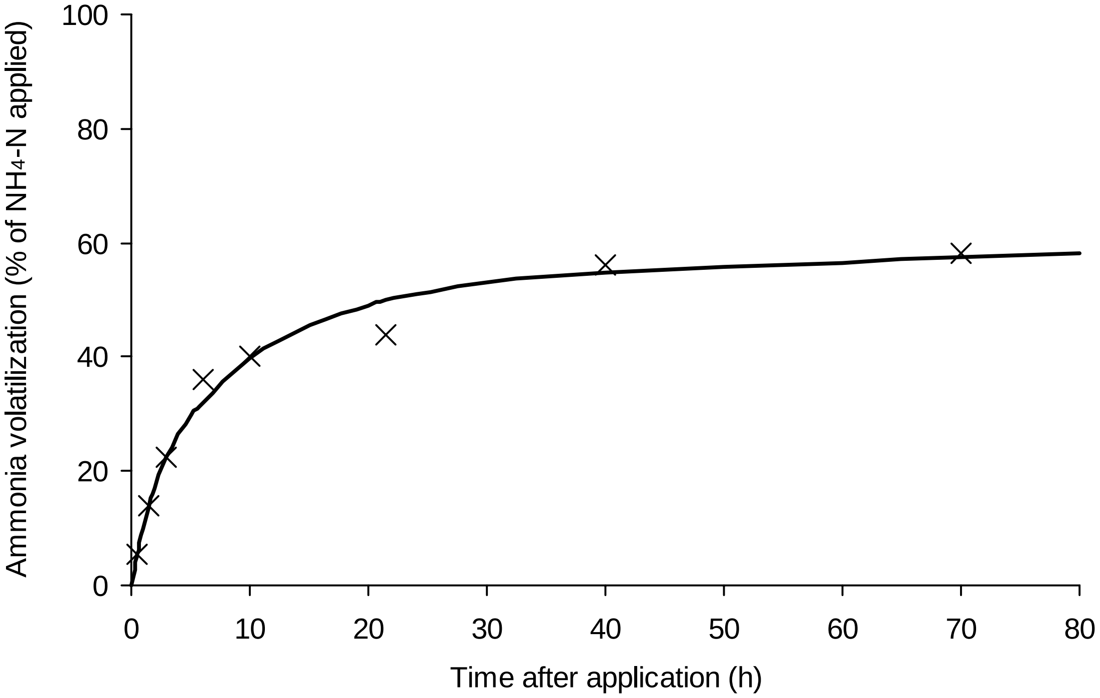

Figure 5.1. Cumulative ammonia volatilization after slurry application as a percentage of the ammonium nitrogen applied (after Huijsmans & Hol, 1995).

5.2.1 Definitions, process description and parameters

In practice, a manure spreader applies the manure on a plot until the whole plot is manured. Each time the spreader is empty, it is driven to a manure storage to reload. The manure storage can be nearby at the side of the field or located at some distance. Incorporation can start during or after the manuring of the plot. To calculate the actual time-lag between spreading and incorporation, and the volatilization before and after incorporation some activities and process parameters need to be defined.

5.2.1.1 Definitions

A rectangular plot is considered (Figure 5.2). The operations application and incorporation of manure are performed in *passes* to and fro across the plot. Two successive passes form a *round*. The application equipment is called the *spreader* and the incorporation equipment is called the *incorporator*. Both the spreader and the incorporator have a working speed and an effective working width. To calculate the total volatilization for each point of the plot (before and after incorporation), the plot is divided into *strips* (Figure 5.3). The length of a strip equals the length of the plot; the strip width is taken as the greatest common divisor of the working widths and the plot width. Both the spreader and the incorporator operate on an integer number of strips in each pass.

5.2.1.2 Process description

The process of application and incorporation of manure is influenced by many factors. Technical factors are the dimensions of the plot, the working speeds, the working widths, the manure application rate and the pay load of the spreader. Also, different types of work organization can be distinguished.

1) Working method for manure application. Three working methods are being considered:

whole rounds - a new round (to and fro) is started only if there is enough manure in the tank, otherwise the tank is reloaded first;

whole passes - a new pass (there or back) is started only if there is enough manure in the tank, otherwise the tank is loaded first;

interrupted passes - application continues till the tank is empty and, after reloading, the interrupted pass is continued in the same direction and at the same place where it stopped when emptied.

2) Working method for manure incorporation. Application and incorporation can be carried out simultaneously (*two-man system*) or consecutively (*one-man system*).

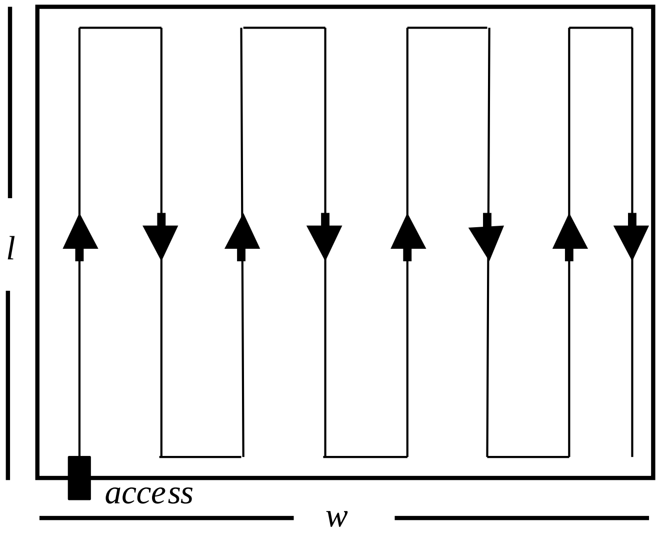

Figure 5.2. Layout of a plot (length l and width w) and the directions of passes of an implement.

In a *two-man system,* one person is available for manure application and another one for incorporation. The spreader and the incorporator can work independently. The spreader is applying manure, alternated with loading of the tank, if needed. The incorporator starts when there is enough manured land available for a whole round or at a later stage after a set waiting time. The incorporator is continuously making whole rounds over the plot. Interruptions can occur when the incorporator catches up with the spreader due to a relative high work capacity of the incorporator or when loading of the spreader takes a lot of time. The incorporator waits till a whole manured round can be incorporated.

In a *one-man system,* one person alternates spreading and incorporating; the spreader and incorporator are alternately active. The spreader starts with loading

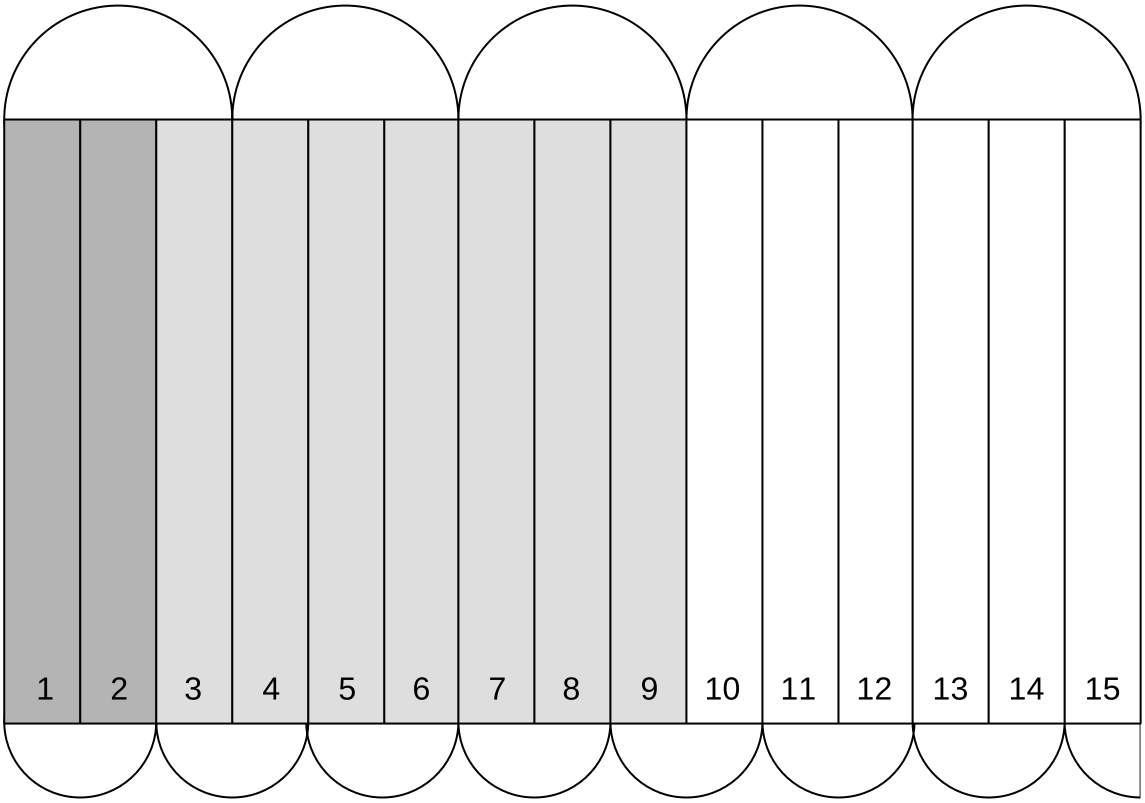

Figure 5.3. Example of a situation during simulation on a plot divided into 15 strips, where manure has been applied on nine strips and where two strips have been subsequently incorporated; the working width of the spreader (top half circle) is 1.5 times that of the incorporator (bottom half circle); strip 10-15: no manure applied; strip 1-9: manure applied; strip 1 and 2: manure incorporated.

of the tank and is working till the tank needs to be reloaded. The spreader drives to the location of the incorporator at the access of the plot, the operator steps over to the incorporator and starts to incorporate the surface-applied manure for as many whole rounds as possible. After the incorporation, the incorporator drives to the access of the plot, the operator steps over to the spreader and continues by reloading. This sequence is repeated till manure is applied and incorporated on the whole plot.

5.2.1.3 Parameters

Input for the simulation model consists of general parameters as well as parameters of volatilization, spreading and incorporation. The general parameters are: one- or two-man system; whole round, whole passes or interrupted passes; length of plot l in m; width of plot w in m; strip width in m; manure application rate m_s in m^3 ha^{-1}; idle travel speed of the spreader and incorporator on the field in m h^{-1}; waiting time for the incorporator in a two-man system; and changing time from spreader to incorporator or reverse in a one-man system in min.

The volatilization parameters are the characteristics of the volatilization function, *i.e.* parameters in Eq. (5.4).

The spreader parameters are: working speed v_s in m h^{-1}; effective working width w_s in m; pay load p_s in m^3; time to turn in s; travel speed on the road in m h^{-1}; distance to manure storage from the field access in m; time for handling and turning before and after reloading in min; and loading capacity in m^3 min^{-1}.

The incorporator parameters are: working speed v_i in m h^{-1}; effective working width w_i in m; time to turn in s; and potential volatilization reduction of the incorporator R_i (a percentage), defined as the volatilization reduction when directly incorporating compared to no incorporation.

The (theoretical) *capacity* (also named spot rate of work by Witney (1995) or theoretical field capacity by Culpin (1992)) of the incorporator is defined as the working speed times the effective working width. The capacity of the spreader is also the work capacity, but taking the time for reloading into account. Formally, the capacity of the incorporator, C_i in ha h^{-1}, is defined as:

$$C_i = \frac{w_i v_i}{10{,}000} \tag{5.1}$$

where w_i is the effective working width of the incorporator in m and v_i is the working speed in m h^{-1}.

The capacity of the spreader, C_s in ha h^{-1}, is defined by:

$$C_s = \frac{1}{(10{,}000/w_s v_s + m_s t_s/p_s)} \tag{5.2}$$

where w_s is the effective working width of the spreader in m; v_s is the working speed in m h^{-1}; m_s is the manure application rate in m^3 ha^{-1}; t_s is the reloading time in h; and p_s is the pay load in m^3. The reloading time t_s is the time required for driving to and fro the storage, handling and turning at the manure storage and filling the spreader.

5.2.2 Model description

5.2.2.1 Time-lag between manure spreading and incorporation

To determine the time-lag between spreading and incorporation, the process of application and incorporation of manure was included in the simulation model CAESAR (Computer simulation of the Ammonia Emission of Slurry application and incorporation on ARable land). The model works with the simulation software package PROSIM (1994). PROSIM makes it possible to simulate discrete and continuous processes simultaneously. Spreading and incorporation are processes interrupted at discrete moments for turning, reloading or waiting. The processes were simulated according to the description in Section 5.2.1.2. The volatilization of ammonia until incorporation is a continuous process.

In a two-man system, the spreader is continuously making passes across the plot and reloading the tank, till the whole plot is manured. In this case, the activities of the incorporator may depend on the activities of the spreader; the incorporator can only start a new round if enough manured land is available to make a whole round. In a one-man system, the spreader and the incorporator are alternately active.

The simulation starts with the spreader (with loaded tank) and incorporator ready at the access to the plot. The access to the plot is located in a corner of the plot (Figure 5.2). In the model, the spreader can be busy with different activities: working, waiting, driving on the plot, reloading or turning. The incorporator may be working, waiting, driving on the plot or turning. In the one-man system, changing from spreader to incorporator or the reverse also takes place. Figure 5.3 shows a possible situation during a simulation run.

The time-lag Δt depends on the operating direction of the spreader and incorporator. If the incorporator operates in the same direction on a strip as the spreader, then:

$$\Delta t(x) = (t_{0i} + \frac{x}{v_i}) - (t_{0s} + \frac{x}{v_s}) \tag{5.3a}$$

but if the incorporator operates in a direction on a strip opposite to the spreader, then:

$$\Delta t(x) = (t_{0i} + \frac{x}{v_i}) - (t_{0s} + \frac{l - x}{v_s}) \tag{5.3b}$$

where x, $0 \leq x \leq l$, is the location on the strip in m, $\Delta t(x)$ is the time-lag at point x in h; t_{0i} is the point of time the incorporator started with the strip in h; t_{0s} is the point of time the spreader started with the strip (equals 0 for the start of the simulation) in h, and l is the length of a strip (equals the length of the plot) in m.

5.2.2.2 Volatilization

The ammonia volatilization from applied manure can be divided into the volatilization until incorporation and the volatilization after incorporation for each point of the plot taking into account the time-lag between the spreading and incorporation at that point of the plot.

The model for the volatilization until incorporation is based on experiments in which the volatilization was determined as a function of the time after application (Figure 5.1). A non-linear volatilization function can be fitted for these data:

$$E(\Delta t) = \frac{\Delta t}{\beta_0 + \beta_1 \Delta t} \tag{5.4}$$

where Δt is the time-lag between application and incorporation in h, $E(\Delta t)$ is the ammonia volatilization for time-lag Δt as a percentage of total NH_4-N applied, and β_0 and β_1 are parameters of the volatilization function. The parameters β_0 and β_1 are fitted using the results of experiments in which the volatilization of non-incorporated manure was measured.

The average volatilization until incorporation for a strip *j* is:

$$E_{u,j} = \frac{1}{l}\int_{x=0}^{x=l} E(\Delta t(x))\mathrm{d}x = \frac{v_i}{l}\int_{t=0}^{t=T_l} E(\Delta t(v_i t))\mathrm{d}t \tag{5.5}$$

where $E_{u,j}$ is the average volatilization until incorporation for strip *j* as a percentage of total NH_4-N applied and T_l is the time needed by the incorporator to incorporate a whole strip in h. The transformation $x = v_i t$ is applied to transform the place-dependent integral to a time-dependent integral that can be used in the simulation model.

The average volatilization after incorporation for a strip *j* is:

$$E_{a,j} = \frac{100 - R_i}{100}(E(\infty) - E_{u,j}) \tag{5.6}$$

where $E_{a,j}$ is the volatilization after incorporation for strip *j* as a percentage of total NH_4-N applied, R_i is the potential volatilization reduction of the incorporator (percentage), and $E(\infty)$ is the total ammonia volatilization from surface-applied manure after Eq. (5.4) as a percentage of total NH_4-N applied.

The measured volatilization reduction when incorporating directly is used in the model as the potential reduction in volatilization of the incorporator R_i. This potential reduction is assumed to be constant for each incorporation method independent of the time-lag between spreading and incorporation. For example, if incorporation with a plough gives a reduction of 90% in case of direct incorporation (potential volatilization reduction), this percentage of reduction is also assumed for the remaining volatilization after a certain time-lag. This means that 10% of the ammonia that would have volatilized from that moment, in case of no incorporation, is volatilized when incorporating at that moment.

The average total volatilization for strip *j* is the sum of the volatilization until incorporation and the volatilization after incorporation:

$$E_j = E_{u,j} + E_{a,j} \tag{5.7}$$

where E_j is the volatilization until and after incorporation for strip *j* as a percentage of total NH_4-N applied.

The average total volatilization of the whole plot is the average over all strips:

$$E = \frac{1}{N}\sum_{j=1}^{N} E_j \tag{5.8}$$

where E is the average volatilization for the whole plot as a percentage of total NH_4-N applied and N is the number of strips.

5.2.2.3 Model output

The main results generated by the simulation model are: average time-lag between manure application and incorporation; average volatilization until incorporation; average total volatilization (before and after incorporation); average reduction in volatilization (compared with no incorporation); total time needed for application and incorporation; and division of the total time over the different activities of the spreader and the incorporator.

5.3 Simulations

With the model, many different situations can be simulated and the total volatilization from a manured and incorporated plot and time needed for application and incorporation can be calculated. From the model description, it is expected that the capacity of the spreader C_s and of the incorporator C_i, as defined in Eq. (5.1) and (5.2), will have a major effect on the reduction of the volatilization. The volatilization when spreading and incorporating in a two-man system can approach the volatilization after direct incorporation when the difference between the capacities of the spreader and the incorporator is minimized, *i.e.* the potential volatilization reduction of the incorporator is approached. In the following case, this hypothesis is examined by studying the relation between the capacity of the incorporator C_i and of the spreader C_s and the resulting reduction of the volatilization compared with no incorporation, taking into account different potential volatilization reduction rates of the incorporator.

5.3.1 Input parameters

The plot size is taken as 4.8 ha (length of 200 m and width of 240 m) and the strip width is 0.5 m. After each pass along the plot, both the spreader and the incorporator turn; the time to turn is 20 and 30 s, respectively. The travel speed of the spreader and incorporator on the field, while not in operation, is 10 km h^{-1}. The manure storage is placed at the edge of the field near the access, eliminating road transport to a manure storage. The loading capacity of the spreader is 3 m^3 min^{-1}, handling and turning before and after the loading of each load takes altogether 2 min. The manure application rate is 15 m^3 ha^{-1}. A common spreader is chosen with a working width of 8 m, a working speed of 6 km h^{-1} and a pay load of 10 m^3. Taking into account these parameters, the resulting capacity of the spreader C_s is 2.93 ha h^{-1}.

The potential volatilization when the manure is not incorporated is based on the volatilization as shown in Figure 5.1. Fitting Eq. (5.4) results in the parameter values: β_0 = 0.087 and β_1 = 0.016, accounting for 98.5% of the variance. The maximum volatilization, when not incorporating, is 60% of the total ammonia applied.

The two-man system and whole rounds are assumed. At the beginning, the incorporator starts 3 min after the spreader if there is enough manured land available for a whole round. The capacity of the incorporator was varied from 0.2 to 6.0 ha h^{-1}. This variation of capacity was obtained by choosing a range of working speeds (2-10 km h^{-1}) and working widths (1-6 m) in which most tillage implements may work in suitable soil conditions. The working widths were chosen in the way that the smaller working widths were more common for a plough and the larger ones for a cultivator. The potential volatilization reductions of the incorporator are 40 - 90%, varying in steps of 10%, corresponding to different kinds of measured reductions (Van Der Molen *et al*., 1990; Huijsmans, 1991; Mulder & Huijsmans,1994; Huijsmans & Hol, 1995).

5.3.2 Simulation results

The input parameters were used to calculate the volatilization reduction for different incorporation capacities and varying potential reductions of the incorporator by using the model [Eqns (5.3) – (5.8)]. The calculated reductions of the volatilization for the capacities of the incorporator and the different potential volatilization reductions are shown in Figure 5.4. When the incorporator capacity increases, the reduction approaches the maximum level of reduction, which corresponds to the potential reduction of the incorporator by direct incorporation. The reduction is lower when the capacity of the incorporator is lower than the capacity of the spreader; at this stage there is a non-linear relationship between the capacity of the incorporator and the reduction of volatilization.

Some combinations of working speed and working width of the incorporator result in the same capacity, *i.e.* large working width and low-speed compared to a small working width and high working speed. The simulations show that different incorporator combinations of work speed and work width with the same capacity may cause differences in the extent of the reduction of the volatilization. This can be explained by the total time needed for turning after each pass, which may differ between combinations, and differences in the waiting time. In Table 5.1, some combinations of working speed and working width with the same incorporator capacity of 1.2 ha h^{-1} are given. Comparing combinations 1 - 3 shows that enlarging the working width decreases the total turning time, resulting in a higher

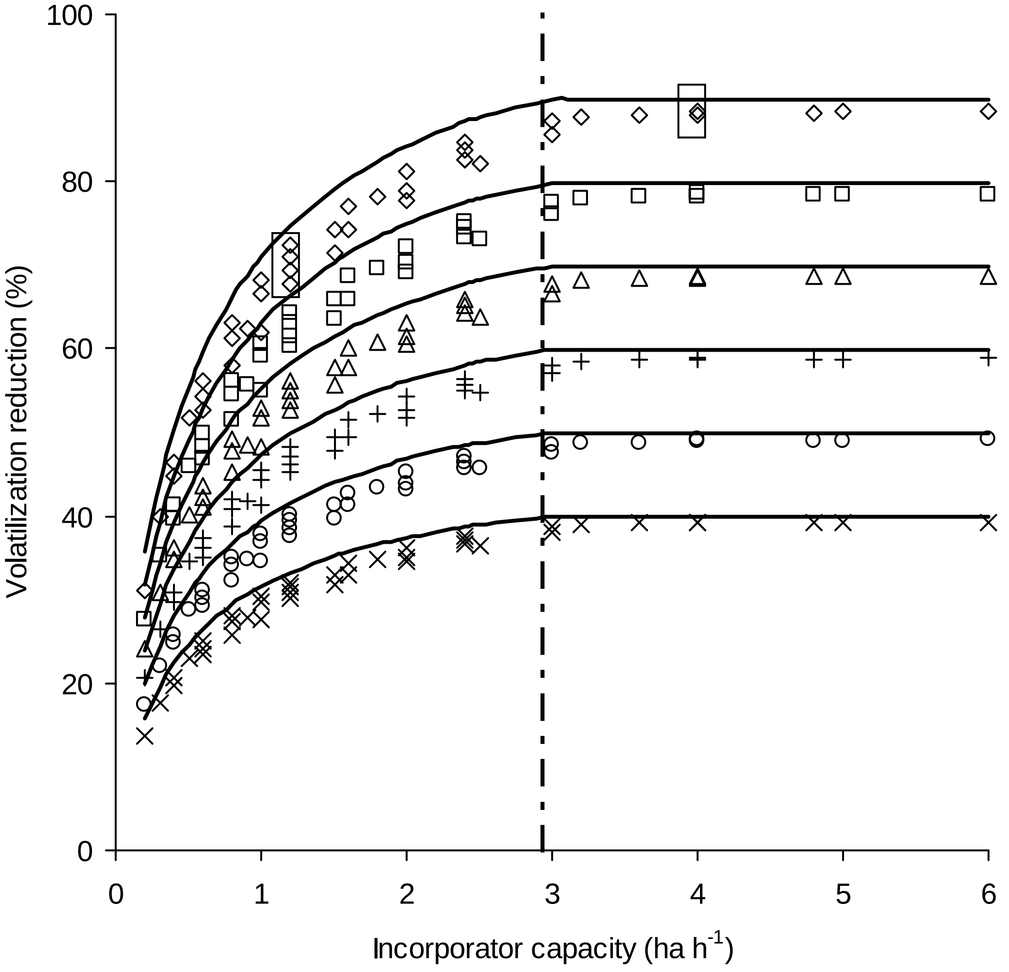

Figure 5.4. Volatilization reduction as a function of the capacity of the incorporator calculated by the detailed model (data points) and the generalized model (curves); the potential volatilization reduction of the incorporator was set at 40 to 90%; × = 40%; ○ = 50%; + = 60%; △ = 70%; □ = 80%; ◊ = 90%; the vertical line shows the capacity of the spreader.

reduction of the volatilization. Also the waiting time for available strips to incorporate a whole round may cause a difference in reduction for the different combinations with the same capacity. The large working width of combination 4 (Table 5.1) causes a longer waiting time than for combinations 1 - 3; combination 4 needs to wait 4.3 min at the start of incorporation for enough manured strips to incorporate a whole round, whereas the combinations 1 - 3 had to wait 3 min (default input setting). However the reduction of volatilization of combination 4 is larger than that for the other combination; the decrease in turning time is larger than the increase in waiting time.

In Table 5.2, two incorporator combinations are given with a capacity of 4 ha h^{-1}, a capacity exceeding that of the spreader. The larger working width of combination 2, compared to combination 1, results in a lower total turning time, but a larger waiting time. The overall incorporation time of combination 2 is larger and therefore results in a lower reduction of the volatilization. This example shows that a larger working width will not in all cases result in a higher reduction of volatilization.

Table 5.1. Comparison of the volatilization reduction by four incorporator combinations of working speed and working width with the same capacity of 1.2 ha h^{-1} and 90% potential volatilization reduction.

	Incorporator			
	1	2	3	4
Working width (m)	1.5	2.0	3.0	6.0
Working speed (km h^{-1})	8.0	6.0	4.0	2.0
Capacity (ha h^{-1})	1.2	1.2	1.2	1.2
Working time (min)	240.0	240.0	240.0	240.0
Waiting time (min)	3.0	3.0	3.0	4.3
Turning time (min)	79.5	59.5	39.5	19.5
Idle-driving time (min)	1.4	1.4	1.4	1.4
Total time (min)	323.9	303.9	283.9	265.9
Reduction volatilization (%)	67.8	69.3	70.9	72.3

Table 5.2. Comparison of the volatilization reduction by two incorporator combinations of working speed and working width with the same capacity of 4 ha h^{-1} and 90% potential volatilization reduction.

	Incorporator	
	1	2
Working width (m)	4.0	5.0
Working speed (km h^{-1})	10.0	8.0
Capacity (ha h^{-1})	4.0	4.0
Working time (min)	72.0	72.0
Waiting time (min)	16.6	24.1
Turning time (min)	29.5	23.5
Idle-driving time (min)	1.4	1.4
Total time (min)	119.5	121.0
Reduction volatilization (%)	88.4	88.0

5.4 Discussion

5.4.1 Spreader capacity

In the case study, the effect of the capacity of the incorporator on the reduction of volatilization was presented for a given spreader. Changes in the capacity of the spreader directly show at which stage a maximum reduction of volatilization can be reached by the incorporator (vertical line, Figure 5.4). The capacity of the spreader depends on different aspects. The manure application rate and the pay load of the tank determine the number of refillings of the tank for a certain plot. The total refilling time depends on the distance to the storage, loading time and travel speed.

The working width, working speed and turning times on the plot determine the time for the actual spreading. Changes in these parameters affect the spreader capacity and thus at which stage a maximum reduction of volatilization can be reached by an incorporator. In the case study, a spreader capacity of 2.93 ha h^{-1} was assumed.

The manure storage was at the access to the plot. Enlarging the distance to the storage lowers the capacity of the spreader. On the other hand, enlarging the pay load of the spreader increases the capacity. Depending on the application rate and plot size, the pay load of the spreader could be chosen in order to optimise the capacity, taking into account the distance to the storage. This optimization could be carried out for the costs, the volatilization and the time required for spreading.

5.4.2 Generalizations

Running the simulation model CAESAR gives exact values for the time-lag and the ammonia volatilization for each point on an arable plot and calculates the average volatilization of a strip and the average volatilization of the whole plot, taking into account all relevant input parameters. The model calculations showed the importance of the capacity of the spreader and incorporator on the overall reduction of the volatilization.

The simulation results are valid for a specific set of input parameters. Many time-consuming simulation runs are required to draw general conclusions. Therefore, a generalized model was also developed to approximate in a simplified way the influence of capacities of the spreader and incorporator on the volatilization reduction without simulating the whole process of spreading and incorporating. This generalization could be made by neglecting waiting and turning times. Equations (5.3) – (5.8) could be presented as follows in a generalized way with the variables presented with an overbar.

A generalization for the time-lag between the moments that the spreader and incorporator are ready for their operations on the whole plot is

$$\overline{\Delta t} = \frac{lw}{10{,}000}\left(\frac{1}{C_i} - \frac{1}{C_s}\right) \tag{5.9}$$

where $\overline{\Delta t}$ is the estimated final time-lag between the spreader and incorporator in h.

A generalization for the average volatilization till incorporation $\overline{E}_u$ as a percentage of total NH_4-N applied, based on the estimated final time-lag, according to Eq. (5.9), can be defined by

$$\overline{E}_u = \frac{1}{\overline{\Delta t}} \int_0^{\overline{\Delta t}} \frac{t}{\beta_0 + \beta_1 t}\,\mathrm{d}t = \frac{1}{\beta_1} - \frac{\beta_0}{\overline{\Delta t}\beta_1^2}\log\left(1 + \frac{\beta_1}{\beta_0}\overline{\Delta t}\right) \tag{5.10}$$

The generalization for the volatilization after incorporation $\overline{E}_a$ as a percentage of total NH_4-N applied, for the plot is calculated in the same way as for a strip in Eq. (5.6):

$$\overline{E}_a = \frac{100 - R_i}{100}(E(\infty) - \overline{E}_u) \tag{5.11}$$

The average generalized total volatilization $\overline{E}$ as a percentage of total NH_4-N applied, is the sum of the volatilization until incorporation and the volatilization after incorporation [comparable with Eq. (5.7)]:

$$\overline{E} = \overline{E}_u + \overline{E}_a \tag{5.12}$$

The generalization of the time-lag is based on the work capacities as defined in Eq. (5.1) and (5.2) and the area of the plot. The time-lag is always positive; when the capacity of the incorporator is greater than the capacity of the spreader, the time-lag approaches a lower limit. This lower limit is estimated by l/v_i, corresponding with the time for the final whole pass of the incorporator. The generalization implies that the time-lag is (about) zero when the operations start and $\overline{\Delta t}$ when they are finished. Equation (5.10) is comparable with Eq. (5.5) where the volatilization for a strip is calculated. Equation (5.10) shows that when $\overline{\Delta t}$ increases, the estimated ammonia volatilization approaches β_1^{-1}, which is in agreement with Eq. (5.4). When $\overline{\Delta t}$ approaches zero, the estimated volatilization till incorporation approaches zero, meaning that direct incorporation is approached and volatilization is only determined by the volatilization after incorporation.

In Figure 5.4, the calculated reductions of the volatilization for the capacities of the incorporator and the different potential volatilization reductions are shown (curves) using the input parameters (Section 5.3.1) and the generalized model. Neglecting the turning and waiting times in the generalized model results in higher reductions than the calculated values by the detailed model (data points in Figure 5.4). The maximum deviation was 9% reduction (absolute units) when the incorporate capacity was lower than the spreader capacity and *ca* 4% reduction (absolute units) when the incorporation capacity was higher than the spreader capacity. These maximum deviations were found for the situations with 90% potential reduction by the incorporator. The generalization shows a good approximation for the effects of the capacity on the reduction of the volatilization.

The potential volatilization reduction by an incorporator can never be reached, because of the time-lag between spreading and incorporation. In the CAESAR (detailed) model, it is assumed that the incorporator starts with a new round only when enough manured strips are available for a whole round; during this waiting time, volatilization takes place. With the generalized model, the waiting time is neglected and therefore the potential reduction of the incorporator can be reached when the time-lag approaches zero, *i.e.* the point where the maximum level of reduction can be approached will be determined by the point where the capacity of the incorporator equals the capacity of the spreader.

5.4.3 Comparison of different incorporation techniques

Figure 5.4 is suitable to analyse the reduction of volatilization when choosing different kinds of tillage implements to incorporate the manure on a plot, given the potential volatilization reduction of the incorporator and its incorporation capacity. For example, a mouldboard plough will give a potential volatilization reduction of 90% and a spring tine cultivator 60%. The plough may have a working speed of 4 km h^{-1} and a working width of 1 m (capacity 0.4 ha h^{-1}); the spring tine 8 km h^{-1} and 6 m, respectively (capacity 4.8 ha h^{-1}). Figure 5.5 shows for both incorporators the calculated reduction of volatilization. The mouldboard plough results in a reduction of 50% and the spring tine cultivator in 60%; calculations with the detailed model give reductions of 45 and 59%, respectively. This example shows that though the potential reduction of the plough is higher than the potential reduction of the spring tine cultivator, the overall volatilization reduction of the plough is lower when incorporating a whole manured plot. A higher capacity of the plough (more than 0.6 ha h^{-1}) will result in a higher volatilization reduction than with the spring tine cultivator. In the same way the capacity of the spring tine cultivator may be lowered to 1.2 ha h^{-1} to reduce the volatilization to the same level as after incorporation with the plough.

5.4.4 Optimization

In the case study some features and possibilities of the model are described. Other parameter settings will result in other outcomes. For example, changing the plot size and/or the volatilization function directly influences the outcome. However, the maximum volatilization reduction is reached when the capacity of the incorporator is at least as high as the capacity of the spreader. The model makes it possible to study the volatilization after incorporation for different situations.

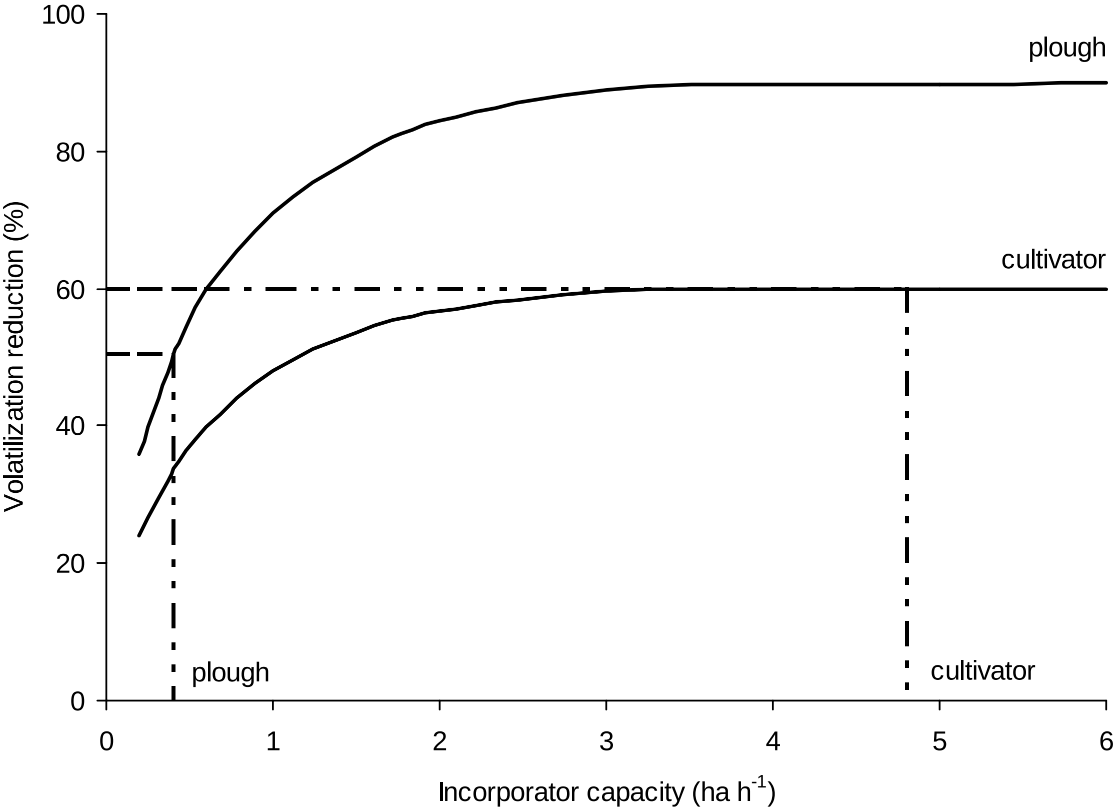

Figure 5.5. Volatilization reduction as a function of the capacity of the incorporator for a plough with a capacity of 0.4 ha h^{-1} and a spring tine cultivator with a capacity of 4.8 ha h^{-1}, with a potential volatilization reduction of 90 and 60%, respectively, results from model calculations.

The model also gives the average time-lag and the spent time over the activities for the spreading and incorporation implement. A next step in the research will be to optimise the process of spreading and incorporation in terms of ammonia losses versus costs.

5.5 Conclusion

Volatilization and reduction of volatilization after surface application and subsequent incorporation of manure on arable land was affected by the time-lag between spreading and incorporation. To calculate the time-lag and subsequent ammonia volatilization, the CAESAR (Computer simulation of the Ammonia Emission of Slurry application and incorporation on ARable land) model was developed. The model includes plot size, work capacity of the spreader, work organization, incorporation method and capacity, volatilization rate of surface applied manure, potential volatilization reduction of the incorporator and application rate. The detailed model CAESAR enables the calculation of the time differences, between spreading and incorporation, and ammonia volatilization for each point of an arable plot and for a whole plot after manure application and incorporation. The case study showed that incorporation by an implement with a higher potential reduction not always results in lower ammonia volatilization than an implement with a lower potential reduction of volatilization due to differences in their incorporating capacities. The input parameters plot size, work capacity of the spreader and the incorporation method, volatilization rate of surface-applied manure, *etc*., affected the overall ammonia volatilization.

The generalized model enables the calculation of the ammonia volatilization of a whole manured and incorporated plot, based on the capacities of the spreader and incorporator. The generalized model neglects the turning and waiting times of the incorporator and therefore overestimates the reduction of the volatilization. The maximum deviation was 9% reduction (absolute units) when the incorporator capacity was lower than the spreader capacity and *ca* 4% reduction (absolute units) when the incorporation capacity was higher than the spreader capacity. The generalization shows a good approximation for the effects of the capacity on the reduction of the volatilization.

The model is shown to be a comprehensive instrument for evaluating the effects of different management strategies for manure spreading and incorporation on the ammonia volatilization when applying and incorporating manure on plot scale.

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6

Costs of emission-reducing manure application

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Abstract

Favourable economics of handling and application of manure are of fundamental importance to encourage the implementation of emission-reducing application techniques. The economics of manure application depend on the costs of the equipment and the time to carry out the field operation. In this study the costs of application techniques designed to reduce ammonia losses were assessed and compared with the costs of conventional broadcast spreading across a range of farm characteristics. A model was developed to calculate the costs and time requirements of manure application. Data on factors affecting the costs were used from different countries in Europe.

The calculations showed that for a range of farm characteristics with a manure production of 1,000 to 3,000 m^3 per year, the costs of manure application by trailing hose, trailing foot, shallow injector and arable land injector were *ca* 2 € per m^3 higher than for broadcast spreading. The cost difference between broadcast spreading and the other application techniques decreased with increasing farm size. The average additional costs of manure application by a trailing foot or a shallow injector decreased with 15% on small extensive farms to more than 50% on intensive farms, when the fertiliser value of the nitrogen was taken into account. The field application itself took less than 50% of the operating time in the process of the manure handling and application. With an increasing application rate, the relative contribution of the time for field application decreased.

Keywords: ammonia reducing, application technique, band spreading, costs, injection, manure, nitrogen, nutrient value, operating time

6.1 Introduction

In many countries across Europe, the reduction of ammonia losses is a major concern and an important component of environmental pollution control strategies. Recently, new liquid manure application techniques have been developed, that considerably reduce ammonia emission following manure application to land (Huijsmans *et al.,* 1997, 2001a). These techniques are based on injection or band spreading of liquid manure. The initial capital investment for these techniques is greater than for conventional broadcast spreading with a splash plate (Rodhe & Rammer, 2002). Furthermore, injection generally requires more draught force (Huijsmans *et al.,* 1998). In particular, when large quantities of manure are handled, it could be profitable to invest in environmental friendly technology (Brundin & Rodhe, 1994). However, the complexity of operations and the perceived high costs of implementing improved practice, *e.g.* extra storage and new machinery, are thought to be responsible for a lack of farmer confidence in new technology (Smith *et al.*, 2000) in some countries. Available data on contractor charges and machinery costs generally cover only the more conventional operations or equipment, *e.g.* a farm yard manure spreader and a manure tanker with splash plate (*Anon*., 1999).

To successfully introduce and implement emission-reducing application techniques, information on the costs of these techniques is necessary. Favourable economics of new application techniques are of fundamental importance to encourage the improved recycling and efficient utilisation of manure. The economics of manure application depend on the costs of the application equipment and the time to carry out the field operation. The objective of this study is to assess the costs of application techniques that reduce ammonia losses and to compare these costs with the costs of conventional broadcast spreading. The outcome of this study should assist farmers in their decision making regarding the purchase and management of emission-reducing application equipment. This study includes the collection of data on farm characteristics and costs of manure application, for a number of farms in each of eight European countries. The data was gathered through the framework of the European research project ALFAM (Ammonia Losses from Field-applied Animal Manure; Sommer *et al.*, 2001). Based on this information, standardised costs calculations for emission-reducing application techniques were carried out and compared with the costs of conventional broadcast spreading.

6.2 MATERIALS AND METHODS

6.2.1 Farm characteristics and choice of simulations for cost assessment

To assess the costs of manure application, specific information on farm system, manure application technique and working method (*i.e.* organisation of machine passes across the field) was needed. Farm characteristics differ between countries and, often, within regions of countries. In the framework of the European research project ALFAM, Huijsmans *et al.* (2001b) gathered information on farm characteristics and costs of manure application in eight European countries. They calculated at the individual farm level, the time-related machine costs, spreading capacity and costs of applying the manure produced at a farm (Appendix 6.1). Machine costs varied from 43 to 285 € h^{-1}. Variation in machine costs was caused by differences in the components of the cost calculation, the application technique and the time needed for spreading the manure produced at the farm. The spreading capacity, expressed as the amount of manure that can be applied per hour, varied across the various farms, from 12 to 55 m^3 h^{-1}. Differences in spreading capacity were caused by the choice and capacity of the application technique, the application rates and the size and location of the fields (especially distance from the store). The costs for manure application were calculated at the individual farm level, taking into account the machine costs and operating time for manure application per year. These costs varied from 1.6 to 13 € per m^3 manure applied (Figure 6.1). The calculated costs gave an estimate of the costs of manure application across the eight European countries. Farm characteristics (particularly manure management), and costs and choice of machinery had a large impact on the calculated costs. An analysis of the major factors affecting costs was not possible, due to the large variation in the data and the small sample size within the study.

The overall costs of manure application clearly depend on a large number of factors, including the farm characteristics. Variation of the costs within a country may be at least as great as the variation between countries. Therefore, to assess the costs of application techniques designed to reduce ammonia losses and to compare these costs with the costs of conventional broadcast spreading, standardised calculations were carried out for a range of representative farm characteristics, described by Huijsmans *et al.* (2001b). These standardised calculations are useful when attempting to explain the cost components of manure application and will allow a systematic comparison of cost components.

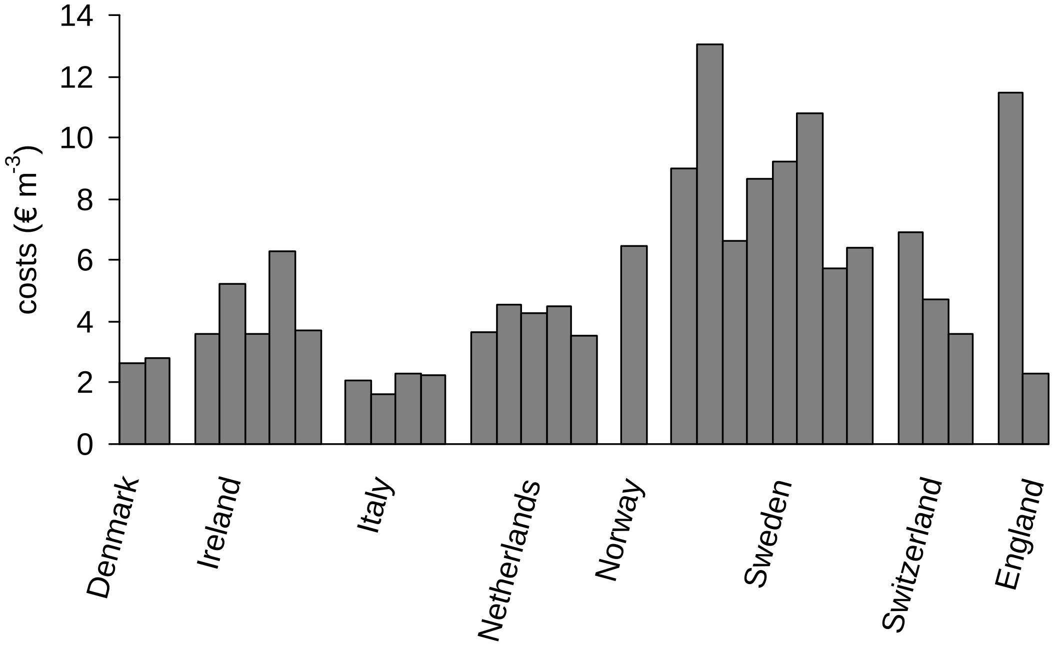

Figure 6.1. Costs of manure application (€ m^{-3}) across 8 European countries (Huijsmans et al., 2001b).

In the standardised calculations of costs, the machine investment costs were assumed to be the same for the various countries and represented average prices for the machinery types. In Table 6.1 the selected range of farm characteristics is given. In Table 6.2 the machine investment costs are given. The investment costs of a tractor depend on the draft power requirement for the application technique. For each combination of a farm characteristic and application technique (in total 1,920 possible combinations) the costs of manure application were calculated, with costs expressed as € per m^3 manure applied. From these calculations, the costs of manure application for a specific farm characteristic and changes in costs for manure application (when changing to low emission techniques) were derived.

6.2.2 Assessment of the costs of manure application

The costs of farm machinery are a substantial part of the costs of farm operations and are an important aspect when evaluating alternative field operations, working methods and the need for new machinery. The costs are divided into the costs of operating the farm machinery and the time required for field operations.

Table 6.1. Selected range of farm characteristics for calculation of costs and time requirements.

Farm characteristic	
Farm scale (manure production, m^3 y^{-1})	500, 1,000, 2,000, 3,000
Application rate (m^3 ha^{-1})	10, 15, 20, 30, 40, 60
Distance to storage (km)	0.5, 2
Average road speed (km h^{-1})	15, 25
Field size (ha)	2.4, 5.4

Tanker size and corresponding working width	Tanker size (m^3)	
	6	10
	Working width (m)	
Broadcast spreader	12	12
Trailing hose	12	12
Trailing foot	4	5
Shallow injector	3	4
Arable land injector	3	4

6.2.2.1 Operating costs of machinery

The assumptions and parameters used to assess the machine operating costs are shown in Table 6.3. In this study, the farmers were assumed to undertake all the work themselves, using their own machinery. The machine use in hours per year is the calculated time needed for application of the total manure production at the farm (see Section 6.2.2.2).

The machine costs per year are the sum of the parameters E-K of Table 6.3. The operating costs of farm machinery include the machine costs, full labour and fuel costs. Costs of labour are the opportunity costs (*i.e.* the price that can be obtained for alternative work). The costs of durable assets like farm machinery are divided into fixed and variable costs. Fixed costs are the costs that must be incurred, independent of whether the machine is used or not. These include depreciation, interest on capital, insurance and shelter. Variable costs are the machine running costs (fuel, oil, repair and maintenance). The division between fixed costs and variable costs is sometimes arbitrary. With intensively-used farm machinery, depreciation depends on operating time, while periodic maintenance is also

Table 6.2. Upper part: investment costs for a tanker and various application implements (derived from Gaakeer, 1998). Lower part: investment costs for the tractor needed for each application technique.

Investment costs (€)	Tanker size (m^3)	
	6	10
Slurry tanker	11,000	16,000
Implement		
Trailing hose	10,500	10,500
Trailing foot	6,800	9,000
Shallow injector	7,700	11,500
Arable land injector	5,500	9,500
Tractor		
Broadcast spreader	43,500 (65)	56,500 (85)
Trailing hose	43,500 (65)	56,500 (85)
Trailing foot	43,500 (65)	56,500 (85)
Shallow injector	56,500 (85)	66,250 (100)
Arable land injector	56,500 (85)	66,250 (100)

Tractor power in parentheses (kW).

required for occasionally-used machinery. The depreciation depends on the wear attributable to increasing age and on wear and tear due to machine operation. Wear on major components will reduce performance and reliability. Replacement of the main components, however, is often not economically viable. The depreciation may also depend on the availability of new equipment with better performance and on laws or regulations, that may outlaw the use of some types of machinery, *e.g.* due to environmental damage or ethical considerations. Some of these factors are independent of use and determine the economic life of a machine. Estimating the economic life of a machine is always difficult due to the need to predict future developments. Machine use determines the ‘effective’ or ‘practical’ life, *i.e.* the maximum number of hours a machine can be used economically. The annual depreciation is determined by the economic life of the machine, the purchase price and the resale value. The period over which depreciation is calculated is determined by the impact of the above factors.

Costs of interest are calculated as a percentage of the average of the replacement costs and the residual value. Insurance and shelter are calculated

Table 6.3. Parameters and assumptions required to assess the operating costs of machinery.

	Parameter	Unit	Calculation
A	Replacement cost	€	
B	Residual value	€	10% of A
C	Depreciation	€	A-B
D	Depreciation time	y	
E	Annual depreciation	€	C/D
F	Interest	€	6.5% of average (A+B)
G	Repairs by others	€	5% of A
H	Own repair	€	60% of G
I	Shelter	€	2% of A
J	Insurance	€	1% of A
K	General costs	€	3% of A
L	Machine use	$h\ y^{-1}$	
M	Fuel costs, *etc*. (tractor)	$€\ h^{-1}$	
N	Labour costs	$€\ h^{-1}$	

over the capital invested in the machinery. For simplicity, a charge-based percentage of the replacement costs has been used. Fuel consumption of the tractor is calculated depending on the power of the tractor (specific fuel consumption at 70% of full load). The costs of periodic replacement of crankcase oil and oil filters is calculated as a percentage of the fuel costs. The costs of repair and maintenance of machinery, needed to ensure reliability and to guarantee performance and work of good quality, comprises the costs of labour for repair, and replacement parts.

In the calculations of the operating costs of machinery the labour costs were 14 € h^{-1}; the depreciation time for the tractor and for the implement 10 years, and for the tanker 12 years. The annual use of the tractor was set at 600 h. The annual use of the tanker and implement is the time needed for application of the manure production at the farm. For other default values see Table 6.1.

6.2.2.2 Time required for field operations

The time required for field operations depends on several operational factors (field area and dimensions, working speed and working width, distance to manure storage, loading time, *etc.*) and the working method (for example manure transport to the field by a separate tanker).

Manure application time was calculated using the model CAESAR, Computer simulation of the Ammonia Emission of Slurry application and incorporation on ARable land (Huijsmans & De Mol, 1999). Field-application of manure is a process interrupted by the specific and discrete requirements for turning, loading or waiting. The model simulates discrete and continuous processes simultaneously. The model allocates time spent on specific work components, *e.g.* spreading, turning, transport and loading. In practice, a manure spreader is considered to apply the manure to the whole field until the complete area is spread. Each time the spreader is empty, it is driven to the manure storage to reload. The manure storage can be located at various distances. To calculate the actual time for application, some activities and process parameters need to be defined. In the model a rectangular spreading area is considered. The application of manure is performed in *passes* to and fro across the field. The process of manure application is influenced by many factors. Technical factors include the dimensions of the area spread (“field”), the working forward speed, the working width, the manure application rate and the payload of the spreader. In the simulations, application continues until the tanker is empty. After reloading, the interrupted pass is continued from the same place and in the same direction as when the application stopped.

6.2.2.3 Simulation and calculation

General input parameters for the CAESAR model are:

- pass length within the field (m),
- field width (m),
- manure application rate (m^3 ha^{-1}).

The spreader parameters are:

- average working speed (km h^{-1}),
- effective working width (m),
- payload (m^3),
- time to turn after each pass (s),

- average travel speed on the road (km h^{-1}),
- average idle travel speed on the field (km h^{-1}),
- distance to manure storage from the field access (m),
- time for handling and turning before and after reloading (s),
- loading capacity (m^3 min^{-1}).

The simulation starts with the spreader (with full load) ready at the access to the field, which is designated to be at a corner of the plot. In the model, the spreader can be busy with different activities: working, idle travel across the field, transport to or from the storage, reloading or turning. The main results generated by the model are total time needed for application and the breakdown of this time over the different activities of the spreader.

In order to assess the time requirement for spreading, it was considered that a known amount of manure is produced at the farm and applied on land within that farm. Depending on the chosen manure application rate, not all fields may receive manure, or manure application may be carried out a number of times during the year on the same field. In the calculations of the operating time the assumed working field speed was 8 km h^{-1} (adjusted if pump capacity was not sufficient). Idle field speed was 10 km h^{-1}; maximum pump capacity 3 m^3 min^{-1}.

6.3 Results

6.3.1 Costs

The costs of manure application were calculated for the selected range of farm characteristics and manure application techniques (Table 6.4). On average, for the different farm sizes (manure production 1,000-3,000 m^3 y^{-1}), manure application by trailing hose, trailing foot, shallow injector or arable land injector costs *ca* 2 € m^{-3} more than broadcast spreading. The cost difference between broadcast spreading and the other application techniques decreased with increasing farm size. For example, with a manure production of 3,000 m^3 y^{-1}, the cost of broadcast spreading is *ca* 1.4 € m^{-3} less than of other techniques. The differences in costs were highest, upto more than 5 € per m^3 applied, on small, extensive farms producing up to 500 m^3 manure per year.

Table 6.4. Mean, minimum and maximum costs of manure application by various techniques for farms with a manure production of 500 to 3,000 m^3 per year (€ per m^3 applied).

Costs of manure application (€ m^{-3})															
Annual manure production (m^3 y^{-1})	Application technique														
	Broadcast spreading			Trailing hose			Trailing foot			Shallow injection			Arable land injection		
	mean	min	max	mean	min	max	mean	min	max	mean	min	max	mean	min	max
500	8.46	6.65	10.43	14.04	12.23	16.01	13.06	10.34	16.00	14.53	11.13	18.14	13.41	9.96	17.08
1,000	5.07	3.89	6.42	7.86	6.68	9.21	7.58	5.77	9.60	8.60	6.32	11.07	8.03	5.74	10.54
2,000	3.38	2.51	4.41	4.78	3.91	5.81	4.84	3.49	6.93	5.63	3.92	7.76	5.35	3.63	7.47
3,000	2.82	2.05	3.77	3.75	2.98	4.70	3.92	2.73	5.55	4.64	3.12	6.96	4.45	2.93	6.77

The application rate did not affect the costs per m^3 applied in the case of a broadcast spreader or trailing hose. In all situations the application rate was assumed to be adjustable by the pump capacity of the manure pump. When the maximum capacity of the manure pump is reached, an increase in application rate was attainable by decreasing the forward working speed. When applying manure by the trailing foot or injection techniques the costs per m^3 did not change for application rates above 25 m^3 ha^{-1}. Differences in the costs between broadcast spreading and trailing hose and between shallow injection and arable land injection are entirely due to the difference in investment costs.

Field size did not greatly affect the mean costs of manure application (Table 6.5). For all application techniques the minimum costs were achieved with the field at a short distance from the store (0.5 km), a high road travel speed (25 km h^{-1}), and assuming high total annual manure spreading requirement (3,000 m^3). In this way, for the range of characteristics considered, minimum costs were achieved at an application rate of 20 m^3 ha^{-1} for broadcast spreading and trailing hose, and of 60 m^3 ha^{-1} for the other application techniques.

6.3.2 Manure management

The use of techniques that reduce ammonia volatilization leads to higher costs for manure application (Table 6.4). The application rate per application event may vary between application techniques. For example broadcast spreading may be

Table 6.5. Mean, minimum and maximum costs of manure application (€ m^{-3}) by various application techniques for different field sizes.

Costs of manure application (€ m^{-3})						
Application technique	Field size (ha)					
	2.4			5.4		
	mean	min	max	mean	min	max
Broadcast spreading	4.84	2.05	10.13	5.03	2.20	10.43
Trailing hose	7.51	2.98	15.71	7.70	3.13	16.01
Trailing foot	7.29	2.73	15.72	7.41	2.84	16.00
Shallow injection	8.27	3.12	17.93	8.43	3.24	18.14
Arable land injection	7.73	2.93	16.87	7.89	3.05	17.08

carried out 4 times per year on grassland with a varying application rate, while (shallow) injection of manure may be carried out 2 to 3 times per year (with varying application rate). The total annual application rate may be the same for both techniques, but the number of times manure is applied may differ and therefore should be considered when comparing the overall costs of different methods for manure application. In Table 6.6 the costs of different application strategies are given for some application techniques. The minimum and maximum values of the costs for the different strategies are affected by field size, distance to storage, tanker size, road speed, *etc*. Comparison of the costs, averaged over application rates (Table 6.4), with the costs for different application strategies (Table 6.6) shows that the strategy of application hardly affects the difference in costs between the techniques. The minor difference can be explained by the fact that the costs are mainly affected by the time required to pump (apply) and transport the manure load, and not the number of times to apply the manure. The minimum application time is determined by pump capacity and realistic working speeds in the field.

Besides on applying the manure to the field, time is spent on transport to and from the store and loading the tanker. In Table 6.7 an overview is given of the proportion of the total time the machinery is actually applying manure on the field. The field application takes less than 50% of the operating time in the process of manure spreading. Differences between application techniques are caused by differences in their inherent working widths. The time spent in non-spreading activity is accounted for by aspects such as transport and loading the tanker, and idle travel across the field. This time is independent of the application technique. With an increasing application rate, the relative part of the time for field application decreases.

6.4 Discussion and conclusions

The average ammonia volatilization after broadcast application or application by a trailing foot or shallow injector is assessed to be 77, 20 and 6%, respectively, of the total ammoniacal nitrogen (TAN) applied by the manure (Huijsmans *et al.*, 2001b). Reduction of volatilization by the trailing foot and shallow injector is associated with additional costs (Table 6.8). However, the costs should be corrected for the potential savings by the nutrient value of the ammonia (nitrogen). A TAN content of the manure of 2 kg m^{-3}, and a nitrogen fertiliser price of 0.65 € per kg N would lead to an economic loss, due to volatilization, of 1.00, 0.26 and

Table 6.6. Mean, minimum and maximum costs of manure application for various techniques and strategies of manure application for farms with a manure production of 500 to 3,000 m^3 per year (€ per m^3 applied).

Costs of manure application (€ m^{-3})															
Annual manure production (m^3 y^{-1})	Application technique and number and rates of application														
	Broadcast spreading			Trailing foot band application						Shallow injection					
No. of applications & rates (m^3 ha^{-1})	*1x20 + 3x10*			*1x30 + 1x20*			*1x20 + 3x10*			*1x30 + 1x20*			*1x30 + 2x10*		
	mean	min	max	mean	min	max	mean	min	max	mean	min	max	mean	min	max
500	8.51	6.76	10.36	13.99	12.24	15.79	13.58	11.40	15.83	14.39	11.71	17.06	15.10	12.39	17.74
1,000	5.13	4.00	6.35	7.82	6.69	8.98	8.09	6.84	9.42	8.45	6.90	9.99	9.16	7.58	10.68
2,000	3.44	2.62	4.34	4.73	3.92	5.58	5.35	4.55	6.22	5.48	4.50	6.48	6.20	5.18	7.29
3,000	2.87	2.16	3.73	3.70	2.99	4.60	4.44	3.79	5.36	4.49	3.70	5.64	5.21	4.38	6.46

Table 6.7. Mean, minimum and maximum proportion of total operational time spent on actual manure application activity in the field (% of the total time spent on manure application).

Actual manure application activity (% of total operational time)															
Application rate (m^3 ha^{-1})	Application technique														
	Broadcast spreading			Trailing hose			Trailing foot			Shallow injection			Arable land injection		
	mean	min	max	mean	min	max	mean	min	max	mean	min	max	mean	min	max
10	25	13	38	25	13	38	41	28	53	46	33	56	46	33	56
15	18	9	28	18	9	28	33	22	44	37	26	47	37	26	47
20	15	7	26	15	7	26	28	17	38	33	21	42	33	21	42
30	14	7	23	14	7	23	21	13	29	24	15	32	25	15	32
40	14	7	23	14	7	23	17	10	24	20	12	28	20	12	28
60	14	7	23	14	7	23	14	7	22	15	9	22	15	9	22

Table 6.8. Average additional costs (€ per m^3 applied) for manure application by trailing foot or shallow injection on grassland, compared to broadcast spreading (gross add. costs), and the additional cost corrected for the savings of fertiliser value of the nitrogen (net add. costs).

Annual manure production (m^3 y^{-1})	Trailing foot		Shallow injection	
	gross add. costs	net add. costs	gross add. costs	net add. costs
500	4.60	3.86	6.07	5.15
1,000	2.51	1.77	3.53	2.61
2,000	1.46	0.72	2.25	1.33
3,000	1.10	0.36	1.82	0.90

0.08 € m^{-3} when broadcast applied, applied by trailing foot or by shallow injector, respectively. In this example the average additional costs of manure application by a trailing foot or a shallow injector will be decreased with 15% on small extensive farms to more than 50% on intensive farms, when the fertiliser value of the nitrogen is taken into account (Table 6.8). On average, for the different farm sizes (manure production 1,000-3,000 m^3 y^{-1}), the net additional costs for manure application by trailing foot or shallow injector would be *ca* 0.95 and 1.61 € m^{-3}, respectively, compared to broadcast spreading.

The calculations show the additional costs for farmers, when changing from broadcast spreading to low-emission techniques. Moreover, the low-emission techniques result in environmental benefits, and its implementation may in this way contribute to overcome complaints in society.

In this study different farm characteristics were chosen and standardised costs calculations for manure application were carried out. The chosen broad range of farm characteristics and the standardisation of the calculations made it possible to assess, in a generalized way, the additional costs of emission-reducing manure strategies. Taking into account the nutrient savings, the assessment of the costs can help farmers in their decision to invest in an emission-reducing application technique. When calculating the costs of manure application, good information on machine use, farm system, field location and manure management is required. The machine costs are based mainly on depreciation and use per year. Both have a significant influence on the costs. Contractors use their machinery more intensively than farmers do, and therefore a contractor machine will inevitably incur lower operating costs. On the other hand, a contractor charges for labour and other costs are increased. The time needed to complete the manure application depends on a number of parameters. The manure application rate and the payload of the tanker determine the number of refillings of the tanker for a specific field. The total refilling time depends on the distance to the storage, loading time and travel speed. The working width, working speed and headland turning times on the field determine the time for the actual spreading. Changes in these parameters affect the spreader capacity and thus the overall costs of manure application. Between countries, regions within a country and farms large differences may occur in the operational conditions for manure application. These differences will result in significant differences in the costs of manure application.

In this study some cost calculations are described. Other parameter settings will often result in different outcomes. The standardised model calculations enabled a meaningful comparison of the additional costs for the use of emission-reducing application techniques in different situations. A logical further stage in the research will be a cost/benefit analysis, which will allow an optimisation of the process of manure application in terms of ammonia losses *versus* costs.

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Appendix 6.1

Characteristics of manure application observed in various countries in Europe (Huijsmans et al., 2001b).

Country	Manure applied (m^3 y^{-1})	Spread capacity (m^3 h^{-1})	Machine costs (€ h^{-1})	Machine costs (€ y^{-1})	Costs of manure application (€ m^{-3})	Application technique [a]
Denmark	3,091	37	97.80	8,118	2.63	Broadcast + [b]
	2,798	36	100.95	7,925	2.83	Broadcast + [b]
Ireland	946	28	100.21	3,407	3.60	
	1,728	16	85.13	9,024	5.22	
	2,247	26	94.44	8,074	3.59	
	964	28	175.44	6,053	6.28	
	1,555	31	114.84	5,742	3.69	
Italy	12,600	31	65.65	26,390	2.09	
	24,500	34	56.73	40,502	1.65	
	6,260	38	88.28	14,522	2.32	
	8,075	38	85.86	18,116	2.24	
Netherlands	1,534	55	206.62	5,785	3.77	Shallow injection
	1,775	32	146.89	8,152	4.59	Shallow injection
	1,887	37	153.60	7,911	4.19	Shallow injection
	1,330	48	209.58	5,868	4.41	Shallow injection
	2,700	33	113.26	9,344	3.46	Trailing foot
Norway	600	16	106.30	3,880	6.47	
Sweden	800	22	196.82	7,184	8.98	
	800	22	285.43	10,418	13.02	Trailing hose
	1,600	18	118.51	10,606	6.63	
	1,600	18	154.64	13,841	8.65	Trailing hose
	1,600	24	222.35	14,786	9.24	Trailing hose
	1,600	24	255.96	17,277	10.80	Shallow injection
	4,800	20	112.52	27,510	5.73	Trailing hose
	4,800	19	120.41	30,645	6.38	Shallow injection
Switzerland	988	21	145.84	6,854	6.94	
	1,248	21	96.68	5,898	4.73	
	3,045	12	43.42	10,920	3.59	
England	290	23	266.01	3,325	11.47	
	5,460	36	82.46	12,493	2.29	

Appendix 6.1 (continued)

[a] In most countries manure is applied by a broadcast spreader (splash plate). For farms in the Netherlands and Sweden cost calculations included farms where manure is applied by trailing foot, trailing hose or shallow injector.

[b] The broadcast spreading on arable land in Denmark is followed by incorporation (broadcast +). No additional costs were taken into account for the latter tillage operation.

7

General discussion

7.1 Background and objectives

7.1.1 Background

In the 1980s and early 1990s, the environmental problems associated with the use of livestock manure became a major issue of the Dutch government's environmental policy. The need arose for an efficient recycling of nutrients to create a sustainable agricultural use of organic manure. Legislation was introduced to reduce both the leaching of nutrients into the environment and the emission of ammonia. Internationally the volatilization of ammonia from livestock manure also got attention (ECETOC, 1994; IPPC, 1996). National targets like the National Emission Ceilings (NEC) directive and National Environment Plan 4 (Anon., 2002a) were set for the total ammonia volatilization. Since 1980, volatilization of ammoniacal nitrogen from livestock manure was responsible for more than 90% of the contamination of the environment by ammonia in the Netherlands (Steenvoorden *et al.*, 1999; Anon., 2000). The annual ammonia volatilization from animal manure was estimated to be more than 200 million kg in 1980 and at about 150 million kg in 1998 and 1999. In 1980 the distribution of the total ammonia volatilization from agriculture over various sources was 37% from animal housing and manure storage, 56% from field application of manure and 7% from grazing cattle. In 1999, these contributions were 50, 41 and 9%, respectively (Anon., 2000). The reduction of ammonia volatilization from field-applied manure drew much attention, because this source contributed largely to the overall ammonia volatilization from livestock production, ammonia volatilization from field-applied manure implied a direct loss of the nutrient nitrogen, and reduction of ammonia volatilization after manure application seemed easily attainable at relatively low costs by technical measures.

The factors that affect volatilization of ammonia from manure and the emission of ammonia into the atmosphere can be grouped into four categories:

- chemical and physical properties of manure;
- meteorological factors;
- interaction between manure and the soil and crop, on which it is applied;
- application technique and incorporation technique.

Interactions between the above four categories may affect the overall volatilization.

The control of the process of ammonia volatilization after manure application to farmland interferes with the mechanisms, which underlie this process. Three main strategies to reduce ammonia volatilization when applying manure can be defined (Chapter 1):

- lower the ammonium concentration in the manure;
- reduce the formation of gaseous ammonia in the manure by lowering the pH of the manure;
- decrease the diffusion of gaseous ammonia by decreasing the contact area between manure and the ambient air.

Lowering the ammonia concentration in the manure can be achieved by adjustment of diet composition, and by dilution of the manure. Lowering the pH of the manure can be achieved by adding acid to the manure in the store, just before application on the field, or during application. The contact area between the manure and the ambient air can be reduced by new application techniques or by improving the infiltration of the applied manure into the soil. In the Netherlands, all three strategies to reduce ammonia volatilization were considered. Dilution of the manure and acidification (*e.g.* with nitric acid) were less feasible, because these measures were difficult to check in practice by supervising authorities. Much effort was put into new techniques for the application and incorporation of manure. The search for new techniques was mainly based on decreasing the contact area between the applied manure and the ambient air.

7.1.2 Objectives

Central theme of this thesis is the evaluation of techniques for the application and incorporation of manure on farmland directed to reduce ammonia volatilization. The efficiency of different techniques of application and incorporation on grassland and arable land in relation to ammonia volatilization was addressed as well as the influence of various conditions on the volatilization. On arable land also the effect of the work organization of manure application and manure incorporation on ammonia volatilization was investigated. For grassland, the application techniques were also evaluated with respect to the draught force required for the application techniques as this may be of influence on the adoption and use of these techniques. Finally, techniques for the application and incorporation of manure, which can be readily adopted by farmers, were subjected to an economic evaluation.

7.2 Research approach

7.2.1 Data

The present study of factors affecting ammonia volatilization following the application or incorporation of manure benefited from a unique set of data available from field measurements on grassland and arable land in the Netherlands. These measurements were primarily conducted for the Dutch government as an inventory of emission levels, and to quantify the relative differences in ammonia volatilization between various application techniques in order to approve and prescribe certain techniques for application in practice. The measurements of ammonia volatilization on grassland and arable land, and the draught force measurements on grassland were all performed under practical conditions. Weather and soil conditions were those at the time of the year when in common practice manure is (allowed to be) applied (February-October). Manures used were obtained from the farms where measurements were performed or from a nearby store. The composition of the manures (Chapters 2 and 3) represented nowadays contents of dairy and pig manures in the Netherlands, both in average contents of ammonia and in the variation thereof (Anon., 2002b). The total ammoniacal nitrogen (TAN) content and the total nitrogen content of the manures were high compared to that of other countries in Europe (Søgaard *et al.*, 2002).

7.2.2 Methodology

The ammonia volatilization rate from applied manure decreases with time. The impact of the atmospheric conditions on total volatilization is highest during the first few hours after application. Information on the effect of factors influencing the magnitude of volatilization during a certain period of the process cannot be utilized adequately when expressing the cumulative volatilization as a function of time after application or incorporation only. Therefore, an analysis of the volatilization profile on the basis of the temporal volatilization rate was better suited for studies intended to gain insight into factors affecting the volatilization process. The statistical analysis of the data, together with the models that were designed, yielded valuable information about the factors that influence ammonia volatilization, and about the magnitude of their effects (see Section 7.2.3). However, part of the variation could not be explained from the factors measured in the experiments. Additional factors that came forward as being possibly responsible for variation in volatilization results are differences within techniques in the positioning of the manure relative to the soil, and the soil structure (loose or compact) at the moment of manure application and incorporation on arable land. Knowledge and inclusion of hitherto unknown factors could improve the prediction and subsequent calculation of volatilization. The unidentified factors may be responsible for the large confidence intervals of predictions of the total volatilization for a certain application technique at a random location and a random point in time (Tables 3.5 and 3.6).

7.3 Main effects

Ammonia volatilization was affected by the application or incorporation technique in all circumstances. Tables 7.1 and 7.2 summarize the factors influencing volatilization on grassland and arable land, respectively. A reduced contact area between the manure and the ambient air and a larger surface area for infiltration of the manure into the soil probably accounted for the effect of application and incorporation techniques that reduce ammonia volatilization.

Table 7.1. Effect of external variables on ammonia volatilization after manure application on grassland by various application techniques ($P < 0.05$).

Influencing variable	Application technique		
	Surface spreading	Narrow bands	Shallow injection
TAN [a] content of manure	+	+	+
Application rate	+	+	+
Wind speed	+	+	+
Grass height	NS	-	NS
Radiation	+	NS	+
Air temperature	NS	+	+
Relative humidity	NS	-	NS

+ : positive effect (*i.e.* volatilization increases with an increase of the magnitude of the variable).

- : negative effect, NS: no significant effect.

[a] TAN, total ammoniacal nitrogen ($NH_4^+ + NH_3$).

On grassland the mean cumulative volatilization was estimated to be 77% of the total ammoniacal nitrogen (TAN) applied for surface spreading, 20% for narrow-band application and 6% for shallow injection. On arable land the mean total volatilization was 68% of the TAN applied for surface spreading, 17% for surface incorporation and 2% for deep placement. On grassland, narrow-band application and shallow injection caused an average reduction of ammonia volatilization of 74% and 92%, respectively, compared with surface spreading. Similarly, on arable land, surface incorporation and deep placement reduced ammonia volatilization by 75% and at least 95%, respectively, compared with surface spreading. These relative reduction data were of importance for the approval of application techniques in the Netherlands.

On grassland manure was surface-spread on top of the grass, which may act as a physical barrier against infiltration, whereas in the case of narrow-band application and shallow injection manure may have infiltrated easier due to the direct contact with the soil. Moreover, when surface-applied, manure has a relatively large contact area with the ambient air, because the manure mainly covers the grass. On the other hand, narrow-band application and shallow injection leave the manure only in contact with the ambient air through a small band or *via* the opening of the injection slit, and smothering of grass leaves with manure is

Table 7.2. Effect of external variables on ammonia volatilization after manure application and incorporation on arable land by various application techniques ($P < 0.05$).

Influencing variable	Application technique		
	Surface spreading	Surface incorporation	Deep placement
TAN [a] content of manure	+	+	+
Application rate	+	+	+
Wind speed	+	+	NS
Air temperature	+	+	+

+ : positive effect (*i.e.* volatilization increases with an increase of the magnitude of the variable).

- : negative effect, NS: no significant effect.

[a] TAN, total ammoniacal nitrogen (NH_4^+ + NH_3).

prevented. Shallow injection further restricts the contact of the manure with the ambient air by placing the manure into the soil. The effect of grass height on ammonia volatilization from narrow-band-applied manure may be due to a change in microclimate around the manure, leading to lower volatilization rates at higher grass heights.

On arable land the contact area between the manure and the ambient air is more reduced by deep placement than by surface incorporation, and may therefore account for the lower volatilization compared to surface incorporation. In the same way, volatilization after shallow injection on grassland was lower than after narrow-band application.

Cumulative ammonia volatilization from surface-applied manure on grassland varied from 27 to 98% of the TAN applied. With narrow-band application the volatilization varied from 8 to 50%, and with shallow injection from 1 to 25% of the TAN applied. The cumulative ammonia volatilization from surface-applied manure on arable land as measured over all experiments, varied from 34 to 100% of the TAN applied. With surface incorporation volatilization varied from 3 to 49%, and with deep placement from 0 to 5% of the TAN applied.

The ammonia volatilization rate was affected by weather conditions. With each of the techniques, the ammonia volatilization rate increased by weather conditions that favour drying, such as by an increase in wind speed, air temperature and radiation, or by a decrease of the relative humidity. An increase of the mean ambient temperature from 10 to 20°C resulted in an increase in total volatilization by more than 50% (Chapters 2 and 3). Evaporation of water from the manure is known to lead to an increase of the aqueous ammonia concentration in the manure and to an increase in ammonia volatilization (Chapter 1). The effect of wind speed on the ammonia volatilization rate can also be explained by an increased diffusion rate of ammonia into the air. Volatilized ammonia is removed by the wind, and the ammonia concentration in the air above the manure remains relatively low, stimulating further ammonia volatilization. An increase in TAN content and application rate did not lead to significant increases of the volatilization, expressed as % of the TAN applied. However, the volatilization in kg ha^{-1} was increased (about linearly) with an increase of the TAN content and of the application rate due to a larger source of ammonia (Chapter 3).

Ammonia volatilization from field-applied manure has been reported to be affected by weather conditions, manure characteristics, soil conditions and crop cover (Brunke *et al.*, 1988; Sommer *et al.*, 1991; Bussink *et al.*, 1994; Braschkat *et al.*, 1997). Many investigations examined only one of the factors influencing ammonia volatilization. Relatively little attention was paid to the influencing factors in combination with various application techniques of manure. In the present study a number of factors were shown to influence ammonia volatilization for the different application techniques and incorporation techniques (Tables 7.1 and 7.2; Chapters 2 and 3). No effect was found of soil type, soil moisture content, type of manure, dry matter content and pH of the manure on the ammonia volatilization rate. The little variation in these variables in the data set could explain why no effect was found. However, the effect of the type of manure was indirectly assessed by the influence of the TAN content of the manure, which was higher in the pig manure than in the dairy manure. Recently, data on ammonia volatilization were gathered from various European countries through the framework of the European research project ALFAM (Ammonia Losses from Field-applied Animal Manure; Sommer *et al.*, 2001). The analyses of this large data set (including the data from Chapter 2) showed the soil water content, air temperature, wind speed, manure type, dry matter and TAN content of the manure, application rate, application technique, and incorporation as influencing factors (Søgaard *et al.*, 2002). Counteracting effects of a decrease in wind speed and an increase of air temperature on the volatilization were found as in this thesis. The study by Søgaard *et al.* and the results from this thesis show that large data sets are necessary to identify and quantify all factors influencing ammonia volatilization.

7.4 Environmental implications

The different aspects of manure application addressed in this thesis have implications for environmental policy and its implementation. At the moment Dutch policy is based on prescription of application techniques. On farm level other factors may be of similar importance for ammonia volatilization. Field and weather conditions (7.1), work organization of manure application and incorporation on arable land (7.2), required draught force (7.3), and the costs (7.4) may all have an effect on the ammonia volatilization and the feasibility of a technique for the farmer.

7.4.1 Field and weather conditions

Inclusion of the effect of the influencing factors on the volatilization has a high potential for practical application and for deepening the insight into the actual ammonia volatilization following the application and incorporation of manure. This insight is important when evaluating total ammonia volatilization on an annual national basis. In nowadays annual evaluations fixed volatilization percentages are used for the different application and incorporation techniques (Steenvoorden *et al.,* 1999). The conditions influencing the volatilization during manure application are not accounted for. However, the results of this thesis show that these conditions may be of much importance.

Narrow-band application and shallow injection on grassland, and incorporation (surface or deep) of the manure on arable land can reduce ammonia volatilization considerably, compared with surface spreading. However, differences between conditions under which the application techniques are used affect the overall reduction of ammonia volatilization. In the Netherlands, volatilization-reducing application techniques were prescribed in the 1990s. In this period it also became forbidden to apply manure outside the growing season (*i.e.* not in autumn and winter) on grassland and on sandy arable land. Before these prescriptions, surface spreading was common and manure was also applied outside the growing season, when the mean ambient temperature is lower. Conditions favouring volatilization are more often met in spring and summer than in autumn and winter. Thus, when comparing the national annual ammonia volatilization between the 1980s and the years beyond 1990, not only the application technique and incorporation technique used, but also the time of the year when manure was applied should be taken into account. Since the 1990s more manure was applied under volatilization favouring conditions. Thus, the contribution of the introduction of the volatilization-reducing techniques in the 1990s to the overall reduction in ammonia volatilization may have been less than predicted, when fixed volatilization percentages are used for the different techniques of application and incorporation.

Nevertheless, the present study shows that prescribing or convincing farmers to inject or incorporate manure will help substantially to control contamination of the environment caused by ammonia volatilization from field-applied manure.

7.4.2 Work organization

When assessing measures to reduce the ammonia volatilization after application and incorporation of manure on arable land, next to the circumstances and the technique of incorporation, the work organization is of great importance (Chapter 5). Deep placement with a mouldboard plough yielded more reduction of ammonia volatilization than surface incorporation by a rigid tine cultivator (Chapter 3). However, in the measurements the effect of a time-lag between surface spreading and incorporation on the ammonia volatilization was not accounted for. On experimental plots manure was directly incorporated and the time-lag was as short as feasible. In practice on whole field scale, direct incorporation is not always achievable. There will always be some time between surface spreading and incorporation and during this time volatilization of ammonia from the surface-applied manure takes place. A model study showed that incorporation by a mouldboard plough does not always result in lower ammonia volatilization than incorporation by a rigid tine cultivator (Chapter 5). The lower capacity of the plough may result in a larger overall time-lag between spreading and incorporation, and by consequence the reduction of volatilization may be lower than that with the rigid tine cultivator, despite the higher potential for reduction of volatilization by the mouldboard plough. The time-lag between spreading and incorporation is an important factor when assessing ammonia volatilization from manure applied and incorporated on arable land. In case of deep placement by injection the time-lag is zero and low volatilization rates can be achieved (Chapter 3). Advicing or prescribing injection or a work organization that minimizes the time-lag between application and incorporation may be effective to control ammonia volatilization from manure applied to arable land.

7.4.3 Draught force

Injection of liquid manure into grassland was the first measure considered to reduce ammonia volatilization. However, Wadman (1988) estimated that only 33% of the grassland in the Netherlands is suitable for injection. The draught force required, the crop damage along the slit on various soil types, and the remnants of tree stubs in the soil often prohibit injection. Thus other application techniques for grassland were developed to reduce ammonia volatilization from field-applied manure under Dutch circumstances. Either these new techniques cut a shallow slit into the sward and the manure is applied into the slit (shallow injection), or the manure is applied in narrow bands onto the soil surface using a trailing-foot implement. These techniques require low draught force compared with conventional deep injectors.

The application technique, working depth and soil conditions can have a major influence on the required draught force (Chapter 4). With increasing soil moisture content the required draught force decreases. Draught force requirement increases with increasing working depth. The increase depends on the injector design. Relative to dry soil conditions, manure injection on grassland under wet soil conditions is a practical way to reduce draught force requirement (Chapter 4). However, under wet conditions the rolling resistance of the implement tyres increases and the traction potential of drive wheels decreases rapidly, both causing an increased risk of sward damage. Furthermore, on clay soil the walls of the injection slits may be smeared under wet soil conditions, leading to a poorer infiltration of the manure into the soil and so causing the risk of more ammonia volatilization. Also the smeared slit walls may become hard when dry, and the slits may remain open for a long period. In contrast to wet conditions, the application of manure under very dry soil conditions may lead to an insufficient working depth and to sward damage due to the fact that grass sods are torn out easily.

In general, shallow injection at reduced depth will lower the draught force. However, in this case the slit in the sward may not offer sufficient space for the manure applied. Insufficient space in the slit may result in an effect on ammonia volatilization that is in between that of narrow-band application and shallow injection. Thus shallow injection at reduced depth may eventually result in a higher ammonia volatilization than in case of shallow injection at sufficient depth. In nowadays practice application of manure at reduced depth increases and has resulted in the development of techniques with a larger working width or in less draught requirement as measures to reduce the costs of manure application (Chapter 6). Application at reduced depth is also named “shallow injection”, but the envisaged reduction of ammonia volatilization (Chapter 2) may not be achieved.

In general, the proper use of manure application techniques and application at favourable soil conditions is crucial to achieve the potential reduction of ammonia volatilization and other expected benefits.

7.4.4 Costs

The machine costs for manure application are based mainly on depreciation and use per year. Both significantly influence the costs (Chapter 6). Contractors use their machinery more intensively than farmers do, and therefore a contractor’s machine will inevitably incur lower operating costs. On the other hand, a contractor charges for labour and other costs are increased. Contractors may invest in large scale application techniques (working width, power required for the draught force) to have enough capacity to serve their clients in time. When investing in large machinery, manure should still be injected properly and at sufficient depth to achieve efficiency in reducing ammonia volatilization.

Economics will always be a point of consideration by farmers to run a sustainable enterprise with perspective. In Chapter 6 various elements of costs associated with available application techniques for manure were highlighted. Apart from the costs of volatilization-reducing application there may be returns (*i.e.* saving nutrients and returns in view of environmental benefits). These factors should also be quantified in order to be able to optimize the process of manure application in terms of ammonia losses *versus* costs.

7.5 Perspectives

In this thesis different aspects of manure application in relation to ammonia volatilization are addressed. Other aspects of manure application may also affect the way manure should be applied nowadays or in the near future. Odour and greenhouse gases from manure applied to farmland are topics of public interest. Also efficient utilization of nutrients (including total ammoniacal nitrogen) applied with manure, and reduction of emission of nitrogenous compounds are important considerations within an environmental policy, and may as such have impact on manure application techniques. On the long term, soil compaction may increase due to the use of larger and heavier application equipment. Compaction may be overcome by the use of umbilical systems, but still care should be taken for proper manure application. A different perspective is the bird protection point of view. The introduction of narrow band spreading, (shallow) injection, and incorporation may be more harmful to nesting birds in the spring period than the use of surface spreading.

7.6 Conclusion

In any situation ammonia volatilization from livestock manure applied on farmland is substantially reduced by appropriate techniques for the application and incorporation of manure.

Actual environmental conditions under which manure is applied, including field and weather conditions, manure composition and manure application rates, also substantially affect the overall ammonia volatilization.

Thus, when reliable predictions of ammonia volatilization are required, for example for farm management or for a national approach to abate ammonia volatilization, both the techniques for application and incorporation, and factors influencing ammonia volatilization must be taken into account.

Sufficient information is available to supply sound and workable guidelines for the application and incorporation of manure to farmers and policy makers. These guidelines must include the work organization, in case of manure incorporation on arable land, and can replace the current use of a fixed volatilization percentage for each technique.

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Summary

Manure applied on farmland is an important source of ammonia (NH_3) volatilization. Ammonia volatilization has in various ways a negative impact on the environment. In the Netherlands, ammonia from livestock manure is by far the most important source of environmental contamination with ammonia. The reduction of NH_3 volatilization from manure applied to farmland is an important instrument in the Dutch environmental policy. Measures to reduce NH_3 volatilization after manure application were considered easy to introduce at relatively low costs. The need arose for more knowledge about the quantity of the NH_3 volatilization and for practical tools to reduce NH_3 volatilization from manure applied to farmland.

The research in the framework of this thesis dealt with the effect of different techniques for application and incorporation of manure on NH_3 volatilization. Furthermore, the draught force required for the application techniques on grassland, and the effect of the work organization on NH_3 volatilization, when incorporating manure on arable land, were addressed. Finally, the techniques for the application and incorporation of manure were subjected to an economic evaluation.

Manure application techniques and NH_3 volatilization

A database of field measurements in the Netherlands from 1989 to 1998 was analysed to identify factors that effect the volatilization of NH_3 from manure applied by various techniques on grassland and arable land. Experiments were carried out in different periods of the year and on different fields, to cover a large range of soil and weather conditions. Factors analysed were application technique, characteristics of the manure, and weather and field conditions. For different techniques of application and incorporation NH_3 volatilization was compared with that after broadcast surface spreading. The statistical analysis of the data, together with the models that were designed, yielded valuable information about the factors that influence NH_3 volatilization, and about the magnitude of their effects.

On **grassland**, narrow-band application and shallow injection significantly reduced NH_3 volatilization, compared with broadcast surface spreading. The mean cumulative volatilization for surface spreading was estimated to be 77% of the total ammoniacal nitrogen (TAN) applied by the manure, 20% for narrow-band application and 6% for shallow injection. The TAN content of the manure, the manure application rate and the weather conditions substantially influenced the NH_3 volatilization rate. The volatilization rate increased with an increase in TAN content of the manure, manure application rate, wind speed, radiation, and air temperature. The volatilization rate decreased with an increase in the relative humidity. The identified influencing factors and their magnitude differed with the application technique. Grass height affected NH_3 volatilization when manure was applied in narrow bands.

On **arable** land, the mean total volatilization, expressed as % of TAN applied, was 68% for surface spreading, 17% for surface incorporation and 2% for deep placement. The volatilization rate increased with an increase in TAN content of the manure, manure application rate and air temperature. When manure was surface applied or surface incorporated, the wind speed had a substantial increasing effect on the volatilization rate.

Draught force on grassland

To assess the suitability of the application techniques under various conditions in practice, the draught force required for the various techniques on grassland needed to be known. In a series of experiments on sandy loam, clay and peat soils, the draught force requirement of a trailed sliding foot element and four new different shallow injection elements was investigated. The application technique, working depth and soil circumstances had a significant influence on the draught force requirement of the injection elements. The lowest draught forces were required on peat soil and the highest forces on dry clay. The trailing foot required a low draught force compared with the injection techniques. The draught force of the trailing foot did not relate to the soil circumstances.

Work organization on arable land

On arable land the work organization, *i.e.* the time-lag between application and incorporation of the manure, is of importance for the reduction of NH_3 volatilization. In practice, there will always be some time between spreading and incorporation of manure, and during this time NH_3 volatilizes from the surface-applied manure. To assess the NH_3 volatilization after spreading and incorporation of manure, the time-lag between these two operations was predicted *via* computer simulation. In a case study, it was shown that incorporation by a mouldboard plough (deep placement) does not always result in lower NH_3 volatilization than incorporation by a fixed tine cultivator (surface incorporation), due to the relatively lower capacity of the plough and the resulting larger time-lag. The time-lag between spreading and incorporation should be considered when assessing NH_3 volatilization. The developed model is a useful and comprehensive instrument to evaluate the effect on NH_3 volatilization of different management strategies for manure spreading and incorporation on a plot scale.

Costs

Favourable economics of handling and application of manure are of fundamental importance to encourage the implementation of application techniques that reduce volatilisation. A model was developed to calculate the costs and time requirements of manure application. The costs of application techniques designed to reduce NH_3 volatilization were assessed and compared with the costs of conventional broadcast spreading across a range of farm characteristics. Data on factors affecting the costs were used from different countries in Europe.
The calculations showed that for a range of farm characteristics and an annual manure production of 1,000 to 3,000 m^3, the costs of manure application by volatilization-reducing techniques were *ca* 2 € per m^3 higher than for broadcast spreading. The cost difference between broadcast spreading and the other application techniques decreased with increasing farm size. The average additional costs of manure application by a trailing foot or a shallow injector decreased, when the fertiliser value of the nitrogen was taken into account. The field application itself took less than 50% of the total operating time in the process of the handling and application of the manure.

Conclusion

Ammonia volatilization from animal manure applied on farmland is reduced considerably by appropriate application techniques and incorporation techniques. The environmental conditions and the composition of the applied manure have a substantial effect on the overall NH_3 volatilization.
Only when both the techniques of application and of incorporation, and factors influencing volatilization are taken into account reliable predictions of the NH_3 volatilization for farmers as well as for the national approach of the abatement of NH_3 volatilization can be made.
The results of the study supply sound and workable guidelines for the application and incorporation of manure to farmers and policy makers.

Samenvatting

Uitrijden van dierlijke mest op landbouwgrond gaat gepaard met de emissie (vervluchtiging) van ammoniak. Dierlijke mest is in Nederland de grootste bron van milieuvervuiling door ammoniak. Een belangrijk doel van het Nederlandse milieubeleid is het terugdringen van de ammoniakemissie bij het uitrijden van mest. Maatregelen om de emissie bij het uitrijden van mest te beperken leken eenvoudig te introduceren tegen relatief lage kosten. Behoefte ontstond aan meer kennis over de werkelijke omvang van de ammoniakemissie en aan praktische maatregelen om de ammoniakemissie bij het uitrijden van mest te verminderen.

Het onderzoek beschreven in dit proefschrift gaat over het emissiebeperkend effect van verschillende toedienings- en onderwerktechnieken van mest onder praktijkomstandigheden. Hierbij is ook de trekkracht onderzocht die nodig is bij emissiebeperkende technieken voor het uitrijden van mest op grasland. Voor bouwland is het effect op de ammoniakemissie onderzocht van de tijd tussen het toedienen en onderwerken van mest (de werkorganisatie). Tot slot zijn de kosten van emissiebeperkende mesttoediening berekend.

Mesttoedieningstechnieken en ammoniakemissie

Gegevens van veldproeven, uit de periode 1989-1998, zijn geanalyseerd om vast te stellen welke factoren van invloed zijn op de ammoniakemissie bij het toedienen en onderwerken van mest met verschillende technieken. De veldproeven waren uitgevoerd op verschillende tijdstippen in het jaar en op verschillende proefvelden, zodat gegevens onder allerlei bodem- en weersomstandigheden verkregen werden. Onderzochte factoren waren de toedieningstechniek, de mestsamenstelling en de weer- en veldomstandigheden. De gemeten ammoniakemissies bij verschillende technieken van toedienen en onderwerken werden vergeleken met de emissie bij het gebruikelijke bovengronds breedwerpig verspreiden van de mest. De statistische analyse van de gegevens en de ontwikkelde modellen gaven samen belangrijke informatie over welke factoren van invloed zijn op de emissie en over de grootte van de effecten.
Op **grasland** gaven mesttoediening in stroken met een sleepvoetenmachine en zodenbemesting een aanzienlijke vermindering van de emissie ten opzichte van bovengrondse breedwerpige toediening. De totale emissie was 77% van de ammoniakale stikstof die met de mest werd toegediend bij breedwerpige toediening, 20% bij mesttoediening met een sleepvoetenmachine en 6% bij zodenbemesting. Diverse factoren beïnvloedden de emissie. De emissie nam toe bij een verhoging van het gehalte aan ammoniakale stikstof in de mest, de

mestgift, de windsnelheid, de zonnestraling en de luchttemperatuur. De emissie nam daarentegen af bij een verhoging van de relatieve luchtvochtigheid. Welke factoren de emissie beïnvloedden verschilde per toedieningstechniek. De grashoogte was van invloed op de emissie bij de mesttoediening met een sleepvoetenmachine.

Op **bouwland** was de gemiddelde totale emissie, uitgedrukt in percentage van de met de mest toegediende ammoniakale stikstof, 68% bij bovengrondse breedwerpige toediening, 17% bij oppervlakkig inwerken en 2% bij diep inwerken van de mest. De emissie nam toe bij een verhoging van het gehalte aan ammoniakale stikstof in de mest, de mestgift en de luchttemperatuur. Bij bovengronds breedwerpige toediening en oppervlakkig inwerken had de windsnelheid een aanzienlijke invloed op de emissie.

Trekkracht op grasland

De trekkracht nodig voor verschillende emissiebeperkende machines, die toegepast worden op grasland, is onderzocht onder verschillende omstandigheden in een serie proeven op zand-, klei- en veengrond. De benodigde trekkracht werd gemeten van een sleepvoetenmachine en vier verschillende zodenbemestertechnieken. De injectietechniek, de werkdiepte en de bodemomstandigheden beïnvloedden de trekkrachtbehoefte van de zodenbemesters. De laagste trekkracht was nodig op veengrond en de hoogste op droge kleigrond. De sleepvoetenmachine vereiste duidelijk minder trekkracht dan de zodenbemesters. De trekkracht vereist voor de sleepvoet werd niet beïnvloed door de bodemomstandigheden.

Werkorganisatie op bouwland

Op bouwland is de werkorganisatie van belang voor de ammoniakemissie. Bij meer tijd tussen het toedienen en onderwerken van mest neemt de emissie toe, omdat gedurende deze tijd een deel van de ammoniak uit de toegediende mest vervluchtigt. Een simulatiemodel werd ontwikkeld om de invloed van de tijd tussen het toedienen en onderwerken bij verschillende werkmethodes op de resulterende ammoniakemissie te berekenen. Het onderwerken met een ploeg (diep inwerken) gaf niet altijd een lagere emissie dan het inwerken met een cultivator (oppervlakkig inwerken). Het ontwikkelde model bleek een effectief instrument te zijn voor het betrouwbaar berekenen van het effect op de emissie bij verschillende strategieën voor het toedienen en het onderwerken van mest.

Kosten

Aanvaardbare kosten voor het toedienen met emissiebeperkende technieken van mest zijn van groot belang voor een snelle praktijktoepassing van deze technieken. Voor een reeks bedrijfssituaties werden de kosten van emissiebeperkende technieken met een model berekend en vergeleken met de kosten voor het conventioneel bovengronds breedwerpig verspreiden van mest. Hiervoor werden gegevens gebruikt uit verschillende landen in Europa. De berekeningen gaven aan dat voor een reeks van bedrijfssituaties en een mestproductie van 1.000 tot 3.000 m^3 per jaar, de kosten van een emissiebeperkende mesttoediening *ca* 2 € per m^3 mest hoger waren dan van bovengrondse breedwerpige toediening. Het kostenverschil nam af bij toenemende bedrijfsgrootte. De gemiddelde meerkosten van mesttoediening met een sleepvoetenmachine of zodenbemester namen af als de bemestende waarde van de stikstof uit de mest verrekend werd. De tijd voor het werkelijk toedienen van de mest was minder dan 50% van de totale werktijd nodig voor alle werkzaamheden gezamenlijk bij de toediening van de mest.

Conclusie

Ammoniakemissie uit op het land toegediende dierlijke mest vermindert aanzienlijk door het gebruik van geschikte toedienings- en onderwerktechnieken. De omstandigheden tijdens en na de mesttoediening en de samenstelling van de mest bepalen mede de hoogte van de ammoniakemissie.

Betrouwbare schattingen van de ammoniakemissie voor de bedrijfsvoering en voor het nationale emissiebeleid kunnen alleen gemaakt worden indien zowel de toedienings- en onderwerktechniek als de invloed van de mestsamenstelling en weer- en veldomstandigheden op de emissie hierbij betrokken worden.

Op grond van de gerapporteerde resultaten kunnen goed werkbare richtlijnen worden opgesteld voor het toedienen en onderwerken van mest.

Dankwoord

Dankwoord

“Nooit geweten dat jij aan een proefschrift werkte”….”Ik dacht dat je er al lang mee gestopt was”….”Hè, hè, rond je het nu eindelijk eens af”….”Met die laatste loodjes ging je wel erg relaxed om”.
Uitspraken die aangeven dat promoveren enige tijd in beslag neemt en dat voor mij het promoveren geen must is. Na de publicatie van een aantal artikelen kreeg ik er pas een goed gevoel bij om het als geheel in een proefschrift op te schrijven.

Sedert mijn werk op het IMAG ben ik betrokken geweest bij de problematiek rond het mest uitrijden, veelal onderzoeksinhoudelijk maar ook beleidsmatig. Een belangrijk aspect bij het mest uitrijden was het beperken van de ammoniakemissie. Het onderzoek dat ten grondslag ligt aan dit proefschrift heeft zijn toepassing gevonden in de manier waarop mest behoort te worden uitgereden in Nederland om de ammoniakemissie te beperken. Het uitgevoerde onderzoek geeft aan dat er nog mogelijkheden zijn de emissie verder te beperken indien rekening wordt gehouden met allerlei factoren die van invloed zijn op de emissie. De methode van uitrijden bleek een effectieve manier om tot emissiereductie te komen. Het onderwerp geniet nog steeds een brede (internationale) belangstelling. Een interessant onderwerp waar enthousiast aan gewerkt is en nog steeds enthousiast aan gewerkt kan worden.

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Maaike en Annemiek: papa weet al genoeg over poep. Jullie kunnen de emissie verminderen door snel zindelijk te worden.

Curriculum vitae

Johannes Fredericus Maria (Jan) Huijsmans werd op 19 november 1960 geboren in Bergen op Zoom. In 1979 behaalde hij aldaar het diploma Voorbereidend Wetenschappelijk Onderwijs (Atheneum-B) aan het Mollerlyceum. Vervolgens startte hij aan de Landbouwhogeschool te Wageningen, met de studie Landbouwtechniek. Deze studie rondde hij in 1985 af met specialisaties Landbouwwerktuigkunde, Wiskunde (Optimaliseringstechnieken), Meet-, Regel- en Systeemtechniek, Landbouwplantenteelt en Agrarische Bedrijfseconomie. Zijn stage doorliep hij aan de universiteit van Noord Dakota (VS).

Na zijn afstuderen werkte hij tot 1987 bij New Holland Company te Zedelgem in België bij de ontwikkelingsafdeling, als verantwoordelijke voor het veldtesten van nieuwe prototypen maaidorsers voor verschillende gewassen in diverse landen.

Sinds 1987 werkt hij bij het Instituut voor Milieu- en Agritechniek (IMAG) in Wageningen als wetenschappelijk onderzoeker, afdelingshoofd Bodem en Teelt, clusterleider Toedieningstechnologie en Emissies, plv. hoofd Precisielandbouw en Management en momenteel als groepsleider Duurzame Teelttechniek. Gedurende deze periode heeft hij onderzoek verricht naar methoden voor de toediening van dierlijke mest op het land met speciale aandacht voor beperking van de ammoniakemissie. Later werd het werkveld uitgebreid met het onderzoek naar de toediening van gewasbeschermingsmiddelen en de driftbeperking.

Bij het mestonderzoek werd geparticipeerd in 3 EU-projecten: ALFAM (Europese database ammoniakemissie na mesttoediening en economische aspecten emissiebeperkende mesttoediening), SWAMP (verbeterde toediening en benutting van organische mest binnen de landbouw) en ROSA (mesttoediening en benutting van vaste organische (mest) produkten binnen de landbouw).

Vanuit het mest- en gewasbeschermingsonderzoek is hij werkzaam geweest in verschillende commissies en werkgroepen voor de advisering van overheidsbeleid. Daarnaast is hij betrokken geweest bij diverse nationale studies over milieuaspecten bij veldtoepassingen van mest en gewasbeschermingsmiddelen.

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