Environmental aspects of improving sow welfare with group housing and straw bedding

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ABSTRACT

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Environmental aspects of improving sow welfare with group housing and straw bedding. PhD thesis, Wageningen University, Wageningen, The Netherlands (146 pp with summaries in English and Dutch).

After intensifying pig husbandry in the second half of the 20th century to improve economical development, public concern brought about legislation to secure animal welfare and ecological values. The development of welfare-friendly sow husbandry in recent years focussed mainly on two purposes: to keep sows loose in groups and to provide the sows with straw bedding. The main objective of this research was to establish the effect on ammonia emission of group housing and straw bedding, and eventually to find tools to reduce the emission. With straw bedding, the greenhouse gases methane and nitrous oxide were also considered, because environmental goals are not served by pollution swapping. The results showed that group housing of sows does not increase ammonia emission compared to individual housing of sows. Given appropriate straw management, providing a straw bed reduces ammonia emission, and emissions of methane and nitrous oxide are not substantial. However more research is needed in order to understand the conditions for low greenhouse-gas emissions. Although the measured effect was modest, shifting feeding time might be a tool to reduce ammonia emission. A model was developed to estimate ammonia emission from a sow house with group housing and straw bedding as the sum of the emissions from straw, solid floors, slatted floors and pits after urinations. The results of simulations show that measures to reduce ammonia emissions are most effective if aimed at decreasing the emission from the solid floor and stimulating relatively more urinations on the straw bed. The model appeared to be a useful tool for designing straw-bedded sow group-housing with low ammonia emissions.

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*) 313-322. Chapter 3 was published as *Journal of Agricultural Engineering* 65, *(1996)*: 269-274. Chapter 4 was accepted by *Biosystems engineering.* Chapter 5 was submitted to *Biosystems engineering*. 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 journal article(s).

1

General introduction

The studies presented in this thesis aimed at elucidating the consequences of improving the welfare of sows on the emission of polluting gases from the sow house. They were based on the premise that it is undesirable to have a conflict of interests in sustainability between improvement of animal welfare and maintaining an ecologically sound environment. The development of welfare-friendly sow husbandry in recent years has had two main purposes: to keep sows loose in groups and to provide the sows with straw bedding. Both of these changes affect the environment, particularly via the emission of the acidifying gas ammonia. As well as examining aspects of ammonia emission, the research reported in this thesis also considered straw bedding in terms of its implications for pollution swapping, i.e. less emission of ammonia, but more emissions of the greenhouse gases methane and nitrous oxide.

1. Background

In the second half of the 20th century, pig husbandry was intensified in pursuit of maximum production. In the Netherlands, the number of farms was reduced by a factor of five and the number of pigs increased fivefold (see the review by Groenestein (2003) and CBS, 2006). In the first 20 years of the intensification, however, improvement of technical results lagged behind. To make pig production more profitable, from around 1970 to 1980 many changes were implemented in housing, climate control, feeding management, breeding and preventive health care. Since then, the technical results have improved considerably (Table 1.1).

Table 1.1. Technical results of pig production from 1965 to 2000 in the Netherlands (review by Groenestein, 2003).

	1965	1970	1980	1990	2000
Breeding					
Piglets/litter raised	8.9	8.7	8.5	9.3	9.9
Litters per sow per year	1.66	1.72	1.85	2.20	2.28
Piglets per sow per year	14.8	15.0	15.7	20.5	22.6
Fattening					
Growth per day (g)	547	563	610	719	770
Feed per day (kg)	1.99	1.95	2.04	2.07	2.04
Feed Conversion Ratio	3.64	3.47	3.4	2.88	2.65
Mortality (%)	3.9	3.6	2.7	2.1	2.1

The changes meant that sows were no longer kept in groups and on pasture, but

inside, individually in crates or tethered, on partly slatted floors and fed restrictedly. The notion grew that the welfare of the sows kept under these conditions was poor (Fraser & Broom, 1990) and would improve if they were kept in groups again (Jensen, 1988; Webster, 1994). Concern for the welfare of pigs was not confined to the Netherlands; it was also expressed throughout the European Union. In 1991, therefore, the European Union adopted minimum standards for the protection of pigs, including sows (Council Directive 91/630/EEC). The Dutch government followed this Directive in 1994 with a national policy on pig welfare (Varkensbesluit).

As well as the concern for animal welfare, there was also concern – particularly among the general public – about the impact of intensive husbandry on the environment. Water and soil were being eutrophied by the high loads of phosphorus and nitrogen being released from the surplus of manure (Voorburg & Ciavatta, 1993), and the gas ammonia (NH_3) was having an acidifying and eutrophying effect (Asman, 1987). In 1989 NH_3 was responsible for 46% of the acidification in the Netherlands; 94% of the emissions were from livestock production (Heij & Schneijder, 1995).

Public concern for animal welfare and environment came to a climax in 1997, mobilised by the outbreak of Classical Swine Fever which revealed the vulnerability of the pig production sector. Additionally, British supermarkets stated to buy only pork and bacon from pigs of sows reared in groups (Brinkman, 1997). In 1998 the Dutch government responded by introducing policy to reconstruct the sector. The aim was to reduce the manure surplus, improve pig welfare, prevent and cure animal disease, and reduce the pressure of concentrations of pig production on landscape, environment and society (Anonymous, 1997). With respect to ammonia, this resulted in legislation to achieve an 80% reduction in the total emission from livestock production in 2030 compared with 1990 (Anonymous, 2001). The new policy, laid down in 1998 in the “Gewijzigd Varkensbesluit”, meant that the tethering of sows would ultimately be banned and that group housing would be compulsory for dry sows. In 2001 the EU amended Council Directive 91/630/EEC with 2001/88/EEC, which, among other things, prohibited tethering from 2006 onwards and made group housing compulsory from 2013. Additionally to the Dutch policy, the European Directive stated that “pigs must have permanent access to a sufficient quantity of material to enable proper investigation and manipulating activities” and “dry pregnant sows and gilts must be given a sufficient quantity of bulky or high-fibre food”.
Welfare legislation was not formulated to achieve environmental goals, and vice

versa. However, the challenge of sustainable development is to reconcile the three P's – with economic values (Profit) at the apex of an optimal eternal triangle, and ecological and social values (Planet and People) at the other two corners.

2. Improving of sow welfare

2.1 Loose Housing

Keeping sows loose in groups instead of individually in stalls enables the sow to perform a variety of behaviours and reduces frustration from unwanted situations. Various authors have argued that group housing is a precondition for sow welfare (e.g. Jensen 1984; De Koning, 1985; Broom *et al.*, 1995). The well-being of an animal can be evaluated using the so-called Five Freedoms (FAWC, 1993): 1) freedom from thirst, hunger and malnutrition; 2) freedom from discomfort; 3) freedom from pain, injury and disease; 4) freedom to express normal behaviour; 5) freedom from fear and distress.

Based on these five freedoms, a comparison of the welfare of individually stalled sows with the welfare of sows kept loose in covered yards leads to the conclusion that the sows kept loose are more capable of expressing normal behaviour and they are less frustrated than sows in stalls (Webster, 1994). As the loose housed sows have the possibility to move and walk around, leg injuries and bedsores are prevented. On the other hand, confrontation with other sows in yards can lead to fighting and injuries. It has been found that aggressive interactions, stereotypic and abnormal behaviour were also related to food restriction (Appleby & Lawrence, 1987; Van Putten & Van de Burgwal, 1990; Terlouw *et al.*, 1991): although their daily ration of concentrates met their nutritional needs, animals were only allowed to eat 60% of what they would consume ad libitum and feeding motivation still persisted (Lawrence *et al.*, 1988), due to hunger and lack of exploration behaviour (Lawrence & Terlouw, 1993). More recently it has been shown that consequential stereotypic behaviour can be avoided by offering a diet high in fibre (Brouns *et al.*, 1994; Whittaker, 1998).

2.2 Straw

As long ago as the 1970s, Fraser (1975) stated that the dietary, recreational and bedding aspects of straw influence different elements of the animal's behaviour, and that they all increase welfare. Arey (1993) added that the occupational value of straw is highly important. The "recreational" and "occupational" aspects to

which both authors referred related mainly to foraging behaviour. Spoolder *et al.* (1995) showed that straw as a foraging substrate reduces stereotypical behaviour in sows. Brouns *et al.*, (1994) and Whittaker (1998) added that it also promotes satiety. The bedding aspect of straw refers to comfort, not just physical, but also thermal: according to Bruce & Clark (1979), when group housed pigs are kept on a straw bed instead of on a bare concrete floor, the lower critical temperature falls by about 5 °C.

The way straw is applied in a housing system varies, depending on the objective. As a fibrous component it can be part of the diet. Brouns *et al.* (1995) tested the voluntary intake of various fibrous diets and observed intakes up to 3.5 kg of straw a day. Straw can also be used as a recreational object, by giving an animal 50-150 g of straw per day in the pen. If used as bedding material, up to 2 kg a day can be supplied per animal. Straw as a bedding material enables pigs to forage and it offers comfort. It can be supplied in bulk in one go every few months or even once a year, or added daily or weekly and allowed to accumulate until the straw/slurry mixture is approximately 0.5 m deep. Both these bedding systems are referred to as deep-litter systems.

As well as straw, other litter materials such as sawdust and wood shavings have been used in the pig industry. Tuyttens (2005) has argued, however, that pigs may prefer substrates with a texture similar to earth for bedding, rather than straw. It is unlikely that alternatives can provide the total combination of welfare-improving functions that straw offers.

3. Impact on ammonia emission

3.1 Effect of loose housing

Ammonia is emitted from slurry during storage, spreading on land, and from livestock houses. In 1980, the contribution of pig husbandry to the total ammonia emission from livestock in the Netherlands was 37%; of this, 42% came from the houses (Oudendag, 1993). The commitment to reduce ammonia emission resulted in the government, agricultural enterprises and research organisations joining forces to develop new methods and techniques to control ammonia emissions. This led to low-emission application of slurry and to statutory regulations about covering stored slurry and about low-emission housing. One way to achieve a low-emission pig barn is to install scrubbers to clean the exhaust air; another was to treat the slurry: (a) acidifying; (b) diluting; (c) cooling; (d)

reducing its surface area. Option (d) is applied frequently in sow houses where the animals are stalled individually. Because the sows are confined, their urine and the faeces drop on a defined area. Instead of the slurry being stored in a pit under a large slatted floor, the slurry can be stored in a narrow channel. The surface area of the slurry in the channel can be reduced even further if the channel has a V-shaped profile and if the slurry is removed from the house at regular intervals. The ammonia emission from slurry channels is 40-60% less (the size of the reduction depends on the construction of the channels and the time between removing slurry) than from pit-based systems (Voermans *et al.*, 1996). The advantages of the channel systems are the simplicity of the technique and the low costs.

Keeping the sows loose in a covered yard enables sows to range over a large area. This implies that they can drop urine and faeces over a large area and thus that the ammonia-emitting area is large. Several studies concluded that there is a linear relationship between emission and emitting area (Muck & Steenhuis, 1981; Elzing & Monteny, 1997b; Aarnink & Elzing, 1998; Monteny *et al.*, 1998). It has therefore been reasoned that the group housing of sows increases ammonia emissions because the emitting area in the barn is larger.

3.2 Effect of straw

The impact that the use of straw has on ammonia emission varies, depending on the purpose of the straw application. When straw is added to the diet as a fibrous component it alters the pig's metabolism (Close, 1993) and so the composition of slurry changes: more fatty acids which lower the pH, more organic nitrogen in the faeces and less NH_4^+ in the urine. Canh *et al.* (1998a) studied the effect of fermentable fibrous components in the diet on ammonia emission and concluded that the ammonia emission from the slurry of fattening pigs fed a diet with 15% sugar beet pulp could be 50% less than that from the slurry of pigs fed a tapioca-based diet.

Adding small amounts of straw to a pen, as is done in a straw flow system, has a recreational purpose (Bruce, 1990). Reitsma & Groenestein (1995) studied a straw flow system in which fattening pigs were provided with approximately 1 kg straw per week. They compared its ammonia emission with the ammonia emission from a traditional slurry-based system and found no difference.

As mentioned earlier in section 2.2, providing straw as a bedding material benefits

pig welfare in many ways. However, prior to the studies reported in this thesis, little information was available on the effect of straw bedding on ammonia emission. Measurements had been conducted on a laboratory scale with mixtures of fresh bedding and faeces (Misselbrook & Powell, 2005; Andersson, 1996) or known ammonia solution (Kemppainen, 1987). Those studies set out to identify differences in ammonia emissions between bedding materials, but not to mimic the real-life situation where litter and excreta accumulate for a year. Andersson (1996), Groenestein & Van Faassen (1996), Thelosen *et al.* (1993) Kaiser & Van den Weghe (1997) and Hol & Groot Koerkamp (1999) conducted long-term measurements to assess the ammonia emissions from housing systems with different types of bedding. They reported emissions from the entire house, but could not distinguish emissions from the different emitting surfaces, including the straw bedding.

When mixtures of slurry with straw or other microbial available carbon sources are considered, emissions of methane (CH_4) and nitrous oxide (N_2O) have to be taken into account (Burton & Turner, 2003) because both CH_4 and N_2O are greenhouse gases, having respectively 21 and 310 times the Global Warming Potential (GWP) of CO_2 (IPCC, 1997). Additionally, N_2O plays a role in the destruction of the ozone layer (Crutzen, 1976). At high C:N ratios and under aerobic conditions, microbial metabolism will enhance nitrogen turnover and may reduce NH_3 emission, but if conditions for the microbial processes are not optimal, NO and N_2O are produced. The availability of oxygen is important: as the availability of oxygen decreases, N_2O production may increase and CH_4 may also be produced (Amon *et al.*, 1997; Veeken *et al.*, 2002). The result is “pollution swapping”: though the acidification and eutrophication by ammonia is diminished, the GWP is raised by the increasing emissions of CH_4 and N_2O and the destruction of the ozone layer by N_2O is intensified. The environment does not benefit.

4. Aim of the research

The research reported in this thesis had four objectives:

- To establish the effect of group housing of sows on ammonia emission from the sow house and to elucidate the factors in the housing system that affect the ammonia output.
- To establish the effect of the feeding schedule and activity pattern of sows on ammonia emission from group housing.
- To quantify the effect of straw bedding on the ammonia emission from a

sow house and use model simulations to study the effects of bedding and floor design on the ammonia emission.
- To elucidate the effect of straw bedding on the emission of greenhouse gases methane and nitrous oxide and clarify the underlying factors, in order to identify ways of preventing emissions of the gases from sow group-houses with straw bedding.

5. Outline of thesis

Chapter 2 compares the ammonia emissions from individual and group-housing systems for sows. The study includes a group-housing system with feeding stalls with which sows are fed simultaneously and a group-housing system with an electronic sow feeder (ESF) where sows are fed sequentially. The total ammonia emission per day and the diurnal emission patterns are analysed.

Chapter 3 focuses on the effect of feeding schedule on ammonia emission from group housing. In an experiment the sows were fed simultaneously or sequentially, housed individually or in groups and feeding times were varied. Animal activity and air temperature were explanatory variables. The hypothesis was that changing the feeding schedule changes the diurnal pattern of the ammonia emission and that feeding in the evening, when ambient temperature is lower, would reduce ammonia emission.

Chapter 4 considers the effect of straw bedding on ammonia emission from a sow house, focussing on the individual contributions from straw bedding, concrete floors, slats, and slurry in the pits. In a laboratory set-up the ammonia release from a urine deposition on the various different emitting surfaces in the house was measured. The hypothesis was that substrates differ in the rate of ammonia volatilisation, but not in the total ammonia volatilisation over a longer time.

Chapter 5 describes a model that predicts ammonia emission from each emitting surface area in a straw-bedded sow group-housing system as well as the emission from the entire house. The model integrates the emissions from the urine pools. The outcome of the model is compared with the emission measured from a reference sow house. The model can be used as a design tool to calculate ammonia emissions, simulating different configurations of the floors and bedding in the house.

Chapter 6 describes the impact of group-housing sows with straw bedding on

emission of the greenhouse gases methane and nitrous oxide. Using information from other research on fattening pigs, a study on the volatilisation of NH_3, NO and N_2O from a deep litter system for fattening pigs is undertaken, to elucidate the nitrogen turnover in a deep litter system.

Chapter 7 places the findings of this thesis research in a general context in three ways: firstly, by evaluating the results and discussions of the previous chapters; secondly, by considering emission results in view of the nitrogen balance; and thirdly, by evaluating where welfare and environmental issues meet in a win–win situation or when win–lose dilemmas exist.

2

Ammonia Emission from an Individual- and two Group-housing Systems for Sows

C.M. Groenestein, J.M.G. Hol, H.M. Vermeer, L.A. Den Hartog & J.H.M. Metz

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Abstract

Given that freedom of movement improves sows' welfare, the implications for the emission of ammonia of keeping sows in groups instead of individually were investigated. Three housing systems were compared: system A, with 64 sows kept individually in feeding stalls with 2.8 m^2 surface area per sow; system B, with 62 group-housed sows, free access stalls with 3.3 m2 surface area per sow; system C, with 65 group-housed sows, electronic sow feeders and with 3.4 m^2 surface area per sow. The sows in systems A and B were fed simultaneously twice a day at 7:30 and 15:30 h. In system C the sows were fed sequentially once a day from 15:30 h onwards.

The study was carried out in winter during three one-week periods. Average outdoor temperature was 3.7 ºC. The average ambient temperatures recorded in the houses were thermoneutral: 19.8 ºC for system A, 19.2 ºC for system B and 19.0 ºC for system C. The average ammonia emission per sow was 0.72, 0.62 and 0.70 g/h for the systems A, B and C respectively. For the systems A, B and C this implied that 23, 20 and 23% of the nitrogen intake emitted as ammonia nitrogen respectively. The emission from system B was significantly less ($P < 0.05$). The diurnal pattern of the ammonia emissions from systems A and B were biphasic and were related to feeding times. In system C the diurnal pattern had a more monophasic course related to the feeding time in the afternoon with an additional small peak in the morning after the lights were switched on.

The diurnal pattern of ammonia emission from sow houses was related to the feeding schedule. Under thermoneutral conditions, giving sows a larger area at their disposal – such as with group housing - did not imply an increase in ammonia emission.

Keywords: sows, group housing, individual housing, feeding schedule, electronic sow feeder, ammonia emission, diurnal pattern

2.1. Introduction

Dutch farmers are switching to group housing of sows in anticipation of legislation that will make it illegal from the year 2008 onwards to keep pigs individually. Keeping sows in groups and giving them freedom of movement improves their welfare compared with housing them individually in stalls (Jensen, 1988; Webster, 1994). However, the impact on the ammonia emission from group housing needs to be clarified. Freedom of movement implies that the sows can drop their excrements anywhere. The larger the group, the larger the area that the individual sow has at its disposal and the larger the area fouled with faeces and urine can be. The resulting larger emitting area will increase ammonia emission (Muck & Steenhuis, 1981; Aarnink *et al.*, 1996; Elzing & Monteny, 1997b; Monteny *et al.*, 1998), bringing animal welfare into conflict with environmental issues as ammonia has an acidifying and eutrophying effect on soil and surface water (Heij & Erisman, 1997). These considerations motivated a study of ammonia emission from individually and group-housed sows.

Individually housed sows are fed simultaneously once or twice a day. Group-housed sows are fed simultaneously if all sows have a feeding place, or sequentially if just one or a few feeding places per group are present. So this study included a group-housing system with feeding stalls for simultaneous feeding and a group-housing system with an electronic sow feeder (ESF) for sequential feeding. The study set out to describe the differences in ammonia emissions between the housing systems. To understand the cause of possible differences between the systems, the diurnal ammonia emission patterns were compared.

2.2. Materials and methods

The experiment was conducted in three different sow-housing systems at the Research Institute for Pig Husbandry in Rosmalen. Figure 2.1 shows the plans of the systems. In system A, 64 sows were housed individually in stalls and fed simultaneously twice a day. Water was available for one hour during feeding time. In system B, 62 sows were kept in six groups (of 13 sows at the most) with free access stalls and were fed also twice a day. At feeding time they were confined to the stalls for one hour, during 40 minutes of which they had access to water. The rest of the day they could drink ad libitum from a nipple in the walking area between the rows of stalls. However, 93% of the water was consumed during feeding time. In system C, 65 sows were kept in five groups (25 sows at the most). Four groups

were fed sequentially, using one ESF per group. The feeding station was able to recognise each sow at the entrance and denied it access if it had already eaten its daily ration. Water was available ad libitum from a drinking nipple. To facilitate feed intake, 1.1 litre of water was supplied in the feeding station. The remaining group in system C comprised 14 dry sows confined to stalls for 7 to 10 days at the time of mating. During this confinement they were fed once a day when feed was available in the ESFs. On average, the sows in system C visited the ESF once a day and ate the entire ration at one go. All sows in the three systems were fed with the same commercial concentrate, containing 12.6 MJ metabolizable energy (ME) and 139 g crude protein (CP) per kg of feed. Table 2.1 presents the feeding schedules and summarizes the most important characteristics of the three systems.

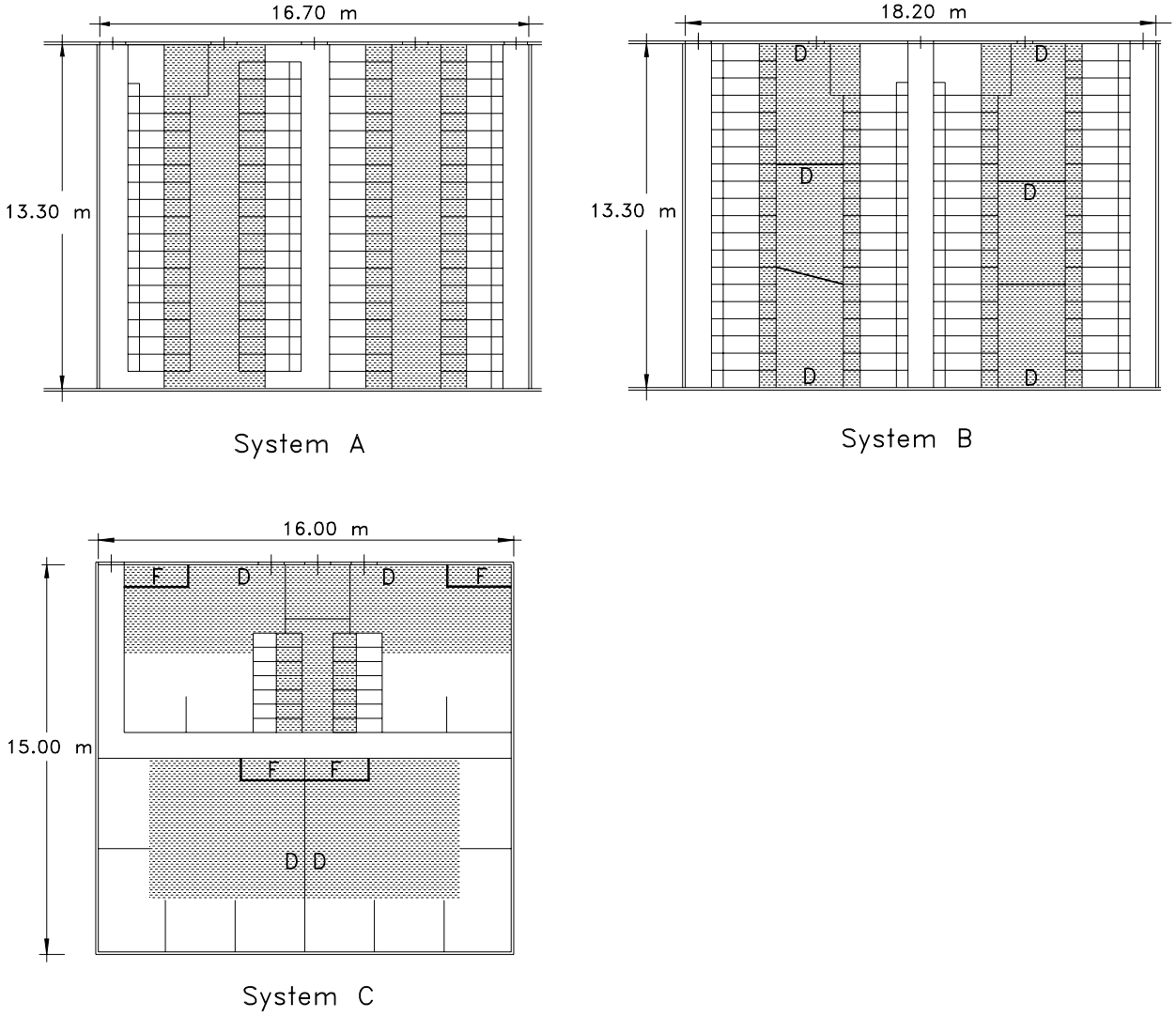

Figure 2.1. Plans of the housing Systems. The shaded parts represent the slatted floor area; solid lines represent stalls and fencing; double solid lines represent walls, drinking places (excluding those in feeding troughs) are indicated with D, feeding stations with F.

Table 2.1. Characteristics of the three housing systems.

	System A	System B	System C
Feeding schedule			
Order	Simultaneous		Sequential
Time	7:30 and 15:30 h		15:30 h
Intake (kg/d per sow)	2.8	2.8	2.7
N intake (g/d per sow)	62	62	60
Water			
Access	Restricted	*Ad libitum*	*Ad libitum*
Use (l/d per sow)	10.7	10.9	9.2
Surface area (m^2)			
Total [1]	178	202	218
Concrete slats	106	52	63
Cast iron slats	-	52	63
Pit	106	104	234
Number of sows	64	62	65
Surface area per sow (m^2) [1]	2.8	3.3	3.4

The housing systems were equipped with a partially slatted floor and were ventilated mechanically. Systems A and B had 74 stalls; system C was equipped for 84 sows so that during the experiment not all sow places were occupied. The surface area per sow was 2.8, 3.3 and 3.4 m^2 for the systems A, B and C, respectively, excluding the feeding alleys, which were only accessible to the stockman. Lights were switched on from 7:15 h to 18:00 h. Daylight was able to enter the systems.

The measurements were taken simultaneously in the three systems in the winter of 1996-1997, during three periods of one week: 16-22 September, 9-15 December and 27 January -2 February. Ammonia (NH_3) concentration, (mg m^{-3}), ventilation rate (m^3 $hour^{-1}$), the ambient and outdoor air temperatures (°C) and the use of water were recorded every 5 minutes. Averages were recorded every half an hour.

The concentration of ammonia was measured at the inlet and in the exhaust air in the ventilation shaft with a NO_x analyser. With this method (Van Ouwerkerk, 1993) an air sample was transported to a thermal ammonia converter where NH_3 was converted into NO. The air sample with the less adsorptive gas NO was then transported from the converter to the NO_x analyser (Monitor Labs Nitrogen Oxides Analyzer, model 8840) where the NO was measured on the basis of the principle of chemiluminescence (Phillips *et al.*, 1998). The efficiencies of the converters were determined before and after the experiment; they were always higher than 90%. The measured concentrations were corrected for the mean of the efficiencies before and after the experiment. The concentration of ammonia in the exhaust air was corrected for the concentration at the inlet. Ventilation rate was determined with an anemometer with the same diameter as the ventilation shaft. The anemometer had been calibrated in a wind tunnel. The emission was calculated as the product of the corrected NH_3 concentration and the ventilation rate. The ambient, inlet and outdoor air temperatures were measured with a sensor (Rotronic®. Proces & Milieu BV, IJzendoorn).

Statistical significance of differences of daily averages between the systems was assessed with analysis of variance and based on the standard errors of differences (SEDs).

2.3. Results

The climatic conditions during the study and the ammonia concentrations are summarized in Table 2.2. The ventilation rate was highest in system B. However, taking into account the number of animals (Table 2.1) and the volume of the accommodation (965, 1051 and 1044 m^3 for systems A, B and C, respectively), the air exchange rate was the same as in system C. Although the settings of the climate computer were the same for the three systems, differences - however small - may have occurred due to different tuning of the separate components of the systems (temperature sensors, position of the ventilation flaps etc.). On average, air exchange rate in system A was 9% less compared with systems B and C, resulting in a higher ambient temperature.

Table 2.2. Mean temperatures, ventilation rate and NH_3 concentration in Systems A, B and C, with the least significant difference (LSD) between systems (P < 0.05).

	System A	System B	System C	LSD
Temperature outdoor air (°C)	3.7	3.7	3.7	-
Temperature inlet air (°C)	14.0	14.0	14.0	-
Temperature ambient air (°C) [1]	19.8 a	19.2 b	19.0 c	0.19
Ventilation rate per sow (m^3 $hour^{-1}$) [1]	52 a	65 b	59 c	3.3
Air exchange rate ($hour^{-1}$) [1, 2]	3.6 a	3.9 b	3.9 b	0.23
NH_3 concentration (mg m^{-3}) [1]	14 a	10 b	12 c	0.8

[1] Means with no common superscript between systems differ significantly *(P* < 0.05*).*

[2] Air exchange rate is calculated as the quotient of ventilation rate (m^3 $hour^{-1}$) and the volume of the house (m^3).

Figure 2.2 presents the results of the measurements of the ammonia emission per system and per period. The highest emission (0.77 g/h per sow) was recorded in system A during the first period. The lowest (0.56 g/h per sow) was recorded in system B during the third period. When periods (n = 3) were considered a factor in the analyses of variance, an interaction was found between system and period

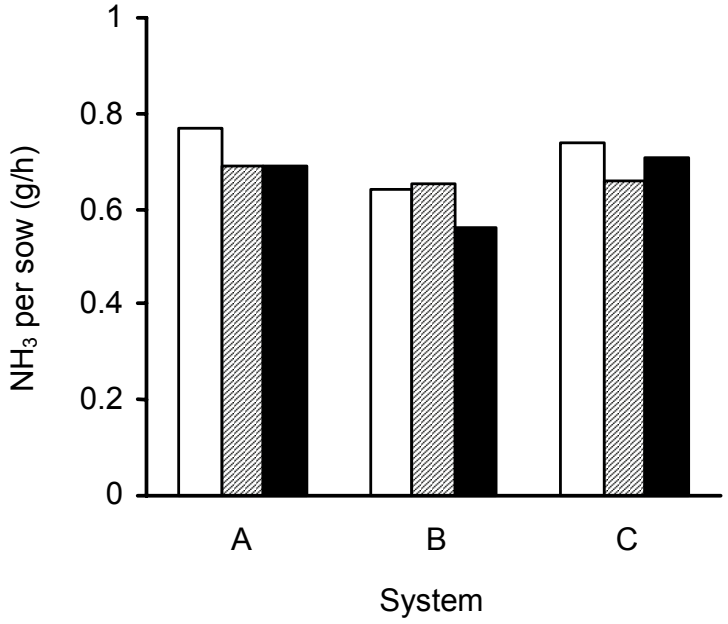

Figure 2.2. Ammonia emission per sow per system during period 1 (white column), period 2 (line upward diagonal column) and period 3 (black column).

($P < 0.05$).
Table 2.3 presents the mean ammonia emission for the three housing systems expressed in g/h per sow and as the percentage NH_3-N of total N intake per sow. In systems A and C the mean emissions during the three periods were the same, whether expressed per hour per sow or expressed relative to the N intake. The emission from system B was significantly lower, although the differences were small: 14% and 11% per sow compared with the systems A and C, respectively, and 13% considering the N intake.

Figure 2.3 presents the daily patterns of ammonia emission expressed as the relative difference (%) from the daily average per system. These patterns are based on the means of the observations recorded at half-hour intervals during the three periods (n=21). The daily variation in ammonia emission was smaller in system C than in systems A and B: the difference between the minimum and maximum mean emission was 13% for system C, 39% for system A and 47% for system B.

The emissions from systems A and B, in which the animals were fed simultaneously twice a day, showed a biphasic diurnal pattern, with maxima related to feeding times. The emission from system C showed a broad maximum with a peak just after feeding had started. In system C a slight rise in emission was observed at the start of the day just after the lights were switched on.

Table 2.3. Ammonia emission per sow from the three housing Systems A, B and C in g/h and expressed as NH_3-N related to total N intake, and the least significant difference (LSD) with $P < 0.05$ (n = 21).

System	Ammonia emission	
	Sow (g hour^{-1})[1]	NH_3-N/N intake (%)[1]
A	0.72 a	23 a
B	0.62 b	20 b
C	0.70 a	23 a
LSD (0.05)	0.022	0.735

[1] Means in the same column with no common letter differ significantly ($P < 0.05$).

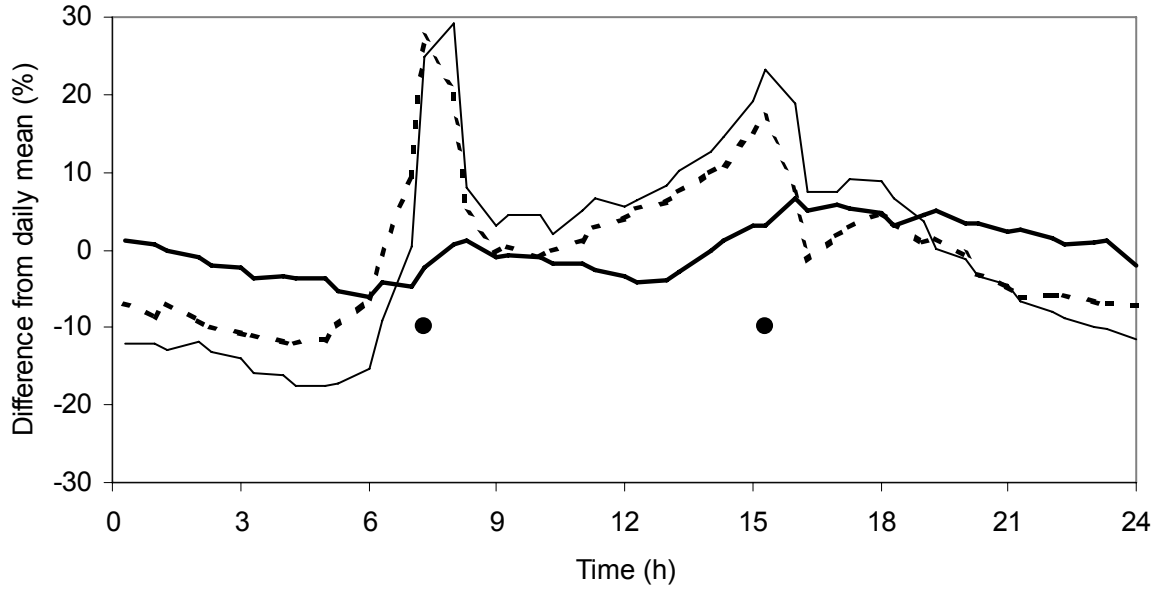

Figure 2.3. Diurnal pattern of the ammonia emission from System A (broken line), System B (solid line) and System C (bold line). The dots represent feeding times: 7:30 and 15:30 h in Systems A and B and 15:30 h in System C.

2.4. Discussion and conclusions

The ammonia emissions from housing systems A, B and C were within the range presented by Groot Koerkamp *et al*. (1998). In a balance trial Everts & Dekker (1994) measured a nitrogen excretion during mid pregnancy of 77% of the N intake (61.4 g/d). Based on this figure the ammonia emissions in the present study would have been 30% of the excreted N for systems A and C, and 26% for system B. Whether the ammonia emission per sow was expressed in g/h or relative to the N intake (Table 2.3), the differences between the systems were relatively small (less than 15%). These differences in ammonia emission need not be caused by system-related differences, but may have something to do with the way the systems were actually implemented and with circumstances that cannot or not sufficiently be controlled. In the present study this concerned the surface area of the floor and the pit, the ambient temperature, the ventilation rate, the seasonal effect and the volume of water used. In this study, the feeding schedule (order and times) and the method of water supply (restricted or ad libitum), were considered to be system-related differences. Animals fed simultaneously are usually fed twice a day, but with an ESF the sows generally eat the entire ration at

one go. The water supply to sows kept individually in stalls was restricted as otherwise the animals would have shown excessive drinking behaviour (Falk, 1971; Stephens *et al*., 1983; Terlouw *et al*., 1991; Robert *et al*., 1993), which could easily have doubled the individual use of water (Stephens *et al*., 1983). In agreement with the findings of Van Der Peet-Schwering *et al*. (1997), if kept in groups sows can have ad libitum access to water nipples without drinking an excessive amount (Table 2.1). This means that the actual volume of water used in the present experiment was not related to the system. This volume was smallest in system C. If the water use had been the same as in system A and B, the urea concentration in the urine from the sows in system C would have been lower (Mroz *et al*., 1996; Van Der Peet-Schwering *et al*., 1997). This would have decreased the ammonia emission from system C, because urea is the main source of ammonia and ammonia emission is linearly related to the urea concentration (Elzing & Monteny, 1997a).

A larger surface area of the pit means a larger emitting area and more emission. A larger surface area of the solid and slatted floor means that a larger area can be fouled with urine and faeces, which also means potentially more emission. If the surface areas had been the same the emission from system C would have been smaller because the surface area of the pit would have been 1.7 m^2 instead of 3.6 m^2 per sow as in systems A and B (Table 2.1). However, the ammonia emission from the pit was not expected to be proportionally larger - as might be expected in theory (Elzing & Monteny, 1997b) - because 1.7 m^2 of the slurry pit in system C was underneath solid floors. Here, the air speed was probably very low so that there would have been less emission than from slurry underneath slats (Elzing & Monteny, 1997a, b).

The temperature in system A was highest because air exchange rate was lowest (Table 2.2). Correcting for the ambient temperature would decrease the emission from system A compared with group-housing systems B and C. However, all or part of this correction would be neutralized because the higher temperature in system A was the results of a lower ventilation rate and a lower air speed (Elzing & Monteny, 1997a).

The seasonal effect was not one of temperature as such, because this was the same for the three systems. During hot summer conditions, however, the excreting behaviour of the sows may change. Pigs define areas for resting, feeding and excretory behaviour depending on pen design and temperature (Hafez, 1975; Steiger *et al*., 1979; Whatson, 1985; Fraser, 1985; Hacker *et al*.,

1994). Under warm summer conditions with temperatures above thermoneutrality, more fouling of the solid flour can occur, which increases ammonia emission (Aarnink *et al*., 1997). The sows in system A, however, would not be able to adjust their excretory behaviour because their movements were restricted to the stalls (1.3 m^2). The sows in system B were able to move around on 25-29 m^2 and in system C on 35-60 m^2, depending on the size of the pens (see Figure 2.1). This difference in available area means that there will be an interaction between season and housing system, i.e., with increasing temperatures the emission from systems B and C would increase more than from system A. Consequently, the results of this study cannot be extrapolated to summer conditions with temperatures above thermoneutrality, when fouling of the solid floors can occur.
The above indicates that under thermoneutral conditions and equal circumstances in system C and systems A and B, emission from system C would have been lower than was actually measured. This, in combination with the relatively small differences in ammonia emission between the systems (Table 2.3), indicates that under thermoneutral conditions, when fouling of the solid floors does not occur, emission from the individual-housing system A tends to be higher than from the group-housing system C. A likely explanation for this is that if sows have a larger surface area at their disposal they do not necessarily excrete on a larger area. As noted above, pigs define areas for resting, feeding and excretory behaviour. So if their environment permits this hygienic behaviour, it is likely that the emitting area will be reduced. If pigs use a specific, limited excretory area, the urine present on the slats and in the pit will be superseded more frequently by fresh urine. The ammonia in the superseded urine is then no longer in contact with air and consequently less of the dissolved NH_3 will volatilize (Monteny *et al.*, 1998). This effect will be reinforced if urinating behaviour is synchronised in time too. According to Aarnink *et al*. (1996) approximately 75% of the urination of fattening pigs occurs during the day.

The diurnal pattern of the emissions from systems A and B was biphasic. Several studies describe a similar pattern of activity when sows are fed simultaneously twice a day (Jensen, 1988; Den Hartog *et al.*, 1993; Robert *et al.*, 1993; Krause *et al.*, 1997). The emission from system C showed less distinct peaks. Aarnink & Wagemans (1997) found the same pattern for growing pigs that were fed sequentially, i.e., a small peak in the morning and a bigger one in the afternoon. This pattern fitted ammonia emission as well as activity, making that ammonia emission and activity are correlated. Furthermore, these patterns fitted the food intake pattern presented by De Haer & Merks (1992).

The present study supports the suggestion that the ammonia emission pattern is related to feeding-induced activity of the sows. It indicates the necessity to measure the ammonia emission continuously when comparing different systems with different feeding schedules. It furthermore implies that when efforts are made to develop group-housing systems for sows and reduce ammonia emission, the feeding schedule should be taken into account. From this study it can be concluded that under thermoneutral conditions, giving sows a larger area at their disposal – such as with group-housing - does not imply an increase in the ammonia emission per sow.

3

Effect of Feeding Schedule on Ammonia Emission from Individual and Group-housing Systems for Sows

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Abstract

The effect of feeding schedule on ammonia emission from housing systems for sows was studied. The hypothesis was that changing the feeding schedule would change the diurnal pattern of the ammonia emission and that daytime feeding would cause more ammonia to be emitted from the manure compared to evening feeding. The experimental units were an individual housing system with 64 dry sows in stalls (system A) and two group-housing systems: system B with 62 dry sows and feeding stalls and system C with 65 dry sows and electronic sow feeders (ESFs). In systems A and B the sows were fed simultaneously twice daily. In system C the sows were fed sequentially once a day. During feeding schedule 1, feeding times in systems A and B were 7:30 and 15:30 h, in system C feed was available from 15:30 h on. During schedule 2, feeding times in systems A and B were 7:30 and 21:30 h, in system C food was available from 7:30 h on. Ammonia emission, indoor temperature and animal activity were measured and the data were analysed considering autocorrelations with a time-series model. The values for the coefficients of determinations R^2 of the models explaining ammonia emission by indoor temperature and animal activity were 48% for system A, 66% for system B and 64% for system C. In all three systems the diurnal patterns of the indoor temperature, animal activity and ammonia emission changed considerably with the feeding schedule. Average ammonia emissions per sow for feeding schedules 1 and 2 were, respectively, 0.71 and 0.68 g/h (probability $P = 0.23$) from system A, 0.60 and 0.61 g/h ($P = 0.75$) from system B and 0.69 and 0.76 g/h ($P < 0.01$) from system C. It can be concluded that changing the feeding schedule alters the diurnal pattern of the ammonia emission, but if the animals are fed simultaneously, changing the feeding time does not affect the total amount of ammonia emitted. However, with the animals fed sequentially, the ammonia emission falls by 10% if the feeding starts in the afternoon instead of in the morning.

3.1. Introduction

Under Dutch legislation, for reasons of animal welfare, from 2013 keeping herds of dry sows individually in pens or stalls will be prohibited. Therefore, group-housing systems in which sow welfare as well as other requirements of modern husbandry such as low emission of the acidifying and eutrophying gas ammonia is met have to be developed (Van Breemen *et al*., 1982; Asman, 1987). Groenestein *et al*. (2001) concluded that under thermoneutral conditions, ammonia emission from urine from group-housed dry sows is not higher than from sows kept individually in stalls. Nevertheless, emissions will have to be reduced in order to meet the target of the Dutch government of a 70% reduction in 2005 compared to 1980.

One important factor influencing ammonia emission is temperature (Freney *et al*., 1983; Groot Koerkamp, 1994; Elzing & Monteny, 1997). According to model calculations performed by Monteny *et al*. (1998) and Aarnink & Elzing (1998), ammonia emission increases by 6-7% per °C temperature rise. The indoor temperature in the house is related to the heat production of the animals. This heat production has a circadian rhythm, which is related to physical activity (Henken *et al*., 1993), photoperiodicity and feeding strategy (Verstegen *et al*., 1987). These relations imply that feeding schedule can affect ammonia emission by animal activity and air temperature. Sows housed individually are essentially fed simultaneously. In group housing, feeding schedule can be carried out in different ways: either simultaneously (trickle feeding, free access stalls, trough feeding, floor feeding) or sequentially (feed hoppers with a limited number of places, electronic sow feeders (ESFs)). If the activity associated with feeding coincides with high indoor temperatures caused by high outdoor temperatures during daytime, ammonia emission might be higher than when feeding activity occurs at night and outdoor temperatures are lower. Therefore, the objective of this study is to model ammonia emission with activity and indoor temperature during different feeding schedules for sows housed individually and in groups and to test the hypothesis that changing feeding schedules can reduce ammonia emission.

3.2. Materials and methods

3.2.1 Animals and housing

The experiment was conducted at the Research Institute for Pig Husbandry in Rosmalen in three different housing systems for cross-bred sows in a commercial herd under practical conditions. In each system, parities of the sows and stages of pregnancy were proportionally present. The comparison of the ammonia emission of the three systems was described by Groenestein *et al.* (2001) as well as the detailed layout and management. In system A, 64 sows were housed individually in stalls. In system B, 62 sows were housed in six groups with free-access feeding stalls. The sows were fed a commercial diet - pellets with 12.6 MJ metabolisable energy (ME) and 139 g crude protein (CP) per kg - according to their gestational stage. On average, each sow in systems A and B received 2.8 kg in two portions daily and each sow in system C received 2.7 kg. Sows in system C generally consumed their daily ration in one visit to the feeder. The water supply in system A was restricted, in systems B and C the sows had *ad libitum* access to water. In all three systems, the volume of the water used (consumption and spillage) was 9-10 *l*/d per sow. The housing systems had a partially slatted floor. The air was ventilated mechanically, regulated according to the indoor air temperature. Treatments and measurements in the three systems took place simultaneously.

3.2.2 Treatment

In each housing system, the sows were fed according to two feeding schedules. In systems A and B, the animals were fed simultaneously twice daily: 7:30 and 15:30 h during feeding schedule 1 and 7:30 and 21:30 h during feeding schedule 2. In system C, 65 sows were kept in five groups. Four groups were fed sequentially, using ESFs. The fifth group (maximum size 14 dry sows coming from the farrowing unit after weaning) was confined in stalls for 7-10 days round insemination. The feeding of all groups started at 15:30 h during schedule 1 and at 7:30 h during schedule 2.

Each feeding schedule lasted 3 weeks. The schedules were alternated three times. The first 2 weeks of the feeding schedule were for adaptation, the third week was the experimental period.

3.2.3 Measurements

Measurements were taken during three consecutive 24 hour periods. This

entailed registering activity by direct observation every 15 min and expressing this as the proportion of animals standing (on a scale from 0 to 1, with 0 being all sows lying and 1 all sows standing). Ammonia concentration in mg m^{-3}, ventilation rate in m^3/h and the temperatures of the indoor air (in the flow of the exhaust air) and of the outdoor air in °C were measured every 5 min and the mean value was recorded every half hour. The concentration of ammonia was measured in the exhaust air in the ventilation shaft with a NO_x analyser (Monitor Labs, model ML 8840). With this method NH_3 is converted into NO and the NO is measured on the principle of chemiluminescence (Phillips *et al.*, 1998). Ventilation rate in m^3/h was measured with a fan wheel anemometer having the same diameter as the ventilation shaft standardised in a wind tunnel. The emission was calculated as the product of the NH_3 concentration and the ventilation rate and expressed per sow (g/h). The indoor and outdoor air temperatures were measured with sensors (Rotronic®).

3.2.4 Statistical analysis

The emission y_t at time t was modelled according to the following time-series model

$$y_t = \eta_t + \varepsilon_t \tag{3.1}$$

where η_t is the mean ammonia emission in g/h at time t and ε_t is an autoregressive process of the first order at time t such that

$$\varepsilon_t = \phi\varepsilon_{t-1} + a_t \tag{3.2}$$

where: a_t is the independent innovation and ø is the correlation parameter of the first-order autoregressive process. For every system and both feeding schedules, the effect of temperature (T_{ijt} corrected for the mean of period j, T_{ij} in °C) and activity were modeled. Thus, η_t from Eqn (3.1) could be written as:

$$\eta_{ijt} = C_{ij} + \beta_i(T_{ijt} - T_{ij.}) + \gamma_i \cdot A_{ijt} \tag{3.3}$$

where: C_{ij} as the constant for feeding schedule i in period j, β_i and γ_i are the regression coefficients of, respectively, temperature and activity for feeding schedule i, and A_{ijt} is the animal activity during feeding schedule i in period j at time t. The analysis was carried out with the residual maximum likelihood (REML) procedure, available as a Genstat Procedure (Genstat 5, 1997). To evaluate the

goodness of fit of the systematic part of the model (Eqn 3.3), the coefficient of determination R^2 was calculated. To test whether the times series of the random model (Eqn 3.2) was justified, Q of the Box-Pierce Q-test (Box & Jenkins, 1976) was calculated:

$$Q = n\sum_{k=1}^{m} r_k^2 \tag{3.4}$$

where: n is the number of observations and r_k is the autocorrelation of residuals with lag k. Q has a χ^2 -distribution with (m-p) degrees of freedom with p being the order of the autoregressive process and m the highest lag considered ($k = 1\ m$). In this study, the autocorrelations of the residues were considered up to 5.5 hours before the observation (m = 11). Increasing the lag would not be effective because the time frame would then overlap the emission peaks which were to be modeled. The time series model is justified when Q is small. Significant differences between regression coefficients of the model were assessed based on standard errors of the difference (SEDs).

3.3. Results

Figure 3.1 represents the daily patterns of ammonia emission per sow, indoor temperature and animal activity for systems A, B and C during both feeding schedules. It appears that feeding time as well as feeding order (simultaneously versus sequentially) affect the patterns of activity, temperature and ammonia emission. If the sows were fed simultaneously, activity was concentrated around feeding times. During the first feeding schedule in systems A and B, ammonia emission increased when activity and indoor temperature increased. The second increase of the indoor temperature in the afternoon correlated with the rise of the outdoor temperature in the afternoon. In spite of a peak in the indoor temperature and in activity, the ammonia emission hardly increased round the second feeding time at 21:30 h.

Feeding the sows sequentially (system C) instead of simultaneously (systems A and B) flattened the course of the activity and the ammonia emission. The indoor temperature showed a monophasic pattern. Changing the feeding time hardly affected the course of the temperature. When feeding started in the afternoon, a small activity peak could be distinguished in the morning, which coincided with the switching on of the lights at 7:30 h to start the day.

Table 3.1 presents the daily means per system and per feeding schedule and shows the quantitative effects of changing feeding schedule on temperature, animal activity and ammonia emission. The mean indoor temperature did not differ (probability $P > 0.05$) between treatments. Feeding in the evening (schedule 2 for systems A and B, and schedule 1 for system C) reduced the mean activity in all three systems ($P < 0.05$). The ammonia emission from systems A and B did not change if the sows were fed in the evening ($P = 0.23$ and $P = 0.75$, respectively), but in system C (schedule 1) it was 10% lower ($P < 0.01$).

For systems A, B and C the correlation between the random parts ε and a - 1 of the model were respectively 0.71, 0.79 and 0.78. The Box-Pierce Q-statistic was

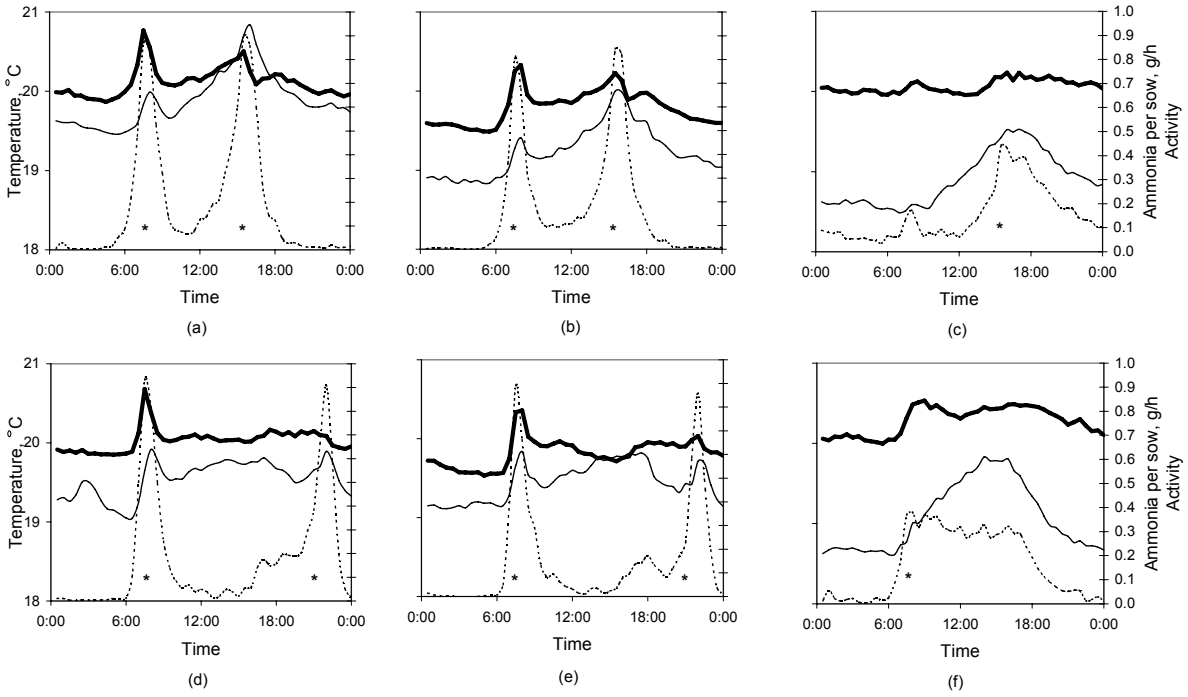

*Figure 3.1. Daily averages (n=9) of ammonia emission per sow (bold line), indoor temperature (solid line) and activity (dotted line) over 24 hours of systems A, B and C during feeding schedules 1 [graphs (a)-(c)] and 2 [graphs (d)-(f)]; feeding times are indicated by *.*

Table 3.1. Ammonia emission per sow in g/h, daily mean of activity (proportion of animals standing), mean indoor temperature in °C, and standard error (SE) per feeding schedule and system.

System	Feeding schedule	Temperature (°C)		Activity		NH_3, g/h	
		Mean	*SE*	*Mean*	*SE*	*Mean*	*SE*
A	1	19.9 [a]	0.16	0.192 [a]	0.004	0.71 [a]	0.017
	2	19.5 [a]	0.47	0.175 [b]	0.007	0.68 [a]	0.015
B	1	19.2 [a]	0.04	0.163 [a]	0.002	0.60 [a]	0.016
	2	19.5 [a]	0.23	0.146 [b]	0.006	0.61 [a]	0.021
C	1	18.9 [a]	0.15	0.152 [a]	0.005	0.69 [a]	0.017
	2	19.1 [a]	0.37	0.166 [b]	0.005	0.76 [b]	0.010

[a, b] Means without a common superscript letter between feeding schedules differ (probability $P < 0.05$ for activity and temperature and $P < 0.01$ for NH_3).

13.7 for system A ($P < 0.05$), 6.1 for system B ($P < 0.05$) and 18.7 for system C ($P < 0.07$) from which it can be concluded that the autoregressive process of the first order ($P = 1$) was justified. The systematic part of the model explained 48% of the variation of the ammonia emission from system A, 66% from system B and 64% from system C.

Table 3.2 presents the regression coefficients of Eqn (3.3) as the results of the time-series analysis. Both temperature and activity had a significant, positively correlated effect on ammonia emission, regardless of whether the sows were kept in groups or individually or whether they were fed simultaneously or sequentially. The fact that the effect of activity was still significant given the effect of temperature, implies an additional effect from activity.

There was a difference concerning interactions between housing system and feeding schedule: in systems A and B, in which sows were fed simultaneously, activity had a greater effect on ammonia emission if the sows were fed in the afternoon (schedule 1) compared with feeding in the evening (schedule 2) ($P < 0.05$). In system C, when the sows were fed sequentially, the effects of temperature and activity were the same for feeding schedules 1 and 2.

Table 3.2 Regression coefficients of temperature β_i and activity γ_i for the ammonia emission model (Eqn 3.3) in systems A, B and C during feeding schedules 1 and 2.

Feeding schedule	Regression coefficients					
	System A		System B		System C	
	Temperature	Activity	Temperature	Activity	Temperature	Activity
1	0.032 [a]	0.14 [a]	0.093 [a]	0.12 [a]	0.032 [a]	0.08 [a]
2	0.045 [a]	0.07 [b]	0.113 [a]	0.07 [b]	0.058 [a]	0.06 [a]

[a,b] Regression coefficients without a common superscript letter within systems differ (probability $P < 0.05$).

3.4. Discussion

The relationship between feeding strategy, heat production, and physical activity on the one hand and temperature and ammonia emission on the other lead to the hypothesis that changing feeding schedules changes ammonia emission. This is the first study in which this hypothesis is tested, as far as we know. The results presented in Figure 3.1 and Table 3.2 show that when the sows were fed simultaneously, changing the feeding time had a notable effect on the diurnal patterns of the indoor temperature, activity and of ammonia emission. Activity decreased if the sows were fed in the evening ($P < 0.05$), but although the second emission peak disappeared because a rise of temperature and activity did not coincide anymore, the daily amount of ammonia emission did not decrease significantly (Table 3.1; $P = 0.23$ for system A and $P = 0.75$ for system B). If the group-housed sows were fed sequentially, however, not feeding during daytime decreased the ammonia emission by 10% and the diurnal patterns of the emission and the temperature fluctuated less compared with the animals fed simultaneously (Figure 3.1). The results imply that it is possible to reduce ammonia emission through feeding schedule, but it depends on the feeding method (simultaneously versus sequentially) and the housing system (individually housed animals are not fed sequentially).

Two factors accounted for the impact of activity and temperature on the ammonia emission when sows were fed simultaneously during the day: firstly the regression coefficient of activity was greater during feeding schedule 1; and, secondly, the

temperature increased more than during schedule 2. The effect on the ammonia emission can be illustrated with an example based on the data in Figure 3.1 and Table 3.2: assume that during feeding schedule 1 temperature rises by 1 ºC and activity by 0.9 after the second meal. According to the model the ammonia emission then rises by 0.16 and 0.20 g/h per sow for systems A and B, respectively. Figure 3.1 shows that the temperature did not rise to the same extent after the second meal during feeding schedule 2. Assuming that temperature rises by 0.5 ºC and activity by 0.9 during feeding schedule 2 results in ammonia emission increasing by only 0.09 and 0.12 g/h per sow for systems A and B, respectively. In system C, the time of the increase of temperature and activity differed between the two schedules, but not the range. During both feeding schedules, the temperature increase was approximately 1 ºC and the activity increase was approximately 0.4 which, according to the model, brought about an increase of the ammonia emission of 0.06 and 0.08 g/h per sow during schedules 1 and 2, respectively. These results show two things: the impact of temperature and activity on the ammonia emission is greater if sows are fed simultaneously in the afternoon instead of in the evening. And secondly, the short-term impact of temperature and activity on the emission tends to be greater if the sows are fed simultaneously instead of sequentially. This has to be taken into account if measures to reduce ammonia emission are considered.

To estimate heat production of pigs, Eigenberg *et al.* (1997) measured body temperatures (near the tympanic membrane) and observed a sharp rise (1-1.5 ºC) associated with a feeding event. Schrama *et al.* (1993) reported that the activity-related heat production of pigs fed restrictively was 27-30% of total heat production. In a later study, they showed that peaks in heat production during the day were associated with feeding time (Schrama *et al.*, 1996). The increased heat production causes the indoor temperature to rise, which will increase ammonia emission (Elzing & Monteny, 1997). In this study, because the air was ventilated mechanically in response to the air temperature, the temperature effect indirectly reflects the effect of ventilation rate. Ventilation rate itself could not be an independent explanatory variable because emission was calculated as the product of concentration and ventilation rate. The idea was that avoiding feeding in the afternoon (which is when air temperature and ventilation rate would be high because of high outdoor air temperature) would change the pattern of ammonia emission and the amount of ammonia emitted would fall because feeding-induced activity and consequential heat production would not coincide with high outdoor air temperature. The ammonia emission from system C did indeed decrease if feeding started in the afternoon and the larger part of feeding activity occurred

during the night. It is noted that in the second and third experimental weeks, the diurnal rhythm of the outdoor temperature had a small amplitude of 2-3 ^{o}C where more than 10 ^{o}C is not unusual. In addition, the outdoor air was heated before entering the systems for reasons of animal health, which reduced the amplitude even more. If there had been more fluctuation of the temperature of the incoming air, the effects of the treatment might have been greater and the total amount of ammonia emitted when animals were fed simultaneously might also have been affected. This effect may be even more explicit in the summer, with high temperatures. The effect of the heat control implies that if changing the feeding schedule to reduce ammonia emission is not favourable for welfare or management reasons, the heat control system could compensate for the temperature effect.

Table 3.2 shows that in addition to temperature, activity has a significant effect on ammonia emission. In this study, activity was expressed statistically as the number of animals not lying down. In terms of heat production caused by physical activity, movement might be a better definition. In fact, 'activity' is a generic term for a variety of behaviours, one of which is urinating. Urine contains urea, which is converted by enzymes into the volatile ammonia. So, urinating is a source of emission. Aarnink *et al.* (1996) expressed urinating frequency in terms of activity of fattening pigs in an empirical model and found that activity, defined as the number of animals not lying down, explained 65% of the variation of urinating frequency. Part of the effect of urinating on emission of ammonia will be caused by temperature, because fresh urine has a temperature of 38 ^{o}C and so is a source of heat. Defining activity in terms of movement and including urinating behaviour in the model might improve the prediction of the ammonia emission.

3.5. Conclusions

The present study shows that the daily pattern of ammonia emission is related to the patterns of activity and indoor temperature and is therefore affected by feeding schedule. If the sows are fed sequentially, the amount of ammonia emitted falls by 10% when the feeding starts in the afternoon instead of in the morning. Under these circumstances, less feeding activity occurs during the time of day when outdoor and indoor temperatures are high. For sows fed simultaneously, changing the feeding times does not reduce the total amount of ammonia emitted. The effect of activity on the emission however, declines if feeding is in the evening instead of during the day. The results demonstrate that when developing new

group-housing systems for sows aiming to increase animal welfare and reduce emission of ammonia, it is important to consider feeding management.

Notation

A_{ijt}	animal activity during feeding schedule *i* in period *j* at time *t*
a_t	innovation at time *t*, independent part of the residue
C_{ij}	constant for feeding schedule *i* and period *j*.
i	feeding schedule (1,2)
j	period (1,2,3)
k	lag, h
m	highest considered lag (*k* = 1….*m*) in half hours in Box-Pierce Q-test
n	number of observations
p	order of the autoregressive process
Q	Box-Pierce Q-statistic
r_k	autocorrelation of residuals with lag *k*
T_{ijt}	indoor temperature during feeding schedule *i* in period *j* at time *t*, ºC
t	time, h
y_t	ammonia emission measured at time *t*, g/h
β_i	regression coefficient of temperature for feeding schedule *i*.
ε_t	residue at time *t*
η_{ijt}	mean ammonia emission during feeding schedule *i* in period *j* at time *t*, g/h
γ_i	regression coefficient of activity for feeding schedule *i*
ϕ	correlation parameter of the first-order autoregressive process

4

Potential Ammonia Emissions from Straw Bedding, Slurry Pit and Concrete Floors in a Group-housing System for Sows

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Abstract

To assess the contribution of straw bedding, concrete floors, slats, and slurry in the pits to ammonia emission in a straw-bedded group-housing system for sows, the ammonia volatilisation response of urination on the potential emitting surfaces from a sow house was studied under laboratory conditions. Ammonia is mainly produced by hydrolysis of the urea in the urine: a process that depends on the characteristics of the surface of the emitting area. For the study, substrate samples were obtained from the surfaces of a concrete floor in the walking alley (A), slurry pits under the drinking area and the waiting area (D and W) and from the straw bedding (S1, S2, S3). The latter represented straw with respectively a small (S1), an average (S2) and a high (S3) content of slurry dropped by the sows. The controls were a sample of slurry from a reference conventional housing system with sows kept individually on partly slatted floors (R), and a sample of unsoiled fresh straw from the farm depot (S0). After sprinkling 150 ml of urine on each sample, the ammonia volatilisation (E in mg), maximum volatilisation rate (r_{max} in mg/h) and time of occurrence of the maximum volatilisation rate (t_{max} in h) were measured during seven days. Paired comparisons of the predicted means were based on standard error of differences (SEDs, probability $P<0.05$). The ammonia volatilisation was least from the average and heavily soiled straw (359 and 344 mg respectively, $P>0.05$) and most from the slurry from the reference system (1686 mg, $P<0.05$); the volatilisation from the concrete floor in the walking alley was intermediate (973 mg, $P<0.05$). The lowest maximum volatilisation rates were from the straw bedding, irrespective of slurry content, and from the slurry in the pit under the waiting area; they varied from 4.0 mg/h from average soiled straw to 5.4 mg/h from the slurry in the pit under the waiting area ($P>0.05$). The highest volatilisation rate occurred from the concrete floor in the walking alley (17.5 mg/h, $P<0.05$). The volatilisation rate peaked soonest with heavily soiled straw, slurry in the pit under the waiting and drinking area, concrete floor and slurry from the reference system, and latest from unsoiled straw ($P<0.05$). The results reveal that in a sow house with straw bedding, the largest source of ammonia emission is a urine puddle on the concrete floor in the walking alley, and the smallest is a urination on straw, irrespective of the slurry content of the straw. Only at high slurry contents in the straw bedding does the rate at which ammonia is produced from urea increase. The implication is that straw bedding in a group-housing system for sows decreases the ammonia emission per m^2 after a urination; however, its effect on other gaseous emissions remains to be clarified.

4.1. Introduction

In most commercial pig farms in the Netherlands, sows are kept on bare floors. When kept in groups, the floor is partly slatted where the animals are active and partly solid where the sows rest. However, there is a trend to improve animal welfare by using litter, such as straw, for bedding material. Whereas the surfaces emitting ammonia in conventional housing for pigs are concrete floors and slurry pits, in straw-based systems the straw bedding will be fouled by excreta and must also be considered to be an emitting surface. Most of the ammonia emitted from an animal house originates from urine (Muck & Steenhuis, 1981). Factors related to the urine distribution on the floor surface, such as number of excretions, their volume, and their distribution in space and time, greatly affects the total emission from the animal house (Aarnink, 1997; Elzing & Monteny, 1997b; Monteny, 2000; Groenestein *et al.*, 2003), as does the introduction of straw bedding in sow houses, although little is known about the ultimate effect of the latter.

Given the use of straw in sow houses, more needs to be known about its effect on total emission. The current technique for measuring ammonia emissions from animal houses is based on the ammonia concentration of the air in the house and the volume of air leaving the house. It does not differentiate between the contributions of different emitting surfaces within the house. The laboratory study described in this paper was designed in order to assess the ammonia volatilisation of different floor surfaces in a sow house with straw bedding.

There have been few studies on ammonia volatilisation from bedding in livestock housing systems. Measurements have been conducted on a laboratory scale with mixtures of fresh bedding and faeces (Andersson, 1996; Misselbrook & Powell, 2005) or known ammonia solution (Kemppainen, 1987). These studies set out to identify differences between bedding materials, but not to mimic the real-life situation where litter and excretion accumulate for a year in the animal house. Jeppsson (1998) measured volatilisations from different bedding materials in situ without disturbing the structure and the top layer of the bedding. This is of interest because the rate of the ammonia emission is determined by the characteristics of the emitting surfaces (Zhang *et al.*, 1994). Jeppson measured the emissions after covering part of the bedding material with a measuring chamber. This method, which does not allow long-term measurements, affects the temperature and air velocity; Jeppsson (1998) argued that this was largely responsible for the high ammonia emission rates he measured. Andersson (1996), Groenestein & Van Faassen (1996), Thelosen *et al.* (1993) and Kaiser & Van den Weghe (1997) all

measured the full-house emissions, but they did not distinguish the different emitting surfaces. The characteristics of the surface of the substrate are complex and difficult to define, causing variability of many factors affecting nitrogen turnover and ammonia emission. For the current study, the practical situation was therefore simulated by taking samples representing the top layer of the bedding, the solid and slatted floors and the slurry in the pit, and studying them under standard laboratory conditions similar to average conditions in the sow house. To analyse the volatilisation characteristics of the surfaces a standard dose of urine was applied and the volatilisation was measured continuously for a week. The null hypothesis was that substrates would differ in the rate of ammonia volatilisation, but not in the total ammonia volatilisation over the full period.

4.2. Material and methods

The principle of the approach was to take samples from potential ammonia-emitting surface areas in a sow house, put them in closed vessels, and in the laboratory apply urine and measure ammonia volatilisation. The objective was to ascertain the volatilisation achieved by a discharge of urine at corresponding places in the sow house.

4.2.1 Substrate samples

The sow house from which the samples were taken was a commercial straw-bedded group- housing system for 150 sows. See Figure. 4.1 for a floor plan. The following areas were distinguished: a straw bed used mainly as a resting area (179 m^2), fenced off with a closed partition and a passage of 1.4 m wide to the walking alley (69 m^2); a waiting area in front of the feeding stations (46 m^2); the feeding area with three feeding stations (21 m^2); and the drinking area behind the feeding stations (29 m^2) with three nipple drinkers on the wall left of the exit to the walking alley. The waiting and drinking areas had slatted floors over separated slurry pits. Sows could be selected from the group with a separation station and led into a separate area of 23 m^2. A boar was housed in a pen near the drinking area (7 m^2). The house was ventilated mechanically. Air entered the building through inlet valves over the length of the long side of the straw bed and left through ventilation shafts in the roof above the feeding stations. The sows were fed concentrates (13.2 MJ metabolisable energy and 133 g crude protein per kg of feed with 8% fibre), the daily amount being 2.2 kg at the start of pregnancy, rising to 3.3 kg at the end of pregnancy. To facilitate intake of feed in the station, 30 g of water was administered per 95 g of feed. As a rule, sows took their daily

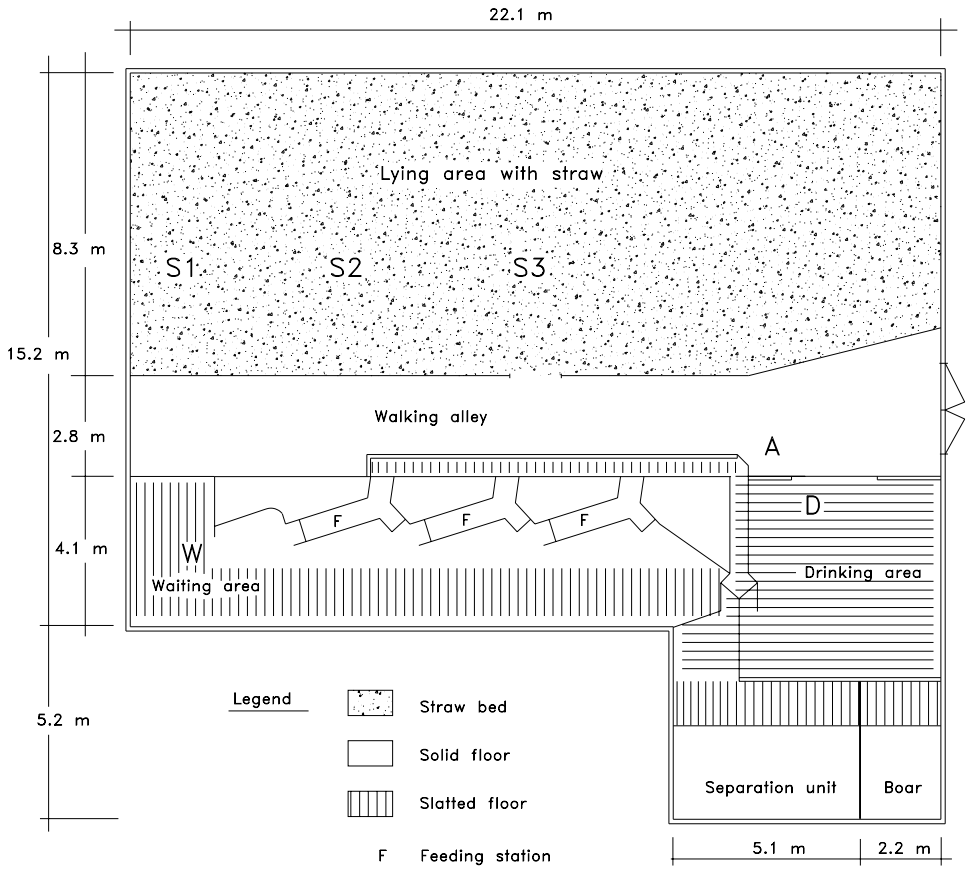


Figure 4.1. Floor plan of the sow house with a lying area with straw, a walking alley, waiting area, feeding stations (F), drinking area, separation area and boar pen; slatted floors are hatched; straw and manure samples were taken from locations S1, S2, S3, W, D and A denoting slightly soiled, medium soiled and heavily soiled straw, slurry from the pits under the drinking and waiting areas and the concrete floor in the walking alley.

ration in one visit to the feeding station. Water was available *ad libitum* in the drinking area.

Twice a week the straw bedding was replenished by putting approximately 400 kg (in bales) in the middle of the bed. The pigs themselves distributed the straw over the bed. The bedding was removed once a year (April-May). By then, the straw bedding was approximately 0.1-0.2 m deep around the edges and 0.5-0.6 m deep in the middle.

In the straw bed, three different areas could be visually distinguished based on

the slurry content: no slurry (around the edges); much slurry (near the entrance to the walking alley and in the middle); and a moderate amount of slurry (the remaining area). Substrate samples were taken from the upper part of the bed in these areas (Figure 4.1). To do so, a mould the same size of the cylindrical laboratory vessel was put on the bed and a slice of approximately 15 cm deep was cut with a fretsaw and a trimmer, leaving the structure of the bedding material intact. The slurry samples from the pits under the drinking and waiting area were scooped from the upper 5 cm of the surface in the required quantity. To obtain a representative substrate sample with the emission characteristics of the slatted and solid floors, a concrete tile was put on the floor of the walking alley in the passage from the drinking area to the walking alley. According to Braam & Swierstra (1999), it takes a fouling period of 15 days to establish representative urease activity, a measure of the rate of hydrolysis of urea into ammonia. In our experiment, the tile was left in place for a month and was fouled as much as the surrounding area.

Two substrate samples were taken as controls: a fresh straw sample from the straw depot and a reference sample of slurry from the pit of another, conventional sow house on the same farm in which the sows were kept on partly slatted floors, without bedding and fed twice a day with the same diet as the group-housed sows, based on concentrates with a fibre content of approximately 8%. Drinking water was available twice a day for one hour around feeding time. Measurements in the laboratory started an hour after sampling due to transport by car.

The build-up of the straw bed had started on 18 April. Substrate samples were taken subsequently on five dates: 14 May; 4 June; 9 July; 8 December, and 18 January the next year. As the laboratory had the capacity to simultaneously measure six vessels containing substrate samples, the samples were assigned randomly to the five sampling dates. Each surface type was sampled and tested in triplicate; the unsoiled straw from the depot was sampled and tested in duplicate. In all cases the samples were taken three to four days after new straw bales had been added. Table 4.1 presents the average weight and specific gravity of the slurry and straw samples. The specific gravity was calculated by dividing the weight by the volume of the sample. The volume was calculated from the height of the sample in the vessel and the surface area of the vessel. The specific gravity differed significantly between the straw samples and slurry samples *($P < 0.05$)*, and also between straw samples with various amounts of slurry *($P < 0.05$)*. The latter confirms the primary visual differentiation between straw samples based on the slurry content of the straw bed.

Table 4.1 Number of substrate samples n per sampled surface type, mean weight W and mean specific gravity SG of the substrate samples and variation coefficient of the specific gravity.

Surface	*Substrate sample*		*Number of samples (n)*	*Sample weight (W), kg*	*Specific gravity (SG), kg/m^3**	*Variation coefficient, %*
	Code	*Description*				
Straw	S1	slightly soiled	3	0.3	73 ^{b}	25
	S2	medium soiled	3	1.1	235 ^{c}	19
	S3	heavily soiled	3	2.0	423 ^{d}	23
Slurry	W	pit waiting area	3	3.3	978 ^{e}	10
	D	pit drinking area	3	3.1	1012 ^{e}	4
Floors	A	walking alley	3	-	-	-
Control	S0	straw depot, unsoiled	2	0.1	29 ^{a}	17
	R	pit control sow house	3	3.6	1048 ^{e}	2

* Differences between specific gravities (Probability $P < 0.05$) are indicated by different superscripts, ordered alphabetically with ^{a} assigned to the lowest value.

4.2.2 Laboratory procedures

The cylinders containing the substrate samples were 0.19 m in diameter and 0.30 m tall. The lids were perforated; each had 24 small holes (diameter 0.001 m) near the edge as air inlets, and a bigger hole (diameter 0.005 m) in the middle as an air outlet. Emission from the floor sample was measured by placing a 0.15 m tall bottomless cylinder on top of the tile. Figure 4.2 gives a schematic view of the laboratory layout. Air flowed continuously over the surface of the substrate samples at a rate of 1 *l*/min, controled by a teflon coated pump and a critical capilair. With headspaces of 0.10-0.15 m, this means the air was being exchanged 14-21 times per hour (number of times per hour total air volume is refreshed), which is comparable to common air exchange rates in sow houses in the Netherlands. The air temperature during the experiment was maintained at 20°C, the relative humidity was 70%.

Urine was collected from urinating sows in various stages of pregnancy in the bedded house. The 4 *l* sample contained 4.45 g/*l* urea-N and 0.018 g/*l* ammonium-N, the pH was 6.0. The sample was divided into doses of 150 ml and frozen. For the measurements, one dose per substrate sample was defrosted and brought to a temperature of 20°C before being sprinkled, by pouring it through a flat sieve, on the substrate samples at the beginning of the experimental period

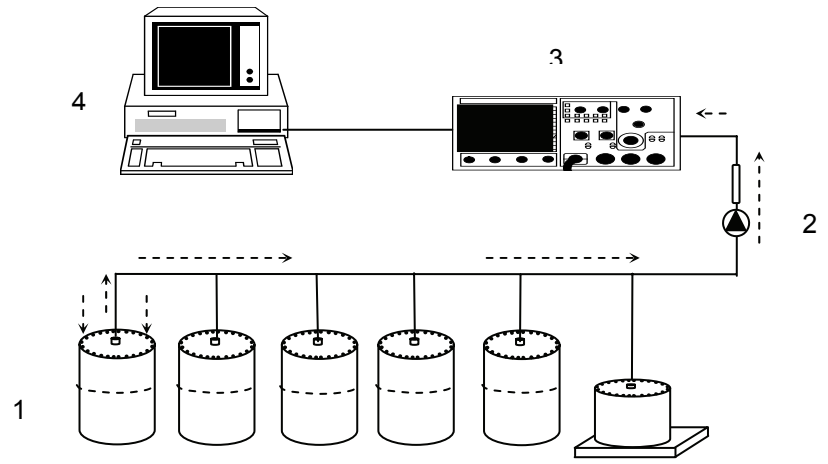


Figure 4.2. Experimental layout with six cylinders with perforated lids (1), pump and critical orifice (2), analyser (3) and data logger (4). The dashed arrows indicate the continuous air flow for all vessels (for clarity, only drawn at one vessel).

(*t*=0). In total, each dose of urine represented a potential ammonia volatilisation of 814 mg. The ammonia concentration of the outgoing air was measured with a non-dispersive infrared (NDIR) analyser (Brüel & Kjaer Multi-gas monitor, type 1302, Nærum, Denmark) equipped with automatic compensation for water vapour and carbon dioxide. The detection range was 0.2-20,000 ppm. The accuracy of the Brüel & Kjaer Multi-gas monitor was evaluated by Hansen *et al.* (2003). The measuring interval per substrate sample was 1 hour. Measuring time per sample was 10 minutes. The measuring period lasted seven days. The ammonia concentration of the incoming air was assumed to be zero because the air containing ammonia was removed from the room with the cylinders. The ammonia volatilisation was calculated as the product of the air flow and the ammonia concentration.

4.2.3 Data handling and procedures

The cumulative volatilisation of seven days after adding urine was calculated for each substrate sample. To derive the maximum volatilisation rate and the time of occurrence of the maximum volatilisation rate, the data were smoothed. The algorithm of the smoothing was based on the weighted moving average (Eiler, 1994).

Data were log transformed and analysed with the restricted maximum likelihood (REML) procedure of Genstat 5 (1997). This procedure accounts for unbalanced

data in a model with fixed and random components (mixed model). The basic model was:

$$Y_{ij} = \mu + S_i + d_j + e_{ij}$$

where Y_{ij} is the log transformation of respectively the cumulative ammonia volatilisation of seven days after adding urine (E, mg), the maximum volatilisation rate (r_{max}, mg/h) and the time of occurrence of the maximum volatilisation rate (t_{max}, h). The emitting surface is represented by S_i (fixed component, with i = 1 to 8). The random components are represented by d_j (day of sampling, with j = 1 to 5) and e_{ij} (residual variation). The statistical significance of differences between the volatilisations from surfaces was assessed by the Wald test and the paired comparison of the predicted means was based on standard error of differences (SEDs).

4.3 Results

The day of sampling d_j was not larger than the residual variation e_{ij}, implicating there was no effect of day of sampling. Table 4.2 shows that application of urine on the straw samples and on slurry from the waiting area resulted in the lowest volatilisation of NH_3 and the lowest rate of volatilisation of NH_3. The volatilisation and the rate of volatilisation of NH_3 for the straw samples did not increase concomitantly with an increasing slurry content: indeed, the volatilisation of NH_3 from S2 and S3 was even significantly lower than from S1 and S0. The amount of slurry appeared to be an indicator of the t_{max}: the larger the slurry content, the sooner the maximum rate of volatilisation occurred. In terms of the characteristics of the volatilisation, the most similar substrates were the slurry from the pit in the waiting area and the straw samples: there was no significant difference between the maximum rate of ammonia volatilisation for the straw samples and the slurry sample from the waiting area. The time of the maximum rate of volatilisation was not significantly different for S3, the straw sample with the largest slurry content. The NH_3 volatilisation from the slurry from the waiting area was not significantly different from that from S0 and S1, but was about 30% more than the emissions from S2 and S3 *($P<0.05$)*. Much more ammonia was emitted from the substrate samples from the drinking area, from the floor and from the slurry from the conventional system *($P<0.05$)*. The latter even exceeded the ammonia potentially present in the urine (814 mg).

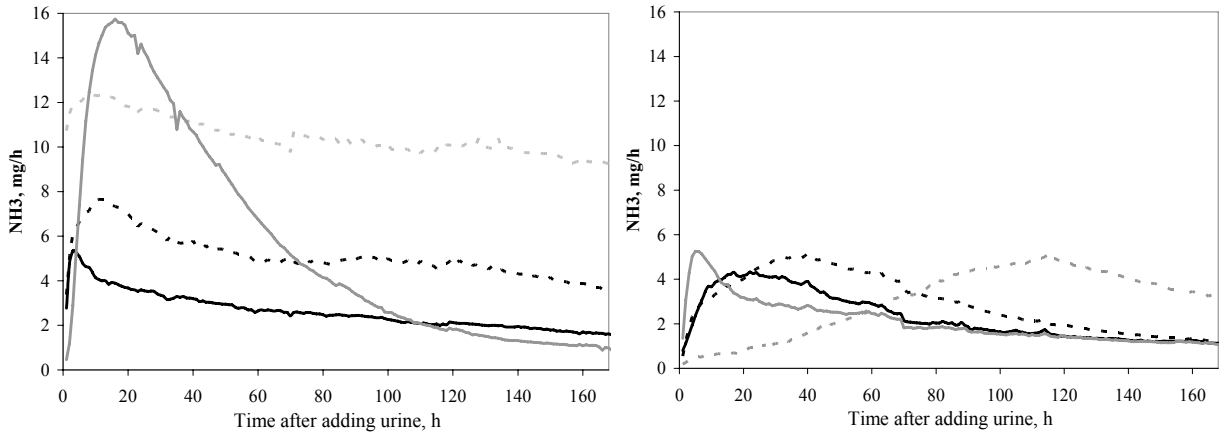
Table 4.2 Predicted means of the total ammonia volatilisation of seven days after adding urine E, maximum volatilisation rate, r_{max} and time of occurrence of maximum volatilisation rate, t_{max} of the substrate samples of the different surface types and the respective variation coefficients.

Surface	Substrate sample		Number of samples (n)	E, mg*	r_{max}, mg/h*	t_{max}, h*
	Code	Description				
Straw	S1	slightly soiled	3	469 b	4.8 a	33 d
	S2	medium soiled	3	359 a	4.0 a	19 c
	S3	heavily soiled	3	344 a	5.0 a	7 a
Slurry	W	pit waiting area	3	455 b	5.4 a	5 a
	D	pit drinking area	3	863 c	7.7 b	8 ab
Floors	A	walking alley	3	973 c	17.5 d	13 ab
Control	S0	straw depot, unsoiled	2	473 b	4.3 a	107 e
	R	pit control sow house	3	1686 e	12.2 c	8 bc
Variation coefficient, %				12	16	25

* Differences within a column (Probability $P < 0.05$) are indicated by different superscripts, ordered alphabetically with a assigned to the lowest value.

Figure 4.3 shows that after the addition of urine, the volatilisation increased, peaked and then declined. The highest volatilisations were identified from the concrete floors and the pits (Figure 4.3a). After seven days the NH_3 volatilisation from D was still *ca* 4 mg/h, but that from A had declined to 0 mg/h. The greatest volatilisation was from the control substrate sample from the pit from the conventional individual housing system: its curve was flattest and the volatilisation was still *ca* 10 mg/h after seven days. The volatilisation from the straw control S0 shows that ammonia is produced even when no faeces are present, albeit very slowly (Figure 4.3b).

The average air exchange rates (standard deviation in parenthesis) were 24 (5.1) times per h for the straw samples, 19 (3.0) for the slurry samples D and W, 28 (1.6) for the floor sample from the alley A and 20 (1.0) times per h for the slurry sample R. The average air exchange rates of the straw samples were not



(a) (b)

Figure 4.3. Mean ammonia volatilisation rates from substrate samples from different emission sources: (a) concrete floor in the walking alley (solid grey, A), the pit of the waiting area (solid black, W), the drinking area (dashed black, D) and a control sow house without a straw bed (dashed grey, R); and (b) straw from the bedded area slightly soiled (dashed black, S1), medium soiled (solid black, S2) and heavily soiled (solid grey, S3), and unsoiled straw from the depot (dashed grey, S0).

significantly different from those of D, W and A *(P>0.05)*. The air exchange rate of A was higher than that of D and W *(P<0.01)*.

4.4. Discussion

The results of the experiment indicate that if a sow urinates on the straw bedding, irrespective of slurry content the ammonia volatilisation will be less than if the sow urinates on a solid floor or on a slatted floor over a slurry pit. From the control measurements it is clear that urination on the slurry of the pit from a conventional house produces more volatilisation than urination on the slurry of the pit in the straw-based system. Figure 4.3 shows that the maximum volatilisation rate from R was high, *i.e.* that much ammonia was present, and that depletion was slow (a gradually declining curve). Ultimately, more ammonia was emitted than was applied. This implies that the source of ammonia was the substrate sample itself, and that diffusion of ammonia from the slurry plays a role (Figure 4.4).

The pattern of the ammonia volatilisation after application of urine in this experiment (Figure 4.3) agrees with the findings of Sherlock & Goh (1984), Elzing & Monteny (1997a) and Monteny (2000): an ascending slope, whose gradient is a

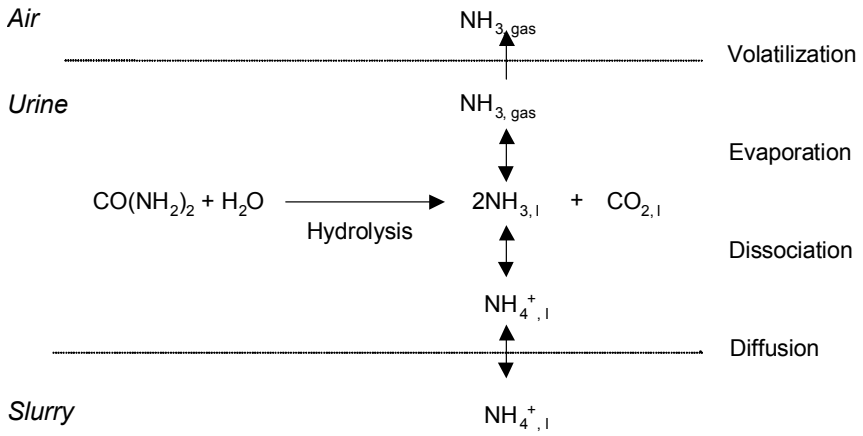


Figure 4.4. Processes of ammonia volatilisation from an aqueous system (l) to a gaseous phase (gas) with NH_3,gas as ammonia in the gaseous phase, NH_3, l as ammonia in the aqueous system, NH_4^+, l as ammonium in the aqueous system, CO(NH2)2 is urea, H_2O is water and CO_2,l is carbon dioxide in the aqueous system (after Monteny, 2000).

measure of the production of ammonia and a descending slope, defined by depletion of ammonia. Production of ammonia depends on the activity of the enzyme urease, which is abundant in the faeces. Depletion of ammonia depends on the chemical and physical factors affecting diffusion, evaporation and volatilisation (Figure 4.4). At the top of the curve, production and depletion are in balance; the height of the curve is linearly related to the concentration of urea (Elzing & Monteny, 1997a).

The volatilisation characteristics of the substrate sample from the waiting area were more similar to those from the straw samples than to those from the drinking area and the concrete floor. This cannot be explained with the present data, but might have to do with the fact that the animals did not excrete so much in this area. The composition of the top layer of the slurry just after receiving a new load of slurry will differ from the composition a day or so after the last deposition, and thus volatilisation of ammonia will be different after simulating an urination.

The lower air exchange rate in the vessels containing the slurry samples from the waiting area, the drinking area and from the conventional reference house probably caused an underestimation of the volatilisation rate of ammonia compared to the substrate samples of the straw bedding and the concrete floor, because the air velocity over the surface of the substrate samples will have been

lower and the partial pressure of NH_3 gas higher (Elzing & Monteny, 1997b). It agrees, however, with the practical situation in a sow house where air velocity underneath the slatted floor will be lower then above. The higher maximum volatilisation rate from the floor sample compared to the slurry samples can be explained by a higher urea concentration at the surface of the substrate, because mixing urine with the slurry dilutes the urea concentrations and thus lowers the maximum volatilisation rates (Elzing & Monteny, 1997a).

The straw samples showed lower volatilisations and rates of volatisation of NH_3 than the substrate samples from the drinking area and the concrete floor. Straw affects NH_3 emission via factors such as adsorption (Kemppainen, 1987), bulk density (Dewes, 1996; Misselbrook & Powell, 2005), pH (Low, 1993; Canh *et al.*, 1998b, 1999) and temperature (Muck & Steenhuis, 1981; Dewes, 1996; Monteny & Erisman, 1998). To allow ammonia to change from the liquid phase to the gaseous phase, the slurry must be in contact with the air. Straw can increase the contact by increasing the surface area (Aarnink *et al.*, 1996), but the contact is diminished each time the emitting area is covered by new straw, as a result of absorption (Misselbrook & Powell, 2005) and as a result of the pigs compacting the litter and thus reducing the air space in the bedding (Groenestein & Van Faassen, 1996). Straw can decrease ammonia emission if microbial activity allows nitrogen to be incorporated in microbial protein or converted into the inert gas N_2. The high C:N ratio in the straw bedding is favourable for these processes. However, other gases such as CH_4, N_2O, and NO can be produced; these are polluting as well (Andersson, 1996; Groenestein & Van Faassen, 1996; Thelosen *et al.*, 1993; Kaiser & Van den Weghe, 1997).

The differences between the volatilisations from S0, S1, S2 and S3 were mainly expressed in the time the volatilisation rate peaked. This implies that the rate at which ammonia is produced from urea in the urine increases concomitantly with slurry content. Total volatilisation during the seven days of measurement was similar, however. Even when no faeces were present (S0), ammonia was produced, albeit at a lower rate, but in the end even more ammonia was emitted from S0 than from S2 and S3. A possible reason is that microbial activity increases with increasing slurry content, and the nitrogen of ammonia is incorporated in microbial protein, or emitted as N_2O, NO or N_2. This implies that a lower NH_3 emission does not necessarily mean that the total N emission is lower or that there is less environmental pollution. This study considered NH_3 emission from the house when straw is applied. When addressing environmental concerns, emissions during storage and the spreading of slurry-impregnated straw on the

land must also be examined.

The low emission rate of the straw samples contrasts with the emission rate from uncoated concrete floors. Braam & Swierstra (1999) stated that development of urease activity on concrete floors is rapid and too high to limit volatilisation of ammonia. Table 4.2 shows that the peak of the volatilisation from the floor sample was high (17.5 mg/h), but the time the volatilisation rate peaked was 13 hours. This is not in agreement with Braam & Swierstra (1999) or with the findings of Elzing & Monteny (1997a), who measured a peak after 2-3 hours, and Sherlock & Goh (1985) who reported a peak less than 2 hours after application of urine. The top layer of the tile, representing the floor, was dry by the time the measurements started due to the time it took to transport the sample to the laboratory and to install the cylinders in the measuring unit. The bacterial population, responsible for the production of the enzyme urease probably needed some time to reactivate.

The null hypothesis, that the rate of emission differs between substrates, is verified. It appears that in straw-based systems the production rate of ammonia limits emission, where in slurry-based systems only depletion of ammonia limits emission. It resulted in a lower rate of volatilisation of ammonia for straw. However, given the same amount of urine load, total volatilisation of ammonia from straw was lower than from the slurry in the pit under the drinking area and from the slatted and concrete floors: the null hypothesis that total amount of ammonia volatilisation would be the same, must therefore be rejected. It appears that the straw bedding reduces NH_3 volatilisation. When the majority of urinations occur on the bedding, however, straw can still contribute the most to the emission in the house, especially if the surface area is large. The distribution of urine puddles, *i.e.* the urinating behaviour of the sows, is an important factor when discussing the full-house emission and the relative contribution of each emitting substrate to the emission from the entire house.

4.5. Conclusion

From the samples of the bedded house, the one of the concrete floor alley emitted 973 mg of ammonia after seven days following a simulated urination; of the slurry in the pit of the drinking area 863 mg; of the slurry in the waiting area 455 mg; and straw 344-469 mg, depending on the slurry load. It can be concluded that the concrete floor is potentially the largest source of ammonia emission per m^2 after a urination, and straw is the smallest.

The ammonia-emitting surfaces in a group-housing system for sows with straw bedding show different ammonia volatilisation characteristics after urination, but less ammonia is emitted from each surface than from the slurry in the pit of a conventional housing system (1686 mg).

For straw, the production rate of ammonia increases concomitantly with slurry content after a urination. However, after seven days following urination, more ammonia volatilised from unsoiled and slightly soiled straw than from medium and heavily soiled straw.

From this study it can be concluded that ammonia emission per m^2 can be reduced by using straw as a bedding material. The consequences of the use of straw on other gaseous emissions need further research.

5

Effect of Urinations on the Ammonia Emission from Group-housing Systems for Sows with Straw Bedding: Model Assessment

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Abstract

A model was developed as a tool for designing straw-bedded sow group-housing systems with low ammonia emission. Using mechanistic and empirical relationships it calculates the total ammonia emission by integrating ammonia volatilisations from all the urine pools in the house. The reference data were from a house with a floor comprising 60% straw bedding, 14% drinking area (slatted floor with pit), 3% waiting area (slatted floor with pit) and 23% alley (solid floor). Simulations were performed to elucidate the effect of the distribution of the urinations over the different surfaces, relating this to the size and distribution of the urine pools, and the area of the surfaces urinated upon. The results were compared with actual emission data from an entire sow house. When the default settings were a urine production of 7 l/d per sow, a urination frequency of 5 times a day per sow, and urinations distributed evenly over the four emitting surfaces the model estimated the ammonia emission from the entire house as 11.7 g/d per sow, and the relative contributions of the straw bed, the drinking area, the waiting area and the alley as respectively 27%, 22%, 9% and 42%. By comparison, the actual emission from the house was 8.7 g/d per sow. The 90% confidence interval was 6.5-10.9 g/d per sow. Increasing the size of the urine pool from 0.14 m^2 to 1.40 m^2 in the model simulations caused ammonia emission initially to increase from 9.7 to 12.1 g/d per sow when the pool volume was 0.47 m^2. If the pool was bigger, emission fell to 10.6 g/d per sow because, though the larger emitting area increases ammonia emission, the increase is outweighed by the reduction in emission caused by successive, superseding urinations on the same spot. If the entire emitting area was assumed to be straw bedding, the calculated emission from the house was 5.8 g/d per sow. Assuming slatted and concrete floors without straw bedding increased the emission to 16.5 g/d per sow. It is concluded that measures to reduce the ammonia emission from the bedded sow house should be aimed at decreasing the emission from the solid floor and/or allowing more urinations on the straw bed. The model is a useful design tool for achieving emission reduction from group-housing systems for sows with straw bedding. Its predictive power would be improved by inputting data on the actual size of the urine pool and urinating behaviour of sows.

5.1. Introduction

As ammonia is a polluting gas, the Dutch agricultural sector is committed to developing ammonia-emission reducing techniques. Furthermore, to improve animal welfare, Dutch pig farmers are using more straw bedding, especially for group-housed sows. The models developed by Aarnink & Elzing (1998) and Monteny *et al*. (1999) to estimate ammonia emissions from floors and slurry pits take no account of straw. Though various authors have described the effect of using litter such as straw on ammonia emission from pig housing (Kemppainen, 1987; Thelosen *et al.*, 1993; Andersson, 1996; Groenestein & Van Faassen, 1996; Kaiser & Van den Weghe, 1997; Jeppsson 1998), there have been no studies of the relative contribution of straw bedding to ammonia emission from the entire house when concrete floors and slurry pits are also present as emitting surfaces. Yet such knowledge is essential if effective emission-reducing measures are to be applied.

A group-housing system for sows can be considered to have four different emitting surfaces: the slurry in the pits, the concrete surfaces of slats and of solid floors, and the straw bedding. Elsewhere (Groenestein *et al*., 2006, chapter 4 of this thesis), laboratory measurements of the volatilisation of ammonia from samples of these surfaces in response to the application of a dose of urine have been described and it was concluded that a urine pool on straw emits less ammonia than a urine pool of the same size on a slatted or solid floor. This implies that the spatial distribution of urinations influences the ammonia emissions from the house and that emission could be reduced by manipulating the surface the sows urinate upon.

The objective of the study described here was to develop a model to assess the contribution of each emitting surface to the ammonia emission from an entire house for group-housed sows on straw bedding. Model simulations were performed to estimate the effect of the size of the urine pool, the distribution of urine pools over the different emitting surfaces, and the size of the emitting surfaces. Our aim was to assess whether the results of such simulations in combination with knowledge of the urinating behaviour of the sows could be important in designing the sow house to reduce environmental pollution (Bos *et al.*, 2003). The outcome of the model was compared with actual emission measured from a reference sow house.

5.2. Materials and methods

5.2.1 Housing system

The reference housing system in this study was a commercial straw-bedded group house for 150 sows. Data on ammonia emission from this housing system had been used in the Dutch Regulation for Ammonia and Livestock (Anonymous, 2005), to provide the ammonia-emission factor of group-housed sows with a straw bed. Table 5.1 summarizes the characteristics of the reference house.

Figure 5.1 is a schematic view of the layout. The following functional areas were distinguished for the purpose of our study: a straw bed mainly used as a resting area *S*, an alley with a solid concrete floor leading to the feeding stations *A*, a waiting area with a slatted floor next to the feeding stations *W*, the feeding area with three feeding stations *F* and the drinking area with slatted floors and three drinking nipples *D*.

Table 5.1. Characteristics of the reference group-housing systems for sows with straw bedding.

Number of sows	150
Surface area (m^2 per sow)[1]	2.25
Straw use (kg/y per sow)	300
Feeding system	Feeding station
Feeding acces	restricted
Feeding start	20:15 h
Feeding intake (kg/d per sow)	2.8
N intake (g/d per sow)	60
Water access	*Ad libitum*
Water use (l/d per sow)	9.1
litters per sow per year	2.38
raised piglets per sow per year	22.8
annual rate of sow replacement (%)	33

1:excluding separation unit and boar pen

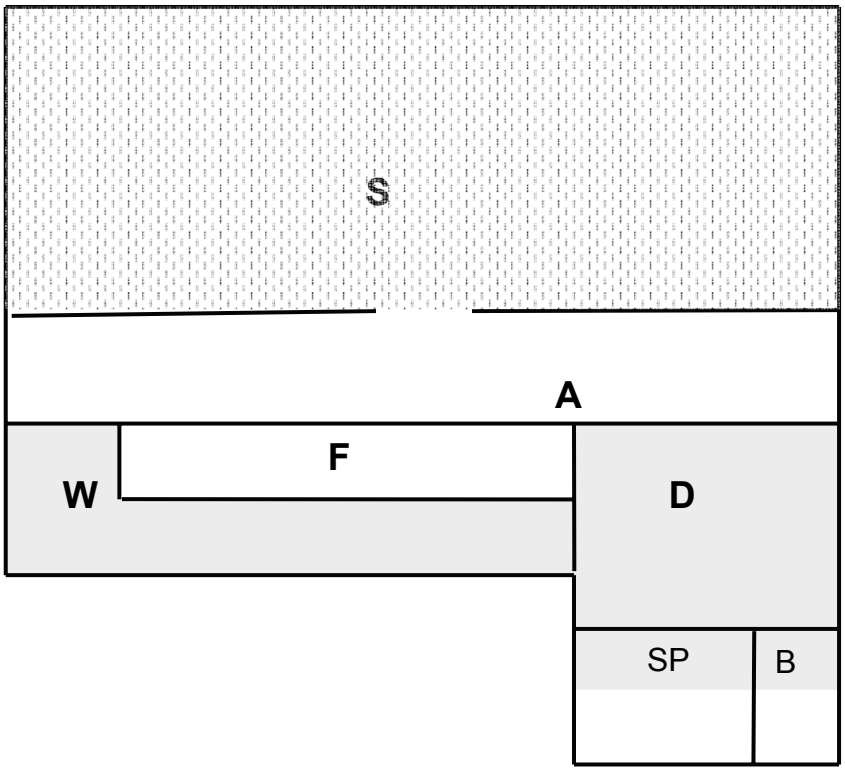

Fig. 5.1. Schematic view of the floor plan of the sow house with straw bedding (S, dashed area), alley (A), waiting area (W), feeding area with feeding stations (F), drinking area (D), separation pen (SP) and boar pen (B), slatted floor is coloured grey (after Groenestein et al., 2006) (chapter 4 of this thesis); the feeding area F, part of W below F and the solid floors of SP and B were excluded as emitting areas.

Surfaces fouled with urine and faeces were assumed to emit ammonia. The following surfaces with few or no excretions were not included as emitting areas: feeding stations, the part of the waiting area below the feeding area (Figure 1), and the solid floors of the boar pen and of the separation pen. As the pit underneath the slatted floors of the boar pen and the separation pen was an extension of the pit in the adjacent drinking area, it was included in the drinking area. The total floor area available to be urinated and defecated upon in the house was 299 m^2 and comprised the straw bed (179 m^2), the alley (69 m^2), the left-hand side part of the waiting area (10 m^2, Figure 1) and the drinking area (41 m^2), amounting to 80% of the total floor area of the house.

5.2.2 IUPE model

The acronym IUPE stands for Integration of Urine Pool Emissions. The principle underlying the model is that the ammonia emission from the entire house is calculated by integrating ammonia volatilisations from all urine pools in the house

deposited by the sows. A urine pool is a puddle of urine on the floor surface; it may consist of one or more urinations. By volatilizing, ammonia produced from urinary urea is transferred from the liquid phase to the gas phase (Muck & Steenhuis, 1981). The IUPE model assumes that conversion of the urinary urea into ammonia starts immediately after a sow has produced a pool of urine, and the volatilisation of ammonia is assumed to continue until the ammonia has been depleted or more urine is deposited in the urine pool. In the latter case, the former urine is assumed to have been superseded and no longer in contact with the air, so that volatilisation cannot take place, emission stops, and the newly deposited urine starts to emit (Monteny *et al*., 1999).

Unlike the data used in the mechanistic models of Monteny *et al*., (1999) and Aarnink & Elzing (1998), the data on ammonia emissions from urine pools provided as input data for the present model came from a laboratory study in which urine was sprinkled on to various substrate samples (straw, concrete, slurry) taken from the reference sow house (Groenestein *et al.,* 2006, chapter 4). Emissions from the floor surfaces in the house then depend on the area of the surfaces and the number of urine depositions. Both factors together determine the time at which a urine pool is superseded and therefore the duration t_x in d^{-1} that a urine pool is emitting:

$$t_x = \frac{A_x}{A_p \times N_{ux}} \tag{5.1}$$

where A_x is the floor area in m^2 of surface type *x*; A_p is the surface area of the urine pool in m^2; and N_{ux} is the number of urinations on surface type *x* in d^{-1}.
The emission from a urine pool on a specific surface type is:

$$E(t_x) = E_{lv}(t_x) \times \frac{A_p}{A_{lv}} \tag{5.2}$$

where $E(t_x)$ is the calculated NH_3 emission during time *t* from a urine pool on surface *x*, g; $E_{lv}(t_x)$ is the measured NH_3 emission from laboratory vessel during time *t* with sample from surface *x*, g; and A_{lv} is the surface area of the laboratory vessel in m^2. The ammonia emission from the entire house is the sum of the emissions from the different surfaces *S*, *D*, *W* and *A*:

$$E = \sum_{x}^{S,D,W,A} E_x \tag{5.3}$$

with

$$E_x = \sum_{t=0}^{t_{\max}} \frac{A_x \times E(t_x)}{A_p} \tag{5.4}$$

where E is the calculated NH_3 emission from the entire house in g/d; and E_x is the calculated emission from surface *x* in g/d.The longest period of time (t_{max}) that elapses between two overlapping urinations occurs in the area with the least urinations per m^2 (initially, the straw bedding). This value for t_{max} is the time used to integrate the emission from the different surfaces (82 h in Figure 5.2). The size of a urine pool A_p depends on its volume V_u and the depth d_u and is assumed to be independent of the surface type:

$$A_p = \frac{V_u}{d_u} \tag{5.5}$$

The assumed depth of a urination from a sow, 5 mm, was derived from Sherlock & Goh (1984), who assumed that 150 ml of sheep urine covered 300 cm^2 on pasture. This is similar to the findings of Aarnink & Elzing (1998) that 0.5 l of urine from fattening pigs covers an area of 850-1110 cm^2 on a slatted concrete floor. In our associated laboratory study (Groenestein *et al*., 2006, chapter 4), the urine in the vessel was also 5 mm deep.

The volume of a urination V_u was calculated as:

$$V_u = \frac{U_d}{f_U} \tag{5.6}$$

where U_d is the urine production per sow in *l*/d; and f_u is the urination frequency per sow per day. If sows urinate on the slatted floor, some of the urine f_{pit} drains into the pit and therefore the N loads from urination in the pit and from urination on the slatted floor were respectively f_{pit} and (1-f_{pit}) times the urea-*N* load. If the calculated ammonia-*N* emission exceeded the urea-N load from urination, it was set to be 100% of the urea-N load. It is possible for the model to calculate that the emissions from slatted floors are greater than 100%; this is because the N-load on the slatted floors was (1-f_{pit}) times smaller than the N-load on the corresponding sample in the experiment of Groenestein *et al.*, (2006) (chapter 4).
Note the following assumptions made in the model:

(a) urinations are evenly distributed over the emitting surface types with number of urinations on straw, drinking area, waiting area and alley being respectively 1, 5, 17 and 3 m^{-2} d^{-1};
(b) the sows urinate at regular intervals;
(c) the slatted floor and the concrete solid floor have the same emission characteristics; and
(d) the area covered by a urination is independent of the type of surface area.

Elsewhere (Groenestein *et al.,* 2006, chapter 4) we reported that the ammonia emission from slatted and concrete floors peaked 13 hours after urine deposition. However, the sample of the floor surface used in that study was dried up before the urine was applied, which delayed the activity of urease and initially slowed down the ammonia emission. In light of this, and because Sherlock & Goh (1985) and Elzing & Monteny (1997a) had reported that emission normally peaked two hours after urine deposition, for the present study, the data presented in Groenestein *et al*. (2006) (chapter 4) were adjusted so that emission from the floor sample peaked two hours after urine application. The default values of the model are summarised in Table 5.2.

5.2.3 Measurements

From 23 June until 23 July, *i.e*. in midsummer, the ammonia concentration NH_3 in mg/m^3, ventilation rate in m^3/h, the ambient air temperature in °C and relative humidity in % were measured every seven minutes and hourly means were recorded. The concentrations of ammonia were measured at the inlet and in the exhaust air in the ventilation shaft with a nitrogen oxide (NO_x) analyser (Monitor Labs nitrogen oxides analyzer, model 8840) (Phillips *et al.*, 1998). To calculate the

Table 5.2. Default values used in the IUPE model.

Variable	Value	reference
A_x	1.19, 0.27, 0.07, 0.46 m^2 per sow for x =*S, D,W, A*	This paper
d_u	5 mm	Sherlock & Goh, 1984
f_{pit}	0.9	Aarnink & Elzing, 1998
Ud	7 l	Mroz *et al.*, 1995
f_U	5 d^{-1}	Ivanova-Peneva *et al.*, 2006
$f_{U,x}$	1.25 d^{-1} for x =*S, D, W, A*	This paper

emission as the product of the NH_3 concentration and the ventilation rate, the NH_3 concentration of the inlet air was subtracted from the NH_3 concentration in the exhaust air. Ventilation rate was determined with an anemometer of the same diameter as the ventilation shaft. A Rotronic® sensor was used to measure the ambient air temperature and relative humidity inside and outside the house. The climate control computer was set to achieve an indoor temperature of 20°C. Ventilation rate depended on the outdoor temperature: the minimum possible rate was 25 m^3/h per sow and the maximum 250 m^3/h per sow.

5.3. Results

5.3.1 Model simulations

The emissions from the different surface types in the reference house calculated by the IUPE model with the default settings (Table 5.2) are presented in Figures. 5.2 and 5.3. Figure 5.2 shows that a urine pool on the straw bed emits for 82 h before it is stopped by a new urination covering it. During that time (t_{max}) the number of urinations received by one urine pool was 5 in the drinking area, 17 in the waiting area and 3 in the alley. After t_{max} the emission pattern resumes. Figure 5.3 gives the total emissions per sow from each surface type in the house, and also the emission rate from the entire house; the latter was calculated to be 11.7 g/d per sow. The estimated contributions of the ammonia emission from the straw bed, the drinking area, the waiting area and the alley to the emission from the entire house were respectively 27%, 22%, 9% and 42%.

5.3.1.1 Size of the urine pool

Emissions were calculated from urine pools varying in area A_p from 0.14 to 1.40 m^2, with depth of a urination varying from 10 to1 mm; other variables remained at default values (Table 5.2). With increasing pool size the ammonia emission from the entire house initially increased from 9.7 to 12.1 g/d per sow at 0.47 m^2 (d_u = 3 mm). As pool size increased, ammonia emission diminished, reaching 10.6 g/d per sow at a value for A_p of 1.40 m^2 (Figure 5.4). Regardless of the value for A_p, the surface contributing most to the ammonia emission of the entire house was the alley: with increasing pool area its contribution increased from 38% to 48%. The comparable figures for the contribution from the other surfaces with increasing were: an increase from 25 to 29% for the straw bed; a decrease from 25 to 20% for the drinking area, and an decrease from 12 to 2% for the waiting area.

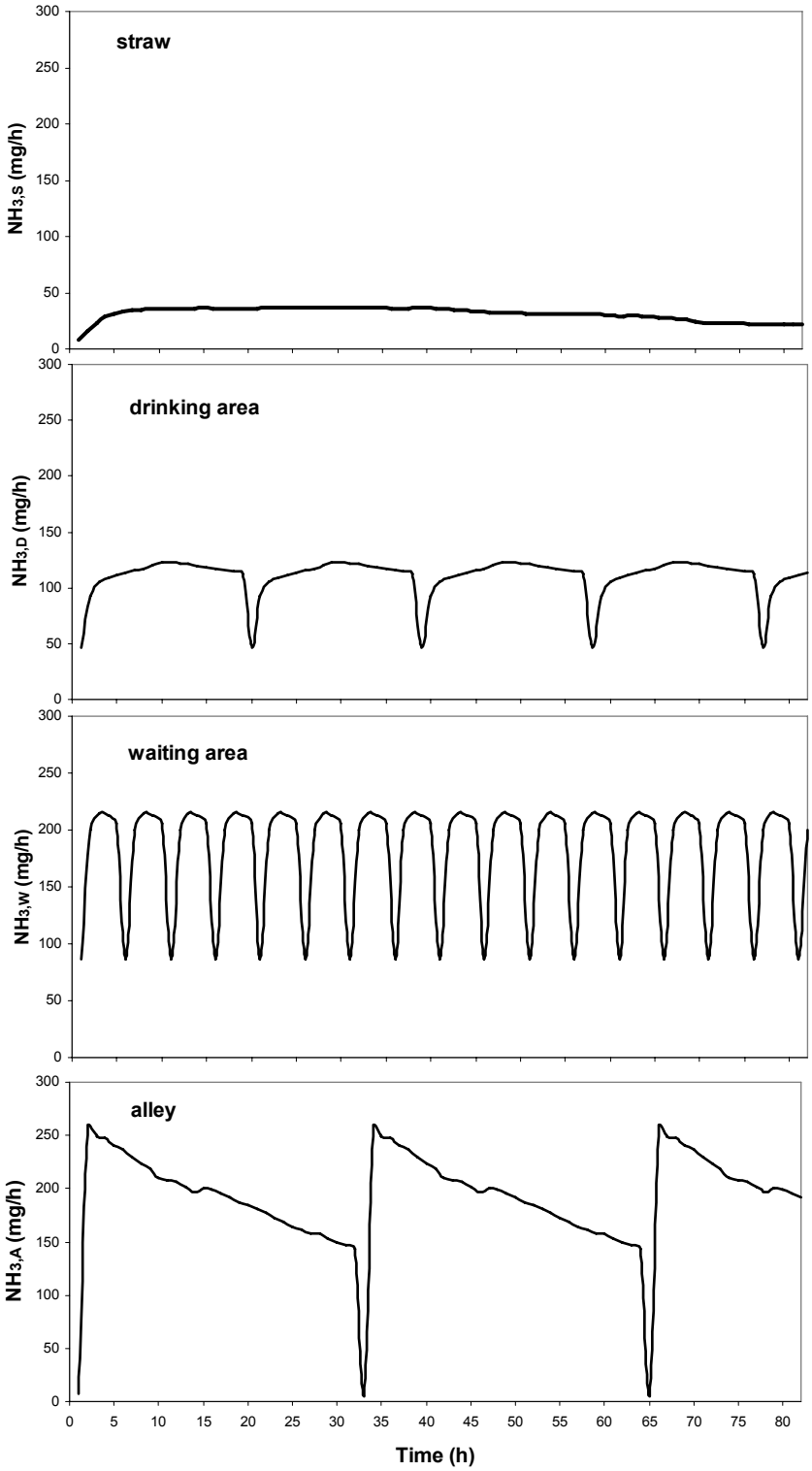

Figure 5.2. Calculated ammonia emissions (mg/h) from a urine pool on the straw bed with one urination in 82 h (t_{max}), in the drinking area (with 5 urinations), in the waiting area (with 17 urinations) and on the alley (with 3 urinations) with f_U = 5 d^{-1}, V_u = 1.4 l and $f_{U,S}$: $f_{U,D}$: $f_{U,W}$: $f_{U,A}$ = 1:1:1:1.

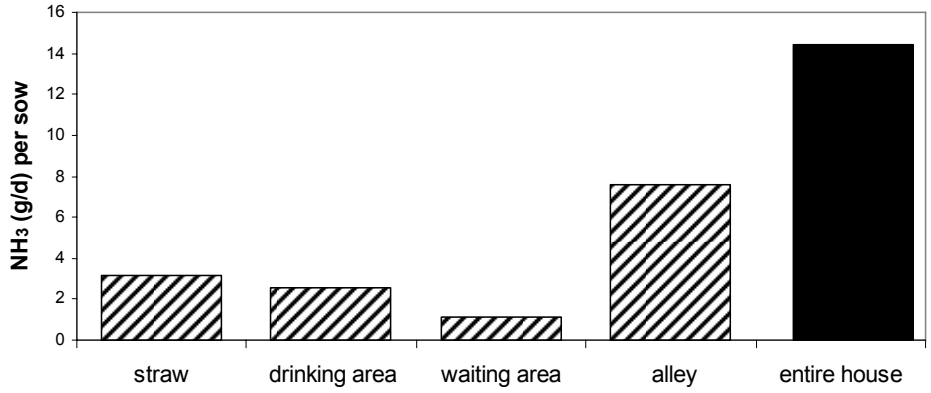

Figure 5.3. Calculated ammonia emissions from straw bed (179 m^2), drinking area (41 m^2) waiting area (10 m^2), alley (69 m^2), and total entire-house emission, with f_U = 5 d^{-1}, V_u = 1.4 l and $f_{U,S}$: $f_{U,D}$: $f_{U,W}$: $f_{U,A}$ = 1:1:1:1.

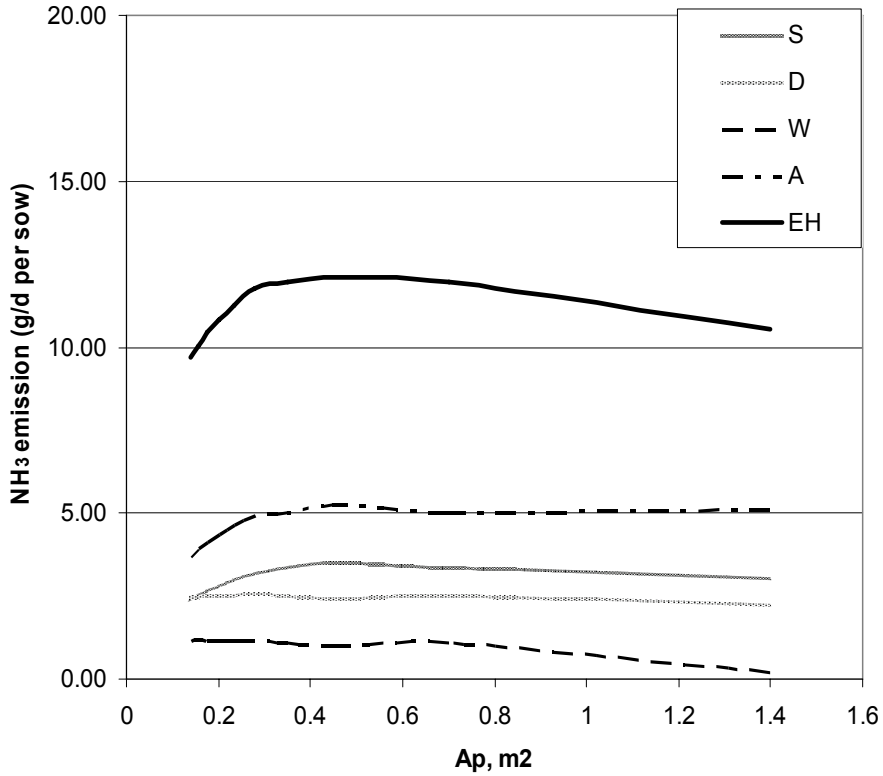

Figure 5.4. The simulated ammonia emissions (g/d per sow) from the entire house (EH) and from the straw bed (S), the drinking area (D), the waiting area (W) and the alley (A) with changing urine pool size (A_p) and f_U = 5 d^{-1}, V_u = 1.4 l and $f_{U,S}$: $f_{U,D}$: $f_{U,W}$: $f_{U,A}$ = 1:1:1:1.

5.3.1.2 Distribution of urinations

Figure 5.5 shows the model calculations of the emission from the entire house and also the contribution of each surface type when the sows preferentially urinate on one surface type (within the surface type, urinations remain evenly distributed). Other variables remained at default values (Table 5.2). With increased frequency of urination on the straw bed, or the drinking area or the alley, the ammonia emission from the area in question increases, but emission decreases by 15% in the case of straw bedding urination, 10% in the case of drinking area urination and 9% in the case of alley urination. The decreases result because urination frequencies and the sum of the ammonia emissions from the less popular areas decrease on a larger scale, and overcompensate for the

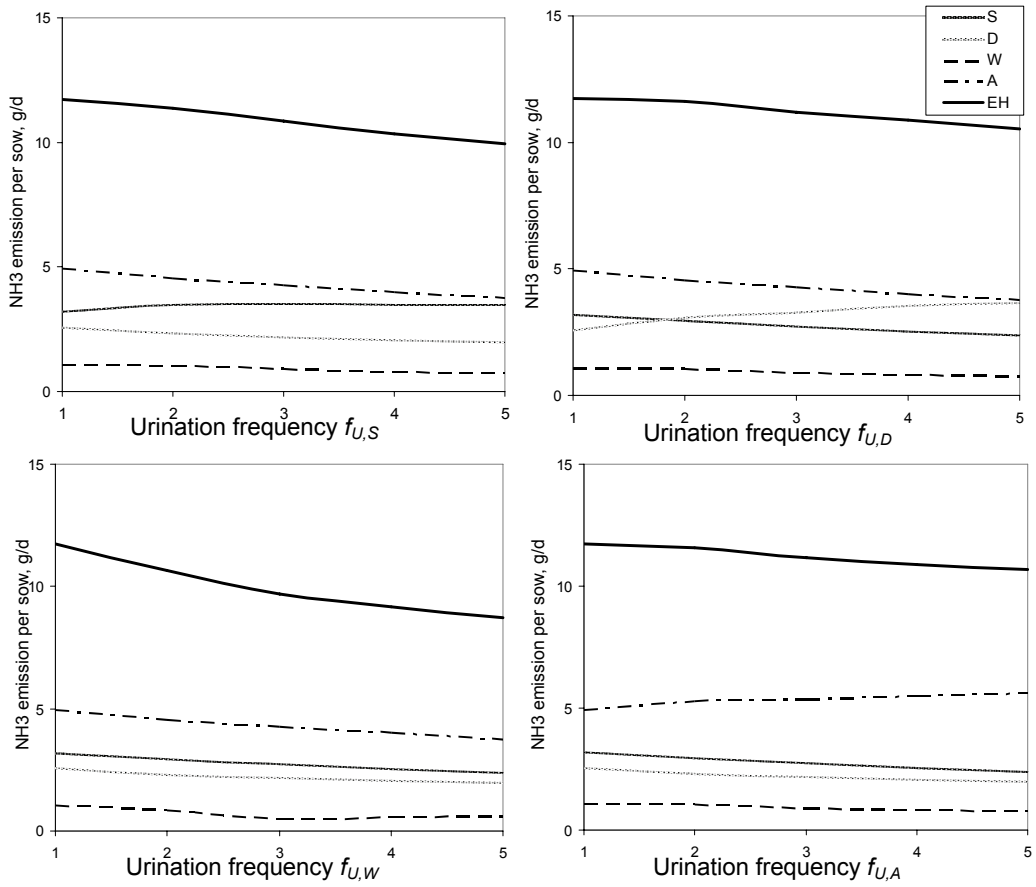

Figure 5.5. The simulated ammonia emissions per sow from the entire house (EH), the straw bed (S), drinking area (D), waiting area (W) and alley (A) with changing distribution of urinations between the surfaces $f_{U,S}$: $f_{U,D}$: $f_{U,W}$: $f_{U,A}$, with $f_{U,x}$=n, that is $f_{U,x}$ is n times the other frequencies (example: if $f_{U,S}$ = 3, $f_{U,S}$: $f_{U,D}$: $f_{U,W}$: $f_{U,A}$ = 3:1:1:1), f_U = 5 d^{-1} and Ud = 7 l/d per sow.

increase in the more popular urination area. In the waiting area, however, no substantial increase of emission is seen with increasing urination frequency. This is attributable to the large number of successive overlapping urinations. The more overlapping, the shorter is the duration of emission per urination. When the emission is curtailed before the maximum is reached, the emission from a urine pool can even decrease. This happens in the waiting area when the time interval between overlapping urinations is less than 5 h (Figure 5.2). When the emission from the waiting area does not increase with increasing urinating frequency, the effect of decreasing urinations on the straw bedding, in the drinking area and on the alley is amplified, resulting overall in 26% less emission.

If it is assumed that urinations are evenly distributed throughout the sow house rather than evenly distributed between surface areas, three out of five urinations per sow per day are deposited in the straw bed, the drinking area is urinated upon by a sow twice in three days, the waiting area is urinated on only once in five days, and the alley is urinated on seven times in six days. The emission rate from the entire house is then 10.6 g/day per sow, with the straw bed, the drinking area, the waiting area and the alley contributing respectively 32%, 19%, 3% and 45%

5.3.1.3 Size of emitting floor area

Figure 5.6 shows the effect of increasing the floor area of the straw bed on the ammonia emission. With no straw bed in the house, the calculated ammonia emission is 16.5 g/d per sow. By contrast, when the total emitting area in the house is covered with straw bedding, the ammonia emission is reduced by 65% to 5.8 g/d per sow. As the floor area of the straw bed and the urination frequency $f_{U,S}$ increases, the areas of the drinking area, the waiting area and the alley decrease proportionally, as do the urination frequencies $f_{U,D}$, $f_{U,W}$ and $f_{U,A}$. In this scenario, the contribution of the emission of the straw bed increases but the emission from the entire house decreases. In the scenario of a current sow house, shown in Figure 5.1, increasing the floor area of the straw bed would probably be at the expense of the alley and decreases emission by 36% (Table 5.3). The contribution of the straw bed to the emission from the entire house would then be 52%, compared with 34% for the drinking area and 14% for the waiting area. Another option in the ‘current sow house’ scenario would be to replace the solid floor in the alley with a slatted floor overlying a pit. This causes total emission to fall by 22%, as the emission from the alley falls by 53% (Table 5.3).

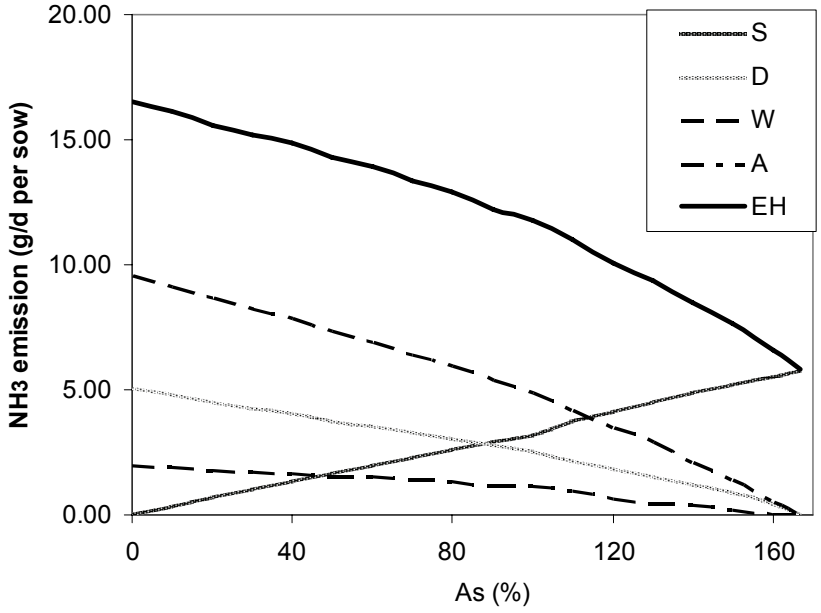

Figure 5.6. The simulated ammonia emission from the entire house (EH), and from straw bed (S), drinking area (D), waiting area (W) and alley (A) with changing surface area of the straw bed As, in % of the default of 179 m^2, considering corresponding change in distribution of urinations with Ud = 7 l and f_U = 5 d^{-1}.

5.3.2 Comparison between model estimates and actual measurements

The actual measurements for the entire house are presented in Table 5.4. Average ammonia emission rate per sow was 8.7 g/d. After 30 days, the lower limit of the two-tailed 90% confidence interval was 6.9 g/d per sow and the upper limit was 10.5 g/d per sow. The daily ventilation rate varied from 92 to 198 m^3/h per sow, with the average being 130 m^3/h per sow. The weather during the summer period in which the data were collected was stable, with small day-to-day variations of outdoor temperature and air humidity. The average temperature was 20.3ºC and relative humidity was 70%. The air exchange rate was 15.6 times per hour and the range was 11-24 times per hour.

Table 5.3. Ammonia emission from the different substrates and the emission from the entire house, assuming a slatted floor or a straw bed in the alley instead of the default solid floor.

	NH_3					
	Alley solid floor (default)		Alley straw bed (simulation)		Alley slatted floor (simulation)	
Substrate	g/d	% of total	g/d	% of total	g/d	% of total
Straw	3.2	27	3.2	42	3.2	35
Waiting area	1.1	22	1.1	14	1.1	12
Drinking area	2.5	9	2.5	34	2.5	28
Alley	4.9	42	0.7	10	2.3	25
Entire house	11.7	100	7.5	100	9.1	100

5.4. Discussion

When programmed with the default values, the model estimated an ammonia emission of 11.7 g/d per sow. Although the straw bed was 60% of the emitting surface area, it only contributed 27% to the emission from the entire house, because of the low number of urinations per m^2 and the relatively low emission from a urine pool in the straw bed. The alley contributed the most – 42% – to the total emission, even though it accounted for only 23% of the total emitting area. Its importance as an emitting area was mainly caused by the high ammonia emission from urine pools on solid concrete. Groenestein *et al.* (2006) (chapter 4) argued

Table 5.4. Daily averages (n=30) and the standard deviation (SD) of temperature, relative humidity and ammonia emission from the bedded sow house from which the substrate samples were taken.

		Average	SD
Air temperature (°C)	Inside	20.3	1.4
	Outside	17.3	2.6
Relative humidity (%)	Inside	71	5
	Outside	75	8
Air exchange rate per hour		15.6	3.0
NH_3 emission (g/d per sow)		8.7	0.9

that the distribution of urinations is an important factor when discussing ammonia emission.

The present study considered three aspects of the distribution of urinations in the house: the surface area of the urinations, the frequency of urine deposition on straw, drinking area, waiting area and on the alley (*i.e.* urinating behaviour of the sow), and the size of these areas. It will be recalled that the depth of a urine pool was assumed to be 5 mm. In reality, however, the depth and size of the urine pool can vary because of variations in the state of the floor surface. On fouled floor surfaces, for instance, a urination pool is deeper; on a slope the urine pool is shallower and covers a larger area; urinations on straw have a larger, three-dimensional emitting area because of the roughness of the surface. An increase of the surface area initially causes the emission to increase (Figure 5.4), because of the positive linear relation between ammonia emission and emitting surface area (Muck & Steenhuis, 1981; Elzing & Monteny, 1997b). When the pool size exceeds 0.5 m^2, however, emission decreases. A possible explanation is that the effect of overlapping urinations in diminishing ammonia emission outweighs the increasing effect of the size of the emitting surface. According to this hypothesis, the effect of superseding will be larger on smaller areas – which was confirmed by the finding that the emissions from the drinking and waiting areas decreased immediately after increasing size of the urine pool (Figure 5.4).

Figures 5.3 to *5.6* show that the model estimates of emissions are often higher than the actual values measured in the reference house: when programmed with default values, the model calculates 11.7 g/d per sow, whereas the measured value was 8.7 g/d (with a 90% confidence interval of 6.9 – 10.5 g/d per sow). Part of the disparity is attributable to ambient differences between the laboratory experiment that provided the default values (Groenestein *et al.*, 2006, chapter 4) and the real-life sow house. Though the temperature and relative humidity were similar (respectively 20ºC and 70%), the air exchange rate during the laboratory experiment was higher (19-28 times an hour during laboratory experiments versus 11-24 in the house). As a result, the model overestimates emission because it was programmed with a faster air velocity over the emitting surfaces. Additionally, the average conditions in the house do not fully represent conditions at emitting surfaces. For instance, the temperature and air velocity in the pit will be lower than the average values in the house, so consequently ammonia emission from the pits in the waiting area and the drinking area are likely to be lower than the model's estimates (Elzing & Monteny, 1997a).

The distributions of the urinations over the straw bed, the alley, the drinking area and the waiting area in the reference house were not known accurately and were therefore assumed to be equal in the default situation. Simulation with varying distribution showed that when sows urinate preferentially in one area, the calculated values are within the 90% confidence interval of the measured NH_3 emission (Figure 5.5). This happened, for instance, when the f_U in the straw bed was 3, 4 or 5 times higher then elsewhere, implying that if each sow urinates five times a day, then two to three urinations are on the straw bed. In other words, an important factor affecting ammonia emission is where the sow urinates. If the distribution of urinations is set at random and thus 60% is deposited in the straw bed, 14% in the drinking area, 3% in the waiting area and 23% on the alley, the calculated emission is 10% lower than with the default settings: 10.6 g/d. However, pigs do not urinate randomly. They tend not to foul the lying, nesting and feeding areas (Stolba & Woodgush, 1984; Hacker *et al.*, 1994; Aarnink *et al.*, 1997). In the default scenario, the feeding area is not an emitting area, but the straw bed, which serves as lying and possibly as a nesting area, is assumed to be randomly urinated upon. If only half of the straw bed is fouled with urine (still with 60% of the urinations), the model calculates an emission of 8.7 g/d (equal to the measured emission). When urinating frequency reduces proportionally, because only half the straw bed is urinated upon, 43% of the urinations are deposited on the straw bed, 19% in the drinking area, 5% in the waiting area and 33% on the alley, and the calculated emission from the entire house is 9.5 g/day per sow (within 90% confidence interval of measured emission).

The default floor areas of the straw bed, the drinking area, the waiting area and the alley were respectively 179, 41, 10 and 69 m^2. Changing the size of the straw bed and the other areas proportionally had a major effect on the ammonia emission (Figure 5.6). When the sow house has no straw bed, but just solid and slatted floors, the estimated emission is 16.5 g/d per sow. If the solid and slatted floors are replaced with straw, the emission falls to 5.8 g/d. However, for reasons of hygiene, labour and economics, it is not practical for the whole floor surface to be covered with straw, with no areas of concrete. If only the alley is replaced with straw, the ammonia emission from the entire house falls by 36% compared to the default value (Table 5.3). In practice it is more feasible to replace the solid floor in the alley with a slatted floor. The emission reduction will then be less compared to replacement with straw, but further reductions could be achieved by applying emission-reducing techniques underneath the slatted floors that reduce the surface area of the slurry, dilute the ammonia concentration in the slurry, acidify the slurry, or lower the temperature of the slurry (Hoeksma *et al.*, 1993;

Groenestein, 1994; Den Brok & Verdoes, 1997; Berg & Hörnig, 1997).

When modifying the design of the house in order to reduce the ammonia emission it must be borne in mind that changing the area of the different floor surfaces may affect the sow's urinating behaviour too. For instance, it is questionable whether the sows would urinate as much in the alley if the solid floor were replaced by a slatted floor.

One of the model's assumptions was the even distribution of urinations in time. By nature, pigs are active during the day and if fed *ad libitum* they urinate less during the night (Aarnink *et al.*, 1996). However, the sows in the reference house were fed restrictively from three feeding stations. With 20 minutes feeding time per sow per day, there is almost 17 h a day feeding activity. Because feeding time started at 20.15 h in the reference house, sows were active 24 hours a day (Groenestein *et al.*, 1999), therefore the assumption of even distributions of urinations in time seems justified.

Elsewhere (Groenestein *et al.,* 2006) three different locations in the straw bed were distinguished, depending on increasing slurry load: S1, S2 and S3. The model calculated the emission from the straw bed as the mean emission from these three subareas. This simplification of reality is justifiable, given the similarity of the emission characteristics of the straw samples reported by Groenestein *et al.* (2006) (chapter 4). To illustrate this similarity, we ran simulations assuming that the entire bed was S1, S2 or S3. Large differences would indicate that emission from the entire house would be affected if the sow urinates on S1, S2 or S3. The estimates of emission from the entire house were respectively 12.6, 11.7, and 11.4 g/d per sow, a deviation of less than 8% compared with the estimate obtained using the mean emission from straw. We consider this deviation to be acceptable. It is striking that simulation with the straw bed with the smallest slurry load gave a higher ammonia emission compared with simulation with larger slurry loads. Groenestein *et al.* (2006) (chapter 4) concluded that this difference is attributable to the microbial activity in the straw being greater if there is more slurry (*S2* and *S3*), which implies that N could have been lost as N_2 or N_2O or incorporated as microbial N (Van Faassen, 1992; Veeken *et al*., 2002).

The model was designed not to predict absolute emissions, but to be used as a design tool in order to achieve bedded sow housing with low ammonia emission. The agreement between the measured values and the calculated emissions demonstrates that the model is a realistic tool. However, as temperature and air

velocity are not factored into the model, the model validity is restricted to a limited range around the standardized values implemented by Groenestein *et al.* (2006) (chapter 4). The model simulations confirm that the distribution of urinations in the house has an important effect on ammonia emission. The model will therefore be useful when designing a house with reduced ammonia emission using the design approach of Bos *et al.* (2003) where design of the house is associated with the behaviour of the animals based on recursive control. Knowledge of the sow's urinating pattern in a group-housing system with a straw bed and of how design affects this behaviour is clearly needed in order to refine the model reliability. At present, however, such knowledge is lacking.

5.5. Conclusions

The IUPE model operates as a useful tool in designing group-housing systems for sows with a straw bed aimed at reducing emission of ammonia. It predicts the ammonia emission level of various possible design options. The model simulations show that the distribution of urinations over the different emitting areas is an important factor influencing ammonia emission. Measures to reduce ammonia emissions from a sow house with straw bedding should be aimed at decreasing the emission from the solid floor and/or stimulating urine deposition on the straw bed. Actual knowledge of the urinating pattern of the sows would improve the accuracy of the model predictions.

Notation

A_{lv}	surface area of base of laboratory vessel, m^2
A_p	surface area of urine pool, m^2
A_x	floor area of surface type *x* per sow, m^2
d_u	depth of a urination, mm
f_{pit}	fraction of urination that drains into pit
N_{ux}	number of urinations on surface type *x*, d^{-1}
$E(t_x)$	calculated NH_3 emission during time *t* from a urine pool on surface *x*, g
$E_{lv}(t_x)$	NH_3 emission from laboratory vessel during time *t* with sample from surface *x*, g
E	calculated NH_3 emission from entire house, g/d
E_x	calculated NH_3 emission from surface *x*, g/d
U_d	urine production per sow per day, l/d
f_U	urination frequency per sow per day, d^{-1}
$f_{U,x}$	urination frequency per sow per surface type *x*, d^{-1}
t_x	duration of emission from a urine pool on surface type *x*, d
t_{max}	longest duration of emission from a urine pool on any surface, d
V_u	volume of a urination, l
x	surface type: *S* (straw), *D* (drinking area), *W* (waiting area) and *A* (alley)

6

Effect of Sow Group-housing with Straw Bedding on Emission of Greenhouse Gases

6.1. Introduction

To achieve sustainability of sow-housing systems, it is necessary to consider the environmental consequences of improving sow welfare. Dutch legislation on environmental pollution and emissions from livestock housing has primarily been aimed at abating ammonia (NH_3) emission. In chapters 2 to 5 the effect of keeping sows loose in groups with straw bedding was analysed. However, from studies on emissions from mixtures of slurry and straw it is clear that emissions of nitrous oxide (N_2O) and methane (CH_4) occur as well (Gibbs & Woodbury, 1993; Martin & Dewes, 1992; Czepiel *et al.*, 1996; Veeken *et al.*, 2002) and have to be taken into account. Environmental goals cannot be reached by pollution swapping, i.e. controlling acidification and eutrophication by reduction of ammonia emission, but concomitantly increasing the global warming potential (GWP) by increasing emissions of the gases CH_4 and N_2O whose GWP values are respectively 21 and 310 times higher than that of CO_2 (IPCC, 1997). Furthermore, N_2O also harms the ozone layer. It is also important to remember that under the Kyoto protocol, formulated in 1997, the Netherlands is committed to decreasing its greenhouse gas emissions by 6% in 2010 compared to 1990.

This chapter begins by reviewing knowledge on the emission of the greenhouse gases CH_4 and N_2O from pig houses with bedding. Though most references focus on deep litter systems for fattening pigs, the results can likely be extrapolated to sow houses with straw bedding. Secondly, a study on the volatilisation of NH_3, NO (nitric oxide) and N_2O from a deep litter system for fattening pigs undertaken to elucidate the nitrogen turnover in a deep litter system is described. The aim is to reveal the possibilities for controlling emissions of N_2O and CH_4 from bedded sow houses.

6.2. Review

6.2.1 Emission results from studies reported in the literature

In a deep litter system, animals are kept on a mixture of litter and slurry. The mixture is not a stable product but is degraded by microbial activity. A high C:N ratio in the mixture means more microbial activity if more metabolic energy (C or carbon) is biodegradable. Anaerobic conditions favour the activity of methanogenic bacteria, resulting in CH_4 emission (Gibbs & Woodbury, 1993) and a reduction of NH_3 emissions (Kirchmann & Witter, 1989). Aerobic environments

stimulate composting processes: oxidation of ammonium (NH_4^+) to nitrate (NO_3^-) (nitrification) and, when the oxygen has been depleted, denitrification can occur to form the harmless gas nitrogen (N2). However, if (as is often the case), conditions are suboptimal, these processes may not run to completion, and so byproducts as NH_3, NO (nitric oxide) and N_2O are emitted as well (Martin & Dewes, 1992; Czepiel *et al.*, 1996; Groenestein & van Faassen, 1996 (see section 2 of this chapter); Amon *et al.*, 1997; Veeken *et al.*, 2002).

Various studies have been undertaken to elucidate the consequence of these microbial activities for emissions from commercial deep litter pig housing; Table 6.1 gives an overview. The gas NO has been excluded for two reasons: only one study reported NO emission (Groenestein & van Faassen, 1996, section 2 of this chapter), and NO has no greenhouse effect.

Most of the studies on emissions from litter systems were carried out with fattening pigs. The reported emissions (expressed as g/d per fattening pig) ranged from 2.5 to 13.4 for CH_4, from 0.03 to 11.3 for N_2O, and from 3.0 to 16.2 for NH_3. The listed NH_3 and N_2O emissions from the sow house study fell within the reported ranges for fattening pigs. The CH_4 emission per sow was higher, even when corrected for liveweight of the animals (assuming that three fattening pigs are equivalent to one sow). The variability of the emissions mirrors the variability in the application of the litter systems: not only the litter material, but also the handling of that material varies widely between the systems described in the literature. The following paragraphs elaborate on the differences and their effects on emissions.

6.2.2 Processes and key factors of emission

Table 6.2 presents the key factors affecting the emission of CH_4, N_2O and NH_3 from bedded housing systems according to the findings of Aarnink (1997), Jun *et al.* (1999) and Monteny (2000). Most factors affect emissions of all three gases. However, the scale of the effect differs, depending on the underlying microbiological processes causing the production of the gases. For instance, the production of all gases is influenced by the pH of the litter/slurry mixture, but the optimum pH for production of N20 is 6–7, compared with 7–8 for CH_4 and above 7 for NH_3. Without oxygen, NH_4^+ cannot be oxidised to NO_3^- (nitrification), but if oxygen is present, methanogenesis (production of methane) does not occur. There is also mutual interaction. For example, methanogenesis decreases with increasing NH_4^+ concentrations (Hashimoto, 1986). As a result of the different

Table 6.1. N_2O, CH_4 and NH_3 emissions from bedded pig housing systems

Pig	Litter type	g/d per animal			Reference
		CH_4	N_2O	NH_3	
Fatteners	Wood shavings		1.7–10.0	9.0–16.2	Hoy *et al*., 1997
Fatteners	Wood shavings		3.3	7.8	Thelosen *et al*., 1993
Fatteners	Sawdust		7.5–11,3	3.5–7.0	Groenestein and Van Faassen 1996
Fatteners	Sawdust	6.8–11.2	4.7–9.3	5.1–5.5	Kaiser, 1999
Fatteners	Sawdust	4.8	3.2	9.5	Delcourt *et al*., 2001
Fatteners	Sawdust	5.0	2.1	12.2	Nicks *et al*., 2004
Fatteners	Sawdust	7.2	0.67	6.4	Aarnink *et al*., 2004
Fatteners	Sawdust+ straw[1] (4:1)	13.4	6.0	6.2	Kaiser,1999
Fatteners	Straw	7.4	0.03	13.6	Nicks *et al*., 2004
Fatteners	Straw[1]	11.1	0.15	10.1	Kaiser, 1999
Fatteners	Straw	2.5–3.0	0.3		Ahlgrimm *et al*., 1998, 2000
Fatteners	Straw	1.9	0.07	6.9–9.2	Aarnink *et al*., 2001
Sows	Straw	39.0	0.5	6.2–8.7	Groenestein *et al*., 1999; Hol & Groot Koerkamp, 1999

1: Kaiser (1999) used short straw of 2-3 cm

varieties of microbes and the diversity of microbiological processes and their mutual interactions, the types of bedding in pig houses are complex ecosystems.

The studies in Table 6.1 do not give full insight into all the factors listed in Table 6.2. However, the large differences described in litter management are largely responsible for the variation in the key factors. Table 6.3 presents the main features of litter management in pig housing as reported in the studies cited in Table 6.1. Litter management affects the availability of carbon (C) and oxygen (O_2) in the slurry/litter mixture and therefore has an important effect on the microbial activity. The type of litter and the depth of the litter bed affect the density and porosity of the bedding which, in turn, affects the supply of O_2 (Veeken *et al.*, 2002).The type of litter, the amount of litter and the regular addition of fresh litter

affect the amount and biodegradability of C. Additives, either a bacterial mass or an easily biodegradable C, are intended to increase microbial activity. Litter mixing has the purpose of bringing O_2 into the bed to stimulate nitrification and subsequent denitrification in order to reduce the emission of NH_3. This, however, increases the risk of N_2O production. Studies on deep-litter systems with additives (Groenestein & Van Faassen, 1996; Thelosen *et al.*, 1993) and on NH_3 and N_2O emissions from deep-litter systems with and without additives in a wood shavings/slurry mixture Hoy *et al.* (1997) did not find that additives reduce or increase emission of NH_3 or N_2O. The litter was removed once a year (Groenestein *et al.*, 1999; Groenestein & Van Faassen, 1996; Thelosen *et al.*, 1993, Nicks *et al.*, 2004) or every fattening period (Kaiser, 1999). Aarnink *et al.* (2004) removed mixtures from litter and slurry daily, for composting in a reactor. The studies listed in Table 6.1 had differently sized areas under bedding and the litter was put down in different locations in the pens. Groenestein & Van Faassen (1996), Thelosen *et al.* (1993), Hoy *et al.* (1997) Nicks *et al.* (2004) and Döhler (1993) describe housing systems in which the entire living area was littered. In Kaiser's (1999) study, 40% of the living area was littered, the resting area was a solid concrete floor and most slurry was deposited in the littered area. Groenestein *et al.* (1999 and 2006) describe a sow house in which the straw bed was ca. 50% of the living area, 30% was solid and 20% was slatted floor. The aim of the arrangement of the functional areas in that sow house was to minimise excreting behaviour in the straw bedding.

Table 6.3 and the following discussion reveal that a litter system has no single definition and that litter management varies, affecting the microbial activity and the metabolic products of that activity, such as CH_4 and N_2O. In the next section the key factors in Table 6.2 affected by litter management are discussed in more detail and the emission of each of these two greenhouse gases is determined.

Table 6.2. Key factors affecting emission of NH_3, CH_4 and N_2O from pig houses (adapted from Aarnink 1997; Jun et al., 1999; Monteny 2000). + indicates a positive correlation, - indicates a negative correlation and 0 indicates no relevant effect.

	CH_4	N_2O	NH_3
Animal-related factors			
Age/Live weight	+	+	+
Amount and composition of feed	+	+	+
Water use	0	0	-
Environment-relating factors			
Housing configuration	+/-	+/-	+/-
Air velocity over emitting surface	0	0	+
Temperature of inside air	+	+	+
Temperature of outside air	+	+	+
Factors related to slurry/litter mixture			
C/N ratio	+	+	-
O_2 concentration	-	+/-	+
Surface area	0	0	+
Maturity of litter/slurry mixture	+	+	0
Optimal pH [1]	7	6	+
Temperature of the slurry/litter	+	+	+
NH_4^+ concentration	-	+	+
Volatile Solids concentration	+	0	0
Drymatter content	-	0	0

1: Values in columns indicate optimums.

6.3. Effect of litter management

6.3.1 Nitrous oxide emission

It has already been noted that N_2O is a byproduct of nitrification and denitrification. Kaiser *et al.* (1999) found no relation between C:N ratio and N_2O emission but observed an increase when sawdust was used as litter instead of straw. Similar results were reported by Nicks *et al.* (2004). The other data from Table 6.1 also show lower N_2O emissions from straw litter than from wood-based litter. Litter consisting of sawdust or wood shavings contains more lignin and hemicellulose than cellulose, so the substrate is biodegradable or digestible (Neely, 1984; Veeken *et al.*, 2001). The findings suggest that N_2O emissions depend more on the biodegradability of C than on the C:N ratio. Although Aarnink *et al.* (2004) did find low N_2O emissions in a sawdust-based system, in their study, unlike the other sawdust-based systems in Table 6.1, the mixture of litter and slurry was frequently removed from the house, new sawdust was added three times a week and the depth of the bed averaged 15 cm. The consequence was that in the house neither biodegradation, nor nitrification, nor denitrification were

Table 6.3. Variation of litter management in a bedded pig housing system as presented in the literature cited in Table 2.4.

Feature	Values
Type of litter	Sawdust, wood shavings, straw (barley, rye, wheat)
Amount of litter	50–1000 g/d per pig
Depth of the litter bed	0–70 cm
Additives	Yes or no
Addition of fresh litter	None to weekly
Litter mixing	None to two or three times a week
Litter removal	partly or completely; daily; weekly; monthly; yearly
Littered surface area	40–100% of total living area
Location of litter	Resting area, feeding area, excretion area

substantial.

In group-housing systems for sows, the straw bedding is not usually deliberately aerated in order to stimulate nitrification followed by denitrification. Straw is added regularly and either the farmer spreads it over the entire bedded area or the pigs distribute it themselves. The pigs walk over the mixture of straw and slurry, compacting it and making the bed denser. Groenestein & Richard (2001, unpublished data) measured densities of over 1000 kg/m3, indicating anaerobic conditions which are unfavourable for production of N_2O. However, under these conditions Groenestein *et al.* (1999) did measure an emission of 0.5 g/d N_2O per animal in this particular housing system. Though low, this still represents 5% of the nitrogen leaving the house as NH_3, which suggests that the bedding was not completely anaerobic.

6.3.2 Methane emission

Methane has two sources in a pig house: it is produced in the digestive tract of the animal (endogene source) and in the excreted slurry. Using the data from Crutzen *et al.* (1986) and Rijnen (2003) it can be calculated that the endogene CH_4 emission from fattening pigs fed a regular diet of concentrates is 3–4 g/d per animal. Higher contents of fibre in the diet will increase metabolic energy losses and endogene CH_4 emissions. From the data given by Rijnen (2003) it can be calculated that an endogene CH_4 production is 10 g/d per fattening pig when there is 250 g/kg dm fermentable rough fibre in the diet. Pigs in the studies mentioned in Table 6.1 received regular diets based on concentrates. However, it is likely that they consumed some straw, sawdust or wood shavings as well. Therefore the endogene CH_4 production was probably higher than that for a slurry-based housing system, though it is impossible to give a figure for this because the amount of litter consumed by the pigs is not known.

Jungbluth *et al.* (2001) reported large variations of CH_4 production from slurry-based housing systems for pigs: from 2.5 to 30 g/d for fattening pigs and 58 g/d for sows. The data in Table 6.1 are within this range, suggesting that CH_4 production in littered systems is not substantially different. Groenestein & Reitsma, (1993), Groenestein & Huis in't Veld, (1994) and Mosquera *et al.* (2005) measured high CH_4 emissions from straw-bedded housing systems for dairy cattle of respectively 1300, 1000 and 800 g/d per animal (endogene and from slurry). According to data collected by Jungbluth *et al.* (2001) CH_4 emission from dairy housing with slurry-based systems is mainly endogene and varies from 194–

390 g/d per LU (1 LU = 500 kg), which is in agreement with Crutzen *et al.* (1986). The implication is that there is high CH_4 production in the deep litter bed of dairy cattle. Given sow houses with large amounts of straw bedding as described in sections 4 and 5 and referred to in Table 6.1 by Groenestein *et al.* (1999), it is likely that the CH_4 production in the bedding is substantial. If this is so, the question then becomes why the emissions from the bedded housing systems are not higher than the emissions from the slurry-based systems. Veeken *et al.* (2002) measured methane concentrations at various depths in a composting reactor. They found high concentrations of CH_4 in the middle layer and low concentrations in the top layer because methane is readily oxidised by methanothrophic bacteria in oxygen-rich zones. Petersen *et al.* (2005) showed that in a straw layer on a slurry storage pit there is so much oxidation of CH_4

to CO_2 that this is an effective way of mitigation of the greenhouse gas effect because the GWP of CH_4 is 21 times that of CO_2. It seems likely that CH_4 produced in deeper anaerobic layers of the litter bed is oxidised in the top layer, which is aerated by the rooting and foraging behaviour of the pigs. This could also explain why the CH_4 emission from deep litter beds in dairy houses is higher: cows do not aerate the top layer of the straw bed because they do not root and forage like pigs.

6.4 Concluding remarks

The emissions of nitrous oxide and methane from littered systems in pig husbandry are very variable. The key factors greatly depend on litter management, which differs hugely between systems.

The data indicate that where slurry-based systems emit no nitrous oxide, emission remains low when the bedding material is straw instead of wood shavings or sawdust. Though there are big variations in the reference data for methane emissions from slurry-based systems, the data suggest that whereas considerable amounts of methane may be produced in deeper layers of the straw bedding, emission is limited because methane is oxidised in the top layer of the straw bedding.

These findings lead to the conclusion that the introduction of straw bedding in sow houses does not cause substantial emission of greenhouse gases, providing the litter management is appropriate.

6.5 Volatilisation of ammonia, nitrous oxide and nitric oxide in deep-litter systems for fattening pigs

C.M. Groenestein & H.G. van Faassen [1]

Abstract

In a deep-litter housing system, animals are kept on a thick layer of a mixture of manure with sawdust, straw or woodshavings. In this study, sawdust was used for two different deep-litter systems for fattening pigs (System 1 and 2). The differences between the systems were the amount of litter per pig, the size of the sawdust particles and the way the bed was treated. From manure NH_3 (ammonia) can volatilize. In a mixture of manure and sawdust the microbial processes nitrification and denitrification can occur which convert NH_3 into the inert N_2 (dinitrogen gas). If conditions are suboptimum and these processes do not run to completion, the air-polluting volatile intermediates N_2O (nitrous oxide) and NO (nitric oxide) are emitted. Field studies were carried out to obtain values of the concentrations in the exhaust air of NH_3, N_2O and NO. Ventilation rates were measured and emissions of these air-polluting nitrogen gases calculated. The results were compared with the emission of a traditional system with manure storage under a fully slatted floor of 0.3 g N/h per pig as NH_3. The nitrogen emitted as NH_3, NO and N_2O measured with System 1 was 0.24, 0.04 and 0.3 g N/h per pig respectively. For System 2 emissions were 0.12, 0.01 and 0.2 g N/h per pig respectively. System 2 tends to reduce the ammonia emission compared with traditional housing systems ($P=0.078$) but for System 1 there was no difference. In both systems, the emission of total air-polluting nitrogen was not reduced compared with a traditional house, System 1 had increased N emission ($P<0.05$). From both systems most of the air-polluting nitrogen was emitted as N_2O, although for System 2 this was not significant. In a laboratory study samples of the deep-litter beds were incubated under various O_2 concentrations to study under which conditions N_2O was produced in the deep litter. The results showed increasing N_2O emission with decreasing O_2 concentration in the bed, indicating that N_2O is mainly produced in the course of nitrification. It is concluded that deep-litter systems for fattening pigs may reduce NH_3-emission compared with

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housing on fully slatted floors, but emissions of air-polluting nitrogen gases tend to be higher due to the formation of N_2O. From an environmental point of view, these two deep-litter systems are therefore not recommended.

6.5.1 Introduction

In the Netherlands 46% of environmental acidification is caused by emission of ammonia, the main source being agriculture (92%) (Heij & Schneider, 1995).The aim of Dutch legislation is to reduce emissions in the year 2005 by 70% with respect to the emissions of 1980. New types of housing systems and manure-handling techniques are required to meet these environmental demands. Deep-litter housing systems are in focus, depending on reasons such as welfare, economics and environment. In a deep-litter system for fattening pigs, the animals are kept on a thick layer of a mixture of faeces, urine and sawdust, straw or woodshavings. The environmental benefit is that the pig waste decomposes *in situ*. This causes heat production by aerobic microbial activity. High temperatures in the bed stimulate evaporation of water and thus the amount of manure is reduced. Secondly, the microbial activity influences turnover of nitrogen and could thus affect ammonia emission. The processes involved are nitrification and denitrification which convert ammonia (NH_3) into the inert dinitrogen gas (N_2). Two polluting volatile intermediate products of these processes are nitric oxide (NO) and nitrous oxide (N_2O). NO, as NH_3, causes environmental acidification. N_2O contributes to the greenhouse effect (Wang *et al.*, 1976) and affects the ozone layer (Crutzen, 1976)

This paper describes a field study to quantify the emission of the air-polluting nitrogen gases from two deep-litter systems for fattening pigs. The emissions were compared with the emission from a traditional housing system for fattening pigs with fully slatted floors. A laboratory study was conducted in which nitrogen turnover was simulated in the deep-litter bed to determine under which conditions the intermediate product of nitrification and denitrification, N_2O was produced.

6.5.2 Materials and methods

6.5.2.1 Field study

Two deep-litter systems were examined during one fattening period. Both houses were mechanically ventilated. The pigs were housed in groups of 18 per pen with a floor space of 1 m^2 per pig. Dry feed was administered *ad libitum* with one feeder per pen, situated in a corner. Water was available *ad libitum* through a

nipple in the feeder. To limit the use of water, the pressure of the water supplied was low. There had been only one fattening period before this one on the same deep-litter bed. The main differences between the two systems were the amount of litter per pig, the size of the sawdust particles and the way the bed was treated.

6.5.2.1.1 System 1

The thickness of the sawdust bed was 40-50 cm. Of the sawdust particles 24% were smaller than 1 mm and 38% were bigger than 2 mm. The bed was treated weekly with a digger. The manure was spread over the bed which was then loosened to a depth of 40 cm to incorporate the manure. Next the bed was sprinkled with the additive “Envistim”, a microbial preparation to stimulate microbial activity and enhance turnover of nitrogen. Besides the regular weekly treatment the manure was removed instead of spread out on day 78 of the fattening period, and 6 m^3 of new sawdust was added.

The measuring period lasted 112 days from 18 October 1991 until 7 February 1992 with 108 pigs. Live weight increased from 31 to 110 kg per pig. The pigs were fed with two different feeds; at first 45 kg of feed per pig with a nitrogen content (N) of 2.70% and next 174 kg of feed with a N-content of 2.84%. Total N input per pig was 6.16 kg. The ratio of feed supplied/liveweight gain was 2.84. Water consumption was 2.0 l/kg of feed.

6.5.2.1.2 System 2

The thickness of the sawdust bed was approximately 70 cm. Of the sawdust particles, 21% were smaller than 1 mm and 47% were bigger than 2 mm. The bed was treated weekly by burying the manure with a digger without incorporating it and then mixing the top layer. Next the bed was sprinkled with the additive ‘Bactostim’ to stimulate microbial activity and enhance turnover of nitrogen. To reduce the moisture content of the bed 10 m^3 sawdust was added on day 75 of the fattening period.

The measuring period lasted 121 d from 13 December 1991 until 13 April 1992 with 288 pigs. Live weight increased from 26 to 107 kg per pig. The pigs were fed with three different feeds; at first 21 kg of feed per pig with 2.96% N, then 49 kg with 2.72% N and next 171 kg with 2.56% N respectively. Total N input per pig was 6.28 kg. The ratio of feed supplied/liveweight gain was 2.95. Water consumption was not measured but was estimated at 2.0-2.5 l per kg of feed.

6.5.2.1.3 Measuring methods

The following variables were continuously measured: concentrations of NH_3 and NO in the exhaust air (mg/m^3), ventilation rate (m^3/h) and ambient air temperature, T (°C) inside the house and outside and relative humidity of the air, RH (%) inside the house and outside.

The concentrations of NH_3 and NO in the exhaust air were measured in the ventilation shaft with a NO_x analyser. With this method NH_3 is converted into NO. NO is measured based on the principle of chemiluminescence (Scholtens, 1990). Ventilation rate was measured with an anemometer with the same diameter as the ventilation shaft. The emission was calculated as the product of the concentration and the ventilation rate. The relative humidity and the temperature of inside and outside air were measured with sensors (C80 Hygromer of Rotronic®).

The following actions were performed weekly: one sample was taken of the exhaust air to determine the concentration of N_2O on a gas chromatograph with an electron capture detector (ECD), the temperature of the litter bed was measured with a thermocouple (NiCr-Ni) at a depth of 10 cm and the measuring equipment was checked and calibrated (Groenestein & Montsma, 1992; Groenestein & Reitsma, 1992)

Emissions of ammonia and total air-polluting nitrogen gas were compared with emissions of a traditional system (Hoeksma *et al*., 1993). The animals were kept on a fully slatted floor with slurry storage underneath, the available surface area was 0.7 m^2 per pig, nitrogen input was 6.7 kg per pig and the rate of feed supplied/liveweight gain was 2.78. Within System I and II the amount of nitrogen emitted as NH_3, NO and N_2O were compared. The comparisons were executed with a one-sided t-test.

6.5.3 Laboratory study

Experiments were carried out to simulate nitrogen turnover in deep-litter beds. In the experiments 0.3 dm^3 litter samples were incubated in 0.5 dm^3 bottles at temperatures between 20 and 35°C, with different oxygen (O_2) concentrations in the head space above the samples to represent situations in the field. In experiment A the bottles were closed, so that the O_2 concentration rapidly declined to zero due to biological oxygen consumption. In experiment B there was a small opening of 1 cm^2, so the O_2 concentration decreased to a quasi-steady

state level. This level depends on O_2 supply (by diffusion) versus O_2 demand. The third experiment (C) was carried out with a perspex column of 60 cm height and a diameter of 12 cm, filled with deep litter to a depth of 45 cm. A continuous air flow was led over the litter surface. The rate was such that the O_2 concentration in the out flowing gas was at least $18x10^4$ p.p.m.v. (18 %vol). The headspace gas phases were analysed periodically for O_2 and N_2O by gas chromatography, using a thermal conductivity and an ECD. Experiment C was extended by compressing the litter in the column by 5 cm (experiment D). The gas in the headspace and gas samples from a depth of 45 cm in the litter column were analysed periodically for O_2 and N_2O.

6.5.4 Results

6.5.4.1 Field study

Emissions of NH_3, NO and N_2O from both systems are presented in *Fig. 6.1.* The sudden decline of ammonia emission on day 78 in System 1 was due to the different treatment of the bed on that day. Immediately after the decline, emission started to increase again. It did not reach the same level as that before removal of the manure but that may be owing to the removal of 21 pigs on day 84 and 32 on day 98. System 2 also had an irregular treatment of the bed on day 75. This day the ammonia emission did not decline as was seen with the new sawdust in System 1. The interruption of the line in the graph represents missing values owing to technical problems with the measuring equipment and corresponds with day 77-83 (the same applies for day 13-19).

The weekly treatment of the bed is visible in both systems as peaks in the emission of NH_3. This was caused by stirring up the bed and thus stimulating volatilisation of NH_3. In general, emission of NH_3 was lowest at the start of the fattening period, and highest in the end.

Table 6.4 shows the mean climatic conditions during the trials of the two systems. The range of the outside temperature of both periods (between -5 and 10°C) was comparable. The lowest temperatures occurred in System 1 during the second half of the fattening period and in System 2 during the first half. The mean temperature of the bed at a depth of 10 cm was 40°C for both systems, indicating aerobic processes.

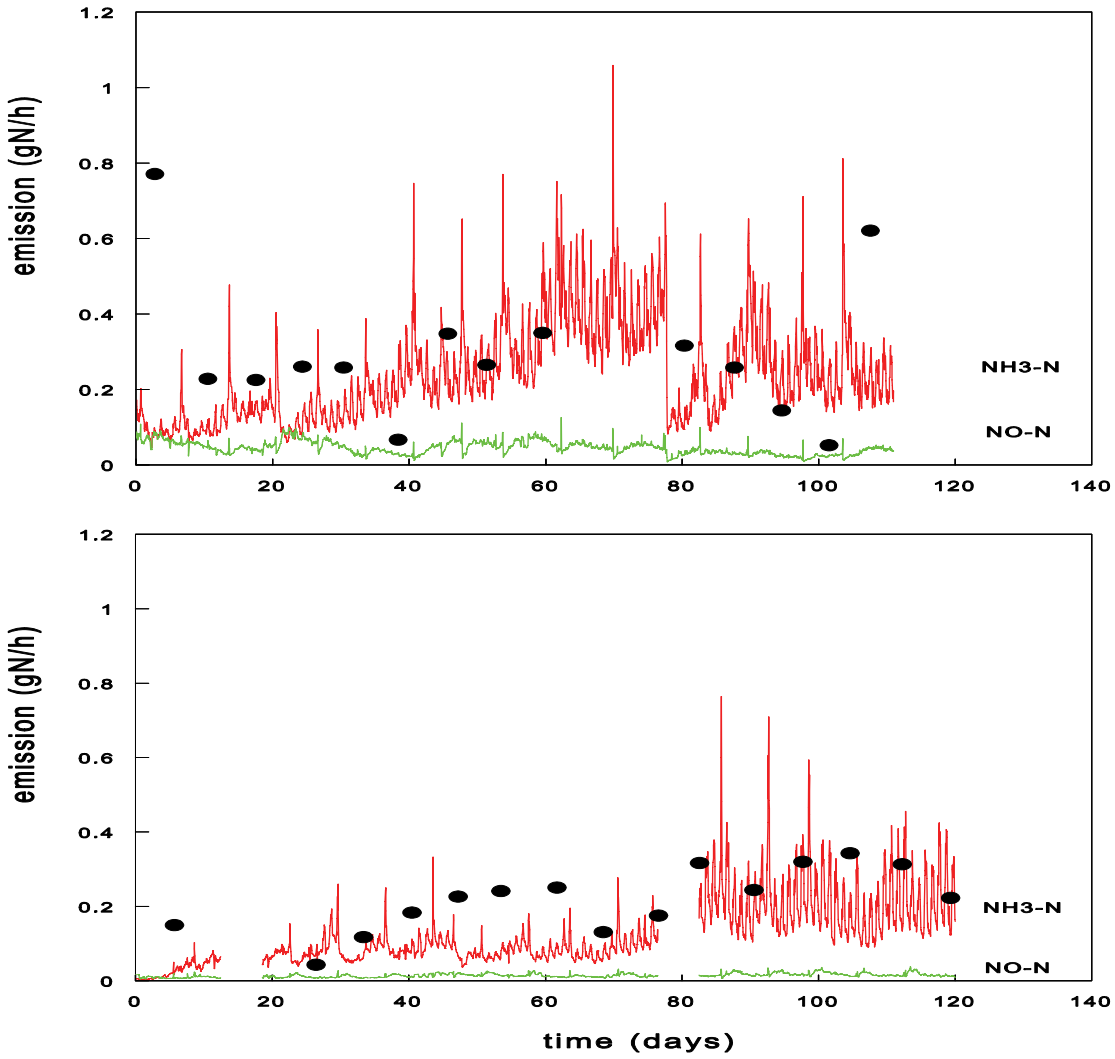

Figure 6.1. Emission of NH_3, NO and N_2O per pig of System 1 (above) and System 2 (below), N_2O is represented by '•'

Emission of NO showed a constant level. Compared with the increasing NH_3 level its relevance diminished over the fattening period. As with NH_3, NO showed a peak at the weekly treatments of the bed, although it is relatively small. Part of the NO peak could have been produced by the NO in the exhaust gases of the diggers that treated the bed.

Figure 6.1 shows that the mean emission of N_2O of both systems was high relative to NH_3, although with great variation, especially with System 2. In System 2 N_2O emission showed a tendency to increase. Table 6.5 presents the total emissions of NH_3, NO and N_2O per animal during the fattening period.

Table 6.4. Mean climatic conditions and ventilation rate during the fattening period in both systems.

	System 1	System 2
Temperature inside, °C	18.4	16.2
Temperature outside, °C	4.1	4.0
Relative humidity inside, %	65	71
Relative humidity outside, %	89	87
Ventilation rate per pig, m^3/h	32	41

Hoeksma *et al.* (1993) measured the ammonia emissions of four complete fattening periods in a traditional housing system with a fully slatted floor over a period of 2.5 yr. Although the measurements were carried out in the same unit they were assumed to be statistically independent. The ammonia emission varied from 0.22 to 0.40 g/h of N per pig. The mean emission was 0.30 g/h of N per pig (s^2 = 6.8x10^{-3}). Assuming the same variance applies for System 1 and 2, the ammonia emission was not reduced with System 1. The difference with System 2 was 0.18 g/h of N, but because of the large variance (standard error of difference, SED = 0.0923) this was only weakly significant (P=0.078) which is given as non-significant in Table 6.5 (differences between systems are shown by the lower cases). When the deep-litter systems are compared at the time of the weekly air sampling for the

N_2O measurements (n_1=14; n_2=15) the variance is smaller (sed = 0.0270) and the difference becomes significant. The mean emission of NH_3 at sampling time was lower than with the continuous measurements as the air samples were taken

Table 6.5. Total emission of NH_3, NO and N_2O from the two systems, g/h of N per pig.

	System 1	System 2	Traditional
NH_3 (continuous)	0.24^{a}	0.12^{a}	0.30^{a}
NH_3 (sampling time)	0.20^{aB}	0.11^{bA}	-
NO	0.04^{aC}	0.01^{bB}	0^{c}
N_2O	0.3^{aA}	0.2^{aA}	0^{b}
Total	0.58^{b}	0.33^{a}	0.30^{a}

Means with no common superscript differ significantly (P<0.05). Comparisons between systems are indicated with lower case letters, within systems with upper case letters.

during the morning whereas in the afternoon temperature and ventilation and thus NH_3-emission, were greater (Muck & Steenhuis, 1982)
It is unlikely that emissions of NO and N_2O occur in traditional systems as in a slurry cellar there are no favourable aerobic conditions for nitrification and thus denitrification cannot occur either. Preliminary results of measurements in a pig house with a fully slatted floor confirm this (Groenestein, unpublished). Therefore these emissions are set at zero. Table 6.5 then shows that emission of air-polluting N from System 1 was significantly greater than from System 2 and the traditional system.

The contribution of the different N-compounds to the emission of air-polluting N was analysed within systems at the time of the weekly air sampling for the N_2O measurements (shown by the upper case letters in Table 6.5). It is shown that most air-polluting N was emitted as N_2O although this was not significant in System 2.

6.5.4.2 Laboratory study
Table 6.6 presents the maximum concentrations of N_2O in the headspaces above the incubated deep-litter samples. The highest N_2O concentration was found under anoxic conditions (experiment A). With a high O_2 concentration at the surface of the deep litter (experiment C) the N_2O was only 10 p.p.m.v. After the compression of the bed (experiment D) it rose to 60 p.p.m.v. The N_2O concentration of the air in the litter at the bottom of the bottle (a depth of 45 cm) increased from 300 to 1500 p.p.m.v. The results show that N_2O production increases with decreasing availability of oxygen.

Table 6.6. Peak concentrations of N_2O, p.p.m.v. in the headspace above incubated deep-litter samples under various O_2 concentrations, 10^4 p.p.m.v.

Experiment	aeration	O_2	N_2O
A	none	0	70 000
B	diffusion	3-7	10 000
C	airflow	18-20	10
D	airflow	18-20	60

6.5.5 Discussion

In a deep-litter system microbial processes are stimulated to enhance composting processes. Two of these processes can prevent emission of NH_3: nitrification of NH_3 followed by denitrification of nitrate (NO_3^-) which produces the environmentally harmless and inert dinitrogen gas (N_2).

$$NH_3 + O_2 \rightarrow NO_2^- \rightarrow NO_3^- \quad (6.1)$$

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2 \quad (6.2)$$

Process (6.1) needs aerobic conditions and process (6.2) needs anaerobic conditions. Deep-litter systems are complex systems with large variations in space and time. Gradients exist in the bed, O_2 decreases with depth, but also within litter aggregates an oxygen gradient may exist. So nitrification will be concentrated near the surface of both the bed and of the aggregates. After that, NO_3^- needs to be in an anaerobic environment in deeper layers of the bed or within aggregates, to allow denitrification to take place. This means that it is relevant when and where oxygen is available for both processes to run to completion. Otherwise the volatile compounds of these processes, NH_3, NO and N_2O, may be emitted. NO and N_2O are part of the anaerobic denitrification and therefore are expected to be emitted when oxygen pressure increases. However, factors that decrease oxygen pressure in the bed can increase N_2O production as well. According to Poth & Focht (1985) this is caused by reduction of NO_2^- (6.1) to NO (6.2) rather than through the nitrification by an aerobic process, and they defined it as nitrifier denitrification. This is in agreement with Burton *et al.* (1993) who found a high production of nitrous oxide from pig manure without producing NO_3^- and NO_2^-. This occurred during aerobic treatment after addition of manure when oxygen consumption tripled within minutes. The laboratory study confirmed the findings of Poth & Focht (1985) and Burton *et al.* (1993).

Oxygen transfer into the bed can decrease as the pigs tramp down the litter, thus increasing the volume where low oxygen concentrations prevails. An increase in moisture content of the litter bed has the same effect. The weekly air samples of the field study were taken 1-7 d after loosening the bed. There was, however, no indication that emission of N_2O increased with increasing intervals between loosening the bed and sampling. This means that the field study did not confirm the laboratory results which implied that increasing the density of the bed by the tramping of the pigs increases N_2O emission. It is however possible that the N_2O formed at low oxygen concentrations cannot escape because of that same

density. Actual emission of NH_3, NO and N_2O will depend not only on its concentration gradient, but also on the resistance of the litter-bed to gas diffusion and thus on density, aggregation and moisture content of the litter bed.

Besides the presence and absence of oxygen, availability of energy is of importance for the performance of the micro-organisms. The low carbon-to-nitrogen ratio (C:N) of pig waste (about 4), implied a low availability of degradable carbohydrates, and thus made it energetically difficult to transform surplus NH_4^+ into microbial cells or into N_2 via nitrification and denitrification. Finally, nitrification and denitrification may be inhibited by high concentrations of NH_4^+ and NO_3^- (Focht & Verstraete, 1977).

6.5.6 Conclusions

Because of non-optimal conditions in the litter of deep-litter systems for fattening pigs, nitrification and denitrification do not appear to run to completion to form dinitrogen gas. Ammonia and the volatile intermediates NO and N_2O were emitted. The availability of oxygen is a key factor.

System 2 appeared to reduce the emission of ammonia compared to a traditional housing system with fully slatted floors but System 1 did not.

It appears that deep-litter systems emit more N as N_2O than as NO and NH_3 and that because of this emission, air-polluting nitrogen gases were not reduced and even increased compared with traditional housing systems. This leads to the conclusion that from an environmental point of view both deep-litter systems are not recommended.

7

General discussion

7.1 Contours of the thesis

The studies described in this thesis were carried out to establish how improving the welfare conditions of sows would affect the emission of ammonia and greenhouse gases. The underlying premise was that improving the welfare of animals should not prevent environmental goals being reached. Two main housing conditions which benefit sow welfare were focused on: keeping the sows loose in groups instead of individually and restrained, and providing them with straw bedding instead of keeping them on a bare floor. To implement these conditions in sow husbandry in the Netherlands would entail large adjustments of sow farmers: they would have to learn new procedures and be able to manage the new system properly.

In the mid-1990s, the pig sector in the Netherlands argued against introducing the group housing of sows, claiming that giving the animals more space and freedom of movement would increase the surface area in the barn fouled with slurry and therefore increase ammonia emission – thereby going against the Dutch government's legislation to cut this emission drastically. Though the argument did make some sense, it was not based on scientifically validated research. These developments coupled with the Dutch government's commitment to the agreements made under the Kyoto protocol concerning the reduction of emission of greenhouse gases made it necessary to study the environmental aspects of improving sow welfare. The research has been initiated to learn the environmental consequences of the two major improvements in sow welfare through system modifications.

7.2 Effect of group housing on ammonia emission

From the research described in chapter 2 in which measurements were done simultaneously in group housing and in housing with sows kept individually in pens, it appeared that group housing did not increase ammonia emission compared to the 0.72 g/h per sow measured with sows in individual pens. However the aim of the Dutch government was not to maintain but to reduce ammonia emission compared to the emission factor (emission per animal per year) from traditional individual housing. In Dutch legislation the emission factor for sows is set at 4.2 kg ammonia (Anonymous, 2005), which is a rate of 0.50 g/h per sow. To obtain the environmentally friendly status needed for a Dutch environmental permit, emission would have to be reduced to 2.5 kg a year per

sow for housing systems with bare floors and 2.6 kg a year per sow for straw-bedded housing systems. Expressed as hourly rates, this is 0.30 g/h of ammonia emission per sow from housing systems with bare floors and 0.31 g/h per sow from housing with straw bedding (Anonymous, 2005). In housing systems with sows kept individually, a reduction of 40–60% compared to the emission factor could be easily achieved by having small V-shaped slurry channels underneath the slatted floor (Voermans *et al.*, 1996). But because group-housed sows walk around, the area on which they excrete is not as well defined as it is with sows penned individually and so such channels would not be as effective in reducing ammonia emission – especially if the groups of sows are large (>50) as is common in the Netherlands. Clearly, another approach is needed in order to reduce ammonia emissions from these housing systems. The second study was carried out to find such an approach. It investigated whether feeding management could be deployed to reduce the ammonia emission from group-housing systems for sows.

Feeding induces activity (Verstegen *et al.*, 1987; Henken *et al.*, 1993). The study described in chapter 2 showed a relation between the activity of the sow and ammonia emission on an hourly base. The presumed effect of activity on the emission of ammonia has two components: sow behaviour as such and air temperature. An important behavioural aspect that affects ammonia emission is urination, which brings urea, the main source of ammonia, into the house. Air temperature rises when animals are active, because active animals produce more heat (Schrama *et al.*, 1996). A higher air temperature increases ammonia volatilisation (Elzing & Monteny, 1997a), and it also increases ventilation rates; the latter additionally increases ammonia emission by higher air velocities above the emitting surface (Elzing & Monteny, 1997a).

In order to distinguish the effect of temperature on ammonia emission from the effect of behaviour, both air temperature and sow activity were factors in the statistical model for predicting ammonia emission used in the second study (chapter 3). Dutch pig farmers generally feed their individually kept sows in stalls simultaneously in the morning and in the afternoon, the latter being the warmest time of day with highest ventilation rates. The effect of temperature and ventilation rate will then accumulate and have an additional increasing effect on ammonia emission. The effect of activity on ammonia emission significantly reduced when the afternoon feeding shifted to the evening (Table 2 in chapter 3). However, ammonia emission did not decrease. A modest effect of changing feeding time to the evening and night of 10% emission reduction was achieved if sows were fed

sequentially by an ESF. These results may suggest that changing the feeding time is not an effective way of reducing ammonia emission. However, during the experiments the average outdoor temperatures were low (3.7°C) and furthermore, the difference between day and night temperatures outdoors was only 2– 3°C (a difference of 10°C would not be unusual). When the difference is this small, the range of the indoor temperature is smaller, and so is the range of the ventilation rate regulating that temperature. This could explain why the regression coefficient of temperature did not change significantly. Given the effect of feeding time on the regression coefficient of activity in the case of simultaneously fed sows and also the reduction (albeit modest) of emission from sequentially-fed sows, the effect of changing feeding time on ammonia emission may be substantially larger when there are larger differences in outdoor temperature between day and night

Elzing & Monteny (1997a) showed that ammonia emission starts immediately after urine production and peaks within two hours. The activity – urinating – is therefore an important variable in determining ammonia emission. Urination also raises air temperature because of activity-related heat production as mentioned earlier, and also because the urine (which has a temperature of 38 ºC as it leaves the body) heats the emitting surface when it falls onto it. In chapter 3 it was argued that instead of looking at activity in general it might be effective to include urinating behaviour (defined as the time at which a sow urinates) in the statistical model to predict ammonia emission.

7.3 Effect of straw bedding on ammonia emission

In most bedded sow houses in the Netherlands the bedding is straw, applied on part of the living area. The bed is not aerated; at frequent intervals it is replenished with fresh straw (up to 200–400 kg per year per sow) and once a year the bedding is removed. Aarnink & Elzing (1998) and Monteny *et al.* (1999) describe models to predict ammonia emission from slatted floors and slurry surfaces in the pit where physical and chemical parameters are decisive factors. Ammonia emission from the straw bed, however, also depends on the nitrogen turnover of various kinds of micro-organisms that are difficult to describe by mechanistic models. A few studies have measured ammonia emissions from straw bedding in the laboratory (Misselbrook & Powell, 2005; Andersson, 1996; Kemppainen, 1987) or in situ (Jeppson, 1998). They aimed to assess differences in emissions from different bedding materials but not from other sources in the house. The studies described in chapters 4 and 5 set out to estimate the individual contribution of the straw bedding, the slatted floors and the solid floors

to the emission from an entire house, using a combination of a laboratory set-up and model calculations. The results were compared with measurements from a reference house with 150 sows living on a surface area of 2.25 m2 each, of which approximately half was covered with bedding and the other half consisted of slatted and concrete floors. It was in this housing system that the ammonia emission data used to obtain the emission factor of 2.6 kg per sow a year for straw-bedded housing systems for sows were measured (Groot Koerkamp & Hol, 1999; Anonymous, 2005). The emission during summer time, which represents the conditions during the laboratory experiment, was 8.7 g/d per sow, which was 26% less than the model calculations of 11.7 g/d per sow. Given the 90% confidence interval of the measurements (6.5–10.9 g/d per sow), the difference was significant. Given the variation coefficient of ammonia emission within sow houses companies of 20% calculated by Mosquera *et al.* (2005) the difference was within a reasonable range. Because no empirical data were available on the urinating behaviour of sows kept in groups with a straw bed, the model calculations were performed with default even distributions of urinations in time and place. In the discussion of chapter 5, simulations with more realistic scenarios taking into account the natural excreting behaviour of pigs were evaluated and it was found that the emissions were smaller and fell within the confidence interval of the measured emission.

A straw bed for lying on allows air temperature in the house to fall because it decreases the lower temperature of the thermoneutral zone (TNZ) of pigs (Edwards & Robertson, 1988, cited by Edwards, 1990). A lower air temperature in the house reduces the ammonia emission (Elzing & Monteny, 1997a), which implies that a straw bed and accompanying lower ambient air temperature may cause less emission compared to houses with bare floors and higher ambient air temperature. In the Netherlands, however, most pig houses are insulated and climate controlled; the latter means in this situation that heat produced by the animals is removed. The indoor temperature can then only be reduced if it is cooler outdoors than indoors, so the ventilation rates and air velocity increase – which increases ammonia emission (Elzing & Monteny, 1997a) and will diminish the effect of a lower air temperature. The net effect of the lower TNZ resulting from applying straw bedding remains to be studied under practical conditions.

From the results of the study it appeared that urination on straw caused the least ammonia emission compared to urination on a slatted floor, pit or solid floor; ammonia emission was highest from urination on a solid floor. With the straw bedding covering 60% of the potential emitting area, the model calculated that the

bed contributed 27% to the ammonia emission of the entire house; the slatted floor (17% of the potential emitting area) contributed 31%, and the solid floor (23% of the potential emitting area) contributed 42%. The conclusion is that the ammonia emission from a bedded sow house depends greatly on which surface is urinated on.

7.4 Effect of urinating behaviour on ammonia emission

As argued in sections 2 and 3 of this chapter, one way ammonia emission might be controlled – within certain limits – is by manipulating the timing and location of the urination. 'Feeding time' affects many circadian biological rhythms; Aschoff (1970) therefore referred to it as a 'Zeitgeber' (timing controller). As feeding time also affects the sow's activities, such as urination, it might therefore be a tool for reducing ammonia emission. The results of the study described in chapter 3 showed that altering the diurnal activity pattern of the animals by changing their feeding time changed the pattern of the ammonia emission accordingly. Aarnink *et al.* (1996) had earlier shown that the daily urinating pattern of fattening pigs was similar to the ammonia emission pattern. Combining these results with the fact that ammonia emission peaks two hours after urination (Elzing & Monteny 1997a) also indicates that the time a sow urinates affects ammonia emission. The findings presented in chapter 3 furthermore show that shifting sow activity to cooler times of the day by changing feeding times can reduce ammonia emission.

The areas pigs use for resting, feeding and excretion depend on pen design and temperature (Hafez, 1975; Steiger *et al.*, 1979; Whatson, 1985; Fraser, 1985; Hacker *et al.*, 1994). When pigs assign a specific area for excretory behaviour, urinations will overlap and supersede one another more frequently on the surface of the slats or in the pit, so a smaller amount of the dissolved NH_3 will volatilise (Monteny *et al.*, 1998) and less ammonia is emitted. Overlapping and superseding occurs even more frequently when urinating behaviour is also synchronised by feeding simultaneously; the result is a shorter emission time per urination and a greater reduction of ammonia emission by comparison with the sequential urinating behaviour of sows fed by an ESF. Because the type of substrate a sow urinates upon also determines the ammonia emission, it is important that the pigs can define their excretory behaviour on a substrate with low emission potential. Pen design is therefore an important factor in determining ammonia emission. The IUPE model described in chapter 5 calculates ammonia emission based on the location of the urination and the duration of emission (i.e. the interval between two overlapping urinations). Therefore the model can be used to quantify the effect of

pen design on ammonia emission. The ammonia emission of the reference house was calculated to be 11.7 g/d per sow. Given that a urination on the straw bedding emits less than a urination on a slatted or solid floor, it was calculated that if slatted and solid floors were also bedded, the total emission would be 5.8 g/d: a reduction of 50%. The effect of a completely bedded area on animal welfare, farm management, manure management and emissions of other polluting gases is not considered here, but these issues should be considered.

Pigs are hygienic animals and prefer to urinate and defecate in areas where they do not eat or lie. They can do so if they are kept in groups. Given that the results of this study indicate that directing urinating behaviour is a means of reducing ammonia emission, it would therefore be possible to exploit this in sow group-housing. The housing could be designed in order to allow the sows to perform their natural behaviour in a way that allows environmental goals to be met.

7.5 Effect of group-housing with straw bedding on emission of greenhouse gases

This thesis studied NH_3 emission from litter-based systems and also reports on emission of CH_4, N_2O and NO because environmental goals are not served if there is pollution swapping between NH_3 and other polluting gases. N_2O and NO are part of the nitrogen balance, as is NH_3. To fully understand the nitrogen balance, data are required on the inert gas N_2 which is the end product of the nitrogen turnover. Because 80% of the air is N_2 (8 * 105 ppm), the additional production of one or several tens of ppms of this gas cannot be reliably detected in air. Most research on nitrogen balances has measured the amount of N in the slurry/litter mixture before and after a treatment. The difference, corrected for the measured gaseous losses (NH_3, N_2O and NO) is considered to be lost as N_2. In this way, a composting experiment done by Veeken *et al.* (2002) calculated that over 80% of the N losses were N_2. In a bedded house with fattening pigs, Kaiser & Van den Weghe (1997) calculated that 63% of the nitrogen loss was N2, whereas calculations using the data from Thelosen *et al.*, (1993) yielded a loss of N_2 of 69%. The three systems had in common that the slurry/litter mixtures were treated to enhance aerobic conversion of NH_4^+ to NO_3^- (nitrification) to be followed by the conversion of NO_3^- to N_2 (denitrification). N_2O and NO are intermediate products of these processes.

Kirchmann & Witter (1989) reported that under aerobic conditions the nitrogen losses as NH_3 increased with decreasing C:N ratio. Under anaerobic

circumstances however, they measured only a loss of 1% of the initial nitrogen as NH_3 and no nitrogen was incorporated in biomass (no immobilisation of nitrogen). Veeken *et al.* (2002) confirmed these results by measuring no significant nitrogen losses from a mixture of slurry and straw on an organic pig farm of which the density of this mixture was 1100-1290 kg/m3; the high density suggests that the conditions were mainly anaerobic.

Emissions do not occur in the animal house alone, but also when slurry is stored outdoors and when it is spread on fields. Few studies have reported on emissions during the spreading of mixtures of slurry and straw (deep-litter manure). Amon *et al.* (1997) recorded that when anaerobically stored solid manure was spread on land, more NH_3 was emitted than from composted solid manure. Overall, however, composting caused almost three times more NH_3 emission than anaerobic storage. Compared to slurry, solid manure and deep-litter manure emit less NH_3 during spreading (Mulder, 1992). However, slurry injection, a technique that cannot be used for solid or deep-litter manure, enables ammonia emissions from slurry to be reduced considerably (Thompson *et al.*, 1987). On the other hand, slurry injection increases emission of N_2O (Velthof *et al.*, 2003).

The anaerobic breakdown of organic material by bacteria causes CH_4 to be produced (Zeeman, 1991). In chapter 6 it was argued that it is likely that CH_4 is produced in straw bedding, as large emissions of CH_4 emissions have been measured from such deep-litter systems with cattle. However, there may be much less emission of CH_4 from bedded sow houses than from bedded cattle houses, because sows aerate the top layer of the bed by rooting and foraging and this encourages the oxidation of CH_4 to CO_2. In total, 39 g/d of CH_4 was emitted per sow from the sow house with straw bedding described in chapters 4 and 5. To be able to evaluate this emission of CH_4, a reliable baseline emission figure is needed. The reference is a sow house with a slurry pit. In the context of global warming, the Intergovernmental Panel on Climate Change (IPCC) has put much effort into calculating national emissions of greenhouse gases. Using the IPCC guidelines for slurry with a volatile solids content of 800 g/kg dry matter (Moller *et al.*, 2004) and a slurry production of 7 l/d per sow with 100 g/l dry matter (Van der Peet Schwering *et al.*, 1997), CH_4 emission from sow slurry is estimated to be 7.6 g/d. Taking into consideration an endogene CH_4 production of 4 g/d per animal (Klein Goldewijk *et al.*, 2005), the CH_4 emission in the straw-bedded sow house (39 g/d per sow) would be over three times more than the CH_4 emission from a slurry-based house (11.6 g/d per sow), which suggests that adding straw to sow housing increases CH_4 emission considerably. However, Groot Koerkamp &

Uenk, (1997) recorded 58 g/d CH_4 from slurry-based sow housing systems, which suggests that addition of straw reduces CH_4 emission. Jungbluth *et al.* (2001) reported large variation in CH_4 emissions from slurry-based housing systems for fattening pigs: 5–30 g/d per pig. These data and the high coefficient of variance reported by Groot Koerkamp & Uenk (1997) of 48% show that there are big variations not only in data from litter-based systems as reported in Table 1 of chapter 6, but also in data from the slurry-based reference houses. More research needs to be done on straw-based as well as on slurry-based reference systems, in order to explain the cause of the observed variations and to be able to ascertain the impact of straw bedding on the CH_4 emission.

From the above it can be concluded that in order to avoid emission of the greenhouse gas N_2O when straw is used as bedding, it is best not to turn the bed over to incorporate oxygen and initiate nitrification. The anaerobic environment thus created may cause CH_4 to be produced, but emission may be lessened due to the CH_4 being converted to CO_2 in the aerobic top layer of the bed (Petersen *et al.*, 2005; Veeken *et al.*, 2002). To prevent pollution being swapped between the animal house on the one hand and outside storage and land spreading on the other, more integrated research is needed in which the slurry rather than the treatment or storage device is considered to be the emitting system.

7.6 Other aerial emissions

Just as loose housing and straw bedding do not cover all aspects of sow welfare, NH_3 and the greenhouse gases CH_4 and N_2O do not cover all the environmental consequences of keeping sows. Other environmental problems of keeping sows and other livestock are caused by manure surplus (Voorburg & Ciavatta, 1993), emission of odour (VROM, 1998) and dust (Chardon & Van der Hoek, 2002). As Westhoek *et al.*, (2004) have described, the nitrogen (N) and phosphorus (P) in the animal feed imported into the Netherlands have resulted in the country having a surplus of these minerals. Though keeping sows in groups with straw bedding will not affect the status of P, it will change the nitrogen balance as described in section 7.3 and 7.5 and will probably decrease the surplus through the production of N_2. Ogink & Lens (2001) reported an odour emission of 6.8 OUe/s per sow measured in the group house with straw bedding described in chapters 4 and 5. This was 64% less than the emission from slurry-based reference houses with sows penned individually. On the basis of the measurements presented by Roelofs *et al.* (1993) it is estimated that deep-litter systems may reduce dust emission by 50% (the amount will depend on the straw management) compared

to slurry-based reference systems (CIGR, 1994; Aarnink & Van der Hoek, 2004). The above implies that pollution from emissions of odour and dust is not inevitable in bedded group-housing systems for sows. However, more detailed research is needed to confirm these preliminary findings.

7.7 Weighing welfare against environment

Though loose housing and straw bedding – the two conditions for sow welfare considered in this thesis – are important, there are other welfare issues. In 2003, the blue print of the Comfort Class housing system for pigs was completed (Projectgroep Diergericht Ontwerpen, 2003). Its design is intended to meet the biological needs of a pig (adapted from Bracke *et al.* 1999). The house was developed for fattening pigs, but as sows have basically the same needs as fattening pigs, the results of that research are considered to be largely applicable to sows. The methodological approach of the design procedure (Kroonenberg & Siers, 1999) made it possible to evaluate the designers' brief of requirements in terms of aspects other than welfare, such as environmental or economic impact. In this section, the impact of the welfare requirements on ammonia emission are evaluated.

The brief consisted of 58 requirements (Groenestein & Schouten, 2003). Four experts on welfare scored these according their contribution to welfare: the better

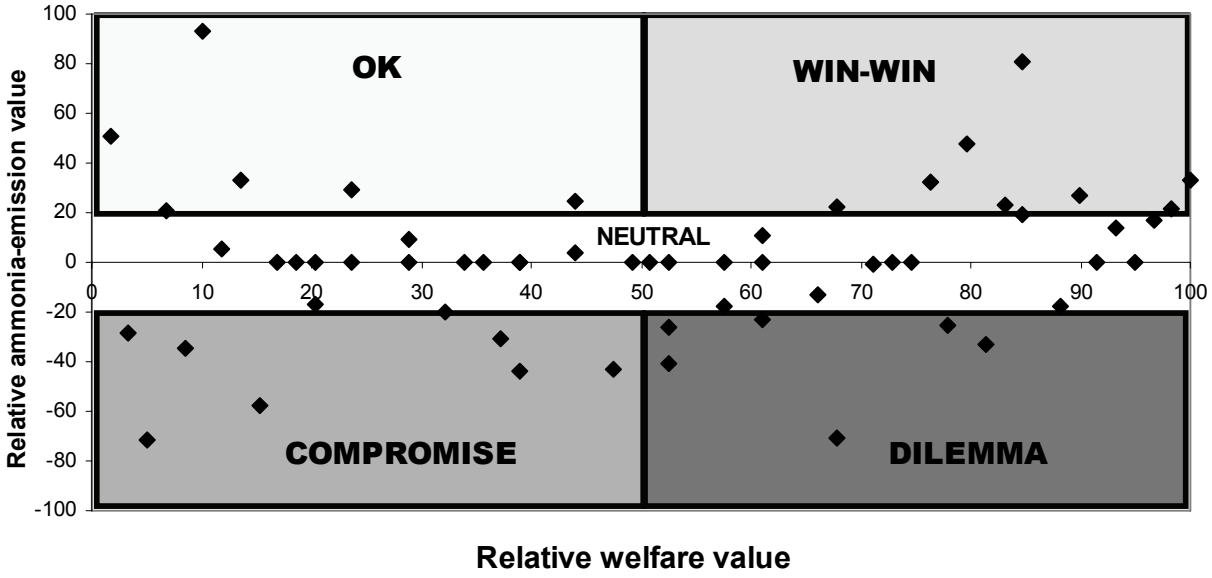

Figure 7.1. Welfare requirements formulated for the design of a pig house in which animal needs are met, scored on their impact on welfare and their effect on ammonia emission.

the requirement served welfare, the higher its score on a scale between 0 to100. A low score for welfare is still beneficial for the pig's well-being, because, as a starting point all requirements were based on the needs of the pig. Two environmental experts also scored the requirements in terms of their likely impact on ammonia emission: a negative score was given if implementation of the requirement would increase ammonia emission, and a positive score if it would diminish it. The higher the score on a scale between -100 to +100, the more beneficial the requirement would be for the environment. Based on the scores the requirements were then put together in a diagram and divided into five groups (Figure 1): low scores for welfare, high scores for ammonia (OK); high for welfare and high for ammonia (WIN-WIN); low for welfare and low for ammonia (COMPROMISE); high for welfare and low for ammonia (DILEMMA); and low and high for welfare and around zero for ammonia (NEUTRAL). Each diamond in Figure 1 thus represents a requirement. For details on all the requirements, see Groenestein *et al.* (2003).

Implementing the 31 requirements in the NEUTRAL area into the design of a pig house will have little or no effect on ammonia emission. In Table 1, the other 27 requirements are presented: 12 will reduce ammonia emission (OK and WIN-WIN), so welfare and environment are both served. The remaining 15 requirements, however, (COMPROMISE and DILEMMA) show a conflict of interest: good for welfare, less good or bad for the environment. The dilemmas are mainly the requirements concerning the surface area of the pen.

Implementing these requirements in the design of a pig house does not in itself enhance ammonia emission, but the requirements do have the potential to do so: if fouled with slurry, the floors can become emitting areas and the larger an emitting surface is, the greater the ammonia emission will be (Muck & Steenhuis, 1981; Elzing & Monteny, 1997b; Aarnink & Elzing, 1998; Monteny *et al.*, 1998). Changing from individual housing to group housing gives the sows more surface area to foul, and is thus potentially unfavourable for ammonia emission. However, the results of the research described in chapter 2 show that group housing does not increase the emissions of ammonia. Additionally, the data in Figure 1 and Table 1 show that covering the area with a substrate like straw creates a win-win situation. The results presented in chapters 4 and 5 confirm that straw bedding decreases ammonia emission. If the design of a sow house with straw bedding takes account of the natural hygienic excreting behaviour of sows in order to prevent urinations on solid and slatted floors, the welfare requirements causing the environmental dilemmas can be neutralised. Additionally, available emission-

Table 7.1. Description of welfare requirements in the categories Win-win, OK, Compromise and Dilemma as presented graphically in Figure 7.1.

Group	Description of requirement
Win-win	Air velocity at animal level must not be more than 0.2 m/s
	To prevent claw problems a floor area must be covered with a substrate
	Water must be available ad libitum
	At least one watering place per ten animals
	Dry lying area, covered with substrate (i.e. straw, wood shavings, rubber mats)
	Social stability based on subgroups
OK	Undisturbed resting period agreeing with biorhythm
	Negative interaction between pig and farmer must be avoided or compensated for
	The sickbay must be able to accommodate 2% of the total number of pigs
	Accumulation of urine and manure must be avoided
	Feeding place between lying and manuring area without hampering traffic between these areas
	Excretion place available
Compromise	Floor must be rough enough to prevent slipping while excreting
	Ample surface area of dunging place based on body size and number of animals excreting at the same time
	Permanent opportunity to root and forage
	Light of correct spectrum
	Opportunity to explore living area
	Positive interaction between pig and pig farmer must be stimulated
	Ammonia concentration must be below 10 ppm
Dilemma	Freedom of movement based on size of pig and turning circle (πr^2)
	Ample surface area to root and forage based on body size and number of animals excreting at the same time
	Roughness of surface of walking area must be less than 2 cm
	Sick or affected animals must be cured or culled
	Sick or affected animals must be isolated
	Ample surface area to play and fight based on body size and number of animals excreting at the same time
	Floor must be rough enough to prevent slipping while playing and fighting
	Ample surface area to turn for body care

reducing techniques can be implemented to reduce emissions from the solid and slatted floors. The IUPE model can be used to estimate the intended effect of a design on ammonia emission, or quantify the risk if the sow does not urinate where expected.

7.8 Conclusions

- The comparison of housing systems for sows revealed that group housing does not cause an increase in ammonia emission compared to housing with sows penned individually.

- Shifting feeding time to the evening and night decreases ammonia emission from group-housing systems when sows are fed by an electronic feeding station. This effect is likely to increase in proportion to the difference between daytime temperature and night-time temperature.

- Shifting feeding time to the evening and night reduces the effect of the activity of simultaneously fed sows on ammonia emission.

- If straw management is appropriate, providing a straw bed in a group-housing system for sows will result in ammonia emission being less than if there is no bedding.

- The rate at which ammonia is produced after a urination in a straw bed increases concomitantly with slurry content of the bed. Total volatilisation of ammonia, however, is less in areas with higher slurry contents; this is probably because of the microbial conversion of nitrogen.

- The emissions of greenhouse gases, odour and dust from a group-housing system for sows with straw bedding are not substantial if the litter is managed appropriately, but more research is needed in order to be able to understand the conditions for these emissions.

- The simulation model developed in this study calculates ammonia emission from the entire sow house as the sum of the emissions from straw, solid floors, slatted floors and pits after urinations. The results of simulations showed that measures to reduce ammonia emissions from a sow house with straw bedding are most effective if aimed at decreasing the emission from the solid floor and stimulating relatively more urinations on the straw bed.

Summary

In the second half of the 20th century, pig husbandry was intensified in pursuit of maximum production. Technical results were improved by implementing many changes in housing, climate control, feeding management, breeding and preventive health care. The changes meant that sows were no longer kept in groups and on pasture, but inside, individually in crates or tethered, on partly slatted floors and fed restrictedly. In society, but also from animal behaviour scientists, the notion grew that the welfare of the sows kept under these conditions was poor and would improve if the sows were kept in groups again. Particularly among the general public, there was also concern about the impact of intensive husbandry on the environment. Water and soil were being eutrophied by the high loads of phosphorus and nitrogen being released from the surplus of manure brought in the field. Moreover vast amounts of the gas ammonia (NH_3) were emitted to the atmosphere causing acidification and eutrophication of nature. In 1989 NH_3 was responsible for 46% of the acidification in the Netherlands; 94% of the emission was from livestock production. Welfare legislation was not formulated to achieve environmental goals, and vice versa. However, the challenge of sustainable development in livestock production is to reconcile the three P's – with economic values (Profit) at the apex of an optimal eternal triangle, and ecological and social values (Planet and People) at the other two corners.

The development of welfare-friendly sow husbandry in recent years focussed mainly on two purposes: to keep sows loose in groups and to provide the sows with straw bedding. It was often argued that both of these changes could affect the environment negatively, particularly via the emission of ammonia. The main objective of this research was to establish the effect on ammonia emission of keeping sows in groups and, additionally, giving them straw bedding and eventually to find tools to reduce the emission. The effect on the emission of the greenhouse gases methane and nitrous oxide was also considered because pollution swapping needs to be prevented.

Ammonia emission and group housing

It had to be established what the ammonia emission of group-housing systems for sows was compared to the emission from a standard housing system with sows kept individually. At the experimental farms of the Research Institute for Pig Husbandry in Rosmalen three housing systems were compared: A standard individual housing system with 64 sows in feeding stalls with 2.8 m^2 surface area per sow (system A); a group-housing system with 62 sows in free access stalls with 3.3 m^2 surface area per sow (system B); a group-housing system with 65 group-housed sows fed with electronic sow feeders and with 3.4 m^2 surface area

per sow (system C). The sows in systems A and B were fed simultaneously twice a day and in system C the sows were fed sequentially once a day. The average ammonia emission per sow was 0.72, 0.62 and 0.70 g/h for the systems A, B and C respectively. For the systems A, B and C this implied that 23, 20 and 23% of the nitrogen intake emitted as ammonia nitrogen respectively. The lower emission of system B was statistically significant ($P < 0.05$). The results show that keeping sows in groups with a larger living area does not imply an increase in ammonia emission compared to the current individual housing. The diurnal pattern of the ammonia emission was obviously related to the times of feeding of the sow. This led to the hypothesis that feeding schedule might be a tool to reduce ammonia emission from sow group-housing systems.

Ammonia emission and feeding schedule

Pig farmers generally feed their individually kept sows simultaneously in the morning and in the afternoon, the latter being the warmest time of day with highest ventilation rates. Feeding induces animal activity. The effect of activity on the emission of ammonia seems to be based on two components: sow behaviour as such, including urinating, and extra body-heat production which affects air temperature. The effect of air temperature and consequently on ventilation rate will have an additional increasing effect on ammonia emission, especially when the sows are fed at the warmest time of day. To have tested this effect under practical circumstances, two feeding schedules were imposed on the sows of system A, B and C of the previous experiment, and the effect on ammonia emission, animal activity and indoor temperature was measured. With the animals fed sequentially in system C, the ammonia emission fell by 10% if feeding occurred in the evening and night instead of during daytime. But if the animals were fed simultaneously (system A and B), changing the feeding time from the (warm) afternoon to the evening, did not significantly affect the total amount of ammonia emitted. In all three systems the diurnal patterns of the indoor temperature, animal activity and ammonia emission changed considerably with feeding schedule. In system A and B the effect of activity significantly reduced. It was discussed that during the measurements the difference between day-time temperature and night-time temperature was small which may have attributed to the modesty of the effect of changing feeding time on ammonia emission.

Ammonia emissions and straw bedding

To assess the contribution of straw bedding, concrete floors, slats, and slurry in the pits to the total ammonia emission of a straw-bedded group-housing system for sows, the ammonia volatilization response of urination on each of the potential

emitting surfaces was studied under laboratory conditions. Therefore substrate samples were taken from the surfaces of a concrete floor in the walking alley, top layer of slurry in the pits under the drinking area and the waiting area (in front of the feeding stations) and from the upper part of the straw bedding. The latter represented straw with respectively a small, an average, and a high content of slurry dropped by the sows. The sampling of the straw bedding was carried out leaving the structure of the bedding material intact. In the laboratory 150 ml of urine was sprinkled on each sample and the ammonia volatilization was measured during a period of seven days. The total ammonia volatilization was least from the average and heavily soiled straw (359 and 344 mg respectively, $P>0.05$) and most from the concrete floor in the walking alley (973 mg, $P<0.05$). The lowest maximum volatilization rates were from the straw bedding, irrespective of slurry content, and from the slurry in the pit under the waiting area, the highest rate was measured from the concrete floor in the walking alley ($P<0.05$). The volatilization rate peaked soonest with heavily soiled straw, slurry in the pit under the waiting and drinking area and concrete floor ($P<0.05$), indicating a faster ammonia production rate.

Ammonia emission and floor design

With the results of the laboratory experiment as input, a simulation model was developed that calculates total ammonia emission based on the type of the emitting surfaces. Using mechanistic and empirical relationships it calculates the ammonia emission by integrating ammonia volatilizations from all urinations in the house with the assumption that a urine pool stops emitting when overlapped by another one. The reference data were from a house with a floor comprising 60% straw bedding, 14% drinking area (concrete slatted floor with pit), 3% waiting area (concrete slatted floor with pit) and 23% alley (concrete solid floor). Simulations were performed and the results were compared with actual emission data from an entire sow house. The model estimated the ammonia emission from the entire house as 11.7 g/d per sow, and the relative contributions of the straw bed, the drinking area, the waiting area and the alley as respectively 27%, 22%, 9% and 42%. By comparison, the actual emission from the house was 8.7 g/d per sow with a 90% confidence interval of 6.5-10.9 g/d per sow. Because no scientific knowledge was available of the distribution of the urination, it was assumed that the sows urinate evenly between surface areas. If it is assumed that urinations are evenly distributed throughout the sow house, the emission was within the 90% interval, with the straw bed, the drinking area, the waiting area and the alley contributing respectively 32%, 19%, 3% and 45%. Simulating a larger size of the urine pool initially increased the emission, but with bigger size showed a decrease

of the emission due to a larger effect of overlapping of urinations. Simulating a larger area to be straw bedding decreased the calculated emission. Simulating more slatted and concrete floors showed an increase of the calculated emission. The model is a useful tool for designing straw-bedded sow group-housing systems with low ammonia emissions. Actual knowledge of the urinating pattern of the sows would improve the accuracy of the model's predictions.

Greenhouse gas emission, group housing and straw

The effect of a straw bedding in group-housing systems on the emission of methane (CH_4) and nitrous oxide (N_2O) was studied mainly on the basis of a literature analyses. Most of the studies on emissions from litter systems were carried out with fattening pigs. The reported emissions ranged from 2.5 to 13.4 g/d per fattening pig for CH_4 and from 0.03 to 11.3 for N_2O. The listed N_2O emissions from a sow house study fell within the reported ranges for fattening pigs. The CH_4 emission per sow was higher, even when corrected for liveweight of the animals. The variability of the emissions of CH_4 and N_2O mirrors the variability in the application of the litter systems: not only the litter material, but also the treatment of that material varies widely between the systems described in the literature. Measurements of NH_3, NO and N_2O emissions from a deep-litter system for fatteners with weekly treatment of the saw-dust bed showed that, however the ammonia emission decreased, emissions of total nitrogen increased compared to a traditional slurry-based system mainly because of emission of N_2O-N from the litter.

It was concluded that in order to avoid emission of the greenhouse gas N_2O it is best to use straw as bedding and to avoid turning the bed over to incorporate oxygen and initiate nitrification. The anaerobic environment may cause production of CH_4, but emission may be lessened due to convertion of CH_4 in CO_2 in the top layer of the bed.

Conclusions

- The comparison of housing systems for sows revealed that group housing does not cause an increase in ammonia emission compared to housing with sows penned individually.

- Shifting feeding time to the evening and night decreases ammonia emission from group-housing systems when sows are fed sequentially by an electronic feeding station. This effect is likely to increase in proportion to the difference between temperatures during day and night.

- Shifting feeding time to the evening and night reduces the effect of the activity of simultaneously fed sows on ammonia emission.

- If straw management is appropriate, providing a straw bed in a group-housing system for sows will result in ammonia emission being less than if there is no bedding.

- The rate at which ammonia is produced after a urination in a straw bed increases concomitantly with slurry content of the bed. Over time, the volatilisation, however, is less with higher slurry contents; this is probably because of microbial conversion of nitrogen.

- The emissions of greenhouse gases from a group-housing system for sows with straw bedding are not substantial if the litter is managed appropriately, but more research is needed in order to understand the conditions for low emissions.

- The simulation model developed in this study calculates ammonia emission from the entire sow house as the sum of the emissions from straw, solid floors, slatted floors and pits after urinations. The results of simulations show that measures to reduce ammonia emissions from a sow house with straw bedding are most effective if aimed at decreasing the emission from the solid floor and stimulating relatively more urinations on the straw bed.

Samenvatting

In de tweede helft van de twintigste eeuw intensiveerde de varkenshouderij met als doel de productie te maximaliseren. De technische resultaten verbeterden door veranderingen in de huisvesting, klimaatbeheersing, voedingsmaatregelen, fokkerijprogramma's en preventieve gezondheidszorg. Voor zeugen betekende deze veranderingen dat ze niet langer buiten in groepen gehouden werden, maar binnen, individueel in voerligboxen, al dan niet aangebonden, op gedeeltelijke roostervloer en met beperkte voedering. Bij gedragswetenschappers, maar ook maatschappelijk, groeide het besef dat deze houderij voor zeugen niet welzijnsvriendelijk was en dat groepshuisvesting een verbetering zou betekenen. In de samenleving groeide ook de zorgen om de consequenties van de intensieve veehouderij op het milieu. Mestoverschot veroorzaakte eutrofiering van water en bodem door teveel aan fosfor en stiksof die op het land gebracht werd. Bovendien kwam veel ammoniakgas vrij uit de mest in de atmosfeer die de natuur verzuurde en eutrofieerde. In 1989 werd 46% van de verzuring veroorzaakt door NH_3, 94% van die NH_3 kwam uit de landbouw. Wetgeving t.a.v dierenwelzijn was niet geformuleerd om milieudoelen te halen en vice-versa. De uitdaging van een duurzame ontwikkeling van de veehouderij is het verenigen van de drie P's – met economische (Profit), ecologische (Planet) en sociale (People) waarden als de hoekpunten van een gelijkbenige driehoek.

De ontwikkeling van welzijnsvriendelijke huisvesting voor zeugen richtte zich de laatste jaren vooral op twee belangrijke doelen: groepshuisvesting en de verstrekking van een strobed. Vaak werd gesteld dat deze twee aspecten het milieu negatief zouden beïnvloeden, vooral door een toename van de emissie van ammoniak. Het doel van deze studie was vast te stellen wat het effect van groepshuisvesting en het effect van het verstrekken van een strobed was op de emissie van ammoniak. Daarnaast werd gezocht naar manieren om de emissie te verminderen. Om te voorkomen dat de oplossing voor het ene milieuprobleem een ander milieuprobleem veroorzaakt (afwenteling) werd eveneens gekeken naar de emissies van de broeikasgassen methaan en lachgas.

Ammoniakemissie en groepshuisvesting

Vastgesteld werd wat het effect van groepshuisvesting voor zeugen was op de emissie van ammoniak in vergelijking met een standaard huisvesting met individueel gehouden zeugen. Daartoe werden op het Proefstation voor de Varkenshouderij in Rosmalen drie huisvestingsystemen vergeleken: een standaard huisvestingssysteem met 64 zeugen, individueel gehouden in voerligboxen en 2.8 m^2 vloeroppervlakte per zeug (systeem A); een groepshuisvestingssysteem met 62 zeugen in voerligboxen met uitloop en 3.3 m^2

vloeroppervlakte per zeug; een groepshuisvestingssysteem met 65 zeugen met voerstation en 3.4 m^2 vloeroppervlakte per zeug (systeem C). De zeugen in de systemen A en B werden twee maal per dag simultaan (gelijktijdig) gevoerd, in systeem C kregen de dieren één maal per dag sequentieel (na elkaar) voer in een voerstation. De gemiddelde ammoniakemissie was per zeug respectievelijk 0.72, 0.62 en 0.70 g/u voor de systemen A, B en C. Dit betekende dat voor de systemen A, B en C respectievelijk 23%, 20% en 23% van de stikstofopname emitteerde als ammoniakale stikstof. De lagere emissie van systeem B was statistisch significant ($P < 0.05$). De resultaten geven aan dat het houden van zeugen in groepen met een groter leefoppervlak niet betekent dat de ammoniakemissie toeneemt t.o.v het individueel houden van zeugen. Het dagpatroon van de ammoniakemissie was duidelijk gerelateerd aan de voertijden. Dit gegeven leidde tot de hypothese dat manipulatie van het voerschema een methode zou kunnen zijn om de ammoniakemissie te reduceren.

Ammoniakemissie en voerschema

Over het algemeen voeren varkenshouders hun individueel gehuisveste dieren tweemaal daags ’s ochtends en ’s middags. ’s Middags is tevens het warmste moment van de dag met de hoogste ventilatie. Het voer is de belangrijkste motivatie voor activiteit van de dieren. Het effect van activiteit op de ammoniakemissie is gebaseerd op twee componenten: het gedrag van de zeugen, inclusief urineergedrag, en productie van lichaamswarmte die de temperatuur van de stallucht verhoogt. Het effect op de temperatuur van de stallucht en derhalve op de ventilatie, kan een additioneel toenemend effect hebben op de ammoniakemissie, met name wanneer de zeugen gevoerd worden op het warmste moment van de dag. Om dit effect te testen onder praktische omstandigheden werden in de systemen A, B en C uit eerder genoemd experiment, de ammoniakemissie, de staltemperatuur en de dieractiviteit gemeten bij verschillende voerschema’s. In systeem C, waar de dieren sequentieel gevoerd werden, daalde de emissie 10% toen ’s avonds en ’s nachts gevoerd werd i.p.v. overdag. Bij de simultaan gevoerde dieren in de systemen A en B veranderde de ammoniakemissie niet significant door het verschuiven van de voertijd van ’s middags naar ’s avonds. In alledrie de systemen veranderde het dagpatroon van de staltemperatuur, dieractiviteit en ammoniakemissie aanzienlijk tengevolge van het veranderen van de voertijden. In de systemen A en B nam het effect van activiteit op de emissie significant af. Het werd bediscussieerd dat gedurende de metingen de temperatuurverschillen tussen dag en nacht klein waren en dat dat heeft bijgedragen aan de bescheidenheid van het effect van het veranderen van de voertijden op de ammoniakemissie.

Ammoniakemissie en strobed

Om de afzonderlijke bijdragen van het strobed, de betonnen vloer, de roosters en de mest in de put aan de ammoniakemissie van een zeugenstal met groepshuisvesting en strobed te bepalen werd een laboratoriumproef opgezet waarbij de ammoniakvervluchtiging werd gemeten na simulatie van een urinelozing. Daartoe werden monsters genomen van de betonnen vloer van de loopgang, van de toplaag van de mest in de put van de drinkruimte en de wachtruimte (voor de voerstations) en van de bovenste laag van het strobed. Van de laatste werden monsters genomen van plaatsen waar veel in het stro werd gemest, waar minder en waar nauwelijks werd gemest. Het stromonster werd zodanig genomen dat de structuur van het bed zo min mogelijk veranderde. In het laboratorium werd 150 ml urine over elk monster besprenkeld, de ammoniakemissie werd vervolgens gedurende zeven dagen gemeten. De totale hoeveelheid vervluchtigde ammoniak was het laagst van het gemiddelde en meest bevuilde stro (respectievelijk 359 en 344 mg, $P < 0.05$) en het hoogst van de betonnen vloer van de loopgang (973 mg, $P < 0.05$). De laagste maximale vervluchtigingsnelheden werden waargenomen van het strobed, onafhankelijk van bevuiling, en van de mest in de put van de wachtruimte. De hoogste maximale snelheid werd gemeten van de betonnen vloer van de loopgang ($P < 0.05$). De vervluchtigingsnelheid piekt het snelst na urinelozing op het meest bevuilde stro, mest in de put van de wacht- en de drinkruimte en de betonnen vloer ($P < 0.05$), wat duidt op een snelle ammoniakproductie op deze oppervlakken.

Ammoniakemissie en vloeruitvoering

Met de resultaten van het laboratoriumexperiment als input werd een simulatiemodel ontwikkeld waarmee de totale ammoniakemissie van de stal berekend kon worden gebaseerd op de verschillende typen emitterende oppervlakken. Met mechanische en empirische relaties berekent het model de ammoniakemissie door het integreren van de vervluchtiging van ammoniak na elke urinelozing. Hiervoor werd aangenomen dat een urineplas stopt met emitteren wanneer het door een volgende lozing overlapt wordt. Referentiedata waren afkomstig van een zeugenstal met een vloeroppervlak die voor 60% uit strobed bestond, 14% drinkruimte (betonnen roostervloer met put), 3% wachtruimte (betonnen roostervloer met put) en 23% loopgang (dichte betonnen vloer). Simulaties werden uitgevoerd en vergeleken met de gemeten emissie van de gehele stal. Het model schatte de emissie van de gehele stal op 11.7 g/d per zeug, de relatieve contributie van het stro, de drinkruimte, de wachtruimte en het strobed waren respectievelijk 27%, 22%, 9% en 42%. Ter vergelijking, de

gemeten emissie van de stal was lager: 8.7 g/d per zeug met een 90% betrouwbaarheidsinterval van 6.5-10.9 g/d per zeug. Omdat geen wetenschappelijke kennis beschikbaar was over de verspreiding van urinelozingen, was voor de modelberekeningen aangenomen dat de zeugen op alle typen oppervlakken evenveel urineerden. Als echter werd aangenomen dat de urinelozingen evenredig over het staloppervlak verdeeld werden, berekende het model een emissie die binnen het 90% betrouwbaarheidsinterval viel waarbij de bijdragen van het strobed, drinkruimte, wachtruimte en loopgang aan de stalemissie respectievelijk 32%, 19%, 3% en 45% werden. Simulatie van het vergroten van de oppervlakken per urinelozing resulteerde in eerste instantie in een stijgende emissie, maar met toenemende oppervlakken nam de emissie weer af omdat het emissiereducerende effect van het overlappen van urinelozingen de overhand kreeg. Simulatie van een grotere oppervlakte van het strobed verminderde de berekende emissie. Simulatie van toenemende oppervlakten van de roosters en de dichte betonnen vloer verhoogden de berekende ammoniakemissie. Het model blijkt een bruikbaar gereedschap om groepshuisvestingsystemen voor zeugen met strobed te ontwerpen met een lage ammoniakemissie. Kennis omtrent het urineerpatroon van zeugen zal de voorspelbaarheid van het model verbeteren.

Broeikasgasemissies, groepshuisvesting en stro

Het effect van een strobed in een groepshuisvestingsysteem op de emissie van methaan (CH_4) en lachgas (N_2O) werd bestudeerd, vooral aan de hand van literatuuranalyse. De meeste studies naar emissies van strooiselsystemen werden uitgevoerd met vleesvarkens. De gerapporteerde emissies varieerde van 2.5 to 13.4 g/d per vleesvarken voor CH_4 en van 0.33 to 11.3 voor N_2O. De gerapporteerde N_2O emissie van een zeugenstal viel binnen de ranges die gerapporteerd waren voor vleesvarkens. De CH_4-emissies per zeug waren hoger, zelfs nadat gecorrigeerd was voor het lichaamsgewicht van de dieren. De variabiliteit van de emissie van CH_4 en N_2O spiegelt de variabiliteit van toepassing van het strooisel: niet alleen het strooiselmateriaal, maar ook de behandeling van het strooisel verschilt veel tussen de in de literatuur beschreven systemen. Metingen van NH_3, NO and N_2O in een diepstrooiselsysteem voor vleesvarkens met wekelijkse omzetting van het zaagselbed toonden aan dat de emissie van ammoniak weliswaar afnam, maar dat de totale hoeveelheid ge-emitteerde stikstof t.o.v. die van een standaard drijfmestsysteem toenam, met name door de emissie van N_2O-N.

Er werd geconcludeerd dat om emissie van het broeikasgas N_2O te voorkomen het beter is om stro als strooiselmateriaal te gebruiken en dat omzettingen van het

bed, waardoor zuurstof nitrificatie kan stimuleren, vermeden moeten worden. Een anaerobe omgeving stimuleert echter productie van CH_4, maar de emissie van CH_4 lijkt beperkt te blijven door omzetting naar CO_2 in de toplaag van het strobed.

Conclusies

- De vergelijking van huisvestingsystemen voor zeugen toonden aan dat groepshuisvesting geen toename van de ammoniakemissie veroorzaakt t.o.v. individuele huisvestingsystemen.

- Het verschuiven van de voertijden naar de avond en de nacht vermindert ammoniakemissie uit groepshuisvestingsystemen wanneer zeugen sequentieel gevoerd worden met een voerstation. Dit effect zou proportioneel kunnen toenemen met de verschillen in temperatuur gedurende dag en nacht.

- Het verschuiven van de voertijden naar de avond en de nacht vermindert het effect van de activiteit van simultaan gevoerde zeugen op de ammoniakemissie.

- Met een goed stro-management zal het verstrekken van een strobed in een groepshuisvestingsysteem voor zeugen resulteren in een lagere ammoniakemissie.

- De snelheid waarmee ammoniak geproduceerd wordt na een urinelozing in het strobed neemt toe met toenemende mesthoeveelheid in het bed. Na verloop van tijd is de vervluchtiging van ammoniak echter lager met toenemende mesthoeveelheid; dit wordt waarschijnlijk veroorzaakt door microbiële omzettingen van stikstof.

- De emissie van broeikasgassen van een groepshuisvestingsysteem voor zeugen met een strobed is niet substantieel als het stro-management goed is, maar meer onderzoek is nodig om de omstandigheden te begrijpen die leiden tot lage emissies.

- Het in dit onderzoek ontwikkelde simulatiemodel berekent ammoniakemissie van een stal als de som van de emissies van stro, dichte vloer, roostervloer en mestkelder na urinelozingen. De resultaten van de simulaties laten zien dat maatregelen om de ammoniakemissie te reduceren van een groepshuisvestingsysteem voor zeugen met een strobed het meest effectief

zijn als ze gericht zijn op het verlagen van de emissie van de dichte vloer en op het stimuleren van relatief meer urinelozingen in het strobed.

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Curriculum vitae

Catharina Maria Groenestein werd geboren op 8 augustus 1962 te Tilburg. In 1981 voltooide zij haar Atheneum-B op het Odulphus Lyceum in diezelfde stad en begon aan de studie Zoötechniek aan de toenmalige Landbouwhogeschool te Wageningen. In maart 1988 liep zij gedurende 6 maanden stage bij het Institute for Grassland and Animal Production te Shinfield in Engeland. Ze studeerde af in september 1988 met als hoofdvakken Gezondheids- en Ziekteleer en Ethologie en als bijvak Dierfysiologie. In maart 1989 begon zij bij het toenmalige IMAG met een project dat het modelleren inhield van de energiebalans van leghennen en vleeskuikens. Na een korte onderbreking vervolgde zij haar loopbaan bij het IMAG als editor van een proceedings en als wetenschappelijk medewerker bij de afdeling Milieutechnologie. Hier zette ze de stalmeetploeg op ten behoeve van het vaststellen van emissiefactoren voor de Regeling Ammoniak en Veehouderij (RAV), verrichtte onderzoek naar de ammoniak- en broeikasgasemissies uit de veehouderij, was procesbegeleider en cursusleider projectmanagement. In 2004 zette zij dit werk voort bij Agrotechnology & Food Innovations (A&F) van Wageningen UR. Momenteel is ze werkzaam bij het cluster Milieu, Huisvesting en Energie van de Animal Sciences Group van Wageningen UR.

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