Gas Emissions from Dairy Cow and Fattening Pig Buildings

Effects of Animal Parameters, Climatic Factors and Manure Management on Methane and Ammonia Emissions

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Doctoral Thesis
Swedish University of Agricultural Sciences
Alnarp 2011

Acta Universitatis agriculturae Sueciae
2011:18

Cover: Research building for fattening pigs at the Swedish University of Agricultural Sciences, Alnarp
(All photos were taken by N. M. Ngwabie)

ISSN 1652-6880
ISBN 978-91-576-7553-8

Print: SLU Service/Repro, Alnarp 2011

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Abstract

The objective of this research is to contribute to the knowledge concerning the abatement of gas emissions from livestock production. Investigations regarding the choice of sampling locations for gas concentration measurements, quantification of gas emissions and the factors that affect gas emissions were conducted. NH_3, CH_4, CO_2 and N_2O emissions were measured from two naturally ventilated buildings for dairy cows and from a mechanically ventilated building for fattening pigs. Animal activity, temperature and humidity were also measured. Gas and odour emissions from manure samples with and without the addition of wood shavings were measured in a flux chamber at different air and manure temperatures.

Significant differences existed in the mean concentrations of all the gases at various indoor sampling locations in a naturally ventilated building for dairy cows. The differences in gas concentrations between various sampling locations were much smaller for long-term, relative to short-term, measurements, suggesting that a single sampling location during long-term measurements may generate representative data. Decreasing daily animal activity was associated with increasing pig weight, and with increasing air temperatures for the cows. Diurnal variations in gas emissions were related to feeding/cleaning routines and to animal activity. Daily emissions from the pig building increased with pig weight and temperature. Air temperature was more important than cow activity for daily NH_3 emissions while cow activity was more important than air temperatures for daily CH_4 emissions.

Reducing manure temperatures and increasing manure carbon-to-nitrogen ratio are potential NH_3 abatement techniques. However, low air temperatures may increase cow activity which may in turn increase CH_4 emissions. Increasing the frequency of manure removal from the floor and from animal buildings reduces indoor emissions of most gases. Low N_2O emissions were measured from the buildings in this study; hence the use of liquid manure systems might reduce N_2O emissions.

Keywords: Livestock buildings, Sampling location, Greenhouse gases, Ammonia, Environmental quality, Daily variations, Diurnal variations, Manure management, Animal activity, Temperature

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Dedication

To my loving family, friends and for those who contribute to a sustainable environment.

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I N. M. Ngwabie, K.-H. Jeppsson, S. Nimmermark, C. Swensson, G. Gustafsson (2009). Multi-location measurements of greenhouse gases and emission rates of methane and ammonia from a naturally ventilated barn for dairy cows. *Biosystems Engineering*. 103, 68-77.

II N. M. Ngwabie, K.-H. Jeppsson, G. Gustafsson, S. Nimmermark (2011). Effects of Animal Activity and Air temperature on Methane and Ammonia Emissions from a Building for Dairy Cows. (Submitted).

III N. M. Ngwabie, K.-H. Jeppsson, S. Nimmermark, G. Gustafsson (2010). Effects of Animal and Climate Parameters on Gas Emissions from a Barn for Fattening Pigs. (Submitted).

IV Ngwabie N M, K.-H. Jeppsson, G. Gustafsson, S. Nimmermark (2010). Influence of climatic factors and the addition of wood shavings on ammonia and odour emissions from fresh livestock manure. *Agricultural Engineering International: CIGR Journal*. Manuscript 1660. Vol. 12, No.3.

Papers I and IV are reproduced with the permission of the publishers.

The contribution of Ngwa Martin Ngwabie to the papers included in this thesis was as follows:

I Planned and carried out the measurements in collaboration with co-authors. Analysed the data. Wrote the paper in collaboration with co-authors.

II Planned and carried out the measurements with co-authors. Analysed the data. Wrote the paper in collaboration with co-authors.

III Planned and carried out the measurements in collaboration with co-authors. Analysed the data. Wrote the paper in collaboration with co-authors.

IV Planned and carried out the measurements in collaboration with co-authors. Analysed the data and wrote the paper in collaboration with co-authors.

Abbreviations and Terminology

C/N	Carbon-to-nitrogen ratio
DM	Dry matter content
LU	Livestock unit (500 kg animal weight)
r	Correlation coefficient
R^2	Coefficient of determination
TAN	Total ammoniacal nitrogen
Location: X, Y	Location: latitude, longitude
Diurnal variations	Variations within a day
Daily variations	Variations between different days
Day of Year	A time variable where January 1st is represented by 1 and December 31st is represented by 365 (or 366 for a leap year)
Occupational exposure level limit	Stipulated maximum acceptable average concentration of an air contaminant in respiratory air for a period of eight hours
Odorant	Substances stimulating the human olfactory system so that an odour is perceived

1 INTRODUCTION

Livestock production is a significant source of ammonia, greenhouse gases (methane and nitrous oxide) and odour which may adversely affect animals, stockmen, the surrounding community and the environment. Regional and global climate change has been partly associated with anthropogenic gas emissions, of which agricultural activities are a significant contributor. Specifically, the contribution from livestock production is estimated to be about: 64% for ammonia, 35–40% for methane, 65% for nitrous oxide and 9% for carbon dioxide to the respective global anthropogenic emissions of these gases to the atmosphere (FAO, 2006). It is therefore necessary to refine existing methods and develop new techniques to abate the production and emission of these gases from livestock management. The focus of this study is to improve the knowledge of the factors that affect the production and emission of these gases from animal buildings. This information is important for understanding the variations in emissions, to improve emission models and to aid the research on emission abatement measures.

The importance of livestock to livelihoods is evident as it accounts for about 40% of the agricultural gross domestic products, providing a third of the human protein intake (FAO, 2006). It is important to develop techniques to limit the negative impact of this sector to the environment since meat and milk consumption is expected to double by 2050 relative to 1999/2001 levels (FAO, 2006). The total global livestock population is expected to increase to meet up with the projected meat and milk consumptions even though the number of some livestock categories may decrease regionally (FAO, 2007). Livestock production is undergoing a rapid transformation from small scale family operations to large scale industrial production facilities. These facilities are potential point sources for the emissions of greenhouse gases and ammonia. Parameters such as manure management, animal activity and temperature may influence the production and emission of gases.

1.1 Motivation

1.1.1 Greenhouse gases

Anthropogenic emissions of greenhouse gases have been associated with climate change which has been linked to the rising temperatures, rising sea levels, receding icecaps and melting permafrost (EEA, 2008a; IPCC, 2001). The contribution of livestock production is substantial, accounting for about 18% of the total anthropogenic greenhouse gas emissions when measured in carbon dioxide equivalents (FAO, 2006). The most important climate gases that are produced from animal husbandry are methane and nitrous oxide with global warming potentials of 23 and 296 times that of carbon dioxide, respectively, on a 100-year time horizon (IPCC, 2001).

1.1.2 Ammonia

High levels of ammonia and ammonium can cause damage to vegetation, lead to nitrogen eutrophication and acidification of ecosystems around the source of emission (Fangmeier *et al.*, 1994; Schuurkes & Mosello, 1988). Long range transportation and subsequent deposition at new locations can occur when ammonia combines with sulphate and nitrate (Sommer *et al.*, 2006; Aneja *et al.*, 2001; Fangmeier *et al.*, 1994). In one study, as much as 48% of the total nitrogen excreted in animal buildings in the European Union was lost to the environment during manure storage and directly after manure application to land (Oenema *et al.*, 2007), indicating a significant loss to the environment. The loss in manure nitrogen may reduce the fertilizer efficiency of manure.

1.1.3 Animal and human health

Livestock production with indoor animal housing can create a potentially unhealthy environment for stockmen and animals. Respiratory diseases have been associated with the air quality inside animal buildings (Essen & Romberger, 2003; Zhang *et al.*, 1998; Donham *et al.*, 1989). High ammonia concentrations above the eight hour occupational exposure level limit value of 25 ppm for humans (Swedish Work Environmental Authority, 2005) have been measured in some pig buildings and the concentrations can be especially high in poultry houses (Nimmermark *et al.*, 2009; Groot Koerkamp *et al.*, 1998). Such high ammonia concentrations may affect human and animal welfare and may also reduce production. For example, the percentage yield of deboned meat per broiler decreased slightly with exposure to increasing ammonia concentrations (0, 25, 50, and 75 ppm) in one study (Miles *et al.*, 2004), while the body weight of male broiler chickens declined significantly and proportionally with increasing ammonia concentrations in the air (16, 28, 39, and 54 ppm) in another study (Yahav, 2004). Ammonia and especially odour emissions from livestock production facilities may influence the well-being and health of nearby residents (Donham, 2010; Radon *et al.*, 2007; Nimmermark, 2004).

In order to address the environmental problems associated with gas emissions, emission ceiling targets have been put in place at both the international and the national levels (EEA, 2008b; Swedish-EPA, 2008). Threshold occupational exposure values have been set, for example, in Sweden, for some gases present in animal buildings (Swedish Work Environmental Authority, 2005) for the safety of those working in polluted environments and the exposure level of the stockmen may sometimes exceed these levels. Limiting the emissions would improve the work environment and also constitute a step towards emission ceiling targets. These targets can be achieved by implementing practical emission abatement techniques across the entire livestock production chain which includes animal buildings, grazing fields, manure storage facilities and manure application to farmlands. Animal buildings are an important emission source in the livestock production chain due to the complex nature and diverse number of factors that affect emissions at the level of the building (Banhazi *et al.*, 2008; Sommer *et al.*, 2006).

1.2 Sources of methane, ammonia and nitrous oxide and factors that affect their emissions from animal buildings

1.2.1 Methane

Methane is one of the by-products formed from the degradation of carbohydrates during enteric fermentation in feed and anaerobic digestion in manure. The rumen is the most important part of methane production in ruminants like cattle, while methane is mainly produced in the large intestines for monogastric animals like pigs. Estimates from one study showed that enteric fermentation accounts for about 80% of methane in dairy cow production and about 30% of methane production from pigs (Monteny *et al.*, 2001). Methane production from enteric fermentation is a function of the rate of organic matter fermentation, the type of volatile fatty acid produced and the efficiency of microbial biosynthesis (Monteny *et al.*, 2006; Jensen, 1996). Methane production from animal manure proceeds through hydrolysis of hemicellulose and cellulose, acidogenesis, acetogenesis and finally methanogenesis (Monteny *et al.*, 2006). The rate of methane production from manure is mainly determined by temperature and storage time (Chae *et al.*, 2008; Alvarez *et al.*, 2006; Huther *et al.*, 1997).

1.2.2 Ammonia and nitrous oxide

Cattle and pigs obtain nitrogen compounds from feed and grazing, and convert the nitrogen to meat and milk, with the excess excreted as urea in urine and organic nitrogen in faeces. Animal diet affects the distribution of ingested nitrogen. Estimates have shown that for dairy cows, ingested nitrogen can be approximately distributed in the following proportions; 20–30% in milk, 20–50% in faeces, 50–80% in urine, with 2% retained in the body (Sommer *et al.*, 2006; Tamminga, 1992). In addition to the diet, the excretion of nitrogen in urine and faeces of pigs also depends on their age. One study showed that for piglets (<7.5 kg), about 20% of the ingested nitrogen is excreted in faeces, 62% in urine, with 18% retained in the body (Fernandez *et al.*, 1999). For growing pigs (30–100 kg), about 20% of the ingested nitrogen is excreted in faeces, 43% in urine, with 37% retained in the body (Fernandez *et al.*, 1999). Ammonia is mainly produced from urea hydrolysis, which is catalysed by the enzyme urease that is produced by micro-organisms in faeces (Figure 1). Organic nitrogen in faeces can be transformed to ammonium by micro-organisms (mineralisation) or vice versa (immobilisation). The rate of immobilisation is faster when bedding material is added to animal manure. The bedding material increases the pool of organic nitrogen and the carbon-to-nitrogen (C/N) ratio of the manure, which enhances nitrogen immobilisation and can potentially reduce ammonia emissions (Tasistro *et al.*, 2008; Ekinci *et al.*, 1998). The quantity of ammonia produced from organic nitrogen compounds, such as undigested protein in faeces, is small due to slow mineralisation rates in manure, but can be significant during manure storage (Chadwick *et al.*, 2000; Patni & Jui, 1991). Chemical processes involved in the production and release of ammonia is available in other studies (Sommer *et al.*, 2006; Monteny & Erisman, 1998).

Spatial and temporal variations within litter aggregates in manure amended with bedding material or in deep-litter systems can create an environment where oxygen levels may decrease within the aggregates and also along the depth of the litter bed (Monteny *et al.*, 2006; Monteny *et al.*, 2001; Groenestein *et al.*, 1993; Firestone & Davidson, 1989). In deep litter systems, nitrification will therefore occur near the surface of the aggregates and manure bed where oxygen is available, while denitrification will occur deeper within the aggregates and litter bed where oxygen is scarce. When optimum conditions are not available, both nitrification and denitrification do not go to completion, leading to the production of nitric oxide and nitrous oxide. Nitrification is inhibited by low oxygen concentrations, high ammonia concentrations and low C/N ratios that prevent complete transformation of ammonium through nitrite to nitrate (Monteny *et al.*, 2001; Firestone & Davidson, 1989), while denitrification is inhibited by high oxygen concentrations, high nitrate or nitrite concentrations and low C/N ratios that prevent complete transformation of nitrate through nitrite to nitrogen (Monteny *et al.*, 2001; Firestone & Davidson, 1989). The conditions for nitrification and denitrification are less prevailing in liquid manure as compared to manure amended with bedding material or in deep-litter systems; as such, low levels of nitrous oxide have been measured from liquid manure systems (Philippe *et al.*, 2007; Monteny *et al.*, 2001).

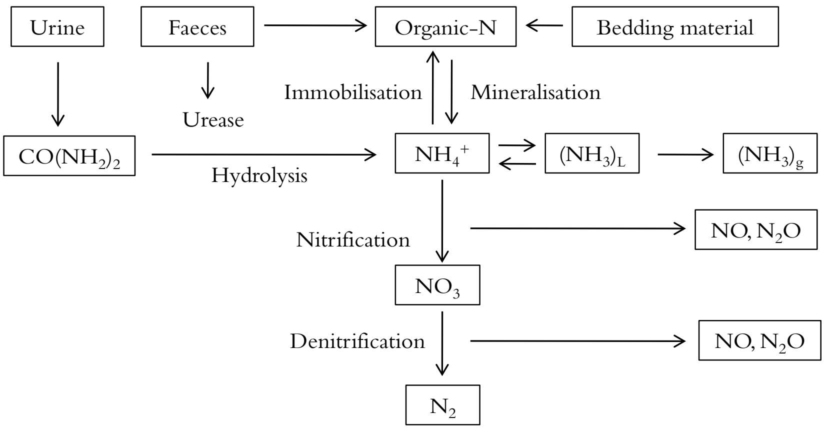

Figure 1. Simplified diagram of nitrogen transformation in animal manure.

1.2.3 Factors that affect the emission rates of methane, ammonia and nitrous oxide from animal buildings

A variety of factors affect the production and emission of greenhouse gases, ammonia as well as odour from animal buildings, of which, some are considered in this section. Based on these factors, abatement techniques have been developed to alter the production and emission of these gases. Abatement techniques can basically alter emissions from animal buildings at three stages:

- *Front of the pipe stage:* The techniques implemented at this stage influence emissions from the animals and the manure prior to gas production, for example, breed selection and diet manipulation, towards greater efficiencies.
- *End of the pipe stage:* The techniques implemented at this stage influence emissions from animal buildings to the outside environment, for example, air cleaning.
- *Middle of the pipe stage*: The techniques implemented at this stage influence gas production and emissions inside animal buildings, for example, manure cooling.

Regarding the techniques that influence emissions at the *front of the pipe stage*, animal feed composition can be manipulated to reduce gas emissions to the environment. For example, adjusting the feed composition as pigs grow can be the most efficient and practical method for reducing the excretion of nitrogen since the nitrogen need in relation to the energy need for a pig decreases as it grows older (Sommer *et al.*, 2006). Reducing the nitrogen excreted in manure results in a reduction in the total ammoniacal nitrogen and consequently a reduction in ammonia emissions. Ammonia emissions from pig manure can also be reduced by decreasing the crude protein and increasing the fermentable carbohydrate levels in feed (Le *et al.*, 2008; Hayes *et al.*, 2004). Pigs offered diets that contained sugar-beet pulp had reduced ammonia emissions from the manure as compared to diets without sugar-beet pulp, while barley based diets produced less ammonia emissions from manure relative to wheat based diets (Lynch *et al.*, 2008; Lynch *et al.*, 2007). Medium chain fatty acids have been shown to substantially reduce methanogenesis in domestic ruminants (Machmuller, 2006). Methane emission can be reduced by increasing the level of rapidly fermentable carbohydrates to enhance propionate production (Monteny *et al.*, 2006). In one study regarding dairy cow management, a change from the baseline model with a 40% dairy cow replacement rate, exporting all bulls after birth and keeping surplus heifers until maturity, to a scenario with a 30% dairy cow replacement rate, exporting all bulls after birth and selling surplus heifers as newborn, has the potential of reducing greenhouse gases by about 11% (Weiske *et al.*, 2006). Options for including greenhouse gas mitigating in livestock breeding schemes with emphasis on reducing wastage (improving lifespan, health, fertility etc) and improving productivity and efficiency have been discussed (Wall *et al.*, 2008).

Air cleaning at the exhaust ducts or inside livestock buildings is the main technique that can reduce emissions in the *end of the pipe stage*. This involves the use of biofilters, air scrubbers or acid scrubbers to reduce the concentrations of ammonia, odour and methane. Research and reviews on the use of biofilters for ammonia emission abatement showed that a reduction efficiency of up to 80% can be achieved (Hoff *et al.*, 2009; Ro *et al.*, 2008; Hartung *et al.*, 1997). In one experiment with biofilters, 49% and 19% methane conversions were achieved when the biofilter materials consisted of an inorganic material and mature compost, respectively (Nikiema *et al.*, 2005). A methane removal efficiency of 85% was measured in another study using a biofilter composed of a mixture of compost and perlite (Melse & Van der Werf, 2005). However, biofiltration seems to synthesize additional nitrous oxide during the oxidation of ammonia (Amlinger *et al.*, 2008) and in one study, where a biofilter composed of polyvinyl alcohol-coated powdered activated carbon particles was used, significant amounts of nitrous oxide were produced while methane production was negligible (Ro *et al.*, 2008). Regarding scrubbers, only water is utilised in air scrubbers while water and acid are used in acid scrubbers to enable mass transfer of ammonia and other odorants from the gas to the liquid phase. Ammonia reductions of up to 98.7% have been achieved with acid scrubbers (Melse & Ogink, 2005; Verdoes & Zonderland, 1999).

This research is focused on the factors that affect emissions at the *middle of the pipe stage*. A summary of the main levels in this stage with major corresponding factors that affect gas production and emissions is presented in Table 1.

Table 1. *Main levels and some corresponding factors that affect the production and emission of gases from animal buildings at the "middle of the pipe stage"*

Level	Factors
Manure	Frequency of removal, efficiency of floor cleaning
	Surface area exposed, urine/faeces separation
	pH, temperature
Bedding	Quantity, C/N ratio, dry matter (DM) content
Building	Housing system, floor type, ventilation system
Climate	Air temperature, relative humidity
	Ventilation rate, air movement pattern
Animal	Urinating/defecating frequencies
	Species, category, weight and age
	Activity, behaviour

The factors in Table 1 are related both within and across the levels, for example, a higher level of animal activity and a larger surface area of manure exposure are expected in free stall housing systems as compared to tied stall housing systems for dairy cows.

Manure

Manure and its management are important for gas emissions from livestock buildings since manure is a potentially significant source of ammonia, nitrous oxide and methane. The quantity of a gas that is emitted from the manure when compared to direct emissions from the animals depends mainly on the animal type (e.g. pigs versus cattle for methane) and on the manure management system (e.g. deep litter versus liquid manure for nitrous oxide and ammonia). Manure management has therefore been at the forefront of the research on emissions abatement in livestock production.

Manure removal from animal buildings to external storage facilities where it can be covered is one of the most effective methods of reducing indoor emissions of gases that originate from the manure (Sommer *et al.*, 2006; Weiske *et al.*, 2006; Hilhorst *et al.*, 2001; Braam *et al.*, 1997). The efficiency of emission reduction depends on the frequency and effectiveness of manure removal. Ammonia emissions can further be reduced by combining manure removal and flushing with water to increase the effectiveness of urine removal from the surface of the floor and to lower the urea and total ammoniacal nitrogen (TAN) concentrations through dilution. There is a potential to reduce ammonia emissions by up to 65% from dairy cow buildings when V-shaped floors (reduced surface area) are used in combination with flushing using water (Monteny & Erisman, 1998). In one review, it was reported that solid floor systems with mechanical scrapers, which remove manure every second hour for temporal indoor storage in partly covered pits, can reduce ammonia emissions in dairy cattle buildings by 16–22% when compared to loose housing systems with slatted floors (Starmans & Van der Hoek, 2007). Temporal indoor storage of manure in partly covered pits decreases air flow above the surface and also reduces air exchange between the pit and the building, thereby reducing gas emissions from the pit (Rong *et al.*, 2009). Ammonia emission peaks were observed within two hours after application of urine/faeces mixtures to a floor surface at temperatures of about 10°C, indicating that urea hydrolysis is a fast process (Elzing & Monteny, 1997). As such, grooved floor systems with partial separation of urine and faeces have been shown to reduce NH_3 by 35–46% as compared to a traditional slatted floor system (Swierstra *et al.*, 2001).

The production and emission rates of ammonia, methane and nitrous oxide from manure have been shown to be slow at lower temperatures (Haeussermann *et al.*, 2006; Weiske *et al.*, 2006; Nimmermark & Gustafsson, 2005; Andersson, 1998; Monteny & Erisman, 1998; Groot Koerkamp, 1994). Regarding ammonia emissions, urease activity has been shown to be slow at temperatures below 5–10°C, increasing exponentially at temperatures above 10°C (Sommer *et al.*, 2006). In addition, the concentration of gaseous ammonia in equilibrium with ammonia in a solution of animal manure is temperature dependent since the equilibrium constant is an exponential function of the temperature of the solution (Sommer *et al.*, 2006). At a practical level, lowering manure temperature was found to reduce ammonia emissions in a cow barn by 11–23% (Gustafsson *et al.*, 2005), while methane emissions have been reported to decrease by 66% if the slurry temperature is reduced from 20°C to 10°C (Hilhorst *et al.*, 2001).

The quantity of ammonia compared to the TAN in manure is determined by, among other factors, the pH; at pH below 6–7, the fraction of ammonium in TAN is high, resulting in less ammonia emission. At pH above 7, most of the TAN is in the form of volatile ammonia, resulting in high ammonia emissions. As such, acidification of pig slurry has been shown to reduce ammonia emissions by 70% when compared to non-acidified slurry (Kai *et al.*, 2008). Acidification of animal manure below a pH of 4.5 can eliminate the emissions of ammonia, methane and nitrous oxide (Hilhorst *et al.*, 2001).

Bedding

Wood shavings and other materials that are utilised as bedding for cattle and pigs also serve as rooting material and absorb manure. These materials increase the DM content and the C/N ratio of the manure. Generally, the C/N ratio ranges from 4 for pig manure to 10 for cattle manure (Chadwick *et al.*, 2000). Increasing the C/N ratio of degradable compounds in the manure provides energy for microbes to immobilise ammonium leading to reduced ammonia emissions (Groenestein & Van Faassen, 1996; Poincelot, 1974). The optimal C/N ratio for microorganisms to immobilise ammonium is between 25 and 38 (Ekinci *et al.*, 1998; Poincelot, 1974). At low C/N ratios, the excess nitrogen is emitted as ammonia, while at high C/N ratios most of the nitrogen is utilised for protein synthesis which limits ammonia emissions. Reductions in ammonia emissions have been measured after adding wood shavings to animal manure in laboratory studies (Tasistro *et al.*, 2008; Luo *et al.*, 2004). Although ammonia emissions are expected to be low for systems with high C/N ratio (e.g. straw-bedded systems), as explained earlier, nitrous oxide and even methane emissions may be higher (Monteny *et al.*, 2006). The type of bedding material that is used may reduce airflow over the emitting surface, increase the infiltration and absorption rates of liquid manure which influence ammonium immobilisation and reduce ammonia emissions (Sommer *et al.*, 2006). A temperature increase, induced by microbial activity when bedding materials are added to manure can rather increase gas emissions during the initial phase of microbial degradation. In an experiment, higher ammonia emissions were measured from solid than from liquid manure during the initial phase of microbial degradation due to a higher self-heating temperature resulting from microbial activities in the solid manure (Dewes, 1999).

Buildings

Livestock buildings are designed to reflect regional climates and production objectives. Factors that may be important for different building designs and management strategies are related to animal welfare, indoor air quality and environmental pollution (Oenema *et al.*, 2007; Fangmeier *et al.*, 1994; Donham *et al.*, 1989). Loose housing systems are favoured over tied-stall housing systems with liquid manure over solid manure for cattle and pig production in most European countries (Sommer *et al.*, 2006). Ammonia emissions from loose housing systems are expected to be higher than with tied-stall housing systems due to a larger manure-fouled and emitting surface area per animal. For example, the manure-fouled surface area per cow is about 3–5 m^2 for loose housing and 1–1.5 m^2 for tied-stall housing systems (Sommer *et al.*, 2006). Besides that, the activity of animals in loose housing systems is expected to be greater when compared to tied-stall housing systems. High animal activity may enhance mixing and spreading of manure over a larger surface area leading to increased ammonia emissions. It is possible to reduce ammonia emissions by up to 55% in tied-stall dairy cattle buildings as compared to loose housing systems with cubicles and slatted floors (Starmans & Van der Hoek, 2007).

Floor systems in animal buildings can be solid or partly slatted. Regarding solid floors for cattle, a sloped floor with a central urine gutter or a grooved floor with the potential to partially separate urine and faeces has been recommended to reduce ammonia emissions (Starmans & Van der Hoek, 2007; Swierstra *et al.*, 2001). Various combinations of slatted and solid floor surface areas have been tested for ammonia emissions in a pig building and it was concluded that reducing the slatted floor and slurry pit areas reduces ammonia emissions (Aarnink *et al.*, 1996). However, reducing the slatted floor surface area may not always linearly reduce ammonia emissions due to a possible increase in the fouling of the solid floor (Sommer *et al.*, 2006; Aarnink *et al.*, 1996). In addition, the choice of pigs to lie down on slatted or solid floor sections (which affects the manure fouled area and hence ammonia emissions) depends on the ambient temperature and animal weight (Aarnink *et al.*, 2006; Huynh *et al.*, 2005). Combining different floor types with appropriate manure management systems will optimise emission reduction, e.g. for solid floors, frequent manure removal with scrapers coupled with the use of drainage, and for slatted floors, slurry acidification and the use of scrapers (Zhang *et al.*, 2005).

Climate

A healthy work environment in animal buildings can be achieved through adequate air exchange between the building and the outside environment, which ensures that the concentrations of gases and other pollutants, temperature and humidity levels are regulated**.** The ventilation rate can be monitored and controlled in mechanically ventilated buildings, whereas in naturally ventilated buildings, the wind speed, size of air openings, air temperature and the orientation of the building are among the factors that affect the ventilation rate (Snell *et al.*, 2003; Bruce, 1978). The effect of the ventilation rate on gas emissions from animal buildings has been reported by several researchers with a general increase in emissions with increasing ventilation rates (Kim *et al.*, 2007; Massabie *et al.*, 1999; Ni *et al.*, 1999a).

High indoor air temperatures may increase the temperature at the manure surface and increase gas emissions due to a relationship between air and manure temperatures (Park *et al.*, 2006). Besides that, high indoor air temperatures may affect natural convection and air exchange in naturally ventilated animal buildings (Bruce, 1978), thereby affecting gas emissions. Ammonia emissions have been shown to be influenced by air velocities, turbulence intensities and water vapour pressure (Rong *et al.*, 2009; Nimmermark & Gustafsson, 2005; Elzing & Monteny, 1997). Temperature and humidity affect the lying and excretion behaviour of fattening pigs which may alter the location and affect the size of manure-fouled surfaces, thereby affecting ammonia emissions (Aarnink *et al.*, 2006; Huynh *et al.*, 2005; Huynh *et al.*, 2004; Aarnink *et al.*, 1996). Studies have shown that heat stress (expressed in temperature-humidity index) affects the behaviour and performance of dairy cows (Provolo & Riva, 2008b; Nienaber & Hahn, 2007; De Palo *et al.*, 2005; West, 2003). These authors showed that at high temperature-humidity indexes, free-stall cows increase their standing time, preferring lying materials which easily dissipate body heat and sweat. Similar to pig production, changes in cow behaviour induced by the indoor microclimate may alter gas emissions.

Animals

The emissions of gaseous compounds by animals depend on the species and category due to differences in diets and digestive systems, for example, ruminants (cattle: bulls, dairy cows) as against monogastrics (pigs: sows, fatteners). According to one study, enteric fermentation can account for about 80% of methane production from cattle houses, while about 35% of methane in pig buildings is emitted through flatulence (Monteny *et al.*, 2001). Regarding emissions from animal manure, methane production increases with the organic matter content (cattle slurry << pig slurry) (Groenestein & Van Faassen, 1996). However, more methane is generally produced from cattle manure due to the large quantity of cow manure as compared to pig manure. Emissions of ammonia, carbon dioxide, methane and nitrous oxide from fattening pig buildings are related to animal weight (Philippe *et al.*, 2007; Haeussermann *et al.*, 2006; Ni *et al.*, 2000; Osada *et al.*, 1998). Other parameters which affect gas emissions as fattening pigs grow include the quantity of nitrogen excreted in manure, size of the manure fouled surface and frequency of excretion on solid floor for ammonia (Aarnink *et al.*, 2006; Sommer *et al.*, 2006; Huynh *et al.*, 2005; Huynh *et al.*, 2004; Ni *et al.*, 1999b) and microbial activity of methanogenic bacteria for methane (Jensen, 1996).

Animal activity has been shown to influence the aerial environment in livestock buildings especially with regard to diurnal patterns in emissions (Blanes-Vidal *et al.*, 2008; De Sousa & Pedersen, 2004; Jeppsson, 2002). Animal activity and carbon dioxide emissions have a physiological relationship (Pedersen *et al.*, 2008), while the relationship between ammonia emissions and the activity of pigs has been associated with the urinating frequency and air movements over the manure surface (Blanes-Vidal *et al.*, 2008; De Sousa & Pedersen, 2004). In one study, 44% of the variations in ammonia emissions within the day could be explained by the urinating frequency of growing pigs (Aarnink *et al.*, 1996). The variations in animal activity with animal weight or age may be important for gas emissions since small pigs are more active than large pigs and young pigs are more active than old pigs (Botermans *et al.*, 2000; Botermans & Andersson, 1995).

Generally, abatement techniques are expected to reduce the emissions of most gases as well as odour simultaneously so as to minimise pollution swapping. Pollution swapping may occur when the DM content and the C/N ratio of manure is increased in order to reduce ammonia emissions, since it may rather increase nitrous oxide or methane emissions (Monteny *et al.*, 2006). Analysis of odour has been carried out alongside ammonia abatement measures and in one study, reduced ammonia and increased odour emissions were measured from the manure of pigs offered diets that contained sugar-beet pulp as compared to diets without sugar-beet pulp (Lynch *et al.*, 2008). Some studies regarding the relationship between ammonia and odour report an inconsistent pattern in their concentrations in buildings with low ammonia concentrations and in laboratory reactors (Ogink & Koerkamp, 2001; Fakhoury *et al.*, 2000). One study suggests that the ammonia contribution to odour concentration is significant only in the absence of hydrogen sulphide (Blanes-Vidal & Hansen, 2008). In other investigations, positive correlations between ammonia concentrations and odour intensity as well as between ammonia and odour emission rates have been measured (McGinn *et al.*, 2003; Wood *et al.*, 2001).

1.3 Measurements of gas emission rates

High quality data is essential when monitoring the air quality in animal buildings, studying the effects of different factors on gas emissions and assessing emission abatement techniques. Emission rates are calculated by multiplying gas concentrations and ventilation rates. The quality of emission data, therefore, depends on the accuracy and precision of the measured concentrations and ventilation rates.

1.3.1 Sampling and measurements of gas concentrations

Several principles and instruments are used to measure the concentrations of carbon dioxide, ammonia, methane and nitrous oxide in animal facilities. Table 2 presents some principles and instruments used to measure the concentrations of ammonia, methane, nitrous oxide and carbon dioxide. The choice of an instrument for measuring gas concentrations is determined, among other factors, by the research objectives, number of gases it can measure, number of locations it can measure from, possibility for online results, sampling frequency, duration of sampling and budgetary constraints (Ni *et al.*, 2009; Ni & Heber, 2008). The data quality depends on the sampling technique, instrument accuracy, precision and sensitivity. Studies have been carried out regarding the instruments used for measuring gas concentrations in animal facilities, measurement principles, sampling techniques and discussions regarding errors (Ni *et al.*, 2009; Ni & Heber, 2008; Rom & Zhang, 2008; Heber *et al.*, 2006; Shah *et al.*, 2006; Mukhtar *et al.*, 2003; Wheeler *et al.*, 2000).

Table 2. *Principles and some instruments used for measuring gas concentrations*

Main principle	Instrument (Technique)
Spectroscopy	Photoacoustic analyser (IR spectroscopy)
	FTIR spectrometer (FTIR spectroscopy)
	Opsis analyser (UV-DOAS)
Chemiluminescence	NO_x analyser
Colour change	Colorimeter (colorimetry)
	Spectrophotometer (photometry)
	Dräger and Kitagawa tubes (Detection tubes)
	Chemcassette monitor (photometry)

IR: Infrared, FTIR: Fourier Transfer Infrared, UV-DOAS: Ultra violet differential absorption spectroscopy. Adapted from Ni & Heber, 2008

Air needs to be sampled for gas concentration measurements due to the large volume of air that flows through animal production facilities. Sampling has been defined as "The technique and procedure that specifies the location where air samples are taken, controls the time, interval, frequency and duration of sample taking, and regulates the volume or mass of the sample air to be measured" (Ni & Heber, 2008). Figure 2 presents the main factors that are considered in air sampling and the sampling methods involved.

Spatial variations in gas concentrations inside animal facilities can be due to an uneven distribution of the sources of gas production (manure heaps, urine puddles, animals) and imperfect air mixing (Van Buggenhout *et al.*, 2009; Cnockaert & Sonck, 2007; Jeppsson, 1999). Increasing the number of sampling locations may increase the spatial resolution of measured gas concentrations. However, the number of sampling locations is limited by the measuring instrument. Some instruments, like the photo-acoustic multi-gas analyser, when coupled with a multiplexer, can sample air at twelve locations. The choice of the most representative sampling locations in large animal buildings has great implications on the data quality. At least one indoor location and one outdoor location are needed to calculate emission rates from animal buildings. These sampling locations are chosen relatively easily at the ducts of air exhaust fans and air inlets for mechanically ventilated buildings (Blanes-Vidal *et al.*, 2008; Aarnink *et al.*, 1995). The choice of sampling locations is difficult in naturally ventilated buildings since there are no openings defined as air inlets and outlets. Sampling locations have consequently been chosen at evenly distributed places inside naturally ventilated buildings (Zhang *et al.*, 2005).

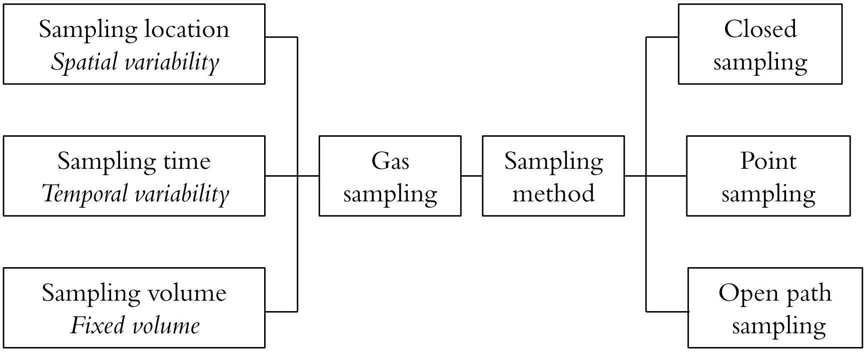

Figure 2. Factors and methods for gas sampling at animal facilities (adapted from Ni & Heber, 2008)

Temporal variations in gas concentrations in animal buildings have been measured on a diurnal, daily and seasonal basis (Philippe *et al.*, 2007; Haeussermann *et al.*, 2006; Jeppsson, 2002). Changes in outdoor climatic conditions (temperatures, wind velocity, wind direction), ventilation rates, parameters related to management (feed, manure removal) and parameters related to the animals (activity, weight) are responsible for the temporal variations in gas concentrations. As such, measurements of gas concentrations at high frequencies to cover short term changes within the day and for a long duration to cover daily changes, improve the quality of the data. Extremely long sampling durations or intermittent measurements are needed to cover seasonal variations.

Active measurement methods (e.g. active detection tubes) require well-defined volumes of air samples for the measurement of gas concentrations. The accuracy and repeatability of the sampled volume is important for the quality of the measured gas concentrations.

Three methods are applicable for gas sampling in animal facilities: closed, point and open path sampling methods (Figure 2). Closed sampling involves the use of flux chambers in outdoor manure storage facilities, feeding areas, grazing areas and indoor floor areas (Park *et al.*, 2010; Jeppsson, 1999). Regarding point sampling, the air samples are taken at a single or multiple locations. Point sampling is mostly used inside animal buildings for indoor concentrations and outside for background concentrations (Ni *et al.*, 2008; Zhang *et al.*, 2005). Concerning open path sampling, optical devices emit and receive ultraviolet or infrared beams at defined wavelengths where the absorbed radiation is related to the concentration of the gas along the path. Open path sampling has been used for measuring gas concentrations in outdoor areas (Loh *et al.*, 2008; McGinn *et al.*, 2006).

1.3.2 Measurements of ventilation rates

One of the most discussed aspects regarding the quality of emission data is the measurement of the ventilation rates. Figure 3 shows some of the methods used to measure the ventilation rate in animal buildings. Direct measurements of the air speed with hot wire or fan wheel anemometers is the standard procedure for determining the ventilation rate in mechanically ventilated buildings (Hinz & Linke, 1998a; Aarnink *et al.*, 1995).

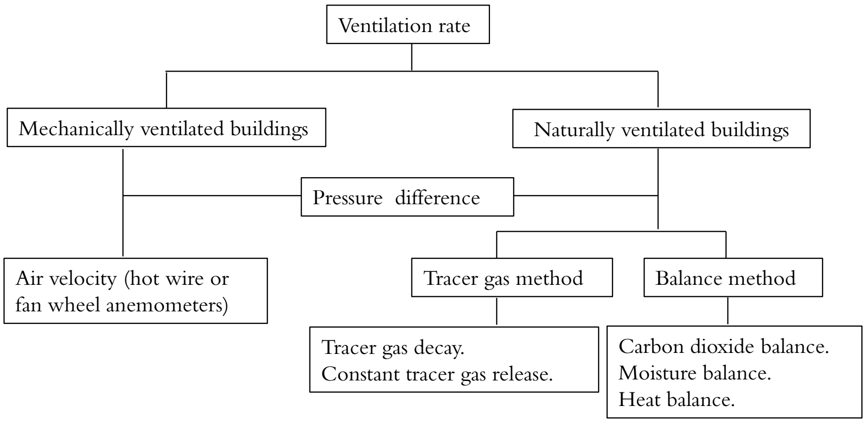

Figure 3. Methods for measuring ventilation rates in animal buildings

It is difficult to determine the ventilation rate in naturally ventilated buildings due to the presence of many air openings which can serve as both air inlets and outlets depending on the wind direction and thermal buoyancy. The ventilation rate is therefore directly influenced by external and internal conditions in naturally ventilated buildings (Snell *et al.*, 2003; Bruce, 1978). A method based on the pressure difference across air openings can be used to estimate the ventilation rate in both naturally and mechanically ventilated buildings (Demmers *et al.*, 2001). The tracer gas method can also be used to measure the ventilation rate in naturally ventilated animal buildings. Tracer gas methods and gases used for ventilation rate measurements are the tracer decay method with sulphur hexafluoride or radioactive Krypton-85 (Berg *et al.*, 2010; Kiwan *et al.*, 2010; Snell *et al.*, 2003) and the constant release method with nitrous oxide or carbon monoxide (Demmers *et al.*, 2000; Demmers *et al.*, 1999). Among the three balance methods, that is, heat balance (Teye & Hautala, 2007; Pedersen *et al.*, 1998), moisture balance (Teye & Hautala, 2007; Pedersen *et al.*, 1998) and carbon dioxide balance, the last method is most commonly used for continuous measurements of ventilation rates (CIGR, 2002; Pedersen *et al.*, 1998; Van't Klooster & Heitlager, 1994; Van Ouwerkerk & Pedersen, 1994).

Different methods for measuring ventilation rates are influenced by factors which affect the quality of the measurements, for example, imperfect mixing for the tracer gas methods (Van Buggenhout *et al.*, 2009), and carbon dioxide production from animal manure for the carbon dioxide balance method (Pedersen *et al.*, 2008; Ni *et al.*, 1999a). The tracer gas method does not provide continuous measurements of ventilation rates except when it is used to calibrate another parameter that can be measured continuously. The carbon dioxide balance method can be used to estimate the ventilation rate with a resolution of one hour or better when the animal activity is measured (CIGR, 2002). The lack of an established standard method for measuring the ventilation rate in naturally ventilated buildings makes it difficult to estimate the uncertainty associated with the available methods. The tracer gas method (which has been widely used for comparison with other techniques) can have errors as high as 86% due to imperfect mixing of the tracer gas and the choice of a sampling location (Van Buggenhout *et al.*, 2009). Measurements in mechanically ventilated buildings for pigs have shown discrepancies in ventilation rates between direct measurements at exhaust fans and the carbon dioxide mass balance of 2–17% (De Sousa & Pedersen, 2004) and 6.5% (Hinz & Linke, 1998a; Hinz & Linke, 1998b). In one study, a comparison of ventilation rates using four methods over a period of 41 days in a mechanically ventilated building for pigs showed that on average, the calculated ventilation rate was 8% lower than the measured ventilation rate (using FANCOM fan) for the carbon dioxide balance, and 9% lower for the moisture and heat balance methods (Blanes & Pedersen, 2005). Some authors report inaccuracies of up to 40–50% in the ventilation rates when estimated using the carbon dioxide balance method (Zhang *et al.*, 2010; Ozcan *et al.*, 2007).

2 HYPOTHESES AND OBJECTIVES

The general hypothesis of this study is that gas emissions from animal buildings are influenced by building parameters, management routines, climatic factors and parameters related to the animals and their feed. The overall objective was to contribute to the knowledge regarding the abatement of gas emissions from livestock production. The reduction of gas emissions improves the atmospheric environment, indoor air quality, animal performance, and the relationship between farmers and the surrounding community. The detailed hypotheses and objectives for each paper were as follows:

The hypothesis of the study in Paper I was that gas concentrations and emissions vary by location and time in naturally ventilated animal buildings. The investigation was aimed at determining the effect of the choice of sampling location on the concentrations of carbon dioxide, methane, ammonia and nitrous oxide in naturally ventilated buildings. The concentrations were measured at nine locations inside a building for dairy cows and emissions were estimated.

In Paper II, it was hypothesised that animal activity is affected by the indoor microclimate and management routines. The animal activity, microclimatic conditions, and management routines also affect gas emissions. The objective was to study the effect of indoor air temperature on the activity of dairy cows in a naturally ventilated building. In addition, the effects of cow activity, indoor air temperature, feeding routines and manure removal routines on the emissions of methane and ammonia were evaluated.

The hypothesis of the investigations in Paper III was that the activity of fattening pigs varies diurnally and daily as pigs gain weight and that these variations affect gas emissions. The degrees to which environmental conditions (temperature, humidity) and animal parameters (weight, activity) affect emissions may depend on the type of gas and on the season. The objective was to study the variations in animal activity, animal weight, indoor air temperature and indoor relative humidity and how they affect the emissions of carbon dioxide, methane, ammonia and nitrous oxide, on a diurnal and daily basis, from a building for fattening pigs.

In Paper IV, it was hypothesised that environmental factors can be manipulated in order to reduce gas emissions from animal manure. Increasing the C/N ratio by adding wood shavings to manure can affect gas and odour emissions. The objective was to study the effects of temperature (manure and air) and the addition of wood shavings on ammonia, methane, nitrous oxide, carbon dioxide and odour emissions from fresh dairy cow and fattening pig manure.

2.1 Structure of the research

The structure of this research is presented in Table 3. Issues regarding measurements in naturally ventilated buildings were studied in Papers I and II. Factors that affect gas emissions from animal buildings were analysed in Papers I–III, with further investigations carried out at the manure level in Paper IV.

Table 3. *Structure of the investigations in this research*

Paper	Animal category	Factors studied and aspects of interest	Main area of focus
I, II	Dairy cows	Gas concentration in naturally ventilated buildings	Number and choice of sampling locations
II, III	Dairy cows, Fattening pigs	Animal weight, animal activity, air temperature and relative humidity	Daily and diurnal variations in gas emissions
IV	Dairy cows and fattening pigs: manure	Air temperature, manure temperature, wood shavings (C/N ratio)	Ammonia and odour emissions

3 MATERIALS AND METHODS

3.1 Housing systems and research design

A summary of the housing systems and production information in the dairy cow and fattening pig buildings where the investigations in Papers I–III were carried out is presented in Table 4. The buildings which were all located in the south of Sweden are shown in Figures 4–6.

Table 4. *Housing systems and production information for Papers I–III*

Description	Paper I	Paper II	Paper III
Measurement period	December 2006 to May 2007	February–May, 2008	Spring, autumn and summer, 2007–2009
Animal category	Holstein dairy cows	Holstein dairy cows	Fattening pigs
Animal number	164–195	108	50–54
Animal weight	~ 600 kg	~ 600 kg	~ 25–110 kg
Feeding	Twice per day	Twice per day	Once per day
Ventilation system	Natural	Natural	Mechanical
Housing system	Loose housing	Loose housing	Loose housing
Bedding material	Wood shavings	Peat on rubber mat	Straw
Floor system	Partly Slatted	Solid inclined	Partly slatted
Manure system	Slurry	Slurry	Slurry
Manure cleaning from the floor	Twice per day	Once every hour in daytime and every second hour at night	Once per day
Manure removal from the building	Twice per day	Twice per day	Once per day

The investigations in Paper I were conducted in a commercial dairy cow building (Figure 4). The concentrations and emissions of carbon dioxide, methane, ammonia and nitrous oxide were measured continuously at nine evenly distributed indoor locations. Outdoor concentrations were measured at one location on both sides of the building. Air temperature and relative humidity were measured continuously. The concentrations of each gas at the indoor sampling locations were analysed for differences in time and place.

Figure 4. Dairy cow building at Västarby (location: 55.80, 13.53) where the measurements in Paper I were carried out.

The investigations in Paper II were conducted in a commercial dairy cow building (Figure 5). The concentrations and emissions of carbon dioxide, methane, ammonia and nitrous oxide were measured continuously at five evenly distributed indoor locations. Outdoor concentrations were measured at two locations. Animal activity, air temperature and relative humidity were measured continuously. The diurnal relative activity together with hourly averages of gas emission rates, air temperature and relative humidity were used to study the diurnal variations. The daily relative activity together with daily gas emissions and air temperatures were used to study the daily variations.

Figure 5. Dairy cow building in Bollerup (location: 55.42, 14.07) where the measurements in Paper II were carried out.

The investigations in Paper III were conducted in an experimental building (Figure 6) where three batches of pigs were fattened in the autumn, spring and summer. The concentrations and emissions of carbon dioxide, methane, ammonia and nitrous oxide were measured continuously for each batch. Animal activity (for one of the batches) and air temperature were measured continuously and relative humidity was calculated on a continuous basis. The pigs were weighed at the beginning, in the middle and towards the end of each fattening period. A linear increase in the weight of the pigs was assumed to calculate the daily weight gain. The diurnal relative activity together with hourly averages of the emissions, air temperature and relative humidity were used to study the diurnal variations. The daily relative activity together with daily averages of the emissions, air temperature, relative humidity and animal weight were used to study the daily variations.

Figure 6. Fattening pig building at Alnarp Södergård (location: 55.65, 13.06) where the measurements in Paper III were carried out.

The investigations in Paper IV were carried out using fresh liquid manure collected from a building with tied-stall dairy cows and from a building for fattening pigs. The manure samples were collected on three separate days (samples 1, 2 and 3) from each animal building. Each manure sample was divided into two portions and wood shavings were mixed with one of the portions. The wood shavings were a combination of flakes from pine (25%) and spruce (75%) trees. The flakes had a main particle size of about 1–20 mm and were mostly 0.1–0.5 mm thick with some measuring up to 1 mm. Odour and gas emissions from equal volumes of each portion of the manure sample were measured in a climate controlled dynamic flux chamber (Figure 7) at different combinations of manure temperatures: approximately 15, 20 and 25°C and air temperatures approximately: 15, 20 and 25°C. Each sample had 18 treatments, (9 without and 9 with wood shavings) giving a total of 54 treatments per animal manure type.

Figure 7. Climate controlled dynamic flux chamber where different air and manure temperatures were simulated for the experiments in Paper IV.

3.2 Measurement methods and accuracy in determinations

3.2.1 Concentrations

The concentrations of carbon dioxide, nitrous oxide, ammonia, methane and water vapour in all the papers were measured with a photo-acoustic multi-gas analyser 1412 and a multiplexer 1309 (Lumasense Technologies SA, Ballerup, Denmark). The instrumental set-up during field measurements is shown in Figure 8. The photo-acoustic analyser was recalibrated by the manufacturer on three different occasions during the measurements in this study. The detection limits of the gases were: 1.5 ppm for carbon dioxide, 0.03 ppm for nitrous oxide, 0.2 ppm for ammonia and 0.4 ppm for methane. The analyzer had a repeatability of 1% and a range drift of ±2.5% of the measured values according to data sheets from the manufacturer.

Concentrations were measured in mg m^{-3} at a reference temperature of 20°C and converted to the actual measurement temperatures.

Multiple-location air sampling for gas concentration measurements was carried out in the naturally ventilated dairy cow buildings in Papers I and II. The indoor or outdoor concentrations of a gas at any time were the mean from all the indoor or outdoor sampling locations. A single indoor sampling location at the air exhaust duct and one outdoor sampling location were sufficient in the mechanically ventilated building for fattening pigs in Paper III.

Gas concentrations in Paper IV were measured at the air exhaust duct of the dynamic flux chamber while the background concentrations were measured at the air inlet duct. Air samples for odour measurements were collected in nalophan bags at the exhaust duct of the flux chamber using a vacuum sampling device manufactured by ECOMA (Honigsee, Germany). The samples were analysed following the procedures described in the European guidelines (CEN, 2003). A standardised panel and an ECOMA (Honigsee, Germany) TO7 olfactometer were used to measure the odour concentrations.

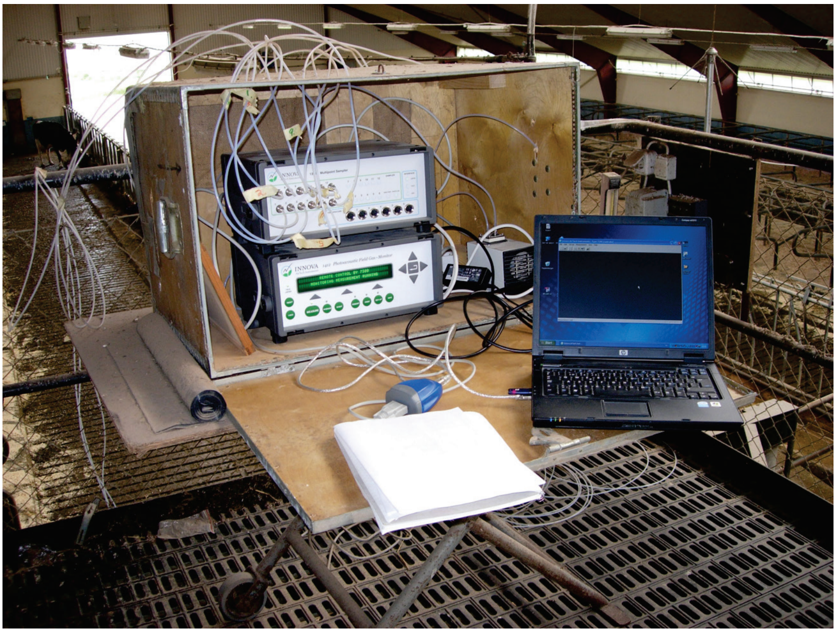

Figure 8. Photo-acoustic analyser coupled with a multiplexer during field measurements.

3.2.2 Animal activity

The activity or movement of the dairy cows in Paper II and the pigs in one of the batches in Paper III were measured using a passive infrared detector and an analogue signal interface, with detail description in another publication (Pedersen & Pedersen, 1995). An analogue signal that is generated is proportional to the temperature difference between the animals and the background, as well as to the velocity of the animals. The activity sensor monitors the total activity in a group of animals. The activity was measured using two sensors in the pig and dairy cow buildings. It was measured every 10 minutes and hourly averages were used in the analysis. The diurnal relative activity was calculated as the ratio between the activity for a specific hour and the mean activity for each day. The daily relative activity was calculated as the ratio between the mean activity for a specific day and the mean activity for the entire measurement period.

3.2.3 Ventilation rates

The ventilation rates in Papers I and II were calculated using the carbon dioxide mass balance method (CIGR, 2002). The ventilation rate was calculated on a 24-hour basis in Paper I and on an hourly basis in Paper II where the animal activity was measured.

The air velocity in the mechanically ventilated building in Paper III was measured with a hot-wire anemometer (VelociCal 9545/9545-A, Minnesota, USA) at nine locations in the cross section of a duct at the exhaust fan. The mean air velocity was used together with the ducts' diameter to calculate the ventilation rate. The standard deviation of the ventilation rate in the pig building was about 10% of the mean.

The air flow rate in Paper IV was calculated from the pressure difference that was measured at an orifice plate in the air exhaust pipe of the flux chamber. It was measured using a pressure gauge (EMA 84, Halstrup-Walcher GmBh, Kirchzarten, Germany) with an error margin of ±0.5% at full scale.

3.2.4 Emission rates

The emission rates of the gases in Papers I–III were calculated as the product of the ventilation rate and the concentrations in the buildings when corrected for background concentrations. Ammonia and carbon dioxide emission rates from the manure samples in Paper IV were calculated using the air flow rates and the concentrations from the flux chamber when corrected for background concentrations. The odour emission rates from the manure samples in Paper IV were calculated using the odour concentrations and air flow rate.

3.2.5 Temperatures

The air temperatures in Papers I–III were measured using Tiny-tag loggers (Gemini Data Loggers, Chichester, UK) with an operating range from -40°C to 85°C and a reading resolution accuracy of 0.01°C or better. The manure and air temperatures in Paper IV were measured with thermocouples (Cu/CuNi) and a data logger (INTAB Interface-Teknik AB, Stenkullen, Sweden.

3.2.6 Humidity calculations

The relative humidity was calculated using the water vapour concentrations measured with the photo-acoustic analyser and the saturated vapour concentration at the corresponding air temperature (Carl, 2010).

3.2.7 Manure chemical contents

The manure samples in Paper IV were analysed at an external laboratory (Eurofins Food & Agro Sweden AB, Kristianstad, Sweden) using standards from the Swedish Standard Institute (SIS, 2008): SS 028113, for the DM content; SS 028101:1-92, for the total nitrogen; KLK 65:1, for the NH_4^+-N; and SS-EN 12176:98, for the pH. The C/N ratios of the samples were also analysed.

3.2.8 Animal weight

The weights of the dairy cows in Papers I and II were obtained from production reports at the farms. The pigs in Paper III were weighed at the beginning, in the middle and towards the end of each fattening period. A linear increase in the weight of the pigs was assumed when calculating the daily weight gain. The animal weights were measured to a resolution of 0.5 kg.

3.3 Statistical analyses

The data was analysed using the R software Project for Statistical Computing, versions 2.7.1–2.10.1 (R, 2010). For purposes of statistical convenience due to the large data in Papers I–III, the time variable was converted to a Day of Year variable with 1 representing January 1st and 365 (or 366) representing December 31st. Hourly averages were considered for the data in Papers II and III so as to synchronise the parameters from the different instruments. When applicable, the data was transformed (Box-Cox transformation) to meet the criteria for statistical analyses. Correlations between parameters were tested by calculating the Pearson's product-moment correlation coefficients. Treatment effects were studied using one-way analysis of variance in Paper I and two-way analysis of variance in Paper IV. When treatment effects were significant in Paper IV ($p < 0.05$), multiple comparison testing was carried out using Fisher's LSD test to rank the treatments. Simple linear regression analyses were used to determine the relationships between different factors in all the papers. Best subset regression analyses were used to determine the relative importance of different factors to gas emissions in Paper III.

4 SUMMARY OF RESULTS

A summary of the main results in all the papers is presented in this section. Detail results are available in the respective papers.

4.1 Gas concentrations in naturally ventilated buildings: Number and choice of sampling locations (Paper I)

Variance analysis of the concentration profiles of carbon dioxide, methane and ammonia showed significant differences in the mean concentrations at all indoor sampling locations. The differences in indoor concentrations between various sampling locations were much smaller for long-term measurements than for the short-term measurements of single days. The mean nitrous oxide concentrations were quite low and showed little variations by sampling location inside the building.

4.2 Diurnal and daily variations in animal activity and gas emissions (Papers I–III)

4.2.1 Animal activity (Papers II and III)

The activity of the dairy cows in Paper II and the fattening pigs in Paper III varied on a diurnal and on a daily basis. The diurnal profile of the cow activity had two peaks of about the same height in the morning and in the afternoon, respectively. Regarding the pigs in batch 3, a higher activity peak with a relatively short duration was measured in the morning while a lower activity peak with a long duration was measured in the afternoon.

The daily activity of the dairy cows decreased with increasing indoor air temperatures during the measurement period. The daily activity of the pigs decreased with increasing animal weight during the measurement period with a correlation coefficient of -0.84.

4.2.2 Gas emissions (Papers I–III)

Emission rates of ammonia, methane and carbon dioxide

The emission rates of ammonia, methane and carbon dioxide from the buildings when the animals were permanently indoors are shown in Table 5. The emission rates from the building in Paper I between 5 p.m. and 9 a.m. with the cows indoors were: 0.89 g NH_3 LU^{-1} h^{-1} and 9 g CH_4 LU^{-1} h^{-1}.

Table 5. *Emission rates from the buildings with the animals indoors during the whole day*

Emissions,	Dairy cow building		Fattening pig building
g LU^{-1} h^{-1}	Paper I*	Paper II♠	Paper III♦
NH_3	0.99–1.13	0.81 ± 0.40	1.36–1.51
CH_4	11.3–13.0	10.8 ± 2.3	2.31–11.49
CO_2	-	-	655–707

LU: Livestock unit (500 kg animal weight) ,*: Range in monthly mean, ♠: Mean ± standard deviation, ♦: Range in mean for three batches of fattening pigs

Factors that affect variations in gas emissions and animal activity

Diurnal and daily variations in gas emissions were affected by qualitative and quantitative factors. The qualitative factors included light availability (day/night) and management routines such as feeding, milking, cleaning and manure removal. The measured quantitative factors were the animal activity, animal weight, ventilation rate, air temperature and relative humidity.

Diurnal variations in gas emissions

Gas emissions from both dairy cow buildings and the pig building showed diurnal variations with high emissions in the daytime relative to night-time periods. The average diurnal variations in methane and ammonia emissions from the cow building in Paper II had two peaks of about the same height in the morning and in the afternoon, respectively. The average diurnal variations in ammonia and carbon dioxide emissions for all the three batches from the pig building (Paper III) had two peaks: a high peak with a relatively short duration in the morning and a low peak with a long duration in the afternoon. Methane emissions from the pig building after the morning peak were significantly lower for batches 1 and 2 but for batch 3 there was a slow increase in the evening with a small peak at about 10 p.m.

Subset regression analyses showed that the activity of the pigs explained most of the diurnal variations in ammonia and carbon dioxide emissions

(Paper III). Further calculations gave significant correlations ($p < 0.001$) between ammonia emissions and the diurnal relative activity of the pigs ($r = 0.68$, where r is the correlation coefficient) and also between carbon dioxide emissions and the diurnal relative activity of the pigs ($r = 0.89$). A weaker correlation was obtained between methane emissions and the diurnal relative activity of the pigs ($r = 0.41$, $p = 0.05$).

Daily variations in gas emissions and animal activity

The daily data in the cow building (Paper II) revealed that the methane emissions were positively correlated with the cow activity ($r = 0.61$), and negatively correlated with the indoor air temperature ($r = -0.84$). The ammonia emissions were positively correlated with the indoor air temperature ($r = 0.66$), and negatively correlated with the animal activity ($r = -0.51$). There was a strong negative correlation between the activity of the cows and the indoor air temperature ($r = -0.78$).

The best subset regressions revealed that daily variations in carbon dioxide, methane and ammonia emissions were mostly influenced by the weight of the pigs (Paper III). However, during warm weather conditions in summer, the air temperature was more important than the weight of the pigs for the daily variations in methane emissions. The animal activity, which was measured for one of the pig batches, affected to some extent the daily variations in ammonia and methane emissions.

4.3 Effects of temperature and wood shavings on gas emissions from animal manure (Paper IV)

Manure samples with wood shavings had higher DM content, C/N ratio and pH levels than samples without wood shavings at the end of the measurements. Manure samples with added wood shavings generally had lower total-N and NH_4^+-N levels than samples without wood shavings at the end of the experiments.

4.3.1 Temperature

Positive correlations were found between the ammonia emissions and the temperatures of the cow and pig manure. Odour emissions were positively correlated with the cow manure temperatures. Odour emissions and manure temperatures had no significant correlation for the pig manure samples without wood shavings, and negatively correlated for the pig manure samples with wood shavings. Air temperatures did not significantly affect ammonia and odour emissions from the manure samples. The emissions from the cow manure were positively correlated to the water vapour pressure.

4.3.2 Wood shavings

Ammonia emissions were significantly higher ($p < 0.05$) from all pig manure samples with wood shavings as compared to samples without wood shavings. Ammonia emissions were lower ($p < 0.05$) from two of the cow manure samples with wood shavings as compared to samples without wood shavings. There was no significant difference in the ammonia emissions from one of the cow manure samples with or without wood shavings.

5 GENERAL DISCUSSION

5.1 Uncertainty in the emissions (Papers I–IV)

The main quantitative parameter with a high level of uncertainty in these measurements was likely the emission rate from the naturally ventilated buildings. The uncertainty in the emission rates is due to uncertainties in the gas concentrations, and to a greater extent, in the ventilation rates.

The uncertainty in the measurement of the concentrations of some gases like ammonia can be due to adsorption or desorption on the surface of the sampling tubes, which is a function of tube material, tube length and temperature (Shah *et al.*, 2006; Mukhtar *et al.*, 2003). Experiments have shown that the response time of the multi-gas analyser is gas dependent with rapid tracking for carbon dioxide (Hinz & Linke, 1998a) and slow tracking for ammonia concentrations (Rom & Zhang, 2008). The experimental setup in this research with a high air flow rate (3.2 *l* min^{-1}) through polytetrafluoroethylene sampling tubes, a single vacuum pump at the air exhaust of the multiplexer and a short tube length (0.4 m) connecting the multiplexer and the multi-gas analyser that conveyed air from all sampling locations, possibly minimised gas losses through adsorption/desorption. As an additional precaution, dust and water filters were used in the sampling tubes. The concentrations of the calibration gases were chosen to reflect possible levels in animal buildings: 3500 ± 70 ppm for carbon dioxide, 203 ppm ± 2% for methane, 74.2 ppm ± 3% for ammonia, and 5.04 ppm ± 2% for nitrous oxide. Low nitrous oxide concentrations in buildings with liquid manure systems suggest that the photo-acoustic analyser may not be the instrument of choice for measuring nitrous oxide in buildings of the type in this study. However, a lower calibration gas concentration for nitrous oxide might have improved its measured concentrations.

The relative error in the ventilation rates when the carbon dioxide balance method is used can vary within 2–50% of the actual values (Zhang *et al.*, 2010; Ozcan *et al.*, 2007; Blanes & Pedersen, 2005; De Sousa & Pedersen, 2004; Hinz & Linke, 1998a; Hinz & Linke, 1998b). Assuming a relative error in gas concentrations measured with the photo-acoustic analyser to be about 2.5% of the actual concentrations (Hinz & Linke, 1998a), the resulting error propagated in the emissions rates should vary to within 2–50% of the reported emissions.

5.2 Number and choice of sampling locations (Papers I–III)

Spatial variations in gas concentrations (Paper I) highlighted the need for multi-location measurements for short-term studies in naturally ventilated animal buildings. Localised sources of gas production, wind speed and wind direction can cause imperfect air mixing, resulting in spatial variations in gas concentrations inside naturally ventilated buildings (Van Buggenhout *et al.*, 2009; Cnockaert & Sonck, 2007; Jeppsson, 1999). In one study involving concentration measurements at eight locations in a naturally ventilated building during a one month period, a maximum difference in the mean ammonia concentrations between two locations was 35%, and based on the wind direction, it could increase to more than 100% (Cnockaert & Sonck, 2007).

The average values in measured gas concentrations at the various indoor sampling locations (Paper I) became closer to each other with increasing sampling duration. As such, the differences in mean concentrations between any two sampling locations were smaller for longer measurement periods when compared to short-term measurements of single days. This indicates that a good choice of a single sampling location may give satisfactory concentration data for long-term measurements. However, the optimum number of sampling locations in naturally ventilated buildings probably depends on the measurement device, sampling duration, animal distribution in the building, building size and prevailing winds.

In the cow building in Paper II, five sampling locations were chosen above the cubicles and at the centre of the building since the measurement duration was long (~ four months). In the mechanically ventilated building for pigs (Paper III), a single exhaust fan was in operation. A single location close to the duct of the exhaust fan should therefore be ideal for sampling the average indoor gas concentrations and for calculating the emissions from the building.

5.3 Animal activity and gas emissions (Papers I–III)

5.3.1 Animal activity (Papers II and III)

Diurnal variations in the activity of the cows (Paper II) were probably related to the feeding, milking and urinating/defecating routines. The morning feeding session started at about 8 a.m. and the morning activity peak was measured one hour later at about 9 a.m. Similarly, the afternoon feeding session started at about 4 p.m. and the afternoon activity peak was measured at about 5 p.m. The morning activity peak in the pig building (Paper III) was most likely related to feeding and cleaning of the manure on the floor. Competition for feed from the single feeder in each pen increased the activity of the pigs (Botermans *et al.*, 2000). The activity of pigs has been shown to vary considerably with changes in the feeding schedule (Groenestein *et al.*, 2003). The afternoon activity peak was probably due to the behaviour of the pigs during eating, urinating and defecating. A positive relationship has been reported between the urinating frequency and the activity of pigs (Aarnink *et al.*, 1996).

The decrease in the daily activity of the cows during the measurement period (Paper II) was probably related to the increase in average indoor air temperatures as the season changed from winter to spring. A possible influence of the animal weight on the activity was most likely small since small changes were expected in the animal weight. A reduction in the time cows dedicate to feeding and ruminating with increasing heat stress (De Palo *et al.*, 2006; West, 2003) should probably decrease the activity of cows with increasing temperatures. On average, the indoor air temperature increased from about 5°C at the start of the measurement period to about 15°C towards the end of the measurement period. Occasionally, during the last part of the measurement period, indoor temperatures were above 20°C with a maximum of about 26°C. High temperatures cause heat stress and studies have shown that heat stress may alter the behaviour of dairy cows (De Palo *et al.*, 2006; West, 2003). The behaviour of dairy cows has also been shown to have significant seasonal variations during daylight periods (Provolo & Riva, 2008a).

The decrease in the daily activity of the fattening pigs (Paper III) was probably due to the increasing weight and age of the pigs. Experiments have shown that at the same age, small pigs are more active than large pigs, and young pigs are more active than old pigs (Botermans *et al.*, 2000; Botermans & Andersson, 1995). In addition to the differences in the natural behaviour between smaller and larger pigs, a reduction in the surface area available to each pig with increasing body weight/size can limit its area of free movement and, consequently, reduce its activity.

5.3.2 Gas emissions (Papers I–III)

The ammonia emissions from the pig building (Paper III) were generally higher than the emissions from the dairy cow buildings (Papers I and II), when expressed in livestock units (LU). Methane emissions per LU from the two dairy cow buildings were generally higher than the emissions from the pig building. However, high methane emissions were measured from the pig building during the summer months (batch 3). Higher air and manure temperatures might have contributed to the higher methane emissions from the pig building in the summer.

Ammonia and methane emission rates from the cow building in Paper II were slightly lower than the emissions from the cow building in Paper I. In addition to the differences in the ventilation rates (520 ± 250g LU^{-1} h^{-1} in Paper II and 250–401 m^3 LU^{-1} h^{-1} in Paper I), the feed, floor systems and manure management methods (Table 4) might have contributed to the differences in emissions. Ammonia emissions corresponded to a smaller loss in manure nitrogen from the cow building in Paper II (4% of the manure nitrogen) than from the cow building in Paper I (5.6% of the manure nitrogen).

Diurnal variations in ammonia emissions

Diurnal variations in ammonia emissions from both cow buildings (Papers I and II) seemed to be related to feeding routines and animal activity. Manure removal from the buildings and changes in temperatures and ventilation rates should also affect the production and release of ammonia.

Diurnal variations in ammonia emissions from the pig building (Paper III) were related to the activity of the pigs. This relationship has been associated to the urinating frequency and to air movements over the manure surface which is high during the daytime leading to higher emissions (Blanes-Vidal *et al.*, 2008; De Sousa & Pedersen, 2004). In one study, 44% of the variations in ammonia emissions within the day could be explained by the urinating frequency of growing pigs (Aarnink *et al.*, 1996). Measurements have shown that changes in temperature and humidity affect the lying, wallowing and excreting behaviour of pigs (Huynh *et al.*, 2005), which can alter the size of the urine-fouled surface. An increase in the urine-fouled surface with increasing temperatures within the day will lead to high ammonia emissions. High temperatures in the daytime also enhance urea hydrolysis which increases ammonia emissions (Sommer *et al.*, 2006). Manure mixing during cleaning and removal routines might also have contributed to the ammonia emission peaks.

Diurnal variations in methane and carbon dioxide emissions

Diurnal variations in methane emissions from the cow buildings (Papers I and II) were related to the feeding routine and the activity of the cows. The feeding routine has been shown to affect methane emissions from dairy cows with an increase in methane production of up to 50% approximately one hour after feeding (Jungbluth *et al.*, 2001). Diurnal variations in temperatures probably did not have any significant effect on the overall methane emissions from the cow buildings since methane emissions from the manure in these types of buildings are small.

Diurnal variations in methane emissions were to some extent correlated with the activity of the pigs ($r = 0.41$, $p = 0.05$). However, further analysis of the data indicated that the relationship might be stronger ($r = 0.76$) for lighter pigs (< 50 kg) when methane emissions are lower. This might mean that most of the methane in the building at this stage came directly from the pigs. In another study, a rather better correlation between methane emissions and pig activity has been reported for heavier pigs (86–122.5 kg) with fortnightly manure removal (Blanes-Vidal *et al.*, 2008). This might indicate that another factor which varies diurnally and is correlated to animal activity (e.g. temperature) could also be important for methane emission from buildings with indoor manure storage. The relationship between the diurnal activity of the pigs and carbon dioxide emissions can be explained by their physiological relationship (Pedersen *et al.*, 2008) with high emissions during active periods within the day. A similar observation has been reported by other authors (Jeppsson, 2002; Osada *et al.*, 1998).

Daily variations in ammonia emissions

Ammonia emissions from the cow building (Paper II) increased with increasing indoor air temperatures. High indoor air temperatures are expected to lead to increased manure temperatures (Park *et al.*, 2006) and may also increase ventilation rates (Bruce, 1978). It has been found that ammonia is almost exclusively emitted from manure (Jungbluth *et al.*, 2001) and its production and release is temperature dependent (Sommer *et al.*, 2006; Elzing & Monteny, 1997). The daily ammonia emissions increased as the cow activity decreased during the measurement period in Paper II, although increased animal activity with increased feeding and urinating is expected to increase ammonia emissions. The increase in temperatures due to a seasonal change seemed to have had a stronger effect on the ammonia emissions than the effect of the animal activity.

The weight of the pigs was generally the predominant factor that indirectly accounted for the daily variations in ammonia emissions. The effect of animal weight on ammonia emissions might partly be due to an increase in the amount of nitrogen excreted with increasing pig weight, especially as the feed composition was constant. This is because the nitrogen need in relation to the energy need of pigs reduces as they grow older (Sommer *et al.*, 2006). An increase in the daily manure production (Ni *et al.*, 1999b), coupled with an increase in the size of manure-fouled surfaces may also increase ammonia emissions with increasing animal weight. The size of manure-fouled surfaces and the frequency of excretion on solid floor sections are found to be affected by temperature, and to a limited extent, by humidity (Aarnink *et al.*, 2006; Huynh *et al.*, 2005; Huynh *et al.*, 2004). These authors have shown that above a critical temperature, pen fouling increases linearly with temperature and that the critical temperature is lower for heavier (and consequently older) pigs.

Daily variations in methane and carbon dioxide emissions

The positive relationship between methane emissions and cow activity (Paper II) could be physiological, since methane is predominantly emitted directly by cows through enteric fermentation (Jungbluth *et al.*, 2001; Monteny *et al.*, 2001). The negative correlation between daily methane emissions and indoor air temperatures indicated that the quantity of methane emitted from the manure (which should be temperature dependent) was small and did not contribute significantly to the overall methane profile in the cow building in Paper II. Increased daily temperatures resulted in decreased cow activity which, in turn, decreased methane production by the cows (Paper II).

The importance of pig weight to the daily methane emissions in batches 1 and 2 (Paper III) where the mean indoor air temperatures were lower than for batch 3 could partly be due to an increase in the microbial activity of methanogenic bacteria in the intestines of the pigs with increasing animal weight (Jensen, 1996). It could also be due to an increase in the daily quantity of manure in the building with increasing animal weight. In batch 3, where methane emissions and mean indoor air temperatures were higher, analysis of the measurements suggested that air temperature was more important than animal weight for daily methane emissions. The differences in daily methane emissions across the pig batches might have been influenced more by the quantity of methane from the manure, than by the quantity that came directly from the pigs, since the pig species and the feed content were the same for all the batches. It could be possible that changes in the environmental conditions for the different batches affected the pigs differently resulting in different levels of methane production through flatulence, a view that needs further investigations.

The weight of the pigs was the most important predictor for the daily carbon dioxide emissions. This is in line with an increase in the respiration quotient with increasing animal weight (Pedersen *et al.*, 2008). The production of carbon dioxide from the manure can be expected to increase with the weight of the pigs since the daily quantity of manure in the barn increases with the weight of the pigs. However, carbon dioxide production from the manure is small and has been estimated to be less than 10% of the total production in buildings with frequent removal of liquid manure (Pedersen *et al.*, 2008). Daily manure removal from the pig building in Paper III suggests that carbon dioxide production from the manure in the building was small.

5.4 Effects of temperature and wood shavings on gas emissions (Paper IV)

5.4.1 Temperature

Increased ammonia emissions with increasing manure temperatures (Paper IV) could be explained by the effect of temperature on urease activity and the subsequent ammonia release processes (Sommer *et al.*, 2006). Notably, the ammonia emissions were about 2 times lower at manure temperatures of about 15°C when compared to emissions at about 25°C. Lowering manure temperatures should be an effective ammonia abatement technique which is in conformity with other investigations (Van der Stelt *et al.*, 2007; Gustafsson *et al.*, 2005; Andersson, 1998). It can be reasonable to conclude that manure temperature also contributed to the diurnal and daily variations in ammonia emissions from the animal buildings in Papers I–III.

The observed increase in odour emissions with increasing cow manure temperatures could be due to an enhancement of the processes that produce the odorants. However, the positive but insignificant relationship between odour emissions and the pig manure temperature for manure samples without wood shavings and the negative relationship for manure samples with wood shavings indicate that there are also other important parameters that affect the formation and release of odour. Variations in microbial activity due to temperature, manure water content and changes of the manure surface may affect odour emissions.

Regarding the air temperature which varied independently from the manure temperature in Paper IV, no significant effect on the ammonia and odour emissions from the manure samples could be observed. However, at the building level, positive correlations have been reported for studies in some buildings (Nimmermark & Gustafsson, 2005; Jeppsson, 2002) although a negative influence of ambient air temperature on ammonia emission was observed in another building (Aarnink *et al.*, 1993). High indoor air temperatures lead to increased temperatures at the manure surface and in the manure and consequently an increase in gas emissions can be expected. This can explain the positive correlation between air temperatures and ammonia emissions in the dairy cow building in Paper II. In addition, high indoor air temperatures may increase the air exchange rate (Bruce, 1978), thereby increasing gas emissions. The manure temperature in Paper IV should have been affected by the air temperature just to a very small extent since the manure temperature was controlled separately by the water bath.

5.4.2 Wood shavings

The addition of wood shavings to the cow manure in Paper IV increased its C/N ratio to optimum levels of 25–38 (Ekinci *et al.*, 1998; Poincelot, 1974), favoured by microorganisms to immobilise ammonium, resulting in lower ammonia emissions relative to the manure without wood shavings. Reductions in ammonia emissions have been reported after adding wood shavings to animal manure (Tasistro *et al.*, 2008; Luo *et al.*, 2004). Contrary to the cow manure, the increase in ammonia emissions from the pig manure samples with wood shavings could have been because optimum levels of C/N ratio for ammonium immobilisation were not reached after adding wood shavings except for one sample. In addition, the pH of the manure increased after adding wood shavings. Furthermore, the temperature of the manure with wood shavings increased faster than the temperature of the manure without wood shavings, due likely to self-heating resulting from microbial activity. All these circumstances may explain the higher ammonia emissions from the pig manure with wood shavings relative to the manure without wood shavings. Despite the possibility of a temporal increase in ammonia emissions after adding wood shavings to animal manure in laboratory studies, lower emissions are expected over longer periods (Dewes, 1999).

6 GENERAL CONCLUSIONS

This study was aimed at contributing to the knowledge on the subject of gas emissions and emission abatement from livestock production. Measurements of gas concentrations in naturally ventilated buildings were assessed. Factors that affect gas emissions, such as building parameters, management routines, climatic factors and parameters related to the animals were analysed. The following conclusions can be drawn from this research:

- Multi-location sampling of gas concentrations is necessary especially in naturally ventilated buildings where short-term measurements of single days or less are carried out, due to considerable spatial variations in concentrations. Single location sampling of gas concentrations during long-term measurements may generate representative data in animal buildings if the sampling location is strategically chosen.

- Measurements of gas emissions during different times within the day and during different days within the livestock production period are necessary to generate reliable data for inventory and for mitigation purposes. This is due to significantly large diurnal and daily variations in gas emissions.

- Diurnal variations in animal activity are related to management routines (e.g. feeding and cleaning), parameters related to animals (e.g. urinating/defecating frequencies) and climate-related factors (e.g. temperature). On a daily basis, decreasing animal activity can be caused by increasing animal weight or increasing temperatures.

- Diurnal variations in gas emissions are related to the feeding schedule, manure removal routines, animal activity and changes in temperature.

Daily fluctuations in gas emissions are related to animal activity, animal weight and changes in temperature.

- Reducing manure temperatures and increasing manure C/N ratios are practical ammonia abatement techniques. However, low air temperatures may increase the activity of cows which may in turn cause high methane emissions.

- Increasing the frequency of manure removal from the floor and from animal buildings may reduce indoor emissions of most gases. A change from solid manure to liquid manure systems has the potential to reduce nitrous oxide emissions, since very low emissions were measured from the type of buildings in this research.

7 AREAS OF FUTURE RESEARCH

In order to fully comprehend the conclusions derived from this study and to apply the recommendations in practice, more work is needed in some areas where there is currently limited knowledge.

- Detailed quantification of carbon dioxide production from different sources in animal buildings with liquid manure systems will add credibility to ventilation rates calculated based on carbon dioxide mass balance.

- Additional experiments in a climate controlled environment as well as under practical conditions in animal buildings will provide more information regarding the effects of the indoor climate and animal weight on animal activity.

- Information concerning the different sources of methane in various types of fattening pig buildings, how methane production from the various sources vary over the growing period of the pigs and the factors that affect their variations may explain the observed seasonal differences in methane emissions.

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9 ACKNOWLEDGEMENTS

This research was funded by the Sensory System Research School (SENSYS) of the Swedish University of Agricultural Sciences. Additional funds were provided by the Department of Rural Buildings and Animal Husbandry of the Swedish University of Agricultural Sciences.

Field work was funded by the Swedish Board of Agriculture and the Swedish Farmers' Foundation for Agricultural Research.

Grants for research visits to other institutions and participation in conferences were provided by the Swedish University of Agricultural Sciences (Travel grant for internationalisation, Gramens grant) and the Royal Swedish Academy of Agriculture and Forestry (Kungl. Skogs och Lantbruksakademien).

I wish to express my sincere gratitude to all the people who contributed to this work. In particular, I appreciate the contribution of the following persons and institutions:

My main supervisor Professor Gösta Gustafsson for always being quick to respond and for the helpful informal meetings.

My deputy supervisors Dr. Knut-Håkan Jeppsson and Assistant Professor Sven Nimmermark and for their valuable guidance.

Ingvar Johnsson and Alexandra Blomquist for managing the pigs at Alnarp Södergård research farm.

Odour panellists: Emma Nimmermark, Axel Vallgren, Magnus Nilsson and Ingemar Sjölin.

All my colleagues at the Department of Rural Buildings and Animal Husbandry.

The von Wachenfelts (Hans, Eva, Anna and Nils) for the countryside weekends.

The proprietors and staff of the dairy farms in Våstraby and at the Agricultural High School in Bollerup.

Gillian Sjödahl for editing the language in this thesis.

My parents, Ngwa Joseph and Julie, my family and the family of Ambe Lucas for their moral support.