Odour Impact

Odour release, dispersion and influence on human well-being with specific focus on animal production

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Abstract

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Our sense of smell provides us with the opportunity to explore our chemical environment. Upon perceiving an odour our reactions can be approach as well as avoidance. Emissions from a number of different operations are common causes of complaints. This thesis deals primarily with odours from livestock and poultry operations, which are common causes of annoyance. The main hypothesis of the thesis was that odours and odorants may affect health and that a correlation between measurements of various parameters of odours and health exists. The main objective was to contribute to improved well-being and health and to reduce conflicts by studying factors affecting odour release, odour dispersion in the neighbourhood and factors of importance for well-being and health. Another objective was to discuss measurements of the odours in question using electronic noses. Electronic noses can be sensitive enough to measure odours related to farms and a correlation between their response and odour concentrations has been found. Studies of factors affecting odour release in a climate chamber equipped with a floor housing system for laying hens resulted in significant correlations between temperature and humidity and odour as well as ammonia concentrations and emissions. Odour observations reported by neighbourhood monitors indicated that setback distances predicted by the OFFSET (Odour from Feedlot Setback Estimation Tool) model for stable weather conditions were correlated to the exposure. Variation of emission rates and variations in concentration in an odour plume contribute to difficulties in predicting intensities in the neighbourhood. Observed increased frequencies of respiratory symptoms and symptoms like sleeping difficulties, headache, nausea, palpitations and alternations of mood in neighbours of large scale animal operations can be caused by odours mediating the symptoms through stress and annoyance, by the odorants or co-existing compounds or by combined effects. Regarding annoyance, cognition and coping are important as well as odour pleasantness. Odour pleasantness for odours from pigs, poultry and cows showed a consistent decrease by concentration. Low concentrations of these odours are likely to be rated as quite unpleasant. An important factor affecting perceived odour pleasantness is the individual odour sensitivity.

Keywords: odour measurement, olfactometry, electronic nose, emission, humidity, temperature, setback distance, stress, annoyance, health, agriculture, livestock, poultry.

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"To see a World in a Grain of Sand
And a Heaven in a Wild Flower,
Hold Infinity in the palm of your hand
And Eternity in an hour".

William Blake, Auguries of Innocence.

Contents

Terms, definitions and abbreviations

Terms, definitions and abbreviations in this thesis are used as follows:

Adaptation	Decrease of sensitivity following long term or repeated exposure to an odorant.
Annoyance	"A feeling of displeasure associated with any agent or condition believed to affect adversely an individual or a group" (Lindvall & Radford, 1973).
BAW	Bulk acoustic wave sensors; devices based on quartz crystal oscillators. Sensor type used in ENs.
C/N-ratio	Ratio between carbon and nitrogen content.
CP	Conducting polymer sensor. Sensor type used in ENs.
Electronic nose	“An electronic device mimicking the human olfaction. Electronic noses contain electronic-chemical sensors and a pattern recognition system” (Gardner & Bartlett, 1994).
EN	Electronic nose.
Field sniffer	Trained odour panellists reporting odour in field measurements.
Flux hood	A hood used for measuring emissions from area sources.
FMS	Fingerprint mass spectrometry.
GC-MS	Gas chromatography-mass spectroscopy.
Gustation	The sense of taste.
Health	"A state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" (WHO, 1946).
Hedonic tone	Scaled pleasantness. Hedonic tone of an odour is the scaled odour pleasantness.
IMCELL-technique	Type of IMS.
IMS	Ion mobility spectrometry.
INPUFF-2	A software-based meteorological odour dispersion model used for calculation of odour concentration at a specific location around an odour source.
IR	Infrared.
MISiC	Sensors similar to MOSFET. Sensor type used in ENs.
MOS	Metal oxide sensor. Sensor type used in ENs.
MOSFET	Metal oxide semiconductor field effect transistors. Sensor type used in ENs.
MS	Mass spectroscopy.

n-butanol	Commonly used reference odorant in olfactometric measurements.
Odorant	"Substances which stimulate the human olfactory system so that an odour is perceived" (Hangartner *et al.*, 1989).
Odour	"Organoleptic attribute perceptible by the olfactory organ on sniffing certain volatile substances" (CEN, 1999).
Odour concentration	The number of odour units in a sample of air.
Odour intensity	The human perceived strength of an odour. Odour intensity can be expressed by a logarithmic expression of odour concentration.
Odour persistence	Odour persistence or odour pervasiveness describes the rate of change in odour intensity when the concentration decreases.
Odour quality	Odour quality or odour character describes what an odour smells like, *i.e.* earthy, floral.
Odour threshold	The lowest concentration of a gas or a mixture of gases at which an individual observe an odour. At concentrations below the odour threshold no odour is detected by the individual in question.
ODT	Odour detection threshold. ODT and OU are used in the U.S. Similar to OU_E/m^3. Demands regarding olfactometers and procedures for measurement and calculations may deviate somewhat from European measurements.
OFFSET	"Odor From Feedlot Setback Estimation Tool" - a setback model developed at the University of Minnesota.
Olfaction	The sense of smell.
Olfactometer	Instrument used for olfactometric measurements. The instrument is often used for measurements of odour concentration. In such measurements the odorous air is diluted to various concentrations and the dilutions to reach the odour thresholds of the human panellists are determined. From these odour threshold values the concentration of the sample in question is measured.
Olfactometry	Measurements using human panellists to rate an odour. A term often used for measurements using an olfactometer and a human panel analysing an odour.
OU	Odour Unit. OU and ODT are used in the U.S. Similar to OU_E/m^3.

OU_E/m^3	European odour unit. One European odour unit per m^3 is defined as an odour concentration experienced equivalent to the response when exposed to a concentration of 40 ppb n-butanol by volume (123 $\mu g/m^3$) in a mix with neutral gas (for exact definition see CEN, 1999). This represents the odour threshold for a human individual with sensitivity comparable to the average in the human population.
PID	Photoionization detector.
QCM	Quartz crystal microbalances. Sensor type used in ENs.
RH	Relative air humidity.
SAW	Surface acoustic wave transducers. Sensor type used in ENs.
Scentometer	An instrument used for measuring odour concentration/odour strength in the field. A mix of odorous and odourless air is sniffed in by the person doing the measuring.
Sensitization	Increased sensitivity to an odorant after exposure.
SRDT method	The Solar Radiation -delta T method. Method used for classification of weather in atmospheric stability classes (US-EPA, 2000).
TLV	Occupational threshold limit values. Concentrations not to be exceeded during a working day.
VD	Water vapour deficit.
VNO	The vomeronasal organ. A neural system in the nasal cavity said to be important for mediating social and sexual signals for a number of animal species. The existence of a functioning VNO in humans is debated.
VOC	Volatile organic compound.
VP	Water vapour pressure.
Wind tunnel	A hood in which a certain weather condition is simulated in order to obtain emission values with a correlation to emissions at natural conditions.

Appendix

The present thesis is based on the following five papers, which will be referred to by their Roman numerals.

Papers I-V

I. Nimmermark, S. 2001. Use of electronic noses for detection of odour from animal production facilities: a review. *Water Science and Technology 44*, 33-41.

II. Nimmermark, S. & Gustafsson, G. 2004. Influence of temperature, humidity and ventilation rate on the release of odour and ammonia in a floor housing system for laying hens. *Submitted to an international peer reviewed journal.*

    Nimmermark carried out odour measurements and parts of the other measurements. Nimmermark was responsible for analyzing the data and for writing the paper.

III. Nimmermark, S., Jacobson, L.D., Wood Gay, S. & Schmidt, D. 2004. Predictions by the OFFSET odor setback model compared to observations by neighbourhood monitors. *Submitted to an international peer reviewed journal.*

    Nimmermark was involved to a minor extent in the experiment. Nimmermark was responsible for analyzing the data and for writing the paper.

IV. Nimmermark, S. 2004. Odour influence on well-being and health with specific focus on animal production emissions. *Submitted to an international peer reviewed journal.*

V. Nimmermark, S. 2004. Measurements of hedonic tone of odour from animal production facilities. VDI-Report 1850, 209-218.

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Introduction

General introduction

Our sensory systems provide us with information essential for our behaviour and protection. Of the very large amount of information gathered by our senses only a limited amount passes through our consciousness and for the sense of smell a factor 10^{-5} has been mentioned (Nørretranders, 1999). This tiny fraction is the input to our conscious reactions to odours. Such reactions may be essential to us in some cases. Odours may be a warning that triggers avoidance behaviour, they may also trigger approach behaviour (CEN, 1999). Odour can be defined as an "*organoleptic attribute perceptible by the olfactory organ on sniffing certain volatile substances*" (CEN, 1999). The "*substances which stimulate the human olfactory system so that an odour is perceived*" are named odorants (Hangartner *et al.*, 1989). The sense of smell identifies odours and odorants and tells us something about our environment. Concerning food intake, the sense of smell (olfaction) and the sense of taste (gustation) are important for the protection of the body. Odours and taste are identified by different senses but odorants may change the intensity and character of a specific taste (Djordjevic *et al.*, 2004; Prescott *et al.*, 2004; Schifferstein & Verlegh, 1996). A well-functioning sense of smell can be essential for food intake and anosmia may lead to loose of appetite.

Our environment must fulfil a number of requirements if it is to be attractive to us. Aesthetic, social and psychological aspects are important here (Nasar, 1998), but also factors like the sound environment and air quality may be significant. In a Dutch study of the urban environment, air pollution was included as one of the most important attributes for the perceived quality of the neighbourhood (van Poll, 1997). Odours, being a part of air pollution, may affect the quality of life of exposed individuals. It is mentioned that less than 2% of the population in Sweden report annoying odours at the site of their dwellings but odours are in spite of this one of the most common causes for environmental complaints (Forsberg & Lindvall, 2004). Potential influence on well-being and health may be a main factor for annoyance due to odours but also other factors like a drop or expected drop in the value of houses and other dwellings at sites affected by environmental odours may be a reason for annoyance.

This thesis deals with the odour impact on the society and on human individuals. The aim of the thesis is to contribute to improved well-being and health and to a reduced number of conflicts by identifying factors important for odour release, by studying odour dispersion and by improving the knowledge of important factors and mechanisms triggering human reactions to odours.

Odour complaints can be related to operations like, for example, waste water treatment plants, composting plants, rendering plants, paper mills, and livestock and poultry operations. There is much annoyance over odour from animal production giving rise to a good deal of conflict between individuals in the neighbourhood of livestock and poultry operations and farmers. The present work deals primarily with odour related to this sector although the underlying principles are, to a great extent, general.

Olfaction

The main olfactory system mediates what we usually call odour sensations (Doty, 2001). The odour receptors cells are located in the olfactory epithelium situated in a small region at the top of the two nasal cavities below the eyes. A large number of different receptors are connected to the olfactory bulbs at the base of the brain. Compared to many mammals, the human olfactory system is far less efficient. The size of the olfactory epithelium and the number of receptors may be a good indicator of its sensitivity. An olfactory epithelium surface area of 10 cm^2 in humans can be compared to 170 cm^2 in dogs (Bear *et al.*, 1996) and the total number of 12 million olfactory receptor cells in humans can be compared to 4 billion in bloodhounds (Shier *et al.*, 2004).

The 2004 Nobel Prize winners in medicine, Richard Axel and Linda Buck, have contributed greatly to the understanding of the mechanisms involved in olfaction. They searched for receptor proteins on the hair-like cilia connected to each olfactory neuron and found genes containing instructions for proteins in the olfactory epithelium (Axel, 1995a; Axel, 1995b; Buck, 1996; Buck, 1993; Buck & Axel, 1991a; Buck & Axel, 1991b). It is assumed that there are about 500-1000 different genes of this type in humans, giving rise to the same number of different olfactory receptor proteins. The receptor proteins bind odorants and signals are sent to the brain. It is suggested that combined stimulation from different types of receptors can enable the brain to identify a large number of different odours. The literature mentions that humans are capable of recognizing 10 000 odours or more.

Apart from the main olfactory system (1), there are also other neural systems in the nasal chambers of most mammals, *i.e.* the trigeminal somatosensory system (2), the vomeronasal system (VNO) (3), the terminal nerve (4), and the septal organ (5) (Doty, 2001). The trigeminal somatosensory system, also named the common chemical sense, mediates chemical sensations such as stinging when compounds like ammonia or capsaicin (from pepper) are present. It also mediates non-chemical sensations like tickling. An odorant like ammonia can cause an odour to be detected by the main olfactory system at low concentrations and a chemical sensation mediated by the trigeminal system at a higher concentration (Dalton, 2002). The existence of a functioning VNO in humans is debated (Berliner *et al.*, 1996; Doty, 2001; Monti-Bloch *et al.*, 1998; Monti-Bloch *et al.*, 1994; Smith *et al.*, 2001; Smith *et al.*, 1998). However, it is shown to be important for a number of animal species, mediating social and sexual signals. The terminal nerve might play a role for the function of the VNO (Wirsig-Wiechmann & Lepri, 1991), however, its function in humans is questioned (Doty, 2001). The septal organ observed in many mammals may have the same function as the main olfactory system (Doty, 2001).

Gaseous emissions and odour related to animal production

Odour and gases related to agriculture is an international problem. Of the gases emitted, ammonia has been in the focus in Europe for a number of years. Agriculture is a main source of anthropogenic ammonia, which contributes to large scale eutrophication and acidification of ecosystems and ammonia may also cause toxic injuries on the vegetation near the source (Jeppsson, 2000; Fangmeier *et al.*, 1994). In the early 90s, 92% of the ammonia emission in Western Europe was estimated to come from agriculture (ECETOC, 1994). Swedish research regarding emissions from animal production has mainly been focused on ammonia. Lethal amounts of odourless methane and stinking hydrogen sulphide formed under anaerobic conditions may, however, occur. Volatile fatty acids are other odorous compounds present in quite high concentrations (Mårtensson, 1995). Phenols and amines may also be important for odour in this environment (Hartung, 1992) together with compounds like mercaptans, indole and scatole. A large number of different substances related to animal production are identified. A list of 150 different compounds in swine manure was presented in 1980 (Spoelstra, 1980). Some years later a list of 168 volatile compounds related to animal production was presented in 1992 (O'Neill & Phillips, 1992). Another list of 331 identified volatile substances, sampled from lagoons and air at swine production facilities, was presented some years ago (Schiffman *et al.*, 2001). Ammonia is just one of these compounds and its importance for odour annoyance may be limited. Effects of odour are related to humans and human reactions to the mix of gases (Carney & Dodd, 1989).

The air in animal production facilities contains large amounts of dust, bacteria, endotoxins and odorants. Gaseous emissions may be a health problem in the work environment in agriculture and in other operations. The air pollutants in livestock buildings and poultry houses may affect animal health and may also have a negative impact on products like meat, milk and eggs. On the whole, there is a need to improve the air quality in animal production. Knowledge of which systems to choose regarding gas environment must be gained through measurements and it has been mentioned that there may be a great need to study odorous compounds (Nielsen & Pain, 1990). Operations large enough to support a family in Sweden, some decades ago, had an impact on nature, animals and breeders; however, the impact on human individuals in the neighbourhood was not likely to be high. The number of animals at each production facility has increased during the last decades and emissions may therefore influence individuals at greater distances. An increase in the size of the operations is still expected and most large Swedish operations are not large when compared to the size of large operations in, for example, the U.S. or Australia. Odour impact in the neighbourhood in Sweden, as well as in other countries, must be expected to increase unless precautions are taken.

Some years ago odour from animal production was listed as an important area to deal with since newer research had suggested that odour, odorants, biological and particulate emissions from concentrated production sites may have greater secondary health effects than previously documented (Sweeten *et al.*, 2000).

Odour, well-being and health

The World Health Organization defines health as: "*a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity*" (WHO, 1946). Odour and odorants may affect well-being as well as health. Depending on the type and concentration of odour and odorants, the influence may be positive as well as negative. Air pollution is regarded as an environmental stressor (Evans & Cohen, 1987) and psychological impact (Berglund & Job, 1996) and depressive effects (Moghissi & Berglund, 1996) are possible. Odorants may also have physical impact on individuals. Recent research has suggested effects on the health of neighbours to large animal production facilities (Melvin, 1995; Schiffman *et al.*, 1995b; Sidhu *et al.*, 1997; Thu *et al.*, 1997; Wing & Wolf, 2000).

Sensitivity to odour

Long-term or repeated exposure to an odorant typically leads to a decrease of sensitivity to that odorant (Dalton, 2000). This adaptation makes it possible for individuals to react primarily to changes in stimulation. In experiments with acetone, a considerable decrease in sensitivity was obtained after a couple of minutes (Dalton *et al.*, 1997). There may exist two types of adaptation, short-term and long-term. It has been suggested that long-term adaptation to odour from animals for people working daily with livestock might change their odour perception and lead to a non-understanding of odour complaints from neighbours with intermittent exposure (Schiffman, 1998). Individuals may adapt faster and to a greater degree to malodours than to pleasant odours (Jacob *et al.*, 2003). Also sensitization, *i.e.* a decreased odour threshold, may occur after exposure to an odorant (Dalton *et al.*, 2002; Vanderwolf & Zibrowski, 2001; Wang *et al.*, 1993; Yee & Wysocki, 2001).

Women have often shown better results than men in studies regarding odour olfactory sensitivity (Opatz *et al.*, 2000). The olfactory function has also been shown to decline by age in a number of experiments (Evans *et al.*, 1995). Also smoking may decrease olfactory sensitivity (Liu *et al.*, 1995). Previous exposure to high concentrations of a chemical is connected to decreased sensitivity to odours as well as a number of disorders (Doty, 2001).

Reactions to an odour may involve learning and enhanced sensitivity to odours with ecological relevance may occur (Hudson, 1999). Reactions to an odour also involve odour memory and, in some cases, smells can be a powerful reminder of autobiographical experience (Proust phenomenon) (Chu & Downes, 2000). Smells may be important for the sensory quality of the landscape (Coeterier, 1996). Moreover, odours may be important in social contexts (Flemming *et al.*, 1999; Hummel *et al.*, 1991; McClintock, 1971; Pause *et al.*, 1999; Porter & Winberg, 1999; Stern & McClintock, 1998; Vasilieva *et al.*, 2000).

Physical impact of odorants

A possible physical impact is obvious for gases that are present in high concentrations. Occupational threshold limit values (TLVs) exist for a large number of volatiles (see *e.g*. New Jersey Department of Health; Swedish National Board of Occupational Safety and Health, 2000). However, odour or very small amounts of gases and substances may also affect the health, for example, cause asthma-like and allergic symptoms and reactions (Hummel *et al.*, 1996; Millqvist *et al.*, 2000; Millqvist *et al.*, 1998; Ringsberg, 1997).

Annoyance due to odour in the neighbourhood

Emitted malodour and odorants from odour generating operations may be a major problem for the neighbourhood. Odours from livestock and poultry production facilities affect the quality of life of nearby residents by causing nuisance, *etc*. (Jiang & Sands, 1997) and complaints from neighbours are a problem for the breeders (Taylor, 1991). Malodours emanating from faeces and urine constitute a problem when their character and intensity cause annoyance or when they affect the health. There may be disagreement about the magnitude of acceptable intensity and of acceptable character (Nielsen *et al.*, 1988). Annoyance has been defined as *"a feeling of displeasure associated with any agent or condition believed to affect adversely an individual or a group"* (Lindvall & Radford, 1973).

Studies suggest that malodour may cause stress (Tomonobu *et al.*, 2001) and that pleasant rated odours may be used for relaxation (Schiffman & Siebert, 1991). The short time effects of stress may be positive, but in the longer perspective illnesses may be the result, and perhaps then especially heart and blood vessel diseases together with diseases depending on a decline in the immune defence. Hedonic tone or odour pleasantness is most likely to have considerable bearing on annoyance. It has been found to affect the number of highly annoyed individuals among people exposed to a certain modelled odour concentration during a certain time of the year (Miedema *et al.*, 2000).

Generation and release of odorants

Generation and transport mechanisms

Oxygen is important for micro-organisms in composting processes and a limited amount of odorants are usually produced in such processes (Haug, 1993). At anaerobic conditions, large amounts of odorants, like hydrogen sulphide, can be produced in animal waste. Evaporation of gaseous compounds from a liquid surface might be compared to evaporation of water. The amount of evaporated water is related to the energy flow at the boundary level and thus to the temperature of the liquid, the temperature of the ambient air, and the irradiation. Just above the surface of the water, a saturated mixture of water vapour and air is created. The thickness of the boundary layer is dependent on the air velocity, where a higher velocity will decrease the layer thickness and increase the evaporation. A similar process may occur for evaporation of gases from a liquid surface, and their equilibrium in each phase should be important. However, even generation of gases depending on a large number of factors must be expected to affect the amount available for volatilization. The transport of gases from various generation places in the liquid up to the surface is also crucial. Adsorption affects the equilibrium of soluble gases in the solid/liquid phase and the mix of gases, and the type of bindings for a specific gas affects the type of gas released primarily.

Temperature, humidity and dust

Change in temperature and humidity in the environment may lead to a change in emission. Drying material may lead to volatilization of solved and adsorbed compounds during the drying phase, and further to decreased volatilization after drying. Reducing the moisture content reduces the odour production in manure (Jacobs, 1994; O'Neill & Phillips, 1991). Increased emissions of most volatiles from sheep wool were correlated to increased temperature and increased humidity (Lisovac & Shooter, 2003). For dust from air filters, temporary emission peaks were found when the moisture rapidly increased (Hyttinen *et al.*, 2001). Wetting of a material may release gases produced earlier.

Gases and odorants adhere to dust particles and it has been indicated that removal of dust in animal production facilities can reduce the odour in the air by 65-75% (Hartung, 1986; Hoff *et al.*, 1997). Ammonia contents in inhalable dust from livestock and poultry operations have been quantified to 1000-6000 ppm on weight basis (Takai *et al*., 2002). Animal activity, animal weight, type of ventilation and type of housing system affect the dust levels, which can be decreased by spraying water or a mixture of water and oil (Gustafsson, 1999; Gustafsson, 1997).

Factors important for release in animal production facilities

The emission rates from poultry and livestock operations are dependent on many factors, for example, the time of year and day, temperature, humidity, and other weather conditions, ventilation rates or wind forces, housing type, manure properties or characteristics, and animal species (Jacobson *et al.*, 2001b). A large amount of the odorous compounds related to animal production originate from exhaust air from production facilities and from storages for manure. Activities like spreading manure, emit large amounts of gases but the impact on the surroundings may be less from these emissions than from those from the buildings, since the former are emitted during a limited time. Odours related to animal production emanate primarily from urine, manure, animals and feed (Carney & Dodd, 1989). Odour emissions from animals and feed are considered to be low and are not likely to cause annoyance. Odorants causing malodour are produced by micro-organisms decomposing various substances like undigested feed particles in manure. Factors considered to have importance for the production and release of ammonia (gases) from manure in animal production facilities are primarily: (1) temperature, (2) dry matter content, (3) pH-value, (4) C/N-ratio, (5) air exchange rate, (6) manure storage time inside the building, (7) ratio between exposed area and volume, (8) area of manure surfaces, and (9) feeding (Andersson, 1995; Gustafsson, 1996; Gustafsson, 1992). The above-mentioned factors are likely to be important for the main part of gases but they are mainly studied with regard to ammonia release.

Odour measurement

Odour observations in the neighbourhood of an odour source and reported annoyance from people living in the vicinity are methods used for measuring the impact in the society. Further, measured emissions at the source can be used in meteorological models to predict exposure in the neighbourhood. Evaluation of control technique and emissions in different applications relies on a good measuring technique and it has been stated that a problem in odour research is to find such a good technique (Nielsen, 1991; Nielsen & Pain, 1990).

An important parameter for odour impact is the odour concentration. Odour reflects the human response to odorants in the air and the base for odour concentration is the human odour threshold. Odour thresholds refer to the lowest detectable concentration. An odour contains hundreds of different gases where each gas has its own human odour threshold. The reference gas for European odour units (OU_E) is n-butanol and 1 OU_E/m^3 refers to the concentration of 40 ppb n-butanol by volume (CEN, 1999). Odour thresholds vary in the human population and this concentration refers to a person with average sensitivity, *i.e.* a person with sensitivity near the median in the Gauss distribution of the human population. An interval of 1/16 to 16 times reported average odour threshold is meant to include 95% of the population (Amoore & Hautala, 1983; NIOSH, 1987). A concentration of a couple of OU_E/m^3 is needed to reach the recognition threshold, *i.e.* the concentration at which a certain odour can be recognized.

An odour can be characterized by (Jacobson *et al.*, 2001b):

- Odour concentration
- Odour intensity
- Persistence
- Hedonic tone
- Odour quality

The odour intensity is the human-perceived strength and it may be expressed by a logarithmic expression or by a power function (CEN, 1999). It can be based on a reference gas such as n-butanol (ASTM, 1999). The rate of change in odour intensity when the concentration decreases is not the same for all odours and odour persistence describes this rate of change (Jacobson & Lorimor, 2000). The pleasantness of an odour is described by the hedonic tone (Hamilton & Arogo, 1999; Lim *et al.*, 2001). The character or quality of an odour describes in words (odour descriptors) what it smells like and words from defined lists can be used (Wise *et al.*, 2000). Classification may, however, be influenced by individual differences in labelling related to differences in semantics, hedonics and social convention (Stevens & O'Connell, 1996).

In a number of studies of odour from agricultural sources odour intensity, rated by trained panellists, is used in the field. One of the scales used for odour intensity is the 5-step intensity scale of n-butanol (ASTM, 1999) where a certain intensity level corresponds to a specific concentration of n-butanol. Hedonic tone may have similarity to intensity for offensive odours although individual characteristics may influence the perceived pleasantness. Some methods used or attempted to use for characterisation of odours are shown in Table 1.

Table 1. *Measurements for characterisation of odours*

Measurements	Sensor	Odour characters possible to measure
Olfactometry using: - Olfactometers - Scentometers	Human olfaction	Odour detection Odour recognition Odour concentration Odour intensity Hedonic tone Character Persistence
Olfactometry using: - Field sniffers	Human olfaction	Odour detection Odour recognition Odour intensity (Hedonic tone)* (Character)* (Persistence)*
Electronic noses	Various sensors measuring *e.g.*: - Resistance - Oscillation - FMS - Gas concentrations - *etc.*	EN response may be correlated to: - Odour concentration - Odour intensity - Character
Gas measurements	Various methods: - Detection tubes - Various sensors - GC-MS - *etc.*	Gas concentrations might be correlated to: - Odour concentration - Odour intensity
VOC measurements	A PID sensor can be used	VOC measurement response might be correlated to: - Odour concentration - Odour intensity

* Measurement of these parameters can be performed but is not the normal output

Sampling of odour from livestock and poultry operations

Jacobson *et al.* (2001b) state: "Unfortunately, measurement of building emissions has received more attention than measuring emissions from area sources, *e.g.*, open manure storages or out-door feedlots". The measurement of emissions from buildings is performed by measuring the air exchange rate and the concentration of the pollutant. It might be a problem that some compounds in odour from animal production facilities oxidize fairly fast. However, developments in odour sampling technique may have made it possible to transport odour samples to a laboratory without significantly affecting the odour concentration (Jiang & Kaye, 2001).

Sampling of odorous air in bags of inert materials like Tedlar® is a common procedure accepted in, for example, the draft European norm (CEN, 1999). However, unconventional methods like sampling odour with the help of cloths has also been tested (Gay *et al.*, 2001).

Estimating emission from an area source by sampling air from a wind tunnel or a hood, is the conventional method. The incoming air into the wind tunnel is in some measurements unfiltered air from the surroundings and in other cases filtered air which has passed through one or two adsorbents in order to remove odorants. Wind tunnels are developed in order to get comparable values of gas or odour emission from area sources. A number of different flux hoods and wind-tunnels have been used in studies (Andersson, 1995; Boriack *et al.*, 2004; Edeogu *et al.*, 2001; Lindvall *et al.*, 1974; Ryden & Lockyer, 1985). One of the wind tunnels used is designed to simulate the atmospheric conditions – parallel flow without vertical mixing (Jiang & Kaye, 2001) and activated carbon filtered air is introduced at the inlet using a fan. The air velocity 0.3 m/s is, according to the researchers, chosen because it is the lowest reliably measurable air velocity and because most odour complaints occur at wind speeds less than 1.5 m/s corresponding to 0.2-0.65 m/s at hood level. Jiang and Kaye further state that wind tunnels are superior to flux hoods and that flux hoods are poor tools for measuring odour from area sources since they have been observed to differ up to 300 times in field studies.

Olfactometry using olfactometers

A common method to measure odour concentration is to dilute the sample with an instrument, an olfactometer, and to present increasing concentrations of the odorous air until panellists notice the odour. Odour concentration can be expressed in multiples of a certain reference gas concentration (like 40 ppb n-butanol = 1 OU_E/m^3 in Europe) or in similar terms of how many dilutions it takes before it is no longer detectable (number of odour detection thresholds, ODT). Odour sensitivity in humans can be determined by the use of olfactometrs diluting the sample. Another method is olfactometer tests where various concentrations of odours are attached to sticks presented to the person being tested (Takai *et al.*, 2003). The method using olfactometry for determination of odour concentration in samples was said to give large experimental errors for some years ago. Since then a draft CEN standard has been developed in Europe as well as new standards in other countries resulting in significant improvements (Qu *et al.*, 2001). Most studies of environmental odours, like odour from livestock and poultry, have been using olfactometry and the human nose for measuring concentration, intensity and offensiveness. It has been stated that disadvantages with olfactometry are the expense of the operation and difficulty in collecting representative samples (Hamilton & Arogo, 1999).

Scentometers

A scentometer is a handheld portable instrument, a rectangular plastic box, which can be used by a trained person and intended mainly for use in the field.

Scentometers were developed in the 1950s by the Barnebey and Sutcliffe Corporation. First the person doing the measuring sniffs odourless air passing through a carbon filter. By covering some of the 4-6 openings of different sizes with the fingers, a mix of odorous and odourless air representing different odour concentrations can be sniffed by the user. Scentometers depend on the person doing the measuring, his bias and adaptation to odour; the accuracy using this method may be less good (Jones, 1992). Recently, a new scentometer has been developed by St. Croix Sensory, Inc., Stillwater Minnesota. Measurements using this instrument might show improved accuracy.

Electronic noses

In the 1950s research concerning semiconductor materials and identification of materials possessing sensitivity to chemicals formed a base for artificial olfactory systems (Pearce, 1997). A main advantage with an electronic nose (EN) is that it can produce an instant and somewhat continuous measurement signal, useful in many applications. A number of electronic noses have been developed at different research institutions and there are also a number of electronic noses commercially available.

Electronic noses, by definition (Gardner & Bartlett, 1994), contain electronic-chemical sensors and a pattern recognition system. Progress in data processing has made electronic noses interesting for a number of applications. Research has in recent years been performed involving the use and application of ENs in various food and feed quality aspects (Annor-Frempong *et al.*, 1998; Di Natale *et al.*, 1998; Grigioni *et al.*, 2000; Magan & Evans, 2000; Olsson *et al.*, 2000; Oshita *et al.*, 2000; Schaller *et al.*, 1998; Schnürer *et al.*, 1999; Shaw *et al.*, 2000). An EN with gas sensors has been used successfully to predict the quality of fish (Ólafsdóttir *et al.*, 2000). Medical and biological applications are other interesting fields for this technology.

The commercial ENs use sensors like MOS (metal oxide sensors), CP (conducting-polymer sensors), QCM (quartz crystal microbalances), SAW (surface acoustic wave transducers), BAW sensors (bulk acoustic wave sensors, piezoelectric devices based on quartz crystal oscillators), MOSFET (metal oxide semiconductor field effect transistors) and MISiC sensors (similar to the MOSFET but based on silicon carbide instead of silicon). Other ENs are based on the Mass-Spectrometer technique (MS) and fingerprint mass spectrometry (FMS) and also the IMCELL-technique (advanced form of traditional ion mobility spectrometry, IMS) is used. With the use of advanced mathematics, like neural network or other powerful tools, together with computer power and input signals from the sensor array, the ENs tries to mimic the human olfaction.

The cycle times of ENs with MOS sensors may be 10 minutes (Mielle & Marquis, 2000) and for some ENs the cycle times may be counted in seconds (Staples, 1999). ENs can detect some compounds at considerably lower levels than the human nose while other compounds, offensive to a human nose cannot be detected (Kher, 2000; Strike *et al.*, 1999). The availability of commercial and less costly models intended for environmental studies might suggest that they could be interesting for use regarding environmental odours.

Gas measurements and odour

Gas chromatography-mass spectroscopy (GC-MS) gives information about the concentration of many volatile compounds present. However, the relation between these concentrations in a mixture and the human-perceived odour is not known, although many researchers have tried to find one. In a study, the perceived odour intensity from four major odorants from sewage plants was less than the sum of their intensities but greater than the intensity of each individual constituent (Laing *et al.*, 1994). Perceived odour varies depending on individual concentrations and interactions between odorants and masking, additions, *etc*., may occur (Berglund & Lindvall, 1986).

In Iowa, a 19 component artificial swine odour was studied using GC-MS and a human panel (Zahn *et al.*, 2001). Some correlation was found and it was concluded that direct multicomponent analysis of the gas concentrations present in ambient air near animal production facilities may be applied towards estimating perceived odour intensity.

Detection and measurement of the concentration of one specific gas can be performed using various methods. The correlation to odour may however be weak. It has been stated that research has, without success, tried to correlate concentrations of certain compounds and combinations of compounds to malodour (Hartung, 1992; Univ. of Minnesota, 2000). The correlation between ammonia and odour in livestock and poultry production has been studied by a number of researchers. A positive correlation has been found by some researchers (Pain & Misselbrook, 1990; Wood *et al.*, 2001) and no correlation has been found by others (Heber *et al.*, 1998; Schaefer, 1977; Verdoes & Ogink, 1997). Systems with low ammonia emissions are observed to also have low odour emissions and correlations found in some studies may depend on this (Jongebreur *et al.*, 2003).

Volatile organic compound measurements and odour

Different techniques for measuring odours from livestock wastes were evaluated by Hobbs *et al.* (1995). A photoionization detector (PID) was compared to olfactometry. This detector was equipped with a lamp with ionizing energy 10.2 eV. At this energy level, volatile organic compounds (VOCs), as well as ammonia and hydrogen sulphide, were included in the detection but water vapour, carbon dioxide and methane were excluded. The PID gave a linear response of diluted samples down to 1000 OU/m^3. Another study (Schiffman *et al.*, 2000), trying to correlate the total amount of VOCs and odour concentration using olfactometry, showed a poor correlation between VOC concentration and odour concentration.

Field sniffers

Measurements in the field have used trained odour panels moving in the vicinity of odour sources in order to measure the odour plume (*e.g.* Hartung & Jungbluth, 1997; Zhu *et al*., 2000). When moving towards the odour source they note when and where they notice an odour. In some measurements concentrations exceeding the odour threshold has been noted and in others concentrations exceeding the odour recognition threshold. Another method is based on field sniffers wearing a mask filtering their breath air through, for example, activated carbon. When they take off the masks at a specific time they note a value of the odour intensity at the specific point.

Odour dispersion

Emissions of odours are spread in a plume in the neighbourhood of odour sources. The concentration of odour decreases by the distance and vegetation and objects in the surroundings affect the dispersion. The weather greatly affects the dispersion and for certain weather conditions concentrated odour may occur at a distant range to the odour source. These weather types, however, do not occur so often. The dispersion is affected by the type of source, for example, a tall stack or an area source and the temperature of the emitted gases is also important.

Models that predict odour concentrations in neighbourhoods surrounding animal production sites may be useful tools when evaluating technologies to reduce the odour release at existing operations or when planning new operations. A number of models have been developed to predict the dispersion and the concentrations of pollutants at various distances from a source. A few meteorologically-based dispersion models have focused mainly on agricultural sources (Schauberger *et al.*, 2002; Schauberger *et al.*, 2001; Schauberger *et al.*, 2000; Schulze Lammers *et al.*, 2000; Smith, 1993). In a Danish study, a good correlation between dispersion model predictions and tracer gas measurements was found (Bjerg *et al.*, 2003). Dispersion models can be used for the estimation of setback distances between livestock production facilities and neighbours' residences. Setback distances used in legislation can sometimes be a single specified distance without consideration of source emissions. Other setback models consider source data. At the University of Minnesota a setback model, OFFSET (Odor From Feedlot Setback Estimation Tool) has been developed in order to predict the setback distance needed to obtain a given odour annoyance-free frequency (Jacobson *et al.*, 2001a; Jacobson *et al.*, 2000). The meteorological dispersion model INPUFF-2 was used to predict dispersion when developing the model. The OFFSET model is based on tabulated emission factors and predicts different setback distances for different magnitudes of emissions.

Structure of the work

The studied area in the thesis is shown in Table 2. Odour measurements used or studied in the papers are shown in the same table together with odours studied.

Table 2. *The contents of the papers in the thesis and the odour measurements used or studied*

Paper	Studied area	Odour measurements used / studied	Odour characters measured / studied	Odour types studied
I	Odour measurement (Review)	ENs	Odour concentration Odour character	Mainly farm odours
II	Odour release	Olfactometry using an olfactometer	Odour concentration	Poultry (laying hens)
III	Odour dispersion	Olfactometry using an olfactometer Neighbourhood monitors	Odour concentration Odour intensity	Pig odour Cow odour Poultry (turkey)
IV	Odour and well-being (Mainly review)	-	-	Various pleasant rated and unpleasant rated odours
V	Odour pleasantness	Olfactometry using an olfactometer	Hedonic tone	Pig odour Manure Poultry Cow barn n-butanol Perfume

Objectives

The general hypothesis of the thesis was that odour influences the quality of life, well-being and health of exposed human individuals and that correlations between measurements of various concentrations and properties of odours and human reactions exist. Furthermore, the hypothesis was that odour in and from animal production units has a negative impact. The general objective was to contribute to improved well-being and health by: (1) identifying factors important for odour release, (2) by studying odour dispersion and (3) by gaining knowledge of important factors and mechanisms triggering reactions to odours. The general objective was, moreover, (4) to review odour measurements using artificial sensors.

The detailed objectives for the included papers were:

Paper I:

- To review the literature regarding measurements of environmental odours by electronic noses.
- To discuss if electronic noses might be suitable for measuring farmstead odours at the present stage of development.

Paper II:

- To study odour and ammonia release in a system for laying hens.
- To study if ventilation and climate control strategies influence concentrations and emissions of odour and ammonia.
- To evaluate the influence of temperature, humidity and ventilation rate on odour and ammonia release.
- To study correlations between pollution factors.

Paper III:

- To study odour in the neighbourhood of poultry and livestock operations.
- To evaluate the OFFSET (Odor From Feedlot Setback Estimation Tool) model by neighbourhood monitors.
- To evaluate whether occurrence of annoying odour can be predicted or not.
- To evaluate whether intensities reported by neighbours are higher than those predicted by the model or not.
- To identify situations when predictions might be less good.

Paper IV:

- To review the literature regarding olfaction, olfactory responses, and odour influence on well-being and health. Targeting a deep understanding, the general literature as well as that with specific focus on animal production was reviewed.
- To find possible ways and guidelines for improvement of the quality of life for human individuals with regard to influence of odours.

Paper V:

- To study odour pleasantness.
- To study the relationship between hedonic tone and odour concentration for different types of odour from animal production facilities.
- To study if hedonic tone at a certain concentration is correlated to odour intensity for odour from animal production facilities.
- To examine the importance of personal characteristics like odour thresholds, age, place where a person grew up, and annoyance due to odours.

Materials and methods

*Paper **I*** was a review and information was sought mainly by means of electronic databases, journals and the Internet. Since this review focused on the present stage of the development of electronic noses, the search aimed mainly on finding newer publications published as from late 1980s. *Paper **IV*** was also mainly a review and literature searches were primarily carried out in the same way. A study of hazardous properties of volatile compounds related to animal production was also included in this paper. Documented health symptoms in lists of hazardous chemicals were identified for the 168 volatiles identified by O'Neill & Phillips (1992) and these symptoms were compared to those that might increase in the population around concentrated animal production sites.

Odour sampling and analyses using olfactometry were used in *Papers **II**, **III*** and ***V***. Sampling in *Papers **II*** and ***V*** was done using a vacuum sampling device manufactured by ECOMA (Honigsee, Germany) and Nalophan bags. In *Paper **III*** odour sampling was made with the help of Teflon® tubing connected to Tedlar® bags placed in a box where a vacuum was created by an air pump (Gay *et al.*, 2003). Odour samples from manure storages in *Paper **III*** were taken using a wind tunnel designed to simulate the atmospheric condition parallel flow without vertical mixing and similar to wind tunnels used in Australia (Jiang & Kaye, 2001; Jiang *et al.*, 1995; Schmidt *et al.*, 1999; Zhu *et al.*, 2000). Activated carbon filtered air was introduced at the inlet of the tunnel using a fan.

Odour samples in *Papers **II*** and ***V*** were taken to the laboratory at the Department of Agricultural Biosystems and Technology, at SLU (Swedish University of Agricultural Sciences) in Alnarp. Samples were analysed using procedures described in the European guidelines (CEN, 1999). A standardized panel and an ECOMA (Honigsee, Germany) TO7 olfactometer was used for the measurements of odour concentration (OU_E) in these samples. Odour samples in *Paper **III*** were analysed at the Olfactometry Laboratory at the University of Minnesota with the help of eight panellists and a dynamic dilution olfactometer (AC'SCENT® International Olfactometer, St. Croix Sensory, Inc., Stillwater Minn.). The procedures followed ASTM Standard and the guidelines suggested by the former proposed European standard (ASTM, 1997; CEN, 1997).

Emissions from buildings in *Papers **II*** and ***III*** were calculated from ventilation rates and measured concentrations of odour (and ammonia). Odour emission rates from manure storage units in *Paper **III*** were obtained from storage units and wind-tunnel areas, wind-tunnel air flow rate and measured odour concentrations in the collected samples.

Ventilation rates in *Paper **II*** were calculated from measured air speed in 5 points in a circular duct by using a hot-wire anemometer (Alnor, GGA-65P). Ventilation rates in *Paper **III*** were estimated using the carbon dioxide (CO_2) balance method (Albright, 1990; Phillips *et al.*, 1998). Carbon dioxide concentrations in buildings were measured using either a 0 to 0.2% CO_2 (0 to 2000 ppm) or a 0 to 1% CO_2 (0 to 10 000 ppm) Infrared Gas Monitor (Model 3600, MSA, Pittsburgh, Pa.).

In *Paper **II*** odour and ammonia were measured in a floor housing system in a small scale poultry house, a climate chamber, at the SLU research station Alnarps Södergård. The design of the chamber is shown in Figure 1. The housing system contained a bedding area, a manure bin area and laying nests. Manure conveyors were placed below a draining floor in the manure bin area. The area where the laying hens were kept was 47 m^2. The litter used in the experiment was small pieces of recycled paper. The hens were fed *ad libitum* and had free access to water. The chamber contained 356 hens on average during the experimental period. Manure was removed daily.

The room temperature was adjusted by control of the temperature in the space surrounding the chamber. The air flow rate was manually adjusted with a damper in the exhaust air duct. Temperatures and air flow rates were kept to a specific set point value for three or four days in order to get an approximate steady state balance. Temperatures were set to obtain chamber temperatures of 12, 15, 20, and 25°C. The ventilation rates were set to values ranging from about 1-5.3 $m^3/(h \cdot hen)$.

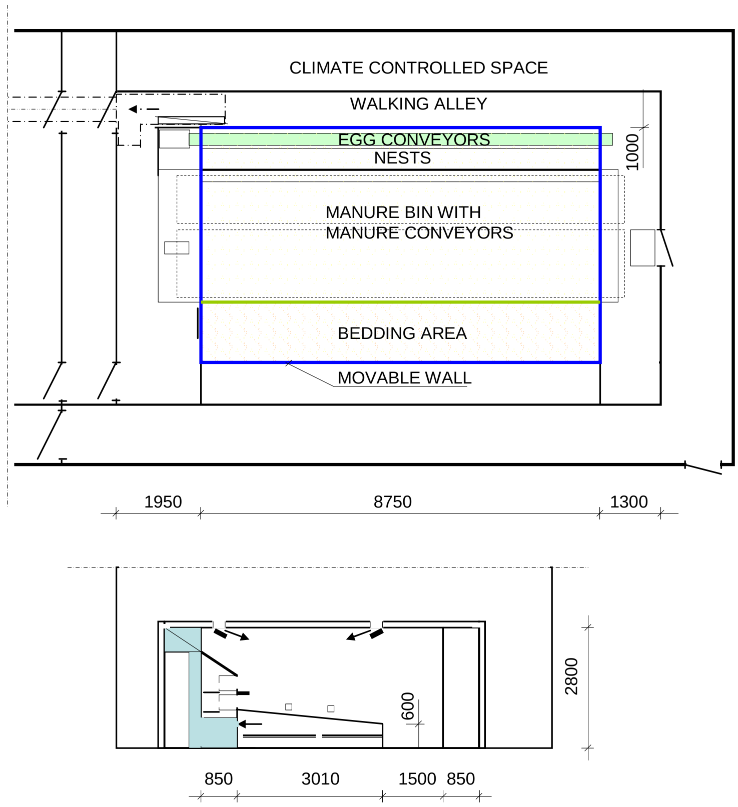

Fig. 1. Design of the chamber with laying hens.

Temperature, relative air humidity (RH), ammonia and carbon dioxide concentration were recorded using sensors and instruments connected to a logger and a computer. Temperatures were measured using thermocouples (type T) and Hygromer®-C80 sensors were used for measuring RH. The gas analyser used for measurement of ammonia was an infrared (IR) spectrophotometer, (Miran 203, Foxboro Analytical). Ammonia was also measured in the mornings by using

Kitagawa detection tubes. Odour samples were collected at about 9 a.m. before the manure on the conveyors was removed.

Values measured at about the same air flow rate were used to evaluate effects of temperature and values measured at about the same temperature were used to evaluate effects of different air flow rates.

In *Paper **III***, odour intensities predicted by OFFSET, were compared to odour intensities observed by neighbourhood monitors living in the vicinity of seven farms in five Minnesota counties. Four farms were swine operations, two were dairy operations, and one was a turkey operation. Emissions were measured at one more turkey farm. The number of neighbourhood monitors for each farm is listed in Table 3. Descriptions of the odour sources at each farm are listed in the same table.

The feature of the OFFSET model can be seen in Figure 2. The model predicts the distance from an animal production site where the odour intensity equals 2 on a scale from 0 to 5 for various emission values and atmospheric stabilities. Annoyance-free frequencies in the model are calculated for weather data in Minnesota. Emissions were measured and compared to values assumed in the model. The same scale of the emissions was obtained by multiplying the measured values by the model scaling factors.

The neighbourhood monitors were trained to estimate odour intensity prior to the study by use of the 5-step intensity scale of n-butanol dilutions (ASTM, 1999). Each neighbourhood monitor received odour event recording forms and when observing an odour, the event was noted on the form. Information was recorded regarding date, time and odour intensity. The scale for odour intensity was as follows: “none” (0), “slight” (1), “noticeable” (2), “very noticeable” (3), “strong” (4) and “extreme” (5).

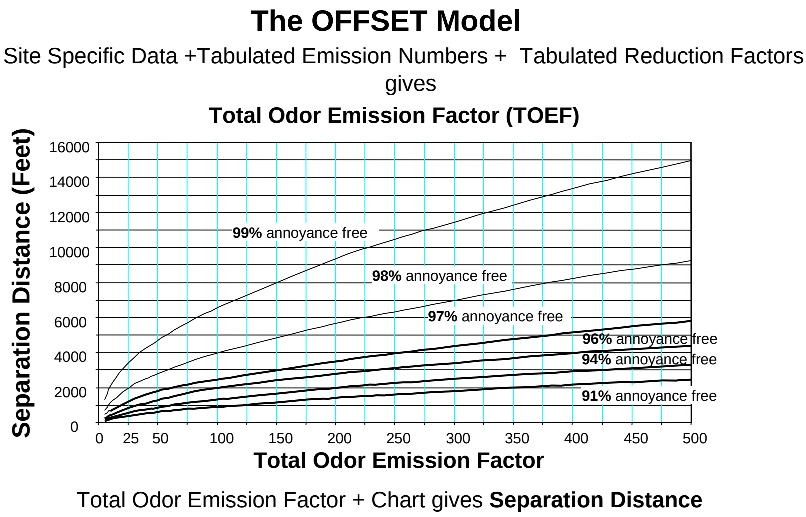

Fig. 2. The OFFSET model.

Table 3. *Description of odour sources at each farm and the number of odour monitors*

Farm *No.*	Animal housing or manure storage type	Houses (Animal capacity) *No. (No.)*	Ventilation	Monitors *No.* (Monitor ID)
1	Swine finishing	1 [1, 4] (360)	Natural and mechanical [a]	4 (1, 3, 8, 9)
	Swine finishing	1 [2, 3] (220)	Mechanical	
	Swine finishing	1 [1, 3] (512)	Natural [g] and mechanical [d, f]	
	Swine finishing	1 [2, 4] (330)	Natural [g] and mechanical [e]	
	Swine gestation	1 [2, 4] (120)	Natural [c]	
	Swine gestation	1 [2, 4] (300)	Natural [g] and mechanical [e]	
	Swine nursery	1 [2, 3] (1200)	Mechanical	
	Manure storage	Above ground tank [Str.]		
2	Swine finishing	2 [3, 5] (1000 + 1000)	Natural [b] and mechanical [d]	5 (61, 62, 63, 64, 65)
3	Dairy cows (Holstein)	1 [2, 6, 9] (462)	Natural [h]	1 (41)
	Dairy cows (Holstein)	1 [2, 7, 9] (330)	Natural [c]	
	Dairy cows (Holstein)	1 [2, 8, 9] (114)	Mechanical	
	Manure storage	1 Earthen basin [Liq.]		
4	Swine finishing	3 [3, 5] (2x500 + 2x500 + 2x500)	Natural [b] and mechanical [d]	1 (42)
5	Turkey brooder or finishing (Hens only)	1 [2, 6, 10] (11000)	Natural [b, s] and mechanical [w]	No observers
	Turkey brooder or finishing (Hens only)	1 [2, 6, 10] (11000)	Natural [c] and mechanical	
	Turkey finishing	1 [2, 6, 10] (15000)	Natural [b, s] and mechanical [w]	
	Turkey brooder (Chicks or poults)	1 [2, 6, 10] (37000)	Mechanical	
6	Turkey	1 [6, 10] (12000)	Natural [c]	3 (51, 52, 55)
7	Swine finishing	2 [3, 5] (1000 + 1000)	Natural [b] and mechanical [d]	2 (56, 57)
8	Dairy cows (Holstein)	3 [1, 7, 9] (500 + 200 + 200)	Natural [c]	4 (31, 32, 33, 34)
	Dairy cows (Holstein)	1 [2, 7, 11] (100)	Natural [c]	
	Manure storage (1st stage)	Earthen basin		
	Manure storage (2nd stage)	Earthen basin [Air]		
	Manure storage (3rd stage)	Earthen basin [Air, Sep.]		

[1] Flush; [2] Scrape; [3] Pens with slatted floor; [4] Pens with partially slatted floor; [5] Deep pit;
[6] Loose housing; [7] Free stall; [8] Tie stall; [9] Straw litter; [10] Sawdust litter; [11] Sand litter
[Str.] Straw cover (15 cm) applied May 5; [Liq.] Liquid manure; [Air] Aerated; [Sep.] Separated solids
[a] Curtain and chimney; [b] Curtains; [c] Curtains and open ridge; [d] Mechanical pit ventilation;
[e] No pit ventilation; [f] No pit ventilation in summer; [g] Nebraska mono slope; [h] Open front
[s] Summer; [w] Winter

Weather data were recorded using weather stations (CM10, Campbell Scientific, Inc., Logan, UT) measuring temperature, air humidity, wind direction and wind speed at 3 m above the ground, and solar radiation. Measured wind directions were used to validate that the farms in the study were likely odour sources for observations. Measured meteorological data was also used to estimate stability classes for which different OFFSET predicted intensities were calculated. In the evaluation, the atmospheric stability classes (Pasquill-Gifford stability categories) were calculated using the "Solar Radiation –delta T (SRDT) method" as a base (US-EPA, 2000).

In *Paper **V*** six different odours were analysed regarding hedonic tone with the help of 16 voluntarily participating panellists. The studied samples were odour from: (1) fattening pigs, (2) pig manure culvert, (3) laying hens, (4) dairy cows, (5) n-butanol, and (6) perfume. Odours from animal production facilities were sampled and n-butanol and perfume odour samples were prepared in the laboratory.

The panellists' odour thresholds for n-butanol were estimated from about 10 measurements for each panellist. Concentrations from low values of about 1 OU_E/m^3 up to high values obtained at the lowest dilution step of the olfactometer (*i.e.* about 1000 OU_E/m^3 for most odours) were presented to the panellists who rated the hedonic tone of the specific concentration. Each concentration was presented to the panellists during a certain specified period and after that they had some time to consider the rating before pressing the button of their choice. Concentrations were selected randomly by a computer program and blanks (*i.e.* no odour) were included. The hedonic scale ranged from "Extremely unpleasant" marked on the first button up to "Neither nor" on the fifth button and further up to "Extremely pleasant" on the ninth button. The panellists were instructed that "Extremely unpleasant" should represent the most unpleasant odour they had ever experienced and that "Extremely pleasant" should represent the most pleasant odour they had ever experienced.

The panellists engaged for rating the pleasantness of the odours were university staff and students. No screening of odour thresholds of the panellist was made prior to the experiment. Panellists were selected to some extent on a gender and age basis. All the panellists filled in a form with questions regarding personal data as well as regarding odour in their home and work environment, frequency of contact with animals at farms, and experience of the air environment within barns *etc*. A summary of this data can be seen in Table 4. The age of the 7 male and 9 female panellists varied from 27 up to 61 years with a mean of 43 years.

Table 4. *Description of the panellists*

Panellist No.	Age	Gender	Environment where panellists grew up	Annoyance to odour at panellists dwelling or staying environment	Symptoms of hay fever or suffering from stuffed nose when visiting a facility for pigs or cows or poultry or horses	Contact frequency with pigs or cows or poultry or horses	Annoyance level to the air environment or the odour when staying inside a facility for pigs or cows or poultry or horses	Annoyance level to odour adhering to clothes or hair or nose etc. when visiting a facility for pigs or cows or poultry or horses
	1= ≤40 years 2= >40 years	1= Male 2= Female	1= Town or village 2= Farm or house on the countryside	1= Annoyed by odour present sometimes or more often 2= Very little or not at all annoyed	1= Declare symptoms 2= No declared symptoms	1= Now and then or more often 2= Seldom or almost never	1= Annoyed 2= Very little or not at all annoyed	1= Annoyed 2= Very little or not at all annoyed
1	1	2	1	1	1	1	1	1
2	1	2	1	1	2	1	1	1
3	1	2	2	2	2	2	1	1
4	1	2	1	2	2	2	2	2
5	2	2	2	1	1	1	1	1
6	1	1	1	1	1	2	1	1
7	1	2	1	2	1	2	2	2
8	2	1	2	2	1	1	2	2
9	2	1	2	2	2	1	1	1
10	2	2	2	2	1	1	1	1
11	2	1	1	1	2	1	1	1
12	2	2	2	2	1	1	1	1
13	2	2	2	2	2	1	2	1
14	2	1	1	1	2	1	1	1
15	2	1	2	2	1	1	1	1
16	2	1	1	2	1	1	1	2

Statistic calculations

The statistics software package MINITAB (MINITAB for Windows, Release 12.21, Minitab Inc.) was used for evaluation of the data in *Papers **II***, ***III*** and ***V***. Besides descriptive calculations, mainly calculations of correlations and regressions between different variables were made in Paper ***II***. In *Paper **III*** data was analysed with the help of ANOVA, paired t-test and regressions. In Paper ***V*** both ANOVA and linear, quadratic and logistic regressions were used. Data was tested for normality in applicable cases.

Accuracy in measurements

By definition, in Europe (CEN, 1999) 1 OU_E /m^3 refers to the odour experienced when 123 mg n-butanol evaporates into 1 m^3 of odour neutral gas. This results in a n-butanol concentration of 40 parts per billion by volume (40 ppb_v). The criteria for qualified panellists are to fall in the range 20-80 ppb_v during ten measurements with a logarithmic standard deviation of less than 2.3. In the guidelines for olfactometers the accuracy for each dilution should be better than 20%. For modern calibrated olfactometers, a value of 10% accuracy compared to the calibration method, may be recommended by the manufacturers. The calibration table for the Ecoma olfactometer used in *Papers **II*** and ***V*** showed a difference of less than 6% compared to the reference measurements. The olfactometer and the panel together may be regarded as one measurement unit. It is stated in the guidelines that the repeatability shall be not greater than 0.477. This will result in a repeatability limit of 3 (=10 to the power of 0.477), *i.e.* the difference between two single measurements performed on the same testing material in one laboratory under repeatability conditions, should not be larger than a factor 3 in 95% of cases. Sampling errors may be greater than the errors in olfactometric testing.

Measurement of ammonia in *Paper **II*** was performed with the help of an infrared analyser (Miran 203). According to the manufacturer the precision is ±5% at full scale deflection.

Ventilation rates in *Paper **II*** were calculated from air speed in a number of measure points in a duct. The hot-wire anemometer used (Alnor, GGA-65P) differed less than ± 2% from measurements used as reference at the calibration and its precision may be estimated to ±2.2%. Regarding this, the accuracy for the ventilation rate can be estimated to ±6% (NVG, 1992).

Ventilation rates in *Paper **III*** were estimated from assumptions of carbon dioxide release and measured concentrations of carbon dioxide. The accuracy using this method may be regarded low. The precision range of the Infrared Gas Monitor was ±1% of the concentration *i.e.* less than ±20 ppm for the 0 to 0.2% model and less than ±100 ppm for the 0 to 1% model.

Results - summary of included papers

Odour measurement

The EN (electronic nose) as an alternative odour measurement method at the present stage of development was discussed in *Paper **I***. An EN and other techniques for measuring odours from livestock wastes were studied by Hobbs *et al.* (1995) and it was found that the EN could distinguish between odours at high concentrations but the response from the electronic nose to concentration was non-linear. In another early study, a signal proportional to the concentration of volatile compounds from artificial pig slurry was found and the chemicals were not observed to damage the sensors (Persaud *et al.* 1996). In a study of odours from acetic acid and synthetic pig slurry, the EN was unable to detect the odour at first but modifications gave a somewhat better result (Classen *et al.*, 1997). An EN response to odour concentrations down to 50 OU/ m^3 was found by Misselbrook *et al.* (1997) and a response line could be fitted to odour concentrations. In another study using an EN (Rieß *et al.*, 2000) a distinction between a beef bull and a dairy cattle barn was found, although the samples were rated very similar by human noses. Samples collected four weeks later differed in type from the original ones. During a week study, diurnal EN odour concentration response was observed in two departments with fattening pigs (Rieß *et al.*, 2000). In studies of waste water treatment plants and composting sites it has been possible to correlate EN responses to odour in a specific location. However, for different locations this has been found hard or unsuccessful (Bockreis & Jager, 1999; Bockreis & Jager, 1998; Stuetz *et al.*, 1999; Stuetz *et al.*, 1998).

Odour and ammonia release

Measured odour concentrations in the floor housing system for laying hens (*Paper **II***) were in the range of 50-1100 OU_E/m^3. Ammonia concentrations were in the range of 1-45 ppm. Measured emissions were 0.6-2.5 OU_E /(m^2·s) and 11-69 µg/(m^2·s) for odour and ammonia, respectively. Increased temperature and increased humidity were followed by increased odour and increased ammonia both regarding concentrations in the exhaust air as well as the emissions (Table 5). A stronger correlation was found to water vapour pressure (VP) than to relative air humidity (RH) or to water vapour deficit (VD). Increased temperature as well as increased VP resulted in a considerable increase in odour and ammonia concentrations and emissions (Figure 3, 4 and 5). In the study, an increase of odour concentration was positively correlated to ammonia and carbon dioxide concentrations.

Table 5. *Correlation coefficients and significance levels found for ventilation rates between 0.93 to 1.21 m^3/(h·hen)*

	Odour concentration Correlation	Odour emission Correlation	Ammonia concentration Correlation	Ammonia emission Correlation
Temperature	0.851**	0.880**	0.683*	0.662 *
RH	N.S.	N.S.	0.694*	0.702*
VD	0.724*	0.704*	N.S.	N.S.
VP	0.869**	0.918***	0.796**	0.775**

N.S. = Not Significant; * = Significance level p≤0.05; ** = Significance level p≤0.01; *** = Significance level p≤0.001

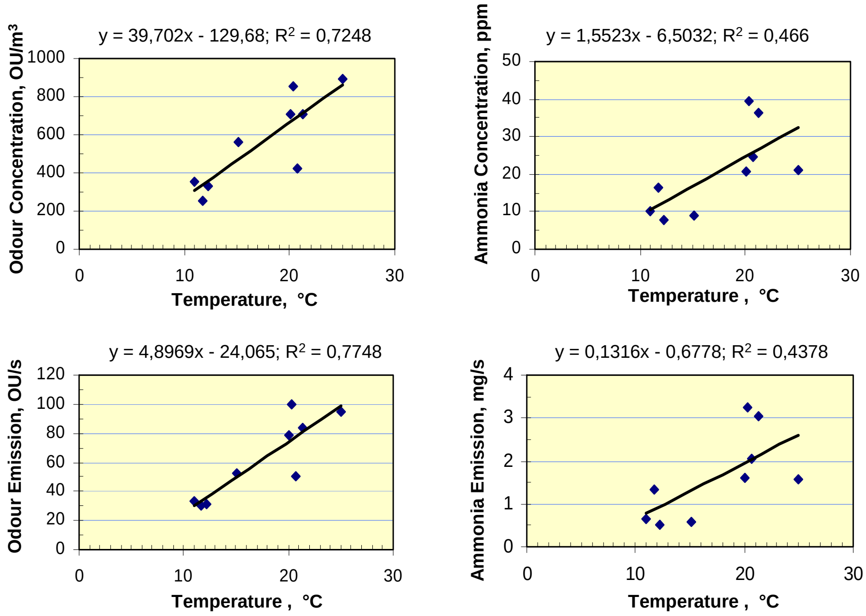

Fig. 3. Odour and ammonia concentrations and emissions versus temperature for air flow rates ranging from 0.93 to 1.21 $m^3/(h{\cdot}hen)$.

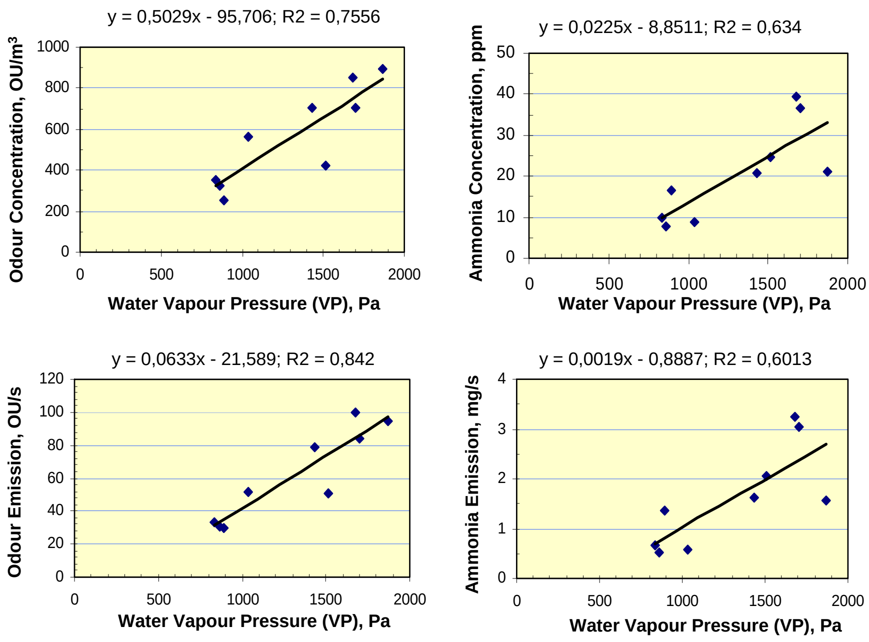

Fig. 4. Odour and ammonia concentrations and emissions versus water vapour pressure for air flow rates ranging from 0.93 to 1.21 $m^3/(h{\cdot}hen)$.

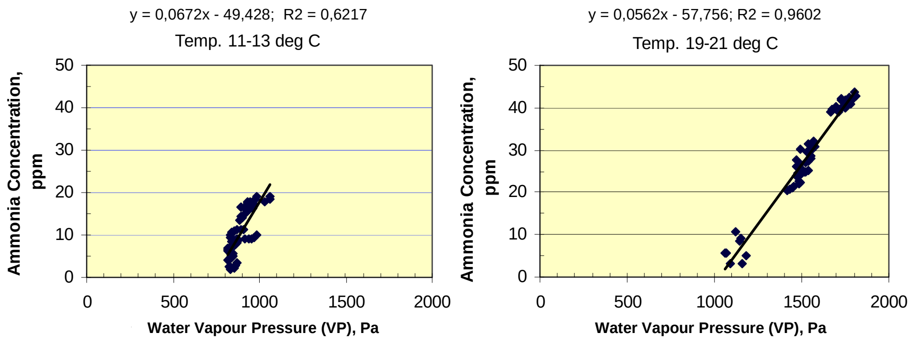

Fig. 5. Ammonia concentration versus water vapour concentration for exhaust air temperatures 11-13°C and 19-21°C for all values between 8 a.m. and 11 a.m. during the experimental period.

The total measured emissions in *Paper **III*** were similar to the OFFSET model emission values for three farms, about 50% higher for two farms, about 100% higher for two farms and more than 10 times higher for one farm.

Odour dispersion and odour in the neighbourhood

A large number of observations of odour intensity of 2 or higher were made by the neighbourhood monitors on occasions when the OFFSET model predicted lower intensities (*Paper **III***). Observed and predicted intensities for two of the farms were in agreement and for one farm observed intensities differed moderately from predicted values. Observed intensities were considerably higher than predicted for three farms. Observed odour intensities were higher than predicted at predicted intensities 0, 1, and 2, similar to predicted at predicted intensities 3 and 4 and lower than predicted at predicted intensity 5 (CI 95%). Some odour was predicted in 94% of the observed odour events. No significant differences between observed and predicted intensities were seen for the meteorological stabilities class E combined with wind speeds below 3.1 m/s and class F combined with wind speeds below 1.3 m/s and between 1.3 and 3.1 m/s. Curves for these stabilities represent 97, 98, and 99% annoyance-free frequencies in the OFFSET model. A number of observations of significantly higher intensities than predicted were observed at less stable weather conditions.

Physical impact of odorants on human well-being

In *Paper **IV*** odour and odorant influence on well-being was reviewed and hazardous properties of volatile substances related to farming were studied. Studies suggest that our brain and our nervous system may react to odorants in low or below odour concentrations without our being conscious of it (Lorig, 1994; Sobel *et al.*, 1999). However, odour is said to precede irritation for most industrial chemicals (Shusterman, 2001). The far greatest number of volatiles present in connection with farming occurs in very small concentrations compared to TLVs (Schiffman *et al.*, 2001).

Table 6. *Symptoms with observed increased frequency in the vicinity of animal production facilities and selected observed chemicals with ability to cause the symptoms*

Symptoms with suggested increased frequency		Chemical compounds with ability to cause observed symptoms at hazardous concentrations [a]
Site/type of irritation	*Symptoms found*	*On symptom and harmfulness basis selected volatiles (from a list containing 168 compounds present in animal production [b])*
Nose	Irritation in nose [c, d, e]	Ethanol, 2-methoxy- ; Ammonia; Benzene; Formaldehyde; Hydrazine; 2-Butenal (Crotonaldehyde); Sulphur dioxide
Eyes	Irritation in the eyes [c, f]	Ethanol, 2-methoxy-; Ammonia; Benzene; Formaldehyde; Hydrazine; Carbon disulphide; 2-Butenal (Crotonaldehyde); Sulphur dioxide; Hydrogen sulphide
Throat	Irritation in throat [c, d, e]	Ethanol, 2-methoxy- ; Ammonia; Benzene; Formaldehyde; Hydrazine; 2-Butenal (Crotonaldehyde); Sulphur dioxide
Respiratory	Breathing difficulties [d] Breathing problems [f] Chest tightness [c, f] Cough [c, e]	Ethanol, 2-methoxy-; 2-Propenal (Acrolein); Ammonia; Benzene; Formaldehyde; Hydrazine; Carbon disulphide; 2-Butenal (Crotonaldehyde); Sulphur dioxide; Hydrogen sulphide
Skin	Skin irritation [c]	Ammonia; Benzene; Formaldehyde; Hydrazine; Carbon disulphide; 2-Butenal (Crotonaldehyde); Sulphur dioxide
Head	Headache [d, e, f]	Ethanol, 2-methoxy- ; Ammonia; Benzene; Hydrazine; Carbon disulphide, Methanol, Sulphur dioxide, Hydrogen sulphide
Gastric	Nausea [d, f]	Ammonia; Benzene; Hydrazine; Carbon disulphide; Methanol; Sulphur dioxide; Hydrogen sulphide
Gastric	Diarrhoea [c, e]	(Micro-organisms or ingested compounds?) *****
Mental	Tiredness [c, g] Weakness [f, g] Less vigour [g]	Ethanol, 2-methoxy-; Carbon disulphide
Mental	Confusion [g]	Hydrogen sulphide
Mental	Depressions [g]	Carbon disulphide
Mental	Tension, Anger [g]	Ethanol, 2-methoxy-, and Carbon disulphide may cause changes of the personality
Mental	Sleeping difficulties [d]	Hydrogen sulphide
Mental	Annoyance [d]	(All odorous compounds at high concentrations) *****
-	Reduced quality of life [e]	(Odorant mix) *****

[a] New Jersey Department of Health; [b] O'Neill & Phillips, 1992; [c] Keller & Ball, 2000;
[d] Sidhu *et al.*, 1997; [e] Wing & Wolf, 2000; [f] (Thu *et al.*, 1997; [g] Schiffman *et al.*, 1995;
* Authors comment

CAS Numbers:
2-Butenal (Crotonaldehyde) - Cas No. 4170-30-3); 2-Propenal (Acrolein) - Cas No. 107-02-8);
Ammonia - Cas No. 7664-41-7; Benzene - Cas No. 71-43-2; Carbon disulphide - Cas No. 75-15-0;
Ethanol, 2-methoxy- - Cas No. 109-86-4; Formaldehyde - Cas No. 50-00-0;
Hydrazine - Cas No. 302-01-2; Hydrogen sulphide - Cas No. 7783-06-4; Methanol - Cas No. 67-56-1;
Sulphur dioxide - Cas No. 7446-09-5

Chemicals in high concentrations may damage the respiratory tract and the olfactory system, however, reflexive responses like halted inhalation, increased secretion, sneezing, and engorgement of the tissue in the nasal passages are triggered with the help of the trigemninal nerve and these may minimize or prevent injury (Doty, 2001; Doty & Hastings, 2001; Schiffman, 1998). Volatiles with high water solubility (*e.g.* ammonia and organic acids) may primarily irritate the eyes and the nose (Shusterman, 2003; U.S. Dept of Health Human Services, 1986). Odorants like acetic acid may decrease the tidal volume (the volume of air in a breath) and change respiration (Warren *et al.*, 1994). A number of chemicals like ammonia, sulphur dioxide, acetone, benzene and trichlorethylene may alter the sense of smell (Amoore, 1986; Doty & Hastings, 2001). Chemicals may also enter the central nervous system (CNS) (Barthold, 1988; Bergman, 2000; Broadwell, 1992; Doty & Hastings, 2001; Langston, 1985; Talamo *et al.*, 1989).

Comparing 168 chemicals listed by O'Neill and Phillips (1992) to a list of chemicals with hazardous properties (Swedish National Chemicals Inspectorate, 2001) gave the result that 80 of these chemicals present in animal production have hazardous properties. Furthermore, among these are chemicals, which at above TLV level, may cause those symptoms reported in the neighbourhood (Table 6).

Stress, mood and annoyance related to odour

A further result described in *Paper **IV*** is that odour may affect stress, mood and annoyance. Release of adrenaline, noradrenaline and cortisol is a stress response in the body. Studies indicate that increased levels of cortisol might be correlated to odours (Pause *et al.*, 1996; Steinheider *et al.*, 1993). Sensitivity to odour might increase depression (Doty *et al.*, 1988). A number of studies has suggested that odours have stressful and relaxing effects. Irritating odours may increase blood pressure and cause alterations in blood sugar levels (Martin, 1996) while pleasant-rated odours may decrease blood pressure, heart rate and respiratory rate (Dayawansa *et al.*, 2003; Nagai *et al.*, 2000). Malodour may cause stress while pleasant odours may cause relief from stress (Tomonobu *et al.*, 2001). A number of studies have suggested that odours affect mood and attitudes (Baron, 1990; Baron, 1986; Baron, 1980; Benton, 1982; Chen & Haviland-Jones, 1999; Knasko, 1992; Lehrner *et al.*, 2000; Martin, 1996; Schiffman, 1991; Schiffman *et al.*, 1995a; Schiffman *et al.*, 1995c). It has been suggested that pleasant odours evoke happiness and surprise (Alaoui-Ismaïli *et al.*, 1997) and that unpleasant odours evoke disgust and anger (Alaoui-Ismaïli *et al.*, 1997; Evans & Cohen, 1987; Vernet-Maury *et al.*, 1999). Studies have also suggested that odours may affect performance in work (Barker *et al.*, 2003; Ludvigson & Rottman, 1989).

Both physical and cognitive expectations may be involved in response to odours (Dalton *et al.*, 1997; Sucker *et al.*, 2001), and irritation increases with time (Clausen *et al.*, 1987; Kerka & Humphreys, 1956). Annoyance due to odour has been suggested to mediate decreased health, although symptoms at great exposure may have other causes (Luginaah *et al.*, 2002; Steinheider, 1999; Steinheider *et al.*, 1998). Studies suggest that neighbours of swine production facilities can experience health problems more frequently than comparable population groups (Keller & Ball, 2000; Schiffman *et al.*, 1995b; Sidhu *et al.*, 1997; Thu, 2002; Thu *et al.*, 1997; Wing & Wolf, 2000). Symptoms like irritation in the nose, eye and throat, cough, shortness of breath, hoarseness and nasal congestion, drowsiness, stress, headache, nausea, palpitations and also alternations of mood, are frequently reported (Schiffman *et al.*, 2000). The development of psychological problems has also been suggested (Melvin, 1995; Schiffman *et al.*, 1995b). Symptoms like headache, gastric trouble, and palpitations are frequently reported in the general population (Rief *et al.*, 2001). Emissions from odour sources may increase these frequencies (Herr *et al.*, 2003). It has been suggested that symptoms might be related to both odour and worry (Shusterman, 2001; Shusterman *et al.*, 1991;). Coping styles are suggested to be important and avoidance may decrease annoyance, mental distraction may decrease annoyance to some extent; trying to solve the problem may increase annoyance (Sucker *et al.*, 2001; Winneke *et al.*, 1996).

Odour frequency is considered to have great significance for annoyance and odour intensity, duration, pleasantness, and location of the receptor are considered to be other important factors (Both, 2001; Jiang & Sands, 1998; Miedema *et al.*, 2000; Schulte, 1997; Steinheider *et al.*, 1998; Sucker *et al.*, 2001). Figure 6 shows an attempt to schematically illustrate the relationship between odour and human reactions related to well-being and health.

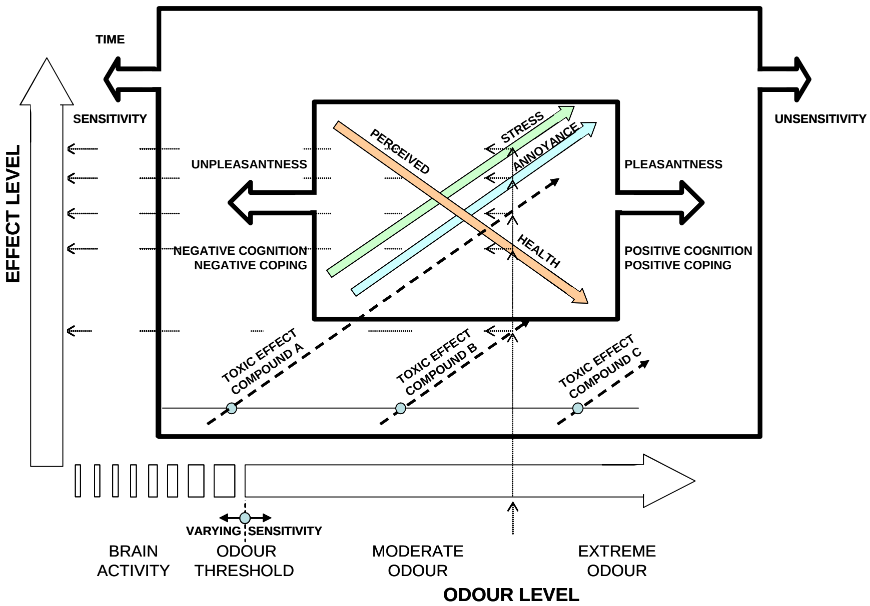

Fig. 6. Schematic illustration of health related response to odour and odorants. Moving boxes illustrate the influence of main factors affecting response levels. For example, increased time moves the large box to the left in the diagram resulting in more annoyance, more stress, lower perceived health and higher toxic effects for compounds present at the same odour level.

Odour pleasantness

In *Paper **V**,* the odour thresholds for the panellists varied between 26 ppb and 466 ppb n-butanol. Female panellists had significantly lower odour thresholds than their male counterparts. Panellists older than 40 years had a higher odour threshold on average than those below the age of 40. At low concentrations, odour from pigs and laying hens were rated pleasant in a few observations. Odour from the cow barn was rated pleasant in more observations and also at 1000 OU_E/m^3 by one observer. Figure 7 shows hedonic tone regressions as a function of log^{10}(odour concentration). Regression lines were similar for odour from pigs and laying hens. The regression lines found for these odours correspond to a hedonic tone of -0.5 at odour concentrations of 4-5 OU_E/m^3, -1 at 14-16 OU_E/m^3, and -2 at about 200 OU_E/m^3. For odour from the cow barn the regression line corresponds to a hedonic tone of -0.5 at an odour concentration of 6 OU_E/m^3, -1 at 37 OU_E/m^3, and -2 at about 1100 OU_E/m^3.

The influence of the characters and backgrounds of the panellists on ratings of hedonic tone is shown in Table 7. A dichotomized rating of hedonic tone compared to average rating was used as response, i.e. (1) higher hedonic tone than the regression line or (2) lower hedonic tone than the regression line. A model with four predictors was used, *i.e.* (1) odour threshold below or above 80 ppb n-butanol, (2) age below or above 40 years, (3) grown up on a farm or in a house in the countryside compared to grown up in a town or village, and (4) very little or not at all annoyed by odours in the dwelling or staying environment compared to annoyed by odours present sometimes or more often. A significant increase of the hedonic tone of odour from animal houses was found for panellists with high odour thresholds. Panellists reporting no annoyance due to odour in their dwelling or staying environment reported significantly increased hedonic tone for odour from pigs, pig manure culvert and cows.

Discussion

Odour measurement

In *Paper **I*** the use of ENs in measuring farm odour was reviewed. Satisfying properties regarding ageing, stability in temperature, humidity and other environmental factors might be a problem at least for some ENs. In a study, constant humidity and constant temperature were suggested in order to avoid sensor changes (Kalman *et al.*, 2000). Different opinions on the stage of development of the EN technology have been expressed. It has been noted that most studies deal with bench-top instruments (Strike *et al.*, 1999), and that no ENs at their present state can be used for *e.g.* measuring fruit ripening and vegetable quality (Sarig, 2000).

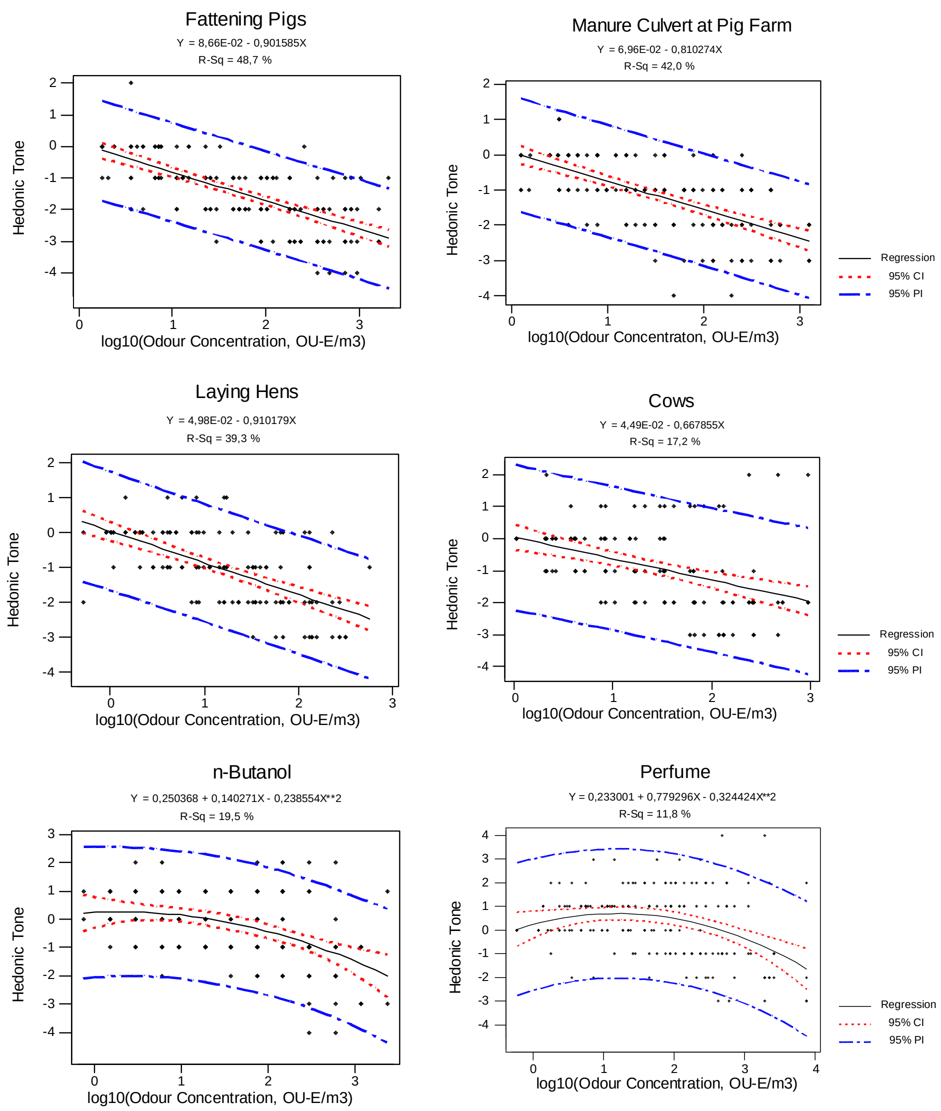

Fig. 7. Hedonic tone as a function of odour concentration with Regression lines, Confidence intervals (CI) and Prediction intervals (PI) at 95% probability levels.

Table 7. *Influence of panellists' characteristics and backgrounds on ratings of hedonic tone*

Sample Type	Predictors	Influence on rating of hedonic tone	Odds, Ratio	Odds, 95% CI
Fattening pigs	High odour threshold	Increase *	2.24	1.07-4.68
	High age	N.S.		
	Grown up on the countryside	Decrease*	0.33	0.12-0.89
	No annoyance to odour at dwelling[1]	Increase**	3.99	1.61-9.93
Manure culvert at pig farm	High odour threshold	Increase**	3.29	1.45-7.48
	High age	N.S.		
	Grown up on the countryside	N.S.		
	No annoyance to odour at dwelling[1]	Increase***	5.64	2.17-14.67
Laying hens	High odour threshold	Increase***	6.50	2.69-15.72
	High age	N.S.		
	Grown up on the countryside	N.S.		
	No annoyance to odour at dwelling[1]	N.S.		
Cows	High odour threshold	Increase**	3.83	1.65-8.90
	High age	N.S.		
	Grown up on the countryside	N.S.		
	No annoyance to odour at dwelling[1]	Increase**	4.45	1.67-11.81
n-Butanol	High odour threshold	N.S.		
	High age	N.S.		
	Grown up on the countryside	N.S.		
	No annoyance to odour at dwelling[1]	N.S.		
Perfume	High odour threshold	N.S.		
	High age	N.S.		
	Grown up on the countryside	N.S.		
	No annoyance to odour at dwelling[1]	N.S.		

[1] Very little or not at all annoyed to odour in their dwelling or staying environment

* Significance level $p \leq 0.05$ ** Significance level $p \leq 0.01$ *** Significance level $p \leq 0.001$

It has been predicted that the use of ENs to measure odours from agriculture, composting and sewage plants lies in the immediate future (Heining & Wiese, 2000). To identify and quantify gases in a binary mixture has been shown to be possible (Eklöv & Lundström, 1999). Emissions from farm houses contain a large number of volatiles, among which some are odourless. A perfect electronic nose should mimic the human olfactory system which has 500-1000 different receptor cells, disregard odourless compounds, humidity and temperature and furthermore know the human perception of different gas mixtures. The reviewed literature in *Paper **I*** suggests that measuring farm odour from a specific source by an EN might be possible during a limited time period. It further suggests that odours which smell about the same to humans might be put in different groups (different characters) by an EN. Results of more recent studies of ENs are mixed. In a study, it was concluded that ENs are still in the development stage (Powers, 2001). ENs have been suggested to have a potential for measuring dynamic changes of odour (Brose *et al.*, 2001) and they may be used to discriminate between different gas mixtures (Bourgeois & Stuetz, 2002; Chavez *et al.*, 2004a; Chavez *et al.*, 2004b). In experiments fast response times have been achieved (Yuwono & Schulze Lammers, 2004). In another study, it was indicated that EN technology can be trained to predict odours from manure lagoons with good correlation to olfactometry and a reasonably good estimation of odour in nine unknown samples was found (Sohn *et al.*, 2003).

Odour release

Measured odour emissions from the floor housing system for laying hens in *Paper **II*** were likely to be reduced by the daily removal of manure in the manure bin area. This has been found to lower ammonia concentrations in similar systems (von Wachenfelt *et al.*, 2002). The odour emissions were somewhat lower than those found for chickens on litter (Jiang & Sands, 1998). Measured ammonia emissions were mainly high compared to values for battery cages reported by Müller, *et al*. (2003). Increased temperature and increased air velocity may together with a number of other factors increase ammonia release (Gustafsson & von Wachenfelt, 2004) as well as odour release (Jongebreur *et al.*, 2003). Temperature and humidity may affect volatilization as well as the activity of micro-organisms. Less anaerobic conditions in manure with low moisture content has been suggested to decrease odour emission (Jacobs, 1994; O'Neill & Phillips, 1991). Both odour and ammonia emissions in the present study showed a strong positive correlation to temperature and humidity (water vapour pressure). Explanations might possibly include adsorption processes and wetting and drying of exposed solids. Emissions did not significantly increase with air flow rate and location of most of the manure below the draining floor in the manure bin area might be an explanation. The found correlation between ammonia and odour concentrations within the house may depend on the fact that both ammonia and odour concentrations were low some periods during the experiment.

Odour in the neighbourhood

To use neighbourhood monitors for reporting odour might be interesting since they stay in the area. Neighbourhood monitors reports in *Paper* ***III*** for weather conditions representing 99, 98, and 97% annoyance-free frequencies in the OFFSET model were in agreement with predictions. The results further suggest that longer distances than those predicted by the OFFSET model might be needed to obtain annoyance free frequencies of 94 and 91% for a number of farms. Differences may to a great extent depend on a variation of emissions. Variations are likely for all sources and are possibly greater for manure storages depending on wind effects *etc*. Observations of higher intensities than predicted may also depend on, for example, manure removal or background odours from land application of manure. Observed differences between observations and predictions could, to some extent, depend on a bias between some neighbourhood monitors and the n-butanol scale.

Variation of odour concentrations in an odour plume is another factor that may affect the result. Considerable variation of odour intensity in the field has been found in other studies (*e.g.* Zhu, 2000) and odour in samples has been observed to differ from observations in the field (Zhang *et al.*, 2001). Variation of odour concentration, or peak to mean ratios, may be far greater for less stable weather conditions than for stable conditions (Schauberger *et al.*, 2002; Smith, 1973). Peak to mean ratios may, furthermore, be greater near the source than for longer distances and greater for point sources than for area sources (Best *et al.*, 2001). It has been speculated how humans respond to varying odour in the environment; Best *et al*. (2001) indicate that "odour response may be more related to the general characteristics of fluctuations of concentrations away from the mean than just the value of peak concentration".

Odour and well-being

In *Paper* ***IV*** odour and well-being was discussed. An odour may produce symptoms without toxic effects and it can be present when toxic effects of pollutants occur (Schiffman *et al.*, 2000). Health problems are common for workers in swine production (Cole *et al.*, 2000), however, similar problems for neighbours seem inexplicable (Donham, 2000). Among substances present in poultry and livestock operations are chemicals which may be hazardous at 1 ppm or below, *i.e.* 2-propenal (acrolein), benzene, formaldehyde, hydrazine, and 2-methoxy-ethanol (New Jersey Department of Health) but concentrations are far below TLVs (Schiffman *et al.*, 2001). Synergistic effects, involving, for example, dust, may occur and increase symptom frequencies (Thu, 2002). However, these effects are not likely to result in similar symptom frequencies for workers and neighbours. The biological effect depends on the product of the stimulus intensity and duration of exposure (Bunsen & Roscoe, 1855; Jacob *et al.*, 2003). Part of an explanation may be that annoyance is the stimulus intensity mediating perceived health. Adaptation may occur in farmers and sensitization may occur in neighbours. Cognition and coping may also affect perceived health.

Regarding air quality in the work environment in animal production facilities, odour might serve as a measure of air pollution. This has been suggested for other types of buildings (Fanger, 1991; Fanger, 1988a; Fanger, 1988b).

Odour pleasantness

In *Paper **V*** odour pleasantness was studied and odour from animal production facilities showed a continuous decrease by concentration. The result suggests that pig odour with a concentration of 70 OU_E/m^3 will be rated unpleasant in 95% of the exposures and that it will be found considerably more unpleasant in an average observation. Furthermore, some odour exposures (5%) with a concentration of 3 OU_E/m^3 will be rated as unpleasant as –2 on a hedonic tone scale where 0 is neutral and -4 extremely unpleasant. On average, the unpleasantness of odour from laying hens and manure culverts in pig production facilities may be similar to odour from fattening pigs at the same concentrations. Personal odour preferences may be quite important for odour from dairy cows and this odour may, on average, be found less unpleasant than the others at the same concentration. Odour from dairy cows was found pleasant by individuals also at high concentrations which was not the case for odour from pigs or from laying hens. The result suggests that concentration explains a good deal of the hedonic tone of odour from pigs and laying hens and also that personal characteristics and preferences are of great importance for odours like n-butanol and perfume. Unpleasant odours were rated more pleasant by panellists with high odour thresholds, which could be expected since such persons do not notice low level odours. In the study, panellists who had grown up in the countryside found odours from fattening pigs more unpleasant than those who had grown up in a town or a village. The opposite could have been expected and a possible explanation might be sensitization. Personality might explain why pig and poultry odours were rated as more unpleasant by persons annoyed by odours in their dwelling and staying environment than by those not annoyed.

On a 5 point hedonic scale the regression lines in the present study suggest that pig odour at concentrations of 8-10, 65-73, and 500-600 OU_E/m^3 represent –1, -2, and –3, respectively. In an American study, pig odour at concentrations of 25, 72, and 216 OU were found to represent intensity of 1, 2 and 3, respectively, on a 5 point intensity scale (Jacobson *et al.*, 2000). Concentrations which resulted in a hedonic tone –2 and intensity 2 in the two studies were similar (OU is similar to OU_E/m^3).

General discussion

Regarding odour release studied in *Paper **II***, attempts were made to find a correlation to expressions describing microbial activity as a function of temperature and to expressions describing evaporation of water. However, no good correlations were found and adsorption phenomena correlated to temperature and humidity might perhaps be more important for the release of odour and gases in the system studied. Regarding the impact on the neighbourhood, manure handling systems might be important. Increased frequencies might occur when using liquid manure systems (Wing & Wolf, 2000).

The reviewed literature in *Paper **IV*** indicates that five types of regulations are used for agricultural odour sources (Mahin, 2001). Regulation specifying a limit for a specific gas may have a weak correlation to odour in the neighbourhood. A given setback distance for a certain type of animals (used, for example, in a Swedish recommendation) does not consider the size of emissions. Limits referring to dispersion modelling may, for a specific site, require some work but for good models this could produce a good result. Measuring odour frequencies in the field, as in the German model (Both, 2001), should be a good method, however, it may involve quite a lot of work. Setback distances with site-specific information were studied in *Paper **III*** and the method might be interesting since it requires a limited amount of work.

A crucial point to consider concerning the influence of odour and odorants on well-being and health is which combinations of time frequencies and odour concentrations produce the following: (1) toxicological effects from gases or co-pollutants, (2) psychological effects on well-being and health, and (3) combined toxic and psychological effects on well-being and health. Regarding the Bunsen-Roscoe law (Bunsen & Roscoe, 1855) the biological effect should be the product of exposed time and intensity of exposure. For odour from livestock and poultry an odour concentration of 7 OU with limited excess has been suggested (Iowa State University and the University of Iowa Study Group, 2002). In *Paper **III***, modelled concentrations of less than 3 OU from buildings and less than 8 OU from manure storages were used. In discussions among researchers, even lower values have been talked about. Odour pleasantness has been found to have a bearing on the annoyance level (Miedema *et al*., 2000). Findings in *Paper **V*** indicate that concentrations as low as 3 OU_E/m^3 may have a considerably low hedonic tone in some observations. A number of factors complicate predictions of annoying odour exposure in the surroundings and among these are variations in concentration and limited knowledge of human response to these variations. Regarding exposed time, it has been suggested that annoyance-free frequencies differing more than a couple of percent from 100% may cause annoyance (Forsberg & Lindvall, 2004). With the assumption in *Paper **III*** that annoying odours are represented by odour intensity 2 on a 5 point intensity scale, distances for annoyance-free frequencies of 97% or more may be calculated by the model used in this paper. In practice, these distances may be difficult to obtain and personal characteristics of exposed individuals may decide whether these individuals will be annoyed or not. Results in *Paper **III*** suggest that odour thresholds are important for rating of odour pleasantness and, in general, women may react more on odours than men since on average they have been found to have lower odour thresholds and to be more sensitive to odours than men.

Conclusions

A large number of factors are involved when odours and odorants are released, dispersed and exposed to human individuals and lead further to an impact on the well-being and health of exposed individuals. The following general main conclusions can be drawn from the studies:

- The main method for measuring odours is olfactometry. ENs can be sensitive enough for measuring agricultural odour concentrations, and the response of an EN can be correlated to concentrations of odours from the same place during a specific time.
- Odour and ammonia release vary by climatic conditions in animal production facilities. Decrease in temperature and in humidity can decrease concentrations and emissions. Climate control may decrease release and emissions. Odour and ammonia may have a stronger correlation to VP than to RH.
- Time frequencies for the occurrence of various odour intensities in the odour source environment can be estimated by dispersion models. The OFFSET setback model may predict 99, 98 and 97% annoyance-free frequencies correctly for those in the surroundings of livestock and poultry operations with odour thresholds close to the median in the population, if the model assumption is correct, i.e. that intensity 2 on a 5 point scale represents the limit for annoyance. Correlations between model predictions and true exposure with less stable weather conditions are weaker. Difficulties in finding the true size of emissions, variation of emissions and fluctuations in odour plumes are factors complicating predictions of odour in the neighbourhood.
- Increased frequencies of symptoms of a respiratory nature, eye irritations, stress, palpitations, headache, nausea and alterations of mood have been reported in the vicinity of livestock and poultry operations. The causes can be odour-mediation through stress and annoyance, co-existing compounds and/or gases where synergistic effects increase the influence, or a combined impact.
- Odour impact on humans can be reduced by: measurements giving a gain in knowledge of systems to choose among, technical arrangements, decrease of odour release and emissions, and planning suitable sites for odour-generating activities. Cognition and individual coping styles influence annoyance and information might decrease their influence.
- Odour pleasantness influences annoyance. The pleasantness of odour from fattening pigs, laying hens and dairy cows decreases by concentration for an average observer. Odour from dairy cows may be rated more pleasant by an average observer than odour from pigs and hens. The hedonic tone may be more strongly correlated to odour intensity for odour from pigs and hens than for odour from cow barns. Individuals with high odour thresholds are likely to find odour from animal production less unpleasant than those who are more sensitive.

Suggested future research

The present research indicates a need for future studies in the area. There is limited knowledge in a number of important fields regarding the impact of odours from livestock and poultry operations as well as from other odours. Some suggestions for important future research are listed below:

- Studies regarding continuous odour measurements. Continuous measurements have a great potential to increase the knowledge in various research fields including odour emissions and occurrence of odours. Further studies of EN technology together with development of the technique used should make it possible to increase the correlation to human odour perception.
- Further studies of factors affecting the release of odorants and gases in animal production facilities, from manure storages and other similar odour sources. Knowledge of the influence and interaction of various parameters would make it easier to decrease concentrations and emissions. More in-depth studies, aiming at a model for release and emissions, are important for this area.
- Studies of emissions and their variations including studies of correlations between wind-tunnel measurements and true emission values for area sources.
- Studies of peak to mean ratios of odour concentrations in the neighbourhood and the correlation between these ratios and human-perceived odour intensity.
- Further studies of correlations between odour dispersion and setback model predictions and exposure.
- Further studies of annoyance due to odours in the neighbourhood, looking at odour pleasantness, odour concentration and frequencies of exposure. Further studies of annoyance and symptom frequencies at different distances from odour sources of various types.
- Further studies of the hedonic tone of different odours. Studies including a considerable number of panellists aimed at confirming the findings in *Paper **V*** and to thoroughly study (1) the Gauss distribution of pleasantness rating and (2) individual factors and characteristics important for pleasantness rating.
- Chamber studies of human exposure to odours of different types and concentrations. Studies of the correlation between these factors and factors important for well-being and health. Factors to study are, for example, self-reported symptoms, mood, perceived air quality, stress and skills when performing various tasks.
- Studies of concentrations of pollutants related to animal production, which in *Paper **IV*** were considered to possibly contribute to reported symptoms. These include: hydrogen sulphide, 2-propenal (acrolein), benzene, formaldehyde, hydrazine, and 2-methoxy-ethanol which are all harmful at low concentrations.

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