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Identification of Risk Factors for Sub-Optimal Housing Conditions in Australian Piggeries: Part 1. Study Justification and Design

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Abstract. *We undertook a literature search related to pig production facilities with two major aims: first, to review all the likely benefits that might be gained from air quality improvements; and second, to review previous research that had identified statistically significant factors affecting airborne pollutants and environmental parameters, so that these factors could be considered in a multifactorial analysis aimed at explaining variations in air pollutant concentrations. Ammonia, carbon dioxide, viable bacteria, endotoxins, and inhalable and respirable particles were identified as major airborne pollutants in the review. We found that high concentrations of airborne pollutants in livestock buildings could increase occupational health and safety risks, compromise the health, welfare, and production efficiency of animals, and affect the environment. Therefore, improving air quality could reduce environmental damage and improve animal and worker health. To achieve a reduction in pollutant concentrations, a better understanding of the factors influencing airborne pollutant concentrations in piggery buildings is required. Most of the work done previously has used simple correlation matrices to identify relationships between key factors and pollutant concentrations, without taking into consideration multifactorial effects simultaneously in a model. However, our review of this prior knowledge was the first important step toward developing a more inclusive statistical model. This review identified a number of candidate risk factors, which we then took into consideration during the development of multifactorial statistical models. We used a general linear model (GLM) to model measured internal concentrations, emissions, and environmental parameters in order to predict and potentially control the building environment.*

Keywords. *Airborne pollutants, Environmental survey, Farm building, Risk factors, Statistical models.*

The main airborne pollutants found in piggery buildings are ammonia (NH_3), excess of naturally occurring carbon dioxide (CO_2), airborne particles, and microorganisms and their components (Wathes et al., 1998). Airborne particles in piggery buildings consist of animal skin, hair, dried urine, feces, bedding material, microorganisms, fungal spores and conidia, pollen, feed, and (to some extent) particulate matter from the outside environment (Takai et al., 1998). The major sources of particles in piggery

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buildings are the hair or skin fragments of pigs, pig excreta, feed, and bedding materials (Heber et al., 1988a). Airborne particles usually act as vectors for pathogenic bacteria, viruses, endotoxins, odorous material, gases (including NH_3), and liquid substances (Seedorf et al., 1998b). Airborne particles are classified into different sub-classes according to their size and the gravimetric measurement method used for their detection (Pedersen et al., 2001). "Total dust" refers to the fraction containing particles less than 20 μm in aerodynamic diameter, collected usually by a cassette filter with 5 mm downward inlets. IOM (Institute of Occupational Medicine) or "seven-hole" samplers are commonly used to collect particles slightly larger than 20 μm, and this fraction is referred to as "inhalable dust" (Pedersen et al., 2001). The fraction collected by a cyclone pre-separator is called "respirable dust" (<5 μm). There is increasing concern about the effects of respirable particles on human and animal health, as inhalable particles are usually filtered out by the upper respiratory tract, whereas respirable particles can penetrate into the terminal bronchioles (Seedorf et al., 1998b).

The microbial environment within piggery buildings tends to be dominated by gram-positive bacteria. Although gram-negative bacteria are responsible for only a small portion (0.02% to 5.2%) of the viable airborne bacteria in animal buildings (Zucker et al., 2000_3), these types of bacteria are important, as their cell-wall component is a key airborne pollutant. The so-called endotoxins are the cell-wall components of gram-negative bacteria, and these compounds are released after the death of the bacteria. These toxins can cause health problems in farm workers and animals alike (Seedorf et al., 1998b). One of the well-recognized gaseous pollutants present in livestock buildings is NH_3. Most NH_3 is produced as a result of chemical and biological breakdown of urea in the urine and of dietary nitrogen in the fecal material of mammals (Groot Koerkamp et al., 1998). The main source of CO_2 in piggery buildings is the normal respiration of animals. A negligible amount is produced as a by-product of bacterial breakdown of waste material (Ni et al., 1999a).

The Motivation for Undertaking the Study

There are essentially three main areas of concern in relation to airborne pollutants. These are: (1) impacts on human health, welfare, and potentially productivity; (2) effects on animal health, production efficiency, and welfare; and (3) the environmental impact of airborne emissions from livestock buildings. In the following pages, these areas of concern will be reviewed briefly, as the elimination of these potentially detrimental effects of sub-optimal air quality was the real driving force behind undertaking the work reported in this series (Banhazi et al., 2008a; Banhazi et al., 2008b; Banhazi et al., 2008c).

Impact on Human Health

The quality of the working environment within livestock buildings and therefore the health of farm workers can be affected by different airborne pollutants (Asmar et al., 2001; Radon et al., 2001). People working long hours in piggery buildings (Pedersen et al., 2001; Wenger et al., 2005) and thus exposed to airborne pollutants have documented increases in morning phlegm production, coughing, scratchy throat, burning eyes, wheezing, shortness of breath, chronic bronchitis, and decline in lung function when compared with individuals who are not agricultural workers (Laitinen et al., 2001; Mackiewicz, 1998; Schwartz et al., 1995). A number of studies have suggested that components of the microorganisms (such as endotoxins) carried by dust particles can trigger acute health effects in individuals working in piggery buildings (Clark et al., 1983; Schwartz et al., 1995; Zhiping et al., 1996). For example, it has been estimated that potentially 25% of piggery workers in the U.S. are affected by non-allergic occupational asthma, and 33% of them have reported episodes associated with organic dust toxic syndrome (Donham, 2000). Work-related respiratory symptoms, such as chest tightness and nasal and eye irritation, were reported by 23 of the 29 workers (approx. 80%) in a European study (Crook et al., 1991). It appears that repeated exposure to gases and particles while working in animal buildings can cause respiratory complications, such as edema and collagen deposition in the lung tissues (Asmar et al., 2001).

Several risk factors, including the size of the piggery and duration of employment, have been identified as factors contributing to the development of respiratory problems in pig farmers (Radon et al., 2000; Radon et al., 2001). However, it has been demonstrated that the negative effects of high concentrations of airborne pollutants on respiratory health are likely to be more pronounced in subjects previously unexposed to piggery environments. Studies have confirmed that exposure to airborne pollutants alters lung function and cytokine production in the blood of human subjects with no prior exposure to piggery environments (Palmberg et al., 2002; Von Essen and Romberger, 2003). Importantly, it has also been demonstrated that a relatively short exposure to the piggery environment (3 to 5 h during the weighing of pigs) causes an intense inflammatory reaction of the airways in healthy subjects (Larsson et al., 1994; Zhiping et al., 1996). These studies demonstrate that only relatively short exposure to high concentrations of total airborne particles and endotoxins is sufficient to cause respiratory problems. These results have important implications for piggery workers employed on farms that house pigs in deep-bedded shelters (DBS). A relatively short exposure to the high dust concentrations commonly found in DBS (Banhazi et al., 2008b) could compromise the health of human subjects, especially new employees previously unexposed to piggery environments.

Impact on Animal Health, Production, and Welfare

One of the earliest reports describing the association between airborne pollutants and the health of pigs was published in the late 1960s (Kovacs et al., 1967). The study found that 87% of pigs affected by severe pneumonia came from buildings with the highest (430 to 460 particles mL^{-1} air) dust concentrations (Kovacs et al., 1967). Other studies have also demonstrated the effects of sub-optimal air quality on production efficiency (Donham, 1991; Urbain et al., 1994). Pigs exposed to 4.4 mg m^{-3} of inhalable flour dust and dust-borne endotoxins in environmental chambers over a 6-day period had increased macrophage counts, and some also exhibited airway inflammation (Urbain et al., 1999). It has been demonstrated that pigs reared in clean environments with better air quality grow faster than pigs living in commercial farm buildings with sub-optimal air quality. In one study, an 8% growth rate improvement was associated with a 17% reduction in the count of viable bacteria, a 42% reduction in inhalable particles, and a 76% reduction in NH_3 concentration (Banhazi and Cargill, 1998). Some authors have reported growth rate reductions in pigs exposed experimentally to various levels of NH_3. Pigs exposed for 4 weeks (immediately after weaning at the age of 27 or 28 days) to 0, 50, 100, or 150 ppm NH_3 and a filtered air mixture showed growth rate reductions of 0%, 12%, 30%, and 29%, respectively (Drummond et al., 1980). However, other studies have demonstrated that exposure of pigs to NH_3 concentrations up to 100 ppm for 6 days had no direct effect on pulmonary permeability and produced no stress response (Gustin et al., 1994). Recent results from the U.K. have demonstrated no effect of NH_3 on production efficiency at concentrations of 37 ppm (Wathes et al., 2004). However, both food intake and live weight gain were lower in weaner pigs (approx. 25 kg at the end of trial) exposed to 5.1 or 9.9 mg m^{-3} dust concentrations than in pigs raised in environments with concentrations below 5 mg m^{-3}.

Probably the most comprehensive study undertaken to evaluate the effects of air quality on production efficiency was published recently (Lee et al., 2005). Growth rates and immune responses of male weaner pigs (aged between 3 and 8 weeks) were assessed in "clean" and "dirty" environments. The "clean" piggery environment was sustained by daily cleaning, while the "dirty" environment was attained by not cleaning the piggery building before and during the experiment. The piggery environment classified as "dirty" had significantly elevated NH_3 (13 vs. 6 ppm), CO_2 (2440 vs. 1770 ppm), and total airborne particle (2.3 vs. 1.5 mg m^{-3}) concentrations when compared with the environment classified as "clean." The main result was that pigs in the "clean" environment grew significantly faster and consumed more feed then pigs kept in the "dirty" environment (Lee et al., 2005). This clearly highlights the importance of good air quality and confirms the results of other Australian publications (Banhazi and Cargill, 1998; Cargill and Banhazi, 1998; Cargill et al., 1998).

Emissions

Damage to the receiving environment can be minimized by reducing airborne pollutant emissions from livestock buildings. Particles, endotoxins, and airborne microorganisms emitted from livestock buildings can get into streams via runoff. Thus, nutrient enrichment and/or bacterial contamination of waterways and the land surrounding these buildings is a major concern for livestock industries in many countries (Hooda et al., 2000). In addition, airborne particle emission has been associated with increased likelihood of the transmission of pathogenic microorganisms among farm buildings. The likelihood of microorganisms surviving (and therefore affecting the health of livestock housed in neighboring buildings) is enhanced when they are carried by airborne dust particles (Hartung and Seedorf, 1999). Furthermore, particles in the ventilation air of livestock buildings have been implicated in transporting odor, thus reducing the environmental sustainability of livestock operations and causing conflict between livestock operators and neighboring residents (Bottcher, 2001; Hammond et al., 1979; Hammond et al., 1981; Liao and Singh, 1998; Oehrl et al., 2001). Dust particles can absorb odorous components and emit them into the surrounding environment (O'Neill and Phillips, 1992). A notable amount of NH_3 is also carried by airborne particles. The NH_3 contents of inhalable particles collected from livestock buildings reportedly range from 1000 to 6000 ppm on a weight basis in the particle mass (Takai et al., 2002). These results indicate that the NH_3 carried by airborne particles might have a greater impact on the health and welfare of animals and farm workers (and potentially on environment) than airborne NH_3 (Takai et al., 2002). Other studies also indicate that a significant proportion of NH_3 might be associated with airborne particles (Reynolds et al., 1988).

Livestock production contributes extensively to atmospheric NH_3 emissions (Groot Koerkamp et al., 1998). Ammonia emitted from livestock buildings can generate secondary aerosols in combination with other atmospheric pollutants such as nitrogen oxide and sulfuric acid. These processes then result in the formation of very small particles (PM 2.5), which in turn may have serious public health consequences (Arogo et al., 2003). Very small particles are believed to cause not only respiratory, but also vascular problems because of their ability to penetrate the body's defenses (Agranovski et al., 2004). Excessive amounts of NH_3 deposited in sensitive ecosystems via emissions can be leached into waterways (via runoff) and cause eutrophication and acidification of both soils and surface water (Groot Koerkamp et al., 1998). This in turn, can lead to a decrease in water quality of natural waterways. Changes in soil pH can result in modification of the composition of native vegetation (Arogo et al., 2003; Misselbrook et al., 2000). Carbon dioxide (together with methane and nitrous oxide) emitted from livestock buildings is considered to be part of the greenhouse gas (GHG) emission load of piggery operations (Sommer and Moller, 2000). GHG emission is increasingly seen as a major threat to the environment, and the reduction of this type of emission is therefore a priority for the agricultural industries (Flessa et al., 2002; Sommer and Moller, 2000).

Table 1. Concentrations of different pollutants measured in previous European studies.

Pollutant	Range of Concentrations	Reference
Ammonia	5 to 18 ppm	Groot Koerkamp et al. (1998)
Inhalable particles	0.63 to 5.05 mg m^{-3}	Takai et al. (1998)
Respirable particles	0.09 to 0.46 mg m^{-3}	Takai et al. (1998)
Respirable endotoxins[a]	74 to 189 EU m^{-3}	Seedorf et al. (1998b)
Total airborne bacteria	1.2×10^5 cfu m^{-3}	Seedorf et al. (1998b)

[a] Converted from ng to EU (endotoxin unit) assuming a conversion factor of 10.

Table 2. Current safe maximum exposure limits recommended in Australia (Cargill et al., 2002).

Pollutant	Maximum Safe Concentration
Ammonia	10 ppm
Inhalable particles	2.4 mg m^{-3}
Respirable particles	0.23 mg m^{-3}
Respirable endotoxins	50 EU m^{-3}
Total airborne bacteria	1.0×10^5 cfu m^{-3}

Indoor Concentrations and Maximum Limits

Considerable amounts of airborne pollutants are present in the airspace of piggery buildings (Chang et al., 2001a; Seedorf et al., 1998b; Takai et al., 1998). For example, mean airborne dust concentrations in pig houses in northern Scotland ranged from 1.7 to 21.0 mg m^{-3}, and mean NH_3 concentrations ranged from 1.5 to 13.2 ppm (Crook et al., 1991). The mean concentrations of inhalable, respirable, and total viable particles in a naturally ventilated finisher building in the U.S. were 2.2 mg m^{-3}, 0.10 mg m^{-3}, and 6.0×10^4 cfu m^{-3} (colony forming units per cubic meter), respectively (Predicala et al., 2001). In Canadian piggery buildings, the mean airborne pollutant concentrations were 2632 ppm for CO_2, 11.3 ppm for NH_3, 2.9 mg m^{-3} for total particles, and 0.1 mg m^{-3} for respirable particles (Zejda et al., 1994). Table 1 summarizes the airborne pollutant concentrations reported by a large multinational project team.

There are different recommendations available for maximum concentrations of major airborne pollutants for both humans and livestock (Donham and Cumro, 1999; Donham, 1995; Donham et al., 2000). The current suggested safe exposure limits advocated in Australia are summarized in table 2 (Cargill et al., 2002). However, these recommendations are not supported by legislation in Australia.

Identification of Potential Model Components

The ultimate aim of the study reported in companion articles (Banhazi et al., 2008a; Banhazi et al., 2008b) was to model and therefore explain the variation observed in concentrations and emission rates of different airborne pollutants. Therefore, a brief literature search was conducted to ensure that all potential risk factors previously reported as influencing air quality were taken into consideration during the model development. During the review; it also became obvious that an extensive statistical modeling study based on air quality information collected in a large number of piggery building has not been attempted before. Thus, the need for this comprehensive multifactorial statistical modeling study, reported in this and other related articles

(Banhazi et al., 2008a; Banhazi et al., 2008b; Banhazi et al., 2008c), was identified. It was hypothesized that by investigating the interaction between different air quality parameters and housing and management features, the key factors affecting the internal concentrations and emissions of airborne pollutants in piggery buildings could be identified, and thus the concentrations and emissions of these airborne pollutants could be reduced.

Seasonal Variation

Many studies on the influence of environmental factors on particle concentrations in piggery buildings have demonstrated a seasonal dependency. Winter airborne particle concentrations were consistently higher than summer concentrations in farrowing, weaner, and finisher buildings in western France (Guingand, 1999) and in a farrowing building in Iowa (O'Shaughnessy et al., 2002). The study conducted in the U.S. also demonstrated a marked diurnal variation in concentrations of both NH_3 and airborne particles (O'Shaughnessy et al., 2002). In terms of seasonality, a significant decrease in concentrations of airborne bacteria, NH_3, and CO_2 has been observed during summer when compared with winter levels in Canadian piggery buildings (Duchaine et al., 2000).

Building Classification and Management

Building type varies with the class of pigs, as different age groups have distinct environmental requirements. The likely effects of building type (class of animals) on airborne particle concentration have been demonstrated. A higher percentage of respirable dust has been found in farrowing and nursery buildings than in finisher buildings, suggesting that the composition of the dust differs in different types of piggery buildings (Donham et al., 1986). Airborne particle concentrations have been shown by other authors to be substantially higher in farrowing and nursery buildings than in finisher buildings (Attwood et al., 1987). It has also been reported that high gas concentrations (both CO_2 and NH_3) are more likely in buildings housing younger animals, because these buildings usually have reduced ventilation levels to save heating cost (Donham and Popendorf, 1985).

Number and Weight of Pigs

There have been a number of studies associating airborne particle concentration with the weight of pigs (Gustafsson, 1999; Pedersen et al., 2001). The concentrations of inhalable and respirable particles inside two piggery buildings in the U.S. were significantly correlated with the weight of pigs ($r = 0.42$ and 0.55, respectively; $p < 0.01$), and a significant but smaller correlation ($r = 0.26$; $p < 0.05$) was also found between the concentration of airborne bacteria and the weight of pigs (Predicala et al., 2001). A significant correlation between endotoxin concentration and the number of animals in the building has been reported by other authors (Duchaine et al., 2000).

Humidity and Temperature

Humidity influences the condition of the air and therefore the density and size of the suspended particles inside piggery buildings. Several studies in piggery and poultry buildings have demonstrated a varied relationship between respirable particle concentration and relative humidity (Butera et al., 1991; Ellen et al., 2000). Significant effects of both humidity and temperature on the concentration of airborne particles have also been demonstrated in the U.S. (Heber et al., 1988b). Airborne particle concentrations decrease with increasing outside temperature in both mechanically and naturally ventilated piggery buildings (Heber et al., 1988b). The concentrations of viable airborne bacteria were significantly reduced at higher temperatures in piggery buildings, but the effects of relative humidity on concentrations of airborne bacteria varied (Butera et al., 1991). On the other hand, one study conducted in nine mechanically ventilated farrowing and weaner buildings found no significant correlation between either airborne bacteria and humidity or NH_3 and humidity levels (Nicks et al., 1993).

Ventilation

Ventilation has a complex effect on the concentration of air pollutants. Ventilation systems are designed to control the thermal environment and facilitate the removal and transportation of airborne pollutants outside the building via exhausted air (Duchaine et al., 2000; Wang et al., 2000). However, the turbulence associated with increased ventilation favors the re-suspension of settled particles. In one study, increasing ventilation rates of 2, 5, or 8 air changes h^{-1} did not affect respirable dust concentrations (Butera et al., 1991). Other studies have also reported the limited effects of ventilation rate increase on airborne particle concentrations when compared with the effects of airflow patterns (Wang et al., 2002). The importance of the design of the ventilation system has been highlighted (Aarnink and Wagemans, 1997; Wilhelm and McKinney, 2001). One study assessed differences in internal gas concentrations between two piggery buildings that used different ventilation systems (Wilhelm and McKinney, 2001): a pit ventilation system was shown to be effective in reducing NH_3 concentrations by approximately 40% compared with a traditional cross ventilation system (Wilhelm and McKinney, 2001). On the other hand, a decline was demonstrated in total dust concentrations in association with a 0.1 to 0.4 m^3 s^{-1} ventilation rate per pig (Gustafsson, 1999; Wang et al., 2000). This indicates that larger particles might be more efficiently ventilated out from livestock buildings.

Hygiene

A number of studies have demonstrated that pen hygiene has an effect on NH_3 concentrations in piggery buildings. Ammonia concentrations increase as the level of pen floor contamination increases (Aarnink et al., 1997; Aarnink et al., 1996; Kovacs et al., 1967; Ni et al., 1999b). Air turbulence associated with increased ventilation favors the volatilization of NH_3 from exposed sources, such as contaminated pen floors (Ni et al., 1999b). However, improved pen cleanliness limits opportunities for volatilization and therefore could improve the effectiveness of the ventilation system. Manure accumulated on pen floors has a negative effect on the concentration of viable airborne bacteria (Chang et al., 2001b). Lack of cleaning and dust accumulation on horizontal surfaces reportedly increases airborne dust concentrations in piggery buildings (Heber et al., 1988b).

Design of the Data Collection Form

On the basis of the brief review detailed above, a standard data collection form was developed to collect all relevant data that described the management and engineering characteristics of the buildings that might influence airborne pollutant concentrations (table 3). This information was later used during the model development phase of the project.

Design of Field Survey, Study Buildings, and Data Collected

A total of 160 piggery buildings from 40 farms were surveyed during the data collection period (between the autumn of 1997 and the autumn of 1999). The sample

Table 3. Information collected about the study buildings.

Item	Comments
Farm identification	Unique identification number
Building identification	Unique identification number
Date of visit	Day/month/year (season)
Management system	Continuous flow versus all-in/all-out management
Building classification	Weaner, grower/finisher, dry sow, farrowing, DBS
Age of pigs	Weeks
Weight of pigs	Average weight of pigs (kg)
Age of buildings	Years
Farm size	Number of sows
Pen size	Length (m), width (m), and area (m^2)
Number of pigs per building space	Number of pigs
Volume of building	Length (m), width (m), height (m), and volume (m^3)
Level of hygiene	Scored as good, fair, or poor
Ventilation type	Natural, mechanical, tunnel-ventilated (deep-bedded) buildings
Ventilation control	Manual, automatic, or other
Air inlet size	Height of shutters/blinds (cm)
Ridge vent size	Width and height (cm)
Roof/wall insulation type	Asbestos, sandwich panels, spray-on/polystyrene bats, or other
Roof/wall insulation thickness	Centimeters

Table 4. Numbers of repeats included in the study for different classes of buildings.

Class of Building	Brief Description	Number of Buildings
Grower[a]	Natural ventilation, liquid manure	37
Finisher[a]	Natural ventilation, liquid manure	27
Deep-bedded shelters	Natural (tunnel) ventilation, straw litter	11
Dry sow	Natural ventilation, liquid manure	22
Farrowing	Natural or mechanical ventilation, liquid manure	30
Weaner	Natural or mechanical ventilation, liquid manure	33
All buildings		160

[a] Combined during analysis to reduce the degrees of freedom used.

included small (less than 300 sows), medium (between 300 and 700 sows), and large (more than 700 sows) farms in similar proportions to those occurring across the whole Australian industry. The building surveyed also included different facilities, such as dry sow, weaner, and grower/finisher buildings, farrowing rooms, and (on some farms) deep-bedded shelters (DBS) (table 4).

In addition to building use, there was a large variation in design (table 5) and management, again providing a representative sample of industry practice in Australia. The buildings studied varied greatly, and it would be impossible to describe them in detail within the limitations of this article (a detailed description is available from the main author on request). However, to give some descriptions of the buildings included in the survey, the main features of the buildings are presented in table 5. Approximately, 28.5% of the buildings were classified either as having a good or poor hygiene level, while the remaining 43% had a fair hygiene level. The vast majority of the buildings included in the study were naturally ventilated (90%), while only 10% of the buildings had some form of mechanical ventilation equipment installed. In addition, 54% of the buildings were surveyed during winter, while 46% were surveyed in summer.

Table 5. Mean features of study buildings.

Feature	Mean	Coefficient of Variation (%)
Average weight of pigs (kg)	99	83
Age of buildings (years)	13	66
Number of sows (number)	684	147
Average pen size (m^2)	16.5	267
Average building size (m^3)	1177	128
Number of pigs per building space (number)	383	146
Air inlet size = height of shutters/blinds (cm)	140	35
Average building length (m)	29	79
Average building width (m)	11	41
Average building height (m)	3.1	23

Table 6. Mean emissions and concentrations of airborne pollutants in the sample piggery building.

Pollutant	Measurement Unit	Mean Value
Microorganism emission	$\times 10^7$ cfu h^{-1} 500 kg^{-1} live weight	16.8
Microorganism concentration	$\times 10^5$ cfu m^{-3}	2.58
Endotoxin emission	$\times 10^3$ EU h^{-1} 500 kg^{-1} live weight	5.9
Endotoxin concentration	EU m^{-3}	9.0
Respirable particle emission	mg h^{-1} 500 kg^{-1} live weight	241.0
Respirable particle concentration	mg m^{-3}	0.37
Inhalable particle emission	mg h^{-1} 500 kg^{-1} live weight	1740.0
Inhalable particle concentration	mg m^{-3}	2.67
Ammonia emission	mg h^{-1} 500 kg^{-1} live weight	961.5
Ammonia concentration	ppm	2.1
Carbon dioxide concentration	ppm	909
Internal temperature	˚C	16.03
Internal relative humidity	%	75.5
Average air velocity	m s^{-1}	0.313
Ventilation airflow	m^3 h^{-1} 500 kg^{-1} live weight	652

The companion articles in this series present detailed results of the survey (Banhazi et al., 2008a; Banhazi et al., 2008b; Banhazi et al., 2008c). This article provides examples of the raw data obtained from one building (table 6) to give the reader an appreciation of the data collected. The sample building was monitored in September 1999 and was located on a small farm in South Australia and used a continuous-flow management system. The age of the pigs at the time of the visit was 14 weeks. There were 204 pigs in the building at the time of the data recording. The hygiene level was rated as poor, and the building was naturally ventilated.

Data Storage and Statistical Analysis

Previous studies have had a major focus on measuring and reporting concentrations and emission rates (Seedorf et al., 1998a; Seedorf et al., 1998b; Takai et al., 1998; Wathes et al., 1998). This Australian study had an alternative focus on multifactorial statistical modeling. The primary aim of the study was to enable researchers to identify the important factors influencing the concentration of each pollutant so that reduction methods could be identified for further testing. The primary aim was to model the variation caused by differences between buildings rather than focusing on effects causing variation within buildings. The inevitable imbalance of such a survey meant that it was analyzed using general linear models (Breiman, 2001; Nelder, 1994; SAS, 1989).

First, the recorded data were downloaded from the data-logging systems using the programs supplied with the individual instruments. The instrumentation and data collection routine are described in detail in the companion articles of this series (Banhazi et al., 2008b; Banhazi et al., 2008c). Data were first screened for outlier values, and then climatic and gas measurements were automatically converted to hourly averages. This was done to reduce data volume and to synchronize the parameters, which were collected at different logging intervals. All continuous data were graphed and used as part of feedback reports for the producers taking part in the project. After this pre-processing, the data were transferred for storage and analysis to a central database specially built for the project in-house (MS Access-based AQ-Pro). The AQ-Pro database formed the basis of the subsequent development aimed at producing an integrated database/software application designed to facilitate routine environmental assessments of farm buildings (Banhazi, 2005).

Given the skewed distribution of airborne pollutants, most of the dependent variables (ventilation airflow rate, concentration of CO_2, and concentrations and emissions of airborne bacteria, respirable endotoxins, NH_3, and inhalable and respirable particles) were transformed to natural log values. The transformed data were analyzed to explain as much of the variation in the dependent variables as possible and to construct descriptive models for each variable. To achieve that, a general linear model procedure (PROC GLM) (SAS, 1989) was used, as the GLM procedure has the capacity to handle unbalanced datasets and simultaneously adjust the data being analyzed for various other effects using the method of least squares to allow model parameters to be estimated. By making such adjustments simultaneously, comparisons of effects of one factor (e.g., hygiene level) can be compared independent of variation in other factors (e.g., temperature, humidity). In addition, interactions between factors can be tested. The output from the analysis is a comprehensive model that could be used for prediction when managing existing buildings as well as designing new buildings.

The models tested a large number of fixed effects (factors) and covariates (table 7) and their first-order interactions. The quadratic terms of farm size, airflow, and temperature were also fitted to the models to determine whether optimal levels exist. Due to model size restrictions, no higher-order interactions could be tested. The models were developed from the maximum model tested by sequentially removing (in a stepwise manner) non-significant interactions and effects ($P < 0.05$, based on type III estimable functions) until only significant effects and two-way interactions remained. This process was undertaken while ensuring that all marginality requirements of the model were met (Nelder, 1994).

Some of these models were very complicated, containing up to 12 main effects and 12 interactions. To simplify these models, the significance level to keep a term was reduced from $P < 0.05$ to $P < 0.01$. Then the models developed at both the $P < 0.05$ and $P < 0.01$ significance levels were compared for each pollutant or emission by calculating the model standard deviation (the square root of the coefficient of determination divided by the total variation). The model standard deviation was used because it is directly proportional to selection response when discriminating between objects of interest (Nelder, 1977). If a simplified model reduced the model standard deviation by more than 20%, it was rejected in favor of the more complicated model. The only model that could not be used with the $P < 0.01$ significance level was that for explaining variation in internal shed NH_3 concentration (Banhazi et al., 2008b).

The results from these analyses are based on back-transformed least squares means, giving the median values (±95% confidence intervals) of fixed effects and best-fit slopes of covariates, where relevant.

Table 7. Fixed effects and covariates considered during the analysis.

Variables considered for NH_3, endotoxins, bacteria, and inhalable and respirable particles	
Fixed Effect	Class
Building type	Weaner, grower/finisher, dry sow, DBS or farrowing
Assessed hygiene level	Good, fair, and poor
Management type	Continuous flow or all-in/all-out management
Season	Winter or summer
Covariate	Unit
Weight of pigs per building	kg
Building volume	m^3
Ventilation airflow	$m^3 h^{-1}$
Internal temperature	°C
Humidity	%
Farm size	Number of sows
Variables considered for ventilation airflow, temperature, and humidity	
Fixed Effect	Class
Building type	Weaner, grower/finisher, dry sow, DBS or farrowing
Ventilation type	Mechanical, natural, tunnel/DBS
Wall ventilation control type	Automatic, manual, other
Roof ventilation control type	Automatic, manual, other
Wall insulation type	Asbestos, sandwich panel, spray-on/polystyrene bats
Roof insulation type	Asbestos, sandwich panel, spray-on/polystyrene bats, other
Season	Winter or summer
Covariate	Unit
Internal temperature	°C
Humidity	%
Building age	Years
Size of wall ventilation opening	cm
Roof ventilation width	cm
Roof ventilation height	cm
Roof insulation thickness	cm
Wall insulation thickness	cm
Stocking density	kg of pig m^{-3}
Building width	m
Building height	m
Building length	m
Ventilation airflow	$m^3 h^{-1}$

Assessment of Study Design

To ensure that the study population of the buildings was representative, a large number of buildings was included in the study, and buildings with varied characteristics were selected. Each building was considered as an experimental unit, and on each monitoring occasion a new barn was visited and thus included in the study. The data collection process was designed after the literature was briefly reviewed to ensure that it was sufficiently extensive to include all potentially important parameters that had to be considered in the subsequent models. The GLM statistical analysis was applied to ensure that the influence of unbalanced design (a typical feature of field studies) could be eliminated, and thus building features could be reliably compared. Further simplification of models was done to ensure that chance fitting of effects could be minimized. The limitation of the analysis was mainly related to the number of factors (main effects and covariates) that could be included in the models, as determined by the available degrees of freedom within the dataset. This restriction was in turn related mainly to the financial limitation of the study, which predetermined the number of buildings included in the survey. Sampling time was considerably extended compared with those of previous studies (Wathes et al., 1998) to obtain more representative averages of the airborne pollutants. This was because, for most airborne pollutants, variation over time is reportedly greater that spatial variation (Groot Koerkamp et al., 1998).

Conclusion

From the results of previous studies, it is evident that improving air quality in livestock buildings could produce important benefits, including reduced environmental damage, improved production efficiency, and a better working environment for farm employees. In separate studies, a number of management, environmental, and housing factors have been identified that might influence the concentrations of airborne pollutants within, and their emission from, piggery buildings. However, all of these factors have not been considered simultaneously. In addition, most of the studies conducted in relation to airborne pollutants in livestock buildings were concerned mainly with the concentrations and/or emissions measured (Wathes et al., 1998). No previous attempts have been made to model, and therefore explain, the variation observed in concentrations and emission rates using statistical modeling and large pollutant dataset. Therefore, a comprehensive multifactorial statistical modeling approach was needed to investigate the interaction between different air quality parameters and housing and management features. This statistical approach allowed the key factors affecting the internal concentrations and emissions of airborne pollutants in different piggery buildings to be predicted, and thus could allow the concentrations and emissions of these airborne pollutants to be reduced.

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