INTERACTIONS BETWEEN HOUSED LIVESTOCK AND THEIR ENVIRONMENT

T.G.M. DEMMERS, C. M. WATHES and A.R. FROST

Bio-Engineering Division, Silsoe Research Institute, Silsoe, Beds MK45 4HS, United Kingdom

SUMMARY

The aerial environment of housed livestock has a significant impact on the behaviour and growth of livestock. Aerial pollutant emissions from livestock production, especially ammonia, form a large part of the total UK emission to the environment. Improvements in the management of livestock and the design of housing systems will have to embrace effects on both the production parameters as well as improvements in the aerial environment to satisfy increasing demands by legislation to improve animal welfare standards and reduce aerial pollutant emissions for livestock production systems. At the same time increased demands are put on livestock managers, who have to satisfy a range of often conflicting criteria, varying from feed strategy through to welfare issues. To aid livestock managers, integrated management systems are being developed to control simultaneously more than one, and ideally all, interrelated processes involved in livestock production. Current developments in integrated management systems show that growth parameters can be effectively controlled and do have a significant impact on pollutant emissions in broiler production.

Keywords: livestock, management, production, environment

INTRODUCTION

Considerable progress has been made in environmental design and management for livestock over the past 40 years and longer. A common and successful approach has been (i) to characterise the physical environment experienced by livestock on the farm, (ii) to measure and model an animal's corresponding physiological, behavioural, production and other responses; and (iii) to use these results in the design and construction of control systems to manage or manipulate the physical environment to which livestock are exposed. Notable examples of this approach include the study and management of the thermal environment for all the farmed species, both when housed and outdoors, and light photoperiod for poultry in so far as it affects reproduction. The design of ventilation systems has been the key to many aspects of environmental control in livestock housing, and the physical principles of air movement have been translated successfully into various proprietary designs employing either natural or mechanical ventilation.

However, current systems of environmental design and management may not satisfy the customer's specifications for livestock products and meet increasingly stringent regulations on farming methods that aim to diminish the environmental impact of livestock production or provide a higher standard of animal welfare, for example. Society's view on what constitutes acceptable agricultural practice is changing rapidly in Europe. Resolution of the various conflicts that arise in livestock production requires integrated solutions if potentially competing demands are to be satisfied. Integration can take many forms and several are presented in this paper.

The interaction between an animal and its physical environment is complex and dynamic. It is emphasised by Monteith (1973) who observed that "the presence of an organism modifies the environment it is exposed to, so that the physical stimulus received *from* the environment is partly determined by the physiological response *to* the environment". Although housed livestock have been selected and bred to thrive in the environment provided, these conditions are significantly different from their natural environment and may significantly change their behaviour. Therefore, the best option is not to attempt to recreate the natural environment of pigs, but instead to provide an artificial physical environment that creates a symbiotic interaction with the animal and satisfies current demands of sustainable agricultural production.

In this paper, we argue that further progress in environmental design and management for livestock production requires development of integrated systems to manage both production and environmental processes. This, in turn, will allow many potential conflicts in livestock production to be identified and, hopefully, resolved. The emphasis is on the aerial environment of housed livestock, particularly pigs. This paper is partially based on articles that have been published elsewhere (Wathes 2001; Wathes *et al.* 2001).

AERIAL POLLUTANTS IN LIVESTOCK PIG BUILDINGS

The air within livestock pig buildings seethes with a cocktail of bioaerosols and gases. Both composition and concentration of the cocktail vary according to animal husbandry and the building's design and management. Table 1 lists the concentration and emission rates of the common aerial pollutants from short-term measurements made over 24 h in a large survey of 64 pig houses in four countries in Northern Europe. Amongst all classes of pigs, the mean mass concentration of dust and endotoxin was highest in weaner buildings with slats. The composition of the dust was not determined in this survey. For comparison, the current UK occupational exposure limit for human health is 10 mg m^{-3} for total inhalable dust and 4 mg m^{-3} for the respirable fraction of dust (Health and Safety Executive 2001), while Donham *et al*. (1995) recommend 2.5 and 0.23 mg m^{-3}, respectivelyalso on grounds of human health.

Table 2 shows that dust can be characterised in a variety of ways though most workers restrict themselves to mass concentration, presumably because of the tedium and expense involved in identifying and classifying individual dust particles. Painstaking work by Heber *et al*. (1988) showed that in samples from finishing buildings, feed was the major source of particles over 5 μm. Measurement of the physical properties showed that starch particles had a geometric median diameter (GMD) of 12.5 μm and a mass median diameter (MMD) of 21.0 μm, while the corresponding values for grain meal were 8.6 μm and 17.9 μm respectively. For all dust particles, the GMD was 2.6 μm and the MMD was 18.5 μm. The finer respirable particles are difficult to identify microscopically. Donham *et al*. (1986) suggest that faecal material is the predominant source of particles about 1-2 Φm diameter while hair and skin account for only 1% and 10% of all particles with a diameter between 11 and 16 Φm (Honey and McQuitty 1979). With the exception of these quantitative studies, most authors are content to state merely that the main sources of pig dust are feed, faeces, bedding and skin squames.

Table 2. Important properties of airborne dust (Wathes *et al*. 2000)

Physical	Concentration of particles by number and mass
	Size distribution of particles by number and mass
Chemical	Chemical composition, particularly of toxins and allergens
	Source materials
Microbiological	Number of viable and non-viable bacteria, viruses and fungi, including
	Fungal propagules
	Endotoxin content

Most studies of noxious gases in piggeries have focused upon ammonia, partly because it is toxic but also because of its role in acid rain. However, over 100 gaseous compounds have been identified in the air of livestock buildings (Hartung 1988); most are simple odourants, that may still give rise to complaint amongst neighbours, while some are greenhouse gases. The concentrations of most of these gases are usually in the parts per million range or lower with the exception of carbon dioxide where the concentration can be 5 to 10 times higher than ambient when the ventilation rate is slow. The mean concentrations of ammonia in Table 1 mask the short term fluctuations of hourly concentrations in livestock pig buildings which ranged between 17.9 and 36.7 ppm in four countries (Groot Koerkamp *et al.* 1998).

The final category of aerial pollutants in weaner buildings is micro-organisms and their components. The majority of these will be non-pathogenic Gram positive bacteria (Crook *et al*. 1991) at a concentration of approximately 10^6 colony forming units (cfu) m^{-3}. Smaller numbers (#10^5 cfu m^{-3}) of Gram negative bacteria and fungi will also be found (Seedorf *et al*. 1998). The majority of airborne microbes will be non-pathogenic. However, some opportunistic pathogens, such as *Pasteurella multocida*, and primary pathogens, e.g. African swine fever virus and *Bordetella bronchiseptica*, can be isolated from the air in numbers that depend on the shedding rate from the host and their viability whilst airborne. Endotoxins arise from the breakdown of the outer cell wall of Gram negative bacteria and have been implicated in occupational respiratory disease in pig stockmen. Typical concentrations range between 14 and 351 ng m^{-3} for the inhalable fraction and 2.7 and 32.6 ng m^{-3} for the respirable fraction (Table 1).

Table 1. Mean concentrations and emissions of aerial pollutants in pig housing in Northern Europe

	Mean concentration					Mean emission rate		
	Inhalable dust ($mg\ m^{-3}$)	Respirable dust ($mg\ m^{-3}$)	Inhalable endotoxin ($ng\ m^{-3}$)	Respirable endotoxin ($ng\ m^{-3}$)	Ammonia (ppm)	Inhalable dust emission ($mg\ h^{-1}$ per pig)	Respirable dust emission ($mg\ h^{-1}$ per pig)	Ammonia emission ($mg\ h^{-1}$ per pig)
Sows on litter, n=16								
England	0.63	0.16	38.0	2.2	5.1	57	23.1	303
Germany	1.64	0.12	566.7	52.4	12.5	301	18.2	1298
Sows on slats, n=32								
Denmark	3.49	0.46	25.8	4.2	8.7	408	60.6	730
England	0.86	0.09	32.6	0.9	11.0	59	5.7	503
Germany	1.13	0.11	7.8	6.4	10.2	47	5.6	325
Netherlands	1.20	0.13	64.4	2.3	17.8	64	7.4	535
Weaners on slats, n=32								
Denmark	3.37	0.15	193.5	19.9	5.3	43	1.6	45.8
England	5.05	0.43	41.4	9.8	7.8	17	1.5	26.0
Germany	2.80	0.29	14.4	2.7	4.5	24	2.3	22.0
Netherlands	3.74	0.32	351.3	32.6	4.6	78	7.4	26.6
Finishers on litter, n=16								
Denmark	1.21	0.10	178.0	21.0	9.1	92	7.1	394
England	1.38	0.15	134.0	9.9	4.3	57	6.5	108
Finishers on slats, n = 34								
Denmark	2.08	0.16	100.0	7.7	14.9	74	7.0	391
England	2.67	0.29	106.0	8.8	12.1	55	8.4	185
Germany	2.31	0.18	99.7	10.4	14.3	78	7.4	308
Netherlands	2.61	0.24	101.2	12.6	18.2	67	4.3	385

Original source: dust – Takai *et al.* 1998; endotoxin – Seedorf *et al.* 1998; ammonia – Groot Koerkamp *et al.* 1998
Each of 64 buildings was surveyed over 24 h once in winter and in summer; two extra buildings were included in the German survey in summer.

The final category of aerial pollutants in weaner buildings is micro-organisms and their components. The majority of these will be non-pathogenic Gram-positive bacteria (Crook *et al*. 1991) at a concentration of approximately 10^6 colony-forming units (cfu) m^{-3}. Smaller numbers (#10^5 cfu m^{-3}) of Gram-negative bacteria and fungi will also be found (Seedorf *et al*. 1998). The majority of airborne microbes will be non-pathogenic. However, some opportunistic pathogens, such as *Pasteurella multocida*, and primary pathogens, e.g. African swine fever virus and *Bordetella bronchiseptica*, can be isolated from the air in numbers that depend on the shedding rate from the host and their viability whilst airborne. Endotoxins arise from the breakdown of the outer cell wall of Gram-negative bacteria and have been implicated in occupational respiratory disease in pig stockmen. Typical concentrations range between 14 and 351 ng m^{-3} for the inhalable fraction and 2.7 and 32.6 ng m^{-3} for the respirable fraction (Table 1).

The variety of both the sources and types of aerial pollutants in livestock pig buildings poses several problems for abatement. Firstly, clear specifications have yet to be set in terms of animal production and health, though the Commission Internationale du Genie Rural has recommended threshold values for ammonia and dust (CIGR 1992) for livestock while Government agencies, e.g. the Health and Safety Executive in the UK, have proposed tolerable limits for aerial pollutants to maintain human health. Secondly, it is not clear whether attempts to control the burden of one pollutant may exacerbate exposure to another. The development of abatement techniques is a topic of active research. Good progress has been made in the use of oil spraying to reduce airborne dust (e.g. Takai *et al*. 1993). This works by minimising the resuspension of dust after it has settled within the building. Although its adoption is less advanced, one promising technique to reduce ammonia emissions from pig buildings and waste stores is dietary manipulation to lower excretion of urea and proteins (Phillips *et al*. 1998). Environmental control in a pig building therefore means more than a thermostat operating a ventilation system and integration of both thermal and air quality criteria will be necessary.

REACTION TO AMMONIA BY PIGS

The ancestors of the domestic pig evolved in a woodland habitat in which pollutant gases were not present at concentrations typically found in modern weaner buildings. There can be no reason *a priori* for the pig to have developed adaptive behaviour when faced with these gaseous pollutants. On the other hand, as the pig roots through the woodland soil, it is likely to be exposed to a heavy burden of inhaled dust particles, which are filtered effectively by the turbinates in the snout.

Ammonia gas is an irritant that, in humans, is detectable at 5 to 50 ppm, causes irritation of mucous surfaces at 100-500 ppm after 1 h and is rapidly lethal after exposure to 10,000 ppm (Nordstrom and McQuitty 1976). Although the occupational exposure limit is 35 ppm for a short term exposure of 15 min or less and 25 ppm over 8 h (Health and Safety Executive 2001), the initial reaction of most people to such atmospheres is avoidance followed by habituation if the exposure is prolonged.

A similar avoidance of ammonia has been observed in juvenile pigs (Jones *et al*. 1996). In a free-choice preference test, pigs made fewer visits of shorter duration to ammoniated atmospheres versus fresh air (Table 3). Overall, 80% of their time was spent in an atmosphere of 10 ppm or lower, indicating a clear preference for fresh air. Although only a small proportion of time was spent in 20 or 40 ppm ammonia, the length of each visit suggested a delayed aversion to ammonia. In subsequent experiments, either single or pairs of juvenile pigs were given a forced choice between either thermal comfort or fresh air (Jones *et al*. 1999). Thus heat was provided along with 40 ppm ammonia (HP) in one compartment while the other was unheated and contained fresh air (FA). As the air temperature fell below the animals' lower critical temperature (16.3-21.0^{o}C), the single pigs became increasingly motivated for warmth rather than fresh air. The mean duration of the visits to HP was six times longer than to FA, over an air temperature range from 0 to 15^{o}C (Table 4). Paired pigs were also given a choice between HP and FA, which was provided in four compartments so that individuals could make separate choices. In this case, the pig's motivation for companionship was stronger than any one individual's preference for an alternative environment. As before, the paired pigs increasingly preferred HP over FA as the air temperature fell.

Table 3. Back transformation (from a logit) of mean relative time spent, visit number and visit duration by all pigs to each ammonia concentration (n = 8 pigs: Jones *et al.* 1996)

	Nominal ammonia concentration (ppm)			
	0	10	20	40
Time spent (%)	53.4	26.9	7.1	5.1
Visit number	46.2	37.1	21.7	17.5
Visit duration (min)	101.4	72.0	39.6	32.1

Table 4. Mean and standard error of the number and average duration of visits made to each option (Jones *et al*. 1999)

Choice option	Single pigs, n= 8				Paired pigs, n=8			
	Heated 40 ppm ammonia HP		Unheated fresh air FA		Heated 40 ppm ammonia HP		Unheated fresh air FA	
	Mean	s.e.	Mean	s.e.	Mean	s.e.	Mean	s.e.
Visit number	27.1[a]	0.1	25.9[b]	0.1	21.4[a]	0.1	20.1[b]	0.1
Average visit duration (min)	207.6[a]	19.4	30.5[b]	19.4	264.5[a]	19.4	29.1[b]	19.4

Within an experiment, means with different superscripts are significantly different (P<0.001).

These findings demonstrate that juvenile pigs prefer to maintain thermal comfort rather than endure a cold environment of fresh air. The reasons for the delayed aversion are unknown but clearly sudden exposure to such high concentrations of ammonia was not sufficiently aversive for the animals to leave immediately. Jones *et al*. (1996) suggest that the animals may have gradually developed a sense of malaise, which eventually drove them to seek fresh air. Presumably, the domestic pig has not evolved a set of behavioural and physiological mechanisms that would allow it to make the necessary adaptive responses in the presence of noxious atmospheres of ammonia.

AERIAL POLLUTANTS AND RESPIRATORY DISEASE IN WEANER PIGS

The effects of aerial environment in pig productivity were reviewed by De Boer and Morrison in 1988. Their major conclusions still apply today and were that (i) the tolerance limits for aerial exposure have not been defined; (ii) potential interactions between aerial pollutants have rarely been examined; (iii) dust plays an important part in the aetiology of disease; (iv) dusts and gases may reduce productivity directly, or indirectly by affecting health; (v) respiratory diseases are of great economic importance world wide; and (iv) the key features of building design and management to control pollutant exposure are not fully understood.

There is good clinical evidence that poor air quality affects the incidence and severity of common endemic respiratory diseases, e.g. porcine reproductive and respiratory syndrome, swine influenza and enzootic pneumonia. These diseases are of commercial importance with no effective vaccine available against many respiratory pathogens. The effects of respiratory disease on pig growth and food conversion efficiency (FCE) are substantial. Muirhead and Alexander (1997) state that FCE and the number of days to reach 90 kg (d) are increased by 0.1-0.3 and 4-15 d for *Actinobacillus pleuropneumonia*, 0.1-0.2 and 4-15 d for atrophic rhinitis and 0.05-0.1 and 3-12 d for enzootic pneumonia during the period of chronic disease.

Much of the early research on lesions induced by exposure to ammonia and dust used concentrations far in excess of those found in piggeries (see Table 1) for short durations and in the absence of specific respiratory pathogens (Done 1991). For example, Drummond *et al*. (1980) reported tracheal and turbinate exudation at 500 ppm ammonia, while Doig and Willoughby (1971) observed tracheal epithelial hyperplasia at 100 ppm ammonia and either 200 mg m^{-3} corn starch or 10 mg m^{-3} corn dust. Conversely, Diekman *et al*. (1993) found no difference in the percentage of lung consolidation and snout grade in gilts exposed to low (4-12 ppm) or moderate (26-45 ppm) ammonia concentrations. The most convincing epidemiological evidence is that of Robertson *et al*. (1990), who found a strong association between commercial concentrations of aerial pollutants and the incidence and severity of atrophic rhinitis.

More recently, Hamilton *et al.* (1996) have shown that ammonia exposure of weaned pigs not only raises the severity of turbinate atrophy induced by *Pasteurella multocida* but also that the damage is maximal at 10-15 ppm and decreases at concentrations above 25 ppm. They explain this surprising result as the net effect of two mechanisms; (i) enhanced colonisation of the nasal cavity by *P. multocida* during ammonia exposure with ammonia providing a source of nitrogen for the bacteria (Hamilton *et al*. 1998a); and (ii) separate but additional turbinate atrophy following ammonia exposure alone (Hamilton *et al*. 1996). Whether these mechanisms also apply to other specific respiratory diseases is not yet known but these results, in the first instance, have important implications for specification of an acceptable concentration of ammonia in weaner houses.

The mechanisms, by which dust affect respiratory disease, are likely to be different from those for ammonia. Organic dusts will be immunogenic (Rylander 1986) while inorganic dusts may block mucociliary clearance. In a related study, Hamilton *et al.* (1998b) reported an increase in turbinate atrophy with ovalbumin dust exposure in weaned pigs following *P. multocida* infection. Simultaneous exposure to both ovalbumin dust (20 mg m^{-3} total mass) and ammonia (50 ppm) caused greater turbinate atrophy than exposure to either pollutant alone (Hamilton *et al*. 1999).

The mechanisms by which aerial pollutants are involved in the aetiology of porcine respiratory disease are complex (Wathes 1998a) and require consideration of specific pathogens, commensal respiratory microflora, and host-specific factors as well as the nature of the pollutants themselves. Simply put, the question is whether the incidence and severity of respiratory disease in weaner pigs are greater when combined with chronic exposure to aerial pollutants. This has being addressed in a large experiment that is co-ordinated by Silsoe Research Institute.

In a specially developed facility, groups of weaner pigs (960 in total) were exposed for 6 weeks to controlled concentrations of airborne dust (approximately 0, 2.5, 5 or 10 mg m^{-3} inhalable fraction) and ammonia (approximately 0, 10, 20 or 40 ppm). The effects on production and respiratory disease were measured. The facility comprises five rooms, each holding 24 pigs. Each room was ventilated mechanically at a constant rate of either 30 or 40 air changes per hour to minimise the background concentration of pollutants. An artificial pig dust was developed, though setting the specifications for composition, particle size distribution and microbial content was hampered by the lack of published values for these parameters. The dust was manufactured from feed, barley straw and faeces, mixed by weight in the proportions 0.5:0.1:0.4. The size distribution of this dust resembles that of literature data for piggery dust. This dust was then resuspended into the supply air of each room via a venturi nozzle fed from an agitated hopper. Ammonia was also injected into the supply air. The dust and ammonia concentrations were monitored continuously. The particle size distribution was measured regularly with an aerodynamic particle sizer and gravimetric samplers. Although all experiments have been completed, statistical analysis of the results is ongoing. The control of the ammonia and dust concentration was excellent (see Tables 5 and 6). Preliminary assessment of the production data suggests that there is an inter-action between ammonia and dust exposure.

Table 5. Mean concentration of ammonia (ppm) measured in the exposure rooms during the weaner phase

	Mean ammonia concentration (ppm)								
	batch 1	batch 2	batch 3	batch 4	batch 5	batch 6	batch 7	batch 8	batch 9
Room 1	0.2	19.8	10.0	19.5	36.8	0.6 *	0.6	0.5	0.8 *
Room 2	9.6	35.2	0.7 *	1.0	1.0 *	0.8	0.6*	17.0	1.0
Room 3	36.0	0.4 *	18.8	11.0	22.0	38.1	10.6	36.2	37.3
Room 4	19.3	9.1	37.3	39.0	0.9	12.3	38.0	0.8 *	9.4
Room 5	0.3 *	0.4	0.0	0.8 *	11.2	21.6	17.3	9.0	17.0

* control room; Batch 6 was abandoned; nominal concentrations 0, 10, 20 and 40 ppm

Table 6. Mean concentration of inhalable dust (mg m^{-3}) measured in the exposure rooms during the weaner phase

	Mean inhalable dust concentration (mg m^{-3})								
	batch 1	batch 2	batch 3	batch 4	batch 5	batch 6	batch 7	batch 8	batch 9
Nominal	*10*	*0*	*5*	*2.5*	*10*	*2.5*	*5*	*0*	*2.5*
Room 1	11.3 / 12.2	1.5 / 1.3	4.5 / 4.5	2.6 / 2.9	8.8 / 9.4	1.8 / 1.6*	5.2 / 4.9	0.7 / 1.2	1.5 / 1.5*
Room 2	11.5 / 12.8	1.7 / 1.2	1.8 / 1.1*	2.5 / 2.7	1.4 / 1.7*	3.5 / 3.0	0.9 / 1.5*	0.8 / 1.4	2.2 / 2.1
Room 3	11.1 / 10.9	1.8 / 1.6*	5.5 / 4.6	2.6 / 2.8	9.2 / 8.9	5.1 / 5.1	5.0 / 5.3	1.0 / 1.5	2.8 / 3.4
Room 4	9.3 / 11.8	1.5 / 1.4	5.2 / 4.2	2.2 / 2.5	9.0 / 8.9	4.1 / 3.6	4.3 / 4.7	0.6 / 1.0*	3.2 / 3.3
Room 5	2.2 / 2.0*	1.4 / 1.3	5.7 / 6.1	0.7 / 1.5*	8.8 / 9.4	4.6 / 3.6	5.3 / 4.6	0.9 / 1.9	3.3 / 2.9

IOM / continuous sampler; * control room; Batch 6 was abandoned

ENVIRONMENTAL IMPACT OF AERIAL POLLUTANT EMISSIONS FROM WEANER PRODUCTION

Table 7 lists the common aerial pollutants emitted from pig buildings and the reasons for concern over their impact upon the environment. In the UK, pig production is not responsible for the bulk of gaseous emissions that are emitted from livestock housing and manure stores or during manure spreading: pigs account for about 14, 3 and 3% of the total emissions of ammonia, methane and nitrous oxide, respectively (Phillips and Pain 1998). The dominant sources of these gases are cattle, followed by poultry.

Interest is now being taken in livestock production as a source of particulate aerosols because of the association that has been demonstrated between fine dust (PM10 – particulate matter less than 10 µm in size) and human respiratory disease in urban areas. An inventory of PM10 emissions from livestock production in the UK has not been published but this source, of which pigs comprise a significant part, is probably about 10% of total emissions. Equally there is uncertainty whether dusts from pig production offer a health hazard over and above that provided by urban PM10.

Table 7. Common aerial pollutants emitted from intensive pig housing (Phillips and Pain 1998)

Type of gas	Mechanism(s) of production	Reasons for concern
Ammonia	Enzymic degradation of urine, or in the case of poultry, uric acid. Microbial (anaerobic) degradation of faeces.	Contributes to acid rain. Upsets natural eco-systems by deposition of N. Increases need for N fertiliser on farmland - which brings both water pollution and economic penalties. Implicated in the aetiology of environmental respiratory diseases of livestock.
Methane	Enteric fermentation, especially in ruminants. Microbial (anaerobic) degradation of excreta.	Greenhouse gas.
Nitrous oxide	Incomplete microbial denitrification or nitrification of mixed bedding and excreta.	Greenhouse gas. Harms ozone layer.
Carbon dioxide	Animals' metabolism. Microbial action on excreta.	Asphyxiant, if allowed to accumulate. Greenhouse gas, although this source is mostly non-fossil in origin.
Hydrogen sulphide	Microbial (anaerobic) degradation of faeces.	Toxic.
Odour (can contain traces of well over 100 gases)	Microbial degradation, especially anaerobic.	Nuisance.

Traditionally, the solution to aerial pollution within a pig building was to discharge the pollutants to the atmosphere via the ventilation exhaust air. This policy is no longer acceptable given the above concerns. Indeed, awareness of the strength of agricultural sources of greenhouse and other gases has prompted European legislation to reduce emissions from intensively housed livestock. The European Union Directive on Integrated Pollution Prevention and Control (Anon, 1996) has been implemented and embraces pig farms comprising at least 750 sows or 2000 growing pigs of over 30 kg live weight.

It requires these pig farmers to limit the emissions of gases by the best available technology not entailing excessive cost (BATNEEC). The EU Directive itself does not specify limits or operating procedures: each Member State has been asked to draw up its own system. Other EU legislation includes the Acidification Strategy. This aims to protect sensitive ecosystems in Europe by reducing atmospheric deposition to less than the 'critical loads'. In turn, 'national ceilings' have been placed on the emission of ammonia and other gases. Each Member State will need to apportion the reductions between different sources.

INTEGRATED SYSTEMS FOR THE MANAGEMENT OF LIVESTOCK PRODUCTION

Sustainable livestock production requires producers to satisfy many environmental and economic demands that may conflict. Not only does the product have to meet certain quality specifications, but it must have been produced profitably while maintaining improved welfare standards, and within prescribed limits on the environmental impact of the production process. Traditionally, livestock management decisions have been based almost entirely on the judgement and experience of the stockman who has to estimate or guess the likely effects of any control action, taking into account the complexities of the processes involved. This leads to dilemmas. A change of diet may increase growth rate, but will the increased feed cost be justified, and will the change of diet make the animal too fat? Increasing the ventilation rate in a building may improve air quality and so help to prevent disease, but will the reduced temperature in the building affect feeding and growth. At the same time the increased ventilation rate might increase the pollutant emission to the external environment.

These dilemmas arise because currently each of the individual processes involved in livestock production is controlled separately. For example, nutrition may be controlled by the stockman according to some predetermined strategy, while ventilation and heating may be controlled so as to maintain the temperature within limits and stocking density may be controlled according to welfare considerations. There are, at best, weak connections between the various aspects of process management. These connections need to be strengthened and formalised through the development of integrated management systems, designed to control simultaneously more than one, and ideally all, interrelated processes involved in livestock production.

The principles of an IMS are taken directly from control theory. Many livestock production processes operate as an open-loop control system (Figure 1). For example, in the case of rearing animals for meat, the input is a desired growth rate; the controller is the farm manager; the actuator is the nutrition supply system, which is operated by the manager; the process is the animal; and the output is the resulting growth rate.

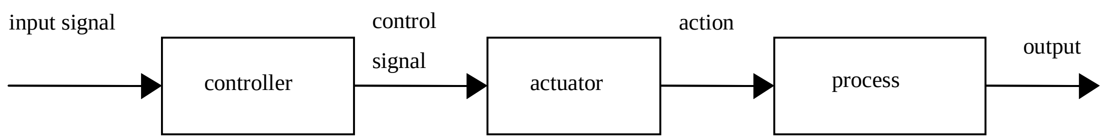

Figure 1. Open-loop control system

Open-loop nutrition control is prescriptive, in that the diet to be fed at any time is calculated in advance. The producer will subject the animals to a nutritional regime, which has been designed in the expectation that it will produce the required result. In a well managed enterprise the nutritional regime will be based on some form of growth model. Growth models enable the nutritional inputs (protein and energy) required by an animal to realise its growth potential to be calculated. However, there are many factors (e.g. disease or unfavourable environment) which may prevent the animals from achieving their potential, and growth targets will be missed. This is a general problem with open-loop control systems; the output is free to drift.

The solution lies in the use of a model-based control system (Figure 2). Consider the example of nutritional management of broiler production for which the control elements can be translated as:

input signal	desired growth rate
controller	calculates the required energy and protein supply.
actuator	a nutritional supply system to deliver specified quantities of energy and protein
process	the birds
model of process	growth model, used to calculate controller parameters
sensor	to monitor growth rate of the birds
output	resulting growth rate

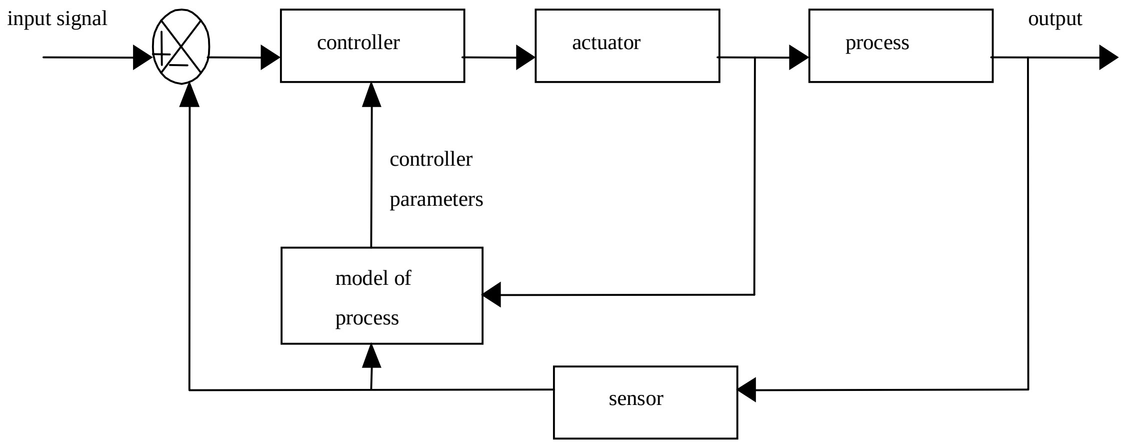

Figure 2. Model-based closed loop control system

This example has been developed at Silsoe in a project aimed at developing a model-based control system for calculating the correct nutrition to be given to broilers to enable a target weight to be achieved on a target date. The experiments were carried out at commercial scale using eight houses each with ≈ 34,000 birds for each trial. The birds were weighed continuously in their houses by perches fitted with strain gauges. Feed supply and all other input variables were monitored automatically. Crucial to the success of the real time growth control system is the performance of the model, which has been developed to predict growth rate from nutrients consumed on a daily basis. A semi-mechanistic model based on published growth models and principles was developed. Adaptation of the model has taken place during the trials and resulted in the use of a genetic algorithm. The example results in Figure 3 show that the model performs well.

Environmental legislation (e.g. Integrated Pollution Prevention and Control, IPPC) has been introduced which restricts annual emissions of ammonia, dust and odour from the livestock production system since these have an adverse environmental impact (Wathes 1998b). The stockman therefore has to manage both the meat production process *per se* as well as the environmental processes occurring within the building. Clearly, the relationship between these processes is complex. In addition to the conventional understanding of these individual processes, stockman needs to understand the inter-relationships between broiler growth, nutrient supply and utilization and pollutant emissions. Unfortunately, these relationships have not been determined quantitatively and, unless his empirical knowledge is sufficient, he may find it difficult to solve the problems, even if means are available to monitor pollutant emissions from the building.

A first stage in the development of an IMS for broiler production and pollutant emissions is to quantify the relationships between growth, nutrient supply and utilization, and emissions. Recently, Robertson *et al*. (in press) have reported results of commercial scale experiments involving some 14000 birds in which nutritional supply was manipulated in the form of four target protein levels (based on lysine content) of 85, 90, 100 or 110% of the normal commercial level. Simultaneous measurements of the emission rates of ammonia, inhalable dust and odour were made.

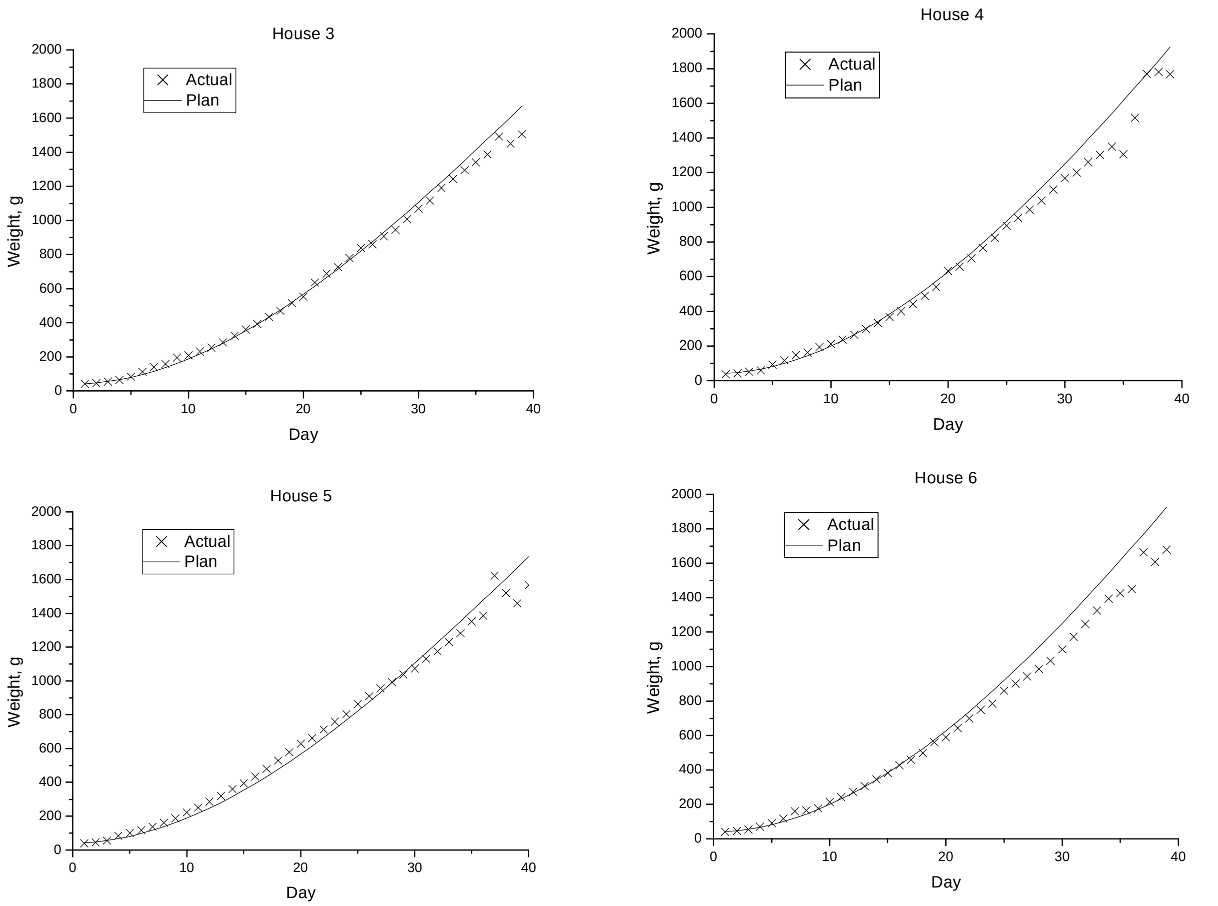

Figure 3. Example results from a trial to illustrate the ability of the new controller to grow birds to a target weight. Houses 3 (pullets) and 4 (cockerels) were grown according to standard practice. Houses 5 (pullets) and 6 (cockerels) were grown by the controller.

Evidence has been obtained of a lower protein intake corresponding to a lower ammonia emission. A 1% reduction in protein intake corresponded to a little less than a 1% reduction in ammonia emission in a trial involving only cockerels. Direct causal relationships are confounded, however, by other factors that were found to be strongly impacting. These included the observations that ammonia emissions were higher for pullets than for cockerels and that coccidiosis outbreaks tended to reduce ammonia emissions. The limited litter sampling and analysis that was undertaken did not show any single litter characteristic to be a reliable indicator of ammonia emission. Multi-parametric relationships were found to be more promising, though more detailed litter sampling would be required to pursue this.

Relationships were also found between diet and emissions of dust and odour. Highest dust and odour emissions occurred with the most extreme diets (lowest protein and highest energy), as a consequence of unusually unsettled bird behaviour.

This project has demonstrated the ability to quantify many of the factors involved in the production of emissions and has provided indicators of the effects of some of these factors on levels of emissions. The results have also made it clear that including environmental parameters into integrated management systems is far from straightforward. In order to further reduce ammonia emissions from broilers, the litter needs to be kept drier, i.e. the ventilation needs to be increased to remove the extra water. This in turn requires additional heating to maintain temperature in the building. The combination of dry litter and increased ventilation rate might increase the level of dust in the building as well as the dust emission. Further research should enable these conflicting scenarios to be modelled and included in an integrated management system thus assisting the stockman to make extremely complex decisions on maintaining the optimal conditions for both the birds and the environment. A further hurdle towards including pollutants in integrated management systems is the lack of affordable and reliable sensors for pollutants such as ammonia and dust. Although very good research tools are available, these are not suitable for every day use by the livestock industry as maintenance time and costs are prohibitively high.

However, this should not stop the inclusion of more or less independent pollutant abatement measures that are currently available, such as oil spraying for abatement of dust (Takay and Pedersen 1999). Recent developments in the Netherlands have shown that ammonia emissions from fattening pigs can be reduced by significant changes to the pen and pit design (Zeeland 1997). The slatted area is reduced to approximately 30 % of the total pen area and comprises a spillage area at the front of the pen and a dunging area at the rear of the pen. Each pit has smooth sloping walls to reduce the surface area of manure. Combined with a novel ventilation system these modifications proved successful in reducing ammonia emissions. A current project by ADAS and Silsoe Research Institute aims to show that this system and other simple retro fit measures, such as reducing the slatted area, are capable of reducing ammonia emissions under present UK conditions.

CONCLUSIONS

We are strongly of the opinion that in the future, environmental design and management for livestock must integrate both the scientific approach and the management of the production and environmental processes. There are two reasons why the gauntlet of integration must be picked up if sustainable livestock agriculture is to flourish over the next 20 to 30 years. Firstly, modern livestock production now comprises a complex set of physical, biological and economic processes. The margin for error in management of these processes is shrinking because of the tighter specification for the products, the dismantling of barriers to international trade in livestock products, and a widespread take up of modern production methods. Additional constraints arise from the growing shortage of skilled labour and slim profits for investment in new technology. Secondly, there is no longer any doubt, if there ever once was, that pollutants from livestock production, especially its intensive form, have a negative impact on local, regional and national environments. Legislation (e.g. IPPC) to limit and reduce pollutant emissions has been introduced in Europe while local communities in North America and Europe have become increasingly intolerant of odour emissions from livestock farms. The development of integrated management systems for production and environmental processes should resolve the conflicts that face producers.

REFERENCES

ANON. (1996). *Official Journal of the European Communities*, **L257**, 26-40.
CIGR (1992). '2nd Report of Working Group on Climatization of Animal Houses'. 2nd Edition. (Commission Internationale du Gϑnie Rural: State University of Gent, Gent, Belgium).
CROOK, B., ROBERTSON, J.F., TRAVERS, S.A., BOTHEROYD, E.M. LACEY, J. and TOPPING, M.D. (1991). *Am. Ind. Hyg. Assoc. J.* **52,** 271-9.
DE BOER, S. and MORRISON, W.D. (1988). 'The effects of the quality of the environment in livestock buildings on the productivity of swine and safety of humans'. (University of Guelph: Ontario).
DIEKMAN, M.A. SCHEIDT, A.B., SUTTON, A.L., GREEN, M.L., CLAPPER, J.A., KELLY, D.T. and VAN ALSTINE, W.G. (1993). *Am. J. Vet. Res.* **54**, 2128-31.
DOIG, P.A. and WILLOUGHBY, R.A. (1971). *J. Am. Vet. Med. Assoc.* **159**, 1353-61.
DONE, S.H. (1991). *Vet. Rec.* **128**, 582-6.
DONHAM, K, REYNOLDS, S., WHITTEN, P., MERCHANT, J., BURMEISTER, L., and POPENDORF, W. (1995). *Am. J. Ind. Med.* **27**, 405-18.
DONHAM, K.J.., SCALLON, L.J., POPENDORF, W., TREUHAFT, M.W. and ROBERTS, R.C. (1986). *Am. Ind. Hyg. Assoc. J.* **47**, 404-10.
DRUMMOND, J.G., CURTIS, S.E., SIMON, J. and NORTON, H.W. (1980). *J. Anim. Sci.* **50**, 1085-91.
GROOT KOERKAMP, P.W.G., METZ, J.H.M., UENK, G.H., PHILLIPS, V.R., HOLDEN, M.R., SNEATH, R.W., SHORT, J.L., WHITE, R.P., HARTUNG, J., SEEDORF, J., SCHRÖDER, M., LINKERT, K.H., PEDERSEN, S., TAKAI, H., JOHNSEN, J.O. and WATHES, C.M. (1998). *J. Agric. Engin. Res.* **70**, 79-95.
HAMILTON, T.D.C., ROE, J.M. and WEBSTER, A.J.F. (1996). *J. Clin. Microbiol.* **34**, 2185-90.
HAMILTON, T.D.C., ROE, J.M., HAYES, C.M. and WEBSTER, A.J.F. (1998a). *J. Clin. Microbiol.* **36**, 1260-5.
HAMILTON, T.D.C., ROE, J.M., HAYES, C.M. and WEBSTER, A.J.F. (1998b). *Clin. Diagn. Lab. Immun.* **5**, 494-8.
HAMILTON, T.D.C., ROE, J.M., HAYES, C.M., JONES, P., PEARSON, G.R. and WEBSTER, A.J.F. (1999). *Clin. Diagn. Lab. Immun.* **6**, 199-203.
HARTUNG, J. (1988). *In* 'Volatile emissions from livestock farming and sewage operations' (Eds. V. C. Nielsen, J. H. Voorburg And P. L'Hermite) pp 54-8 (Elsevier Applied Science: London).

HEALTH AND SAFETY EXECUTIVE (2001) Occupational exposure limits. EH40/97. (Health And Safety Executive: London).

HEBER, A.J., STROIK, M., FAUBION, J.M. and WILLARD, L.H. (1988). *T. Am. Soc. Agric. Eng.* **31**, 882-7.

HONEY, L.F. and MCQUITTY, J.B. (1979). *Can. Agric. Engin.* **21**, 9-14.

JONES, J.B., BURGESS, L.R., WEBSTER, A.J.F. and WATHES, C.M. (1996). *Anim. Sci.* **63**, 437-45.

JONES, J.B., WEBSTER, A.J.F., and WATHES, C.M. (1999). *Anim. Sci.* **68,** 387-98.

MONTEITH, J.L. *Principles Environ. Physics*. Edward Arnold, London. 1973

MUIRHEAD, M.R. and ALEXANDER, T.J. (1997) *Managing pig health and treatment of disease*. (5M Enterprise: Sheffield)

NORDSTROM, G.A. and MCQUITTY, J.B. (1976) Manure gases in the animal environment – a literature review (with particular reference to cattle housing). *University of Alberta Research Bulletin* **76-1**.

PHILLIPS, V.R. and PAIN. B.F. (1998). *In* 'Proceedings of the international workshop on Environmentally-Friendly Management of Farm Animal Wastes, Sapporo, Japan. 25-29 November 1997'(Ed. T. Matsunaka) pp 67-72.

PHILLIPS, V.R., COWELL, D.A., SNEATH, R.W., CUMBY, T.R., WILLIAMS, A.G., DEMMERS, T.G.M. and SANDARS, D. (1998) 'A review of ways to abate ammonia emissions from livestock buildings and waste stores' *Unpublished report*. (Silsoe Research Institute: Bedford).

ROBERTSON, A.P., HOXEY, R.P., DEMMERS, T.G.M., WELCH, S.K., SNEATH, R.W., SHORT, J.L., RICHARDS, A.F., COOK, P.A., FOTHERGILL, A., FILMER, D., HUDSON, N.A.J. and FISHER, C. (in press). *J. Agr. Eng. Res*.

ROBERTSON, J.F., WILSON, D. and SMITH, W.J. (1990). *Anim. Prod.* **50**, 173-82.

RYLANDER, R. (1986). *Am. J. Ind. Med.* **10**, 221-7.

SEEDORF, J., HARTUNG, J., SCHRÖDER, M., LINKERT, K.H., PHILLIPS, V.R., HOLDEN, M.R., SNEATH, R.W., SHORT, J.L., WHITE, R.P., PEDERSEN, S., TAKAI, H., JOHNSEN, J.O., METZ, J.H.M., GROOT KOERKAMP, P.W.G., UENK G.H. and WATHES, C.M. (1998). *J. Agr. Eng. Res*. **70**, 97-109.

TAKAI, H., MOLLER, F., IVERSEN, M., JORSAL, S.E. and BILLE-HANSEN, V. (1993). *In* 'Proceedings of Fourth International Livestock Environment Symposium' pp. 726-33. (ASAE: Louisville, Kentucky, USA).

TAKAI, H., PEDERSEN, S., JOHNSEN, J.O., METZ, J.H.M., GROOT KOERKAMP, P.W.G., UENK G.H. PHILLIPS, V.R. HOLDEN, M.R., SNEATH, R.W., SHORT, J.L., WHITE, R.P., HARTUNG, J., SEEDORF, J., SCHRÖDER, M., LINKERT, K.H. and WATHES, C.M. (1998). *J. Agr. Eng. Res*. **70**, 59-77.

TAKAI, H. and PEDERSEN, S. (1999). *In* 'Dust Control in Animal Production Facilities. Proceedings of Congress in Aarhus, Denmark, 30 May-2 June' pp. 279-85.

WATHES, C.M. (1998a). *In* '15th International Pig Veterinary Society Congress' (eds Done, S., Thomson, J. and Varley M.) Vol I, pp 257-265. (Nottingham University Press: Birmingham, UK).

WATHES, C.M. (1998b). *World Poultry Sci. J.* **54**, 241-51.

WATHES, C.M., DEMMERS. T.G.M., RICHARDS, P.A., TEER, N., TAYLOR, L.L. and GOODMAN, J. (2000) Paper No. 004111 pp 23. (ASAE, St. Joseph, MI, USA).

WATHES, C.M. (2001). *In* 'The Weaner Pig: Nutrition and Management' (Eds M.A. Varley and J. Wiseman) pp. 259-271. (CAB1 Publishing: London).

WATHES, C.M., ABEYSINGHE, S.A. and FROST , A.R. (2001) *In* 'Proceedings of the Sixth International Livestock Environmental Symposium' pp. 5-14. (ASAE: Louisville, Kentucky, USA).

WHITTEMORE, C.T. and SCHOFIELD, C.P. (2000) *Livest. Prod. Sci.* **65**, 203-8.

WOODS, P.S.A., ROBINSON, N.E., SWANSON, M.C., REED, C.E., BROADSTONE, R.V. and DERKSEN, F.J. (1993). *Equine Vet. J.* **25,** 208-13.

ZEELAND van A.J.A.M. (1997). 'Sloped plates in the slurry channel in a fattening pig pen', *Report P4.22*, (Research Institute for Pig Husbandry: Rosmalen: The Netherlands).

Email: theo.demmers@bbsrc.ac.uk