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Modeling and Measuring the Dispersion of Odors from Hog Confinements

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MODELING AND MEASURING THE DISPERSION OF ODORS FROM HOG CONFINEMENTS

An Abstract of a Thesis
Submitted
In Partial Fulfillment
of the Requirements for the Degree
Master of Science

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University of Northern Iowa
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ABSTRACT

A comparison was made between predicted and measured odor concentration downwind of two hog finishing confinements. Two Gaussian dispersion models, STINKBAK and AERMOD, were used. The experimental cases examined odor emanating from a mechanically-ventilated facility and a curtain-sided facility during summer 2003. A field olfactometer was used to measure odor concentration. The odor concentrations served as input to STINKBAK, which then estimated the odor emission rate from the confinement. AERMOD used this emission rate and other meteorological data to predict the peak concentration of odor around the confinement over the sampling hour.

The calculated odor emission rates are slightly higher than those reported in the literature. At 25°C, the odor emission rate is estimated at 27.8 $OU/m^2/s$ for the mechanically-ventilated confinement and 32.7 $OU/m^2/s$ for the curtain-sided confinement. Odor release from the curtain-sided confinement was found to be higher than the mechanically-ventilated facility. A correlation with ambient temperature was observed.

Measured concentrations were compared to predicted peak concentrations over the sampling hour. The forecast odor plume compared well to the observations. The importance of the meteorological information was shown to be of primary importance in plume forecast accuracy.

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CHAPTER 1

INTRODUCTION

Livestock in general and hogs in particular in the United States are essential to the nation's economic well being, contribute to the vitality of rural communities, and ensure the sustainability of America's food supply. Today, the United States ranks second in the world in production, consumption, and exportation of pork and pork products. The American hog herd stands at nearly 60 million animals, 68% of which are raised in the Corn Belt. Iowa leads the nation in pork production with 15.8 million hogs (Iowa Agricultural Statistics Service, 2003).

Pork production has dramatically changed in the last few decades. The number of small, family farms has decreased while factory farms, also known as concentrated animal feeding operations (CAFOs), have multiplied. In 2000, over half of the hogs (50 million head) delivered to market were from only 156 corporate operations (Plain and Lawrence, 2003). Over the past few years, the expansion of corporate farming has become a major environmental concern in Iowa and across the nation. Expansion of residential developments into rural Iowa along with a growing number of CAFOs have led to increasing conflict due to public concern over water and air quality issues (greenhouse gas emissions, allergens, dust). Odor pollution is also becoming a serious point of contention between farmers and their neighbors. Siting of new hog confinements often raises public concern, especially because of the potential loss in property value and the effect on health and quality of life.

Agricultural odor production has received increasing attention from researchers in recent years. Odor production is a complex process (Fig. 1). The origin, emission, and dispersion of odors are described in the following literature review. As a complement to these studies, this research evaluates odor dispersion predictions from the AERMOD computer model by using odor measurements taken with a field olfactometer downwind of hog confinements.

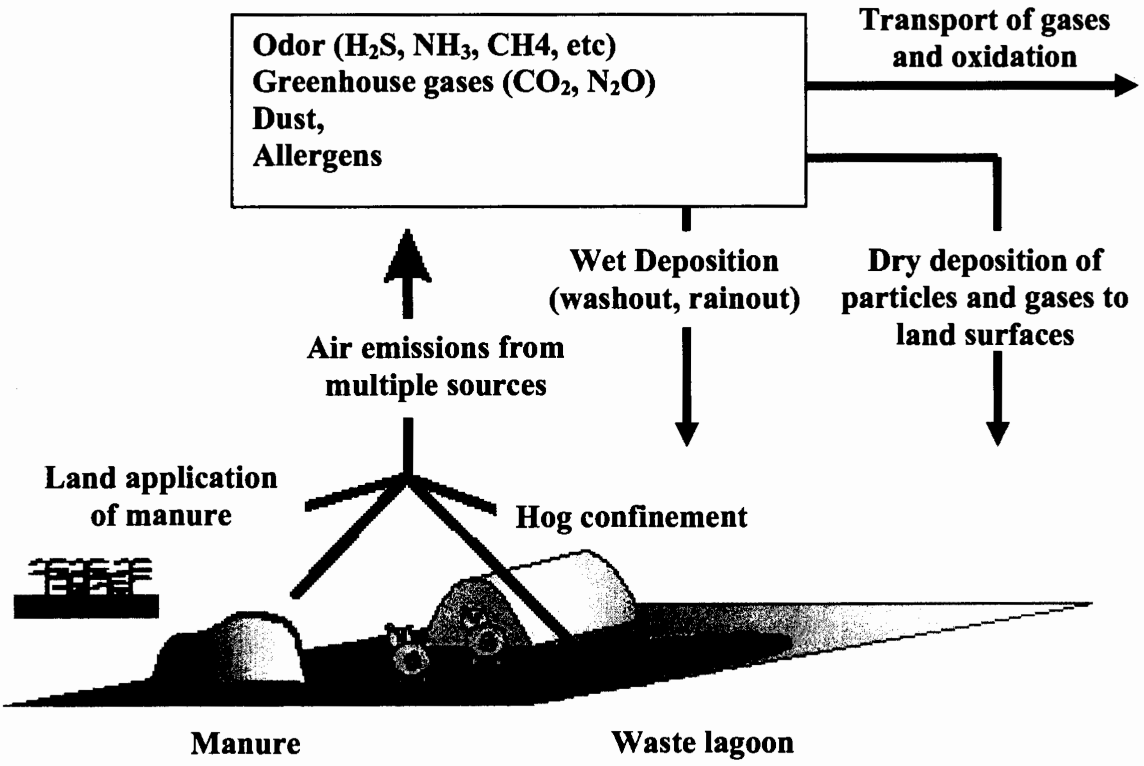

Fig. 1. Fate and transport of air emissions associated with hog production (adapted from Schnoor et al., 2002).

Statement of Problem

The goal of this project is to study the dispersion of odorous plumes from hog confinements via two computer models, STINKBAK and the AMS/EPA Regulatory Model (AERMOD). Little research has been published on the performance of either model for agricultural sources and no previous work has coupled the models. Moreover this research focuses on the differences between two swine finishing facilities with different ventilation techniques (mechanical and natural). In this study, STINKBAK is used to estimate the odor emission rate from a confinement. This approach uses the concentration of odor at a downwind location (as measured with a field olfactometer) and the local wind as inputs. AERMOD then uses this emission rate and other meteorological data to predict the peak concentration of odor around the facility over a 1-hour period.

CHAPTER 2

LITERATURE REVIEW

Odor Formation

Odors from swine production operations come predominantly from the microbial decomposition of the excreta of the animals. Anaerobic reactions begin in the hog's intestines and continue after excretion. Six groups of swine fecal bacteria have been isolated: lactose fermenters, nonlactose fermenters, *Clostridium* sp., *Lactobacillus* sp., Enterococci and *Staphylococcus* sp. (Zhu, 2000). In a first step, bacteria metabolize complex organic substrates into intermediate molecules such as alcohols, aldehydes, organic acids, peptones, sulfides, etc. Then, only if the environmental conditions are favorable, end-products are formed (carbon dioxide, ammonia, methane, hydrogen sulfide, and water), as depicted in Fig. 2. These end-products are the main constituents emanating from CAFOs, but not the most problematic. Usually, the intermediates are much more odorous than the final products. It is important to promote complete digestion by the bacteria in order to reduce odor emission from swine facilities. Bacterial populations will vary according to the environmental conditions, generating differing amounts and types of odor. Environmental parameters, such as moisture content, temperature, pH, or oxygen concentration can greatly affect odor production by modifying the microbial activity. Another parameter to take into account is diet, which determines manure composition and, hence, odor generation (Ni et al., 2000; Powers, 1998).

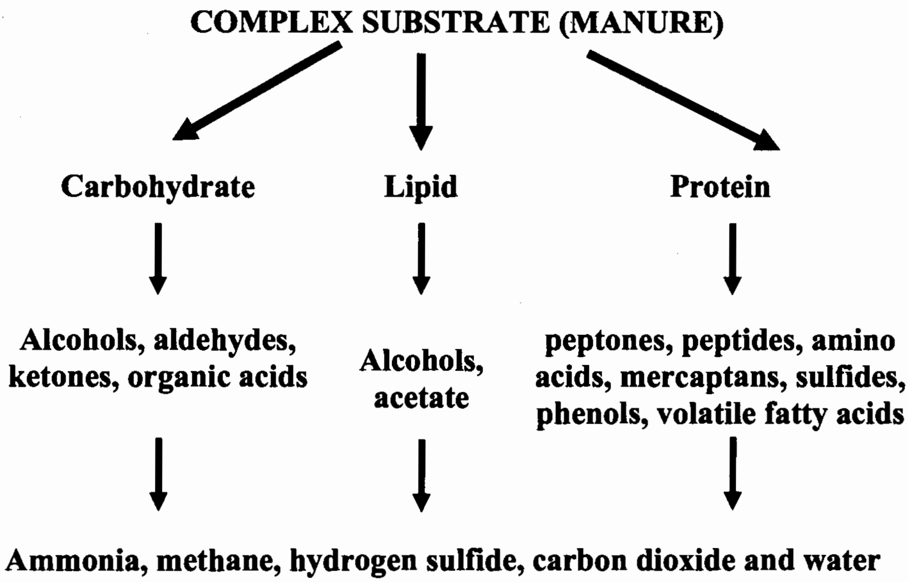

Fig. 2. Degradation pathways that generate odorous compounds (Powers, 1998).

Olfactometry

A considerable amount of research has been conducted on the odorants emitted from swine facilities. A total of 411 gases, including 331 volatile organic compounds (VOCs) and fixed gases, have been found in odorous emissions from swine operations in North Carolina (Schiffman et al., 2001). Many of them have an odor detection threshold of less than 1 $\mu g/m^3$ of air, meaning that humans are very sensitive to a great number of volatile compounds released from swine facilities. An odor is actually the sensation that occurs when a mixture of odorants impacts the sensory receptors in the nasal cavity. The odor from CAFOs is very complex because each individual compound presents unique sensory properties. Table 1 summarizes the main odorants contributing to odor in swine production facilities, their odor detection threshold, and their odor characteristics. Some of the most objectionable gases are the fatty acids, including acetic acid, butyric acid, and

Table 1
Odor characteristics and olfactory threshold for gases identified from air samples at swine production facilities (adapted from Schiffman et al., 2001)

Chemical name	Odor detection threshold (μg/m^3)	Sensory and odor characteristics
Volatile organic compounds		
Acetaldehyde	186	Green sweet
Acetone	14,500	Irritant
Benzene	3,630	Solvent
Ethanol	28,800	Sweet
Formaldehyde	871	Hay, straw like, pungent
Methanol	141,000	Sweet
Phenol	110.0	Medicinal
p-Cresol	1.9	Irritant, pungent
Toluene	1,550	Solvent
n-Pentane	31,600	Irritant
Volatile nitrogen compounds		
Ammonia	5,750	Pungent
Methylamine	18.6	Irritant, putrid, fishy
Trimethylamine	30.9	Irritant, ammoniacal, fishy
Indole	0.031	Intense fecal
Pyridine	85.1	Irritant burnt, sickening
Skatole	0.56	Stench, fecal
Volatile fatty acids		
Acetic acid	145.0	Irritant, pungent
n-Butyric acid	3.9	Rancid butter
Lauric acid	24.6	Irritant, pungent
Isobutyric acid	19.5	Rancid butter
Isovaleric acid	24.6	Stinky feet, cheese
Propionic acid	35.5	Irritant, pungent
n-Valeric acid	4.8	Putrid, fecal smell
Volatile sulfur compounds		
Methyl sulfide	12.3	Stench, decayed vegetables
Methyl disulfide	2.2	Putrid, garlic
Hydrogen sulfide	17.8	Rotten eggs
Phenyl sulfide	1.0	Unpleasant odor
Ethyl mercaptan	1.1	Earthy, sulfidy
Allyl Mercaptan	0.39	Stench

propionic acid; sulfur compounds such as hydrogen sulfide and methyl disulfide; and nitrogen compounds including ammonia, skatole, and indole (Spoelstra, 1980).

Research on analytical methods for malodor detection has been conducted for many years in order to determine if an odor can be monitored or described via one or more of its key components. Hydrogen sulfide and ammonia are often cited as odor indicators but do not seem very suitable. DeBode (1991) found that by covering manure storage units, ammonia emissions were reduced from 75% to 100% while odor intensity was only reduced from 28% to 72%. Both gas emissions and odor intensity were reduced, but in significantly different amounts. Earlier, Spoelstra (1980) reported that ammonia and hydrogen sulfide were not appropriate as odor indicators because they do not reflect the kinetic degradation of manure. Indeed, ammonia comes from urea hydrolysis and not from excreta decomposition and a large part of hydrogen sulfide is derived from sulfate reduction. Moreover, some combinations of gases may be more or less odorous than the sum of the individual gases due to synergetic or antagonist interactions. Thus, studying an odor requires understanding the odor as an entity and not as individual odorants.

The only instrument that can correctly measure an odor is the human nose. Therefore, olfactometry, the psychophysical technique that utilizes the human sense of smell to determine odor concentration, is used as the basis of odor management by regulatory authorities. Several types of equipment, called olfactometers, have been developed in order to reduce the degree of uncertainty and subjectivity associated with odor measurement. In traditional olfactometry, a sample of odorous air with varying dilutions is presented to a human panel. Panelists decide if they can detect the odor or not. In an olfactometer, odorous air is diluted with fresh air. The strength of the odor is designated as the greatest dilution that still results in odor detection. The dilution at which the majority of people first detect the odor becomes the dilution-to-threshold (D/T) for that sample. It is important to note the difference between the detection threshold and the recognition threshold (R/T), which is the dilution at which assessors are able to identify and describe the odorant's characteristics. In olfactometry, the assessor is asked to detect an odor but not to recognize it. The odor intensity is expressed as its D/T, where higher D/T equals higher odor intensity. The unit for odor concentration is odor units per unit air volume (OU/m^3) according to CEN (1999) standards but commonly expressed as OU in North America. It is defined as the volume of filtered air required to dilute a volume of odor until the detection threshold of the odor is obtained. The terms D/T and OU will be used interchangeably in this paper since they represent the same concept (Mahin, 2003).

Dynamic Dilution-Olfactometer

Dynamic olfactometry conducted in a controlled environment is the most popular method for measuring odor concentration because it is the most reliable. The panelist does not experience odor fatigue. In this method, odorous air is collected in Tedlar or PVC bags and later analyzed in a lab. There, panelists determine the detection threshold of the odor. Most dynamic dilution-olfactometers are based on the principle of the 3-port forced-choice method of sample presentation, which is also referred to as Triangular Forced-Choice Dynamic Olfactometry. Each panelist sniffs through three ports (two have clean, odor-free air and one has the odorous mixture) and determines if an odor is detectable in one of them. If they do not indicate the right port, the dilution is decreased and panelists again sniff the mixture (Chen et al., 1999). Dynamic olfactometry is considered the industry standard for measuring odor concentration. However, it is both time consuming and expensive. Van Harreveld (2003) noted numerous issues associated with the storage of odor samples in bags. He found that particulates removed during sampling caused the odor concentration in the bags to be reduced by approximately 20 %. Also, there is no standard design for the dilution equipment, so different labs can give different results for the same sample (Dravniek and Jarke, 1980; Jones et al., 1994; Schultz and van Harreveld, 1996).

Field Olfactometer

In the late 1950's, the United States Public Health Service sponsored the development of a handheld field instrument for odor measurement. The first field olfactometer, manufactured in 1960 by the Barnebey Sutcliffe Corporation, was known as the Scentometer. The original Scentometer, which consisted of a small box with sniffing ports, provided only four dilution factors. The method of producing D/T with this equipment consists of mixing two volumes of carbon-filtered air (non odorous air) with specific volumes of odorous air. The dilution-to-threshold is:

$$\text{Dilution Ratio (D/T)} = \text{Volume of carbon-filtered air}/\text{Volume of odorous air} \qquad (1)$$

Since then, further research has enabled improvement in the accuracy and capabilities of the field olfactometer. The inlet ports now have a series of orifices with differing diameters that allow for a variety of dilutions, typically from 2 to 350.

Olfactometry in the field presents its own set of problems. Being on site may bias the panelists because they anticipate odor, especially near the odor source. Moreover, it is difficult to use the device for a long time without experiencing odor fatigue. However, a study conducted by McGinley and McGinley (2003) showed that the threshold values obtained by field and laboratory olfactometry are consistent with the published threshold for hydrogen sulfide. Field olfactometry is also the least expensive and easiest technique for quantifying odor concentration.

Currently, thirteen U.S. states and several cities in North America use field olfactometers when determining compliance with odor regulations and ordinances (McGinley and McGinley, 2003). Table 2 contains a list of states that use field olfactometry as a standard, as well as the regulatory limit of odors in terms of D/T. In the early years of using the Scentometer (Huey et al., 1960), several adjectives were used to qualify the intensity of an odor as a function of the D/T's (see Table 3). These associations are still valid. Odor laws are established based on the D/Ts (McGinley et al., 2000). When concentrations higher than the regulatory D/T are measured, complaints can be recorded. The odor standard is highly variable from state to state and city to city. Iowa has no state odor regulation but some municipalities within the state do and use field olfactometers to estimate odor intensity. From 1 January 1994 to 15 October 2001, 306 odor complaints involving CAFOs in Iowa were recorded. Of these, 86.9% involved swine operations (Hoff et al., 2002). Malodor from hog operations is one of the main air pollution issues in Iowa, but the state does not presently regulate odor, ammonia, or hydrogen sulfide.

Table 2
Summary of odor standards in the United States using a field olfactometer (adapted from Mahin, 2001; Sweeten, 1990)

State or political division	Regulatory limit (D/T)		
	Residential	Commercial	Industrial
States			
Colorado	7	7	15
Connecticut	7	7	7
Illinois	8	8	24
Kentucky	7	7	7
Massachusetts	5	5	5
Missouri	7	7	7
New Jersey	5	5	5
North Dakota	2	2	2
Nevada	8	8	8
Oregon	-	-	2
Wyoming	7	7	7
Cities or air quality regions			
District of Columbia	1	1	1
Dallas, Texas	2	1	1
Oakland, California	50	50	50
San Diego, California	5	5	5
Southwest Washington State AQMA	1-2	1-2	8-32
Seattle, Washington	5	5	5
Polk County, Iowa	7	7	7
Cedar Rapids, Iowa	4	8	20
Omaha, Nebraska	4	8	20
Chattanooga, Tennessee	0	4	4

Table 3
D/T as a function of the odor intensity (McGinley et al., 2000)

Dilution-to-threshold (D/T)	Description
2	Noticeable
7	Objectionable
15	Nuisance
31	Nauseating

Odor Sources and Emission Rates From Swine Operations

Malodors from swine operations can be the result of a single odor source, a single odor event, or the combination of several sources and events. Therefore, it is important to conduct a thorough inventory of all odor sources on a site. There are three main sources of odor: the animal housing unit, the manure storage unit and the land application of manure. However, many other sources (e.g., the composting of dead animals) can contribute to odors.

Each source does not generate the same nuisance odors. Research has shown that some sources release more odor per second than others. Both the size of the source and its emission rate should be considered when assessing odors. Odor emission rate is quantified by the amount of odor (OU/m^3) released in a unit air volume per second (OU/s). In North America, the odor concentration is often expressed in OU, which results in a unit of OU.m^3/s for odor emission rate. For easy comparison between sources, the emission rate is also often described in terms of odor emission rate per unit floor area (OU.m^3/s/m^2) or per animal unit (OU.m^3/s/AU). Measurement of the odor emission rate poses major problems, mainly because it can vary both temporally and spatially. Several analytical methods have been described by Smith and Watts (1994). They consist of sampling actual point emissions using a wind tunnel or hood. Despite their reliability and ease of use, the direct methods are expensive. Alternatively, indirect techniques using empirically or physically based models are available. In the present study, the emission rate is calculated using an indirect method based on a Gaussian dispersion model known as STINKBAK (Smith, 1993).

Housing Unit

CAFOs were originally developed and introduced in the United States in the 1950s for poultry production. Since then, modifications have improved labor and production efficiencies. Today, animals are housed year round in barns in order to protect them from cold winters and diseases. Animals often spend their entire lives indoors in these facilities. Hogs mature quickly. Approximately 24 weeks are required to raise a pig from birth to an acceptable slaughter weight. On a farm, pigs are grouped in lots that are uniform in size, sex and general health. The phases of pork production are called breeding/gestation, farrowing, nursery, and growing/finishing (Table 4).

The odor emission rate varies widely among the different facilities and within the same type of facility. Gestation and finishing facilities release less odor on average than farrowing and nursery facilities. Reported odor emission rates range from 3 to 20 $OU.m^3/s/m^2$ for gestation confinements, from 4.80 to 12 $OU.m^3/s/m^2$ for farrowing, from 7 to 50 $OU.m^3/s/m^2$ for nurseries, and from 3 to 21 $OU.m^3/s/m^2$ for finishing facilities (Zhang et al., 2002).

Table 4
Pork production phases (EPA, 2004)

Type of barn	Time spent in the barn (weeks)	Animal weight (kg)	Phase description
Breeding/gestation	15	-	Reproduction to pregnancy
Farrowing	4	1-10	Birth to weaning
Nursery	4	10-25	Weaning to finishing
Growing/finishing	16	25-150	Nursery to market

The present study focuses on the finishing facility, the last step in swine production. Table 5 indicates a range of estimated odor emission rates from various studies. The emission rate was found to be variable. The differences can be explained by the fact that barns are built in a variety of styles. They can differ especially because of their ventilation system and their floor design. Figs. 3 and 4 present schematic drawings of typical hog confinements. In the following sections, descriptions of the different parts of the buildings are given.

Ventilation. Ventilation and fresh air supply are very important concerns when any type of livestock is intensively managed. A good ventilation system must provide fresh air to meet respiration needs of the animals, control the moisture build-up within the structure, move enough air to dilute any airborne disease organisms produced within the housing unit, and control and/or moderate temperature extremes. The major carriers of odors are gases from manure, dust, and water vapor.

Table 5
Odor emission rate from swine finishing confinements

Manure collection	Ventilation	Odor emission	Reference
Deep pit	Mechanical	13.9 OU/s/m^2 (avg)	Jacobson et al., 1999
Deep pit	Mechanical	3-15 OU.m^3/s/m^2	Zhu et al., 2000a
Deep pit	Natural (curtain)	2.5 OU/s/m^2 (avg)	Jacobson et al., 1999
Deep pit	Natural (curtain)	2.1-33.9 OU.m^3/s/m^2	Biosystems, 1999
Deep pit	Natural	3-11 OU.m^3/s/m^2	Zhu et al, 2000a
Shallow pit	Mechanical	11-21 OU.m^3/s/m^2	Zhang et al., 2000
Pull plug	Natural	1.3-45.5 OU/s/AU	Smith et al., 1999
Deep litter	Natural	7-42 OU/s/m^2	Payne, 1997

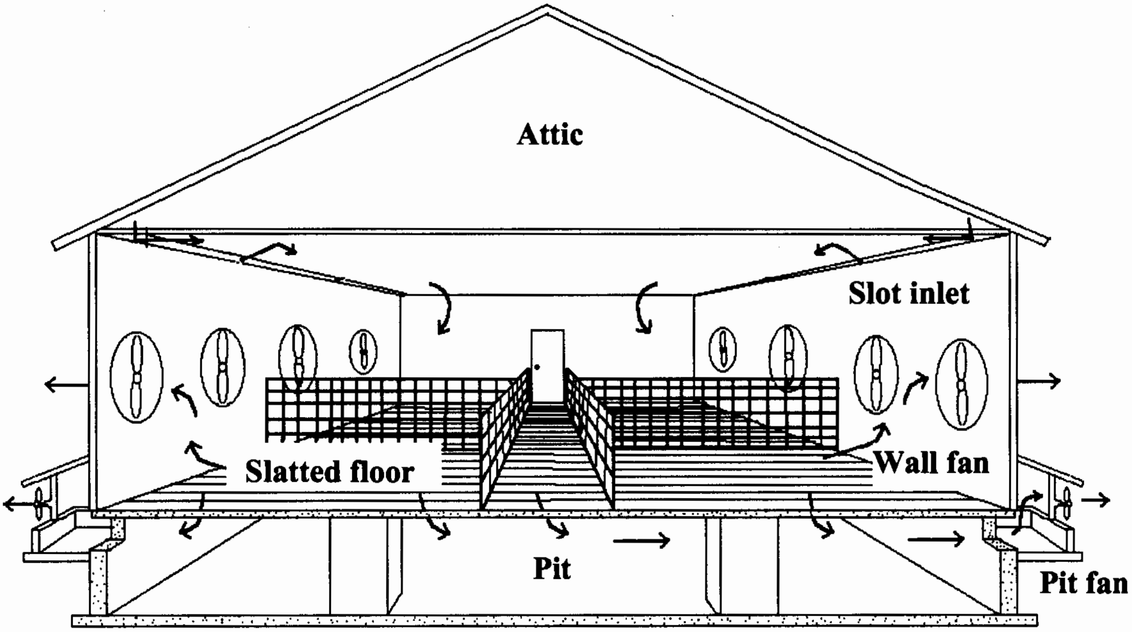

Fig. 3. Airflow pattern in a mechanically ventilated confinement.

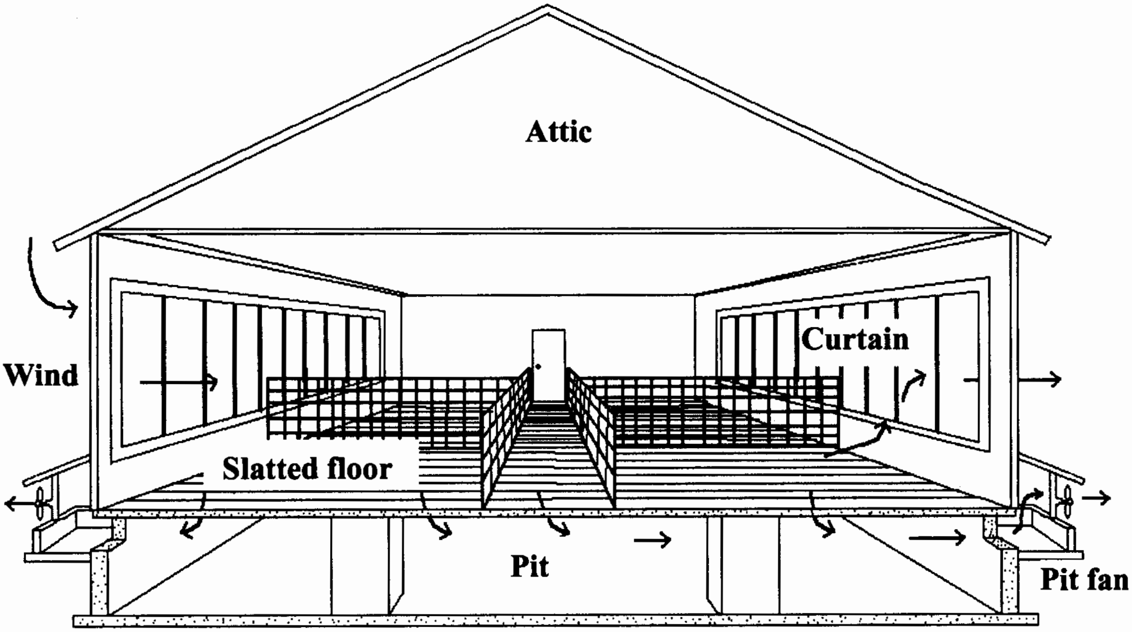

Fig. 4. Airflow pattern in a curtain-sided confinement.

Both mechanical and natural ventilation can be used in CAFOs. Mechanical ventilation relies on the presence of sidewall fans. The fans and inlets must be designed to provide at least three stages of ventilation: a minimum, continuous ventilation rate for winter, an intermediate rate for temperature control during fall and spring, and a maximum rate to control the temperature rise of the building in summer. Energy and maintenance costs make mechanical ventilation expensive.

Natural ventilation uses local wind and thermal buoyancy to move air through the structure. The quantity of airflow, in this case, is not determined by the size and ventilation rate of fans, but by the size and placement of openings and the wind speed. In spite of its reduced operating costs, natural ventilation does not control temperature during cold weather. Thermostatically controlled sidewall curtains are used in some swine buildings to control inside temperature to some extent. The adjustable plastic curtains can be open or shut as desired, according to the outdoor temperature.

Floor design. Within the barn, animals are grouped in pens with slatted or solid concrete floors. The design of the floor can have a large impact on odor production. Solid concrete floors with scrapers or small flush gutters tend to increase the generation of odors. Limiting the exposure between the building airspace and accumulated manure results in reduced odor. Thus, most of the new swine facilities use slatted floors. Slatted floors are made of non-abrasive, non-porous, slip resistant materials. They permit manure and water to drain into a large temporary or permanent underground storage pit, which also keeps the animals clean. Manure is then moved from the deep underfloor pits to outdoor lagoons via manual or mechanical scrapers, gravity-flow gutters, or flushing gutters. Underfloor pits with longer storage capacity are becoming more common, since they tend to reduce odor in comparison to the shallow pit-earthen lagoon system.

Pit ventilation is as important as the ventilation of the animal area. It helps prevent manure gases from seeping back up by the animals, reduces odor levels, permits more uniform air distribution, and helps warm and dry the floor. This results in a cleaner and healthier environment inside the building.

Swine Manure Storage Units

Swine manure can be handled as a solid, semi-solid or liquid. Liquid handling is more common in modern hog production because it requires less time and labor to collect, transfer, and store. Animal manure is usually stored either in an earthen basin or in an outdoor tank. Lagoons are a man-made earth-walled structure designed and managed to encourage microbial decomposition of the manure by adding large quantities of water to dilute the waste. They have been used for many years because of their simplicity in operation and maintenance, and relative low cost compared to other treatment methods. Lagoons can be either aerobic (containing dissolved oxygen) or anaerobic. Agricultural operations almost always use anaerobic lagoons because they are smaller, cost less, and require less management. Aerobic lagoons or oxidation ditches are very effective at reducing odors, but are expensive to maintain. Heber (1998a) showed that an aerated lagoon emitted 82% less odor than similar unaerated lagoon. Lagoon systems essentially dispose of nutrients to the air and the lagoon floor. About 70% of the nitrogen from the waste is volatilized, while phosphorus settles out. Unless the lagoon is vigorously agitated, the phosphorus stays on the bottom as sludge (Koelsch and Shapiro, 1997). Producers who do not have adequate land for nutrient application often use lagoons for long-term storage. Below-ground and above-ground tanks are concrete and steel structures that pose minimal threat of water pollution compared to earthen basins. Covers can also be installed on outside storage facilities for both safety and odor control (Hörnig et al., 1999).

Currently in the upper Midwest and especially in Iowa, earthen basins are the most common type of manure storage systems because they are less expensive to construct (personal conversation with farmer). Concrete and steel storage facilities cost about ten times more per unit of volume than earthen storage structures. Odor emission from earthen manure storage is generally seasonal with very little emission in the winter and more in the spring, summer, and fall. Table 6 summarizes results from several studies conducted in the United States.

Table 6
Odor emission rate from manure storage systems

Site description	Storage type	Odor emission	Reference
Nursery and finishing	Earthen basins	3.8-17.6 $OU/s/m^2$	Jacobson et al., 1999
Farrow to finishing	Earthen basins	4.4-6.8 $OU/s/m^2$	Jacobson et al., 1999
Gestation to nursery	Earthen basins	2.2-3.1 $OU/s/m^2$	Jacobson et al., 1999
Nursery	Above ground tank	0.1 $OU/s/m^2$	Jacobson et al., 1999
Finishing	Above ground tank	19.4 $OU/s/m^2$	Jacobson et al., 1999
Gestation and farrowing	Below ground tank	12.8 $OU/s/m^2$	Jacobson et al., 1999
Gestation to nursery	Below ground tank	51.3 $OU/s/m^2$	Jacobson et al., 1999
Nursery	Earthen basins	12.7-21.7 $OU.m^3/s/m^2$	Biosystems, 1999
Nursery	Earthen basins	82.2 $OU.m^3/s/m^2$	Biosystems, 1999
Gestation and finishing	Earthen basins	20.3 $OU.m^3/s/m^2$	Biosystems, 1999
Breed to wean	Anaerobic lagoon	4.6 $OU/s/m^2$	Heber et al., 2000
Farrow to finishing	Anaerobic lagoon	2.6 $OU/s/m^2$	Heber et al., 2000
Finishing	Aerobic lagoon	1.5-2.1 $OU/s/m^2$	Heber, 1998a
Finishing	Anaerobic lagoon	3.3 $OU/s/m^2$	Heber, 1998a

Land Application

Animal manure can be an economical source of nutrients that can help build and enhance soil productivity. Manure can also improve soil tilth, increase water-holding capacity, lessen wind and water erosion, improve aeration, and promote beneficial organisms. Thus, swine manure has been spread on agricultural land for many years. However, even if it does not last for more than a few days and happens only once or twice a year (usually during the spring or fall), the odors emitted during land application can be objectionable. Unpleasant odor from land application of manure may be the greatest concern the public has with livestock production. There are many ways to limit the impact of odor on neighbors, especially by applying manure in the morning with appropriate consideration of the wind speed and direction. Moreover, working manure into the soil or injecting it below the surface limits the amount of odor produced (Chen and Ren, 2002).

Summary

Confinement equipment and buildings vary from farm to farm for financial and other reasons. Iowa farms may have several buildings and a manure storage system, making it difficult to estimate the odor emission from a specific source. However, hog confinements are the major source of downwind odor throughout the year. Land application of manure can also be significant but it does not cause long-term downwind odor problems (Jacobson et al., 1999; Zhu and Li, 2000).

Odor and Citizens

In spite of the unpleasant smell, malodors do not usually present health hazards for citizens who live near small swine operations because odors are usually present in low concentrations (Bundy et al., 1995). However, community-based studies indicate health and quality of life issues are of great concern to persons residing close to large swine operations. Wing and Wolf (2000) noted that North Carolina residents who lived in the vicinity of a 6000-hog confinement reported increased occurrence of headache, eye irritation, sore throat, excessive coughing, and diarrhea. Thu et al. (1997) also reported that neighbors of a 4000-sow confinement in Iowa experienced more respiratory ailments. In addition, Schiffman et al. (1995) found more negative emotional states (tension, anger, depression, fatigue and confusion) among citizens living in proximity to swine operations. The authors suggested that a variety of psychological and physiological factors may have played a role in the altered mood of residents exposed to odors. These factors include the offensiveness of the odor, the intermittent nature of the stimulus, conditioned repugnance to the odor, potential neural stimulation of immune responses, direct physical effects from certain constituents of the plume (especially hydrogen sulfide), possible chemosensory disorders, and preconceived ideas associated with recent livestock related illnesses (e.g., bovine spongiform encephalopathy or Mad Cow disease, Asian bird flu). Part of the motivation for odor complaints may also be linked to the increased awareness of environmental concerns such as nitrate contamination of well water.

The real toxicity of odors is difficult to establish. The Environmental Protection Agency (EPA) does not regulate odors because the Clean Air Act does not consider them to be toxic. Some state and local agencies regulate odor from swine operations, but this is not widespread. In Iowa, odors are regulated by the Iowa Department of Natural Resources (IDNR) through the issuance of permits for construction, modification, or expansion of a feedlot. Small facilities do not need permits. Site selection, design, and management are evaluated carefully and public input is received before permits are issued. In order to protect citizens again odor nuisance, new confinements must adhere to setback restrictions with respect to neighboring residences, churches, schools, businesses, and public use areas. These distances vary with the size of the operation, land use, and topography (Heber, 1999). Further information can be found at the Water Quality Bureau section of the IDNR website (2004). We can note that current setback distances in Iowa are relatively short compared to other states: 225 m to 750 m versus 450 m to 750 m in North Carolina, 400 m to 1610 m in Illinois and 305 m to 915 m in Missouri (Heber, 1998b).

It is becoming more common now to use atmospheric dispersion models to predict where odor nuisance is likely to occur near and downwind of CAFOs for different meteorological scenarios. However, there is a lack of peer-reviewed research on model validation for odor. Evaluation and validation of a model are vital steps that need to be in place before regulatory guidelines are formulated and control technologies are required. More research needs to be conducted in this field to improve the consistency and accuracy of the atmospheric dispersion models.

Dispersion Models

Atmospheric dispersion models, which have been evolving since before the 1930s, are mathematical tools that predict the movement of pollutants for air quality management. They are used for regulation and in policy making, as well as for applications such as assessing new source impacts. They compute ambient odor concentrations as a function of source configurations, emission strengths, and meteorological characteristics.

Gaussian plume models are now widely used to predict the dispersion of pollutants, particularly from industrial and urban sources. Gas and particulates discharged into the atmosphere are transported by the wind. Dispersion is the combination of advection and turbulent diffusion, which are always present in the air. The plume of contaminated air downwind from an elevated source is roughly cone-shaped with the apex toward the source (Fig. 5). Most dispersion models use the relatively simple Gaussian approximation to simulate the steady-state dispersion of pollutants from an elevated continuous point source. That is,

$$C(x,y,z,H) = E/(2\pi.\sigma_z.\sigma_y.\hat{u}) \times \exp(-y^2/(2\sigma_y^2)) \times [\exp(-(z-H)^2/(2\sigma_z^2))+\exp(-(z+H)^2/(2\sigma_z^2))] \tag{2}$$

where C is the plume concentration (OU); E is the rate of emission from the source (OU.m^3/s); σ_y and σ_z are the dispersion parameters representing the crosswind (lateral) and vertical spread of the plume (m); û is the average wind velocity at the emission height (m/s); H is the effective height of the plume centerline above ground level (m); and x, y and z are the ground level coordinates of the receptor (m) (Beychok, 1995).

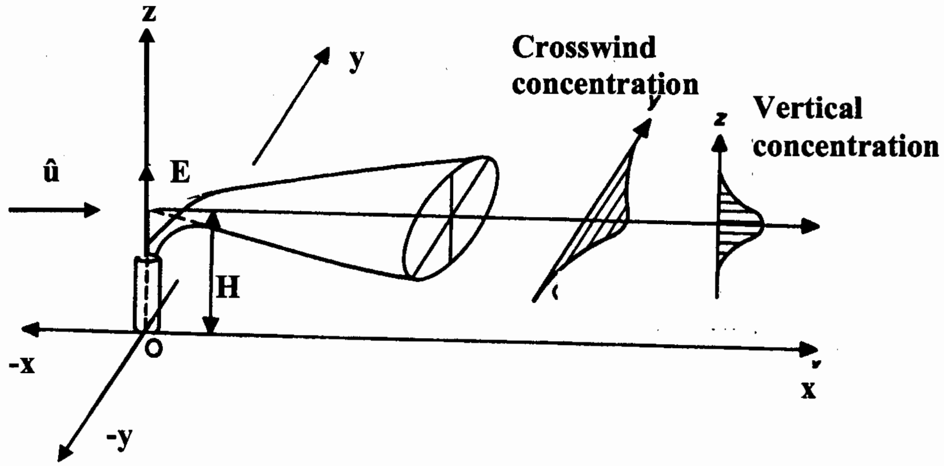

Fig. 5. Gaussian plume distribution (adapted from Carney and Dodd, 1989).

The Gaussian plume model is a reasonable approach for predicting odor concentration, assuming that odors disperse in the same way as other gases. To use a model to predict odor dispersion from agricultural sources, the previous equation must be modified since it was developed for the dispersion of pollutants from elevated smokestacks, whereas CAFOs are surface sources. Eq. (2) can be adapted to incorporate reflection or absorption of odor by the ground. A common simplification is also to assume that H is equal to 0. This allows for the simplification of Eq. (2) to:

$$C(x,y,z,H{=}0) = E/(\pi.\sigma_z.\sigma_y.\hat{u}) \times \exp(y^2/(2\sigma_y^2)) \times \exp(z^2/(2\sigma_z^2)) \quad (3)$$

With odors, there is no plume rise due to the vertical momentum or lower density of a warm air mass as is the case for a stack plume. Finally, the dispersion coefficients σ_y and σ_z should be carefully assessed. Indeed, they represent the degree of "spreading" of pollutants horizontally and vertically during plume movement and thus, they depend on the nature of the source and on meteorological conditions. The next section highlights various data inputs required for dispersion modeling.

Data Inputs

Emission Source

Dispersion models require information about the source type (e.g., point, area, or volume) and the rate at which pollutants (odor) are emitted. There are many ways to represent a source in the dispersion model. For instance, well-defined stacks, chimneys, or vents are commonly modeled as stationary point sources. However, agricultural sources are usually much more complex than industrial sources. It is very important to understand where the odor emissions occur.

There are several common source types in dispersion modeling. The easiest way to model an agricultural source is probably to define it as an area source because this source type is used to model low level or ground level releases with no plume rise (such as lagoons, and earthen basins). The source is represented as a rectangular area with arbitrary orientation. Another approach is to model the agricultural source as a volume source. It is actually a prediction of an upwind virtual point source that would produce the initial size of the volume source plume. This approach is used for emissions from multiple vents, conveyor belts, as well as the wall and pit fans of an enclosed confinement. Indeed, the building itself cannot be modeled as an area source because the interior is not in direct contact with the atmosphere. Because the emission depends on the volumetric flow rate of each fan, it is easier to model each as a volume source. Further information concerning area and volume sources is contained in the Industrial Source Complex (ISC) User's guide (EPA, 1995b).

Receptors

Receptors are defined as the location where pollutant concentrations are to be determined. Many dispersion models have the capability of including multiple receptor networks. If an overall view of pollutant concentration on and off the site is necessary, then a grid of receptors (cartesian or polar) should be defined.

Meteorological Data

Dispersion of odorants in the atmosphere is largely dependent upon meteorological conditions. Emission and dispersion of pollutants occur in the boundary layer, defined as the part of the troposphere that is directly influenced by the presence of the earth's surface and responds to surface forcings with a timescale of about an hour or less. These forcings include frictional drag, evaporation and transpiration, and heat transfer. Wind speed and direction, atmospheric stability, and mixing height are major variables in the boundary layer. The quality of model predictions depends mostly on the accuracy of meteorological and emission data.

Wind. Horizontal winds play a significant role in the transport and dilution of odors. Careful specification of wind speed and direction is important since the Gaussian equation assumes the wind is constant for a given time period. When the wind is calm, the Gaussian approximation cannot be applied because it would compute an infinite odor concentration at the source. However, in the real world, dispersion would still occur through molecular diffusion. Odor dispersion is also significantly affected by variability in wind direction. If wind direction is constant over time, the same area will be continuously exposed to nuisance odors. However, if the wind is shifting regularly, the exposed area will be large and Gaussian plume theory is not appropriate.

Wind speed is greatly affected by friction, which is proportional to surface roughness. Surface features such as lakes, cultivated fields, or buildings determine the roughness of the terrain, which is measured by the surface roughness length. This parameter is the height at which the mean horizontal wind speed is zero. The greater the parameter, the greater the reduction in wind speed. Use of the appropriate roughness length is essential to the study of odor dispersion from ground level sources (Panofsky and Townsend, 1964). EPA surface roughness lengths for a variety of surface types are summarized in Table 7.

Table 7
Surface roughness lengths for various land uses (EPA, 1995a; EPA, 1998a)

Terrain description	Surface roughness length (cm)
Smooth desert	0.03
Grass (4 cm)	0.14
Grass (5-6 cm)	0.75
Alfalfa (15.2 cm)	2.72
Grass (60-70 cm)	11.40
Cultivated land in spring	3.00
Cultivated land in summer	20.00
Cultivated land in autumn	5.00
Cultivated land in winter	1.00
Wheat (60 cm)	22.00
Corn (220 cm)	74.00
Citrus Orchard	198.00
Fir forest	283.00
City land use	
Apartment residential	370.00
Central business district	321.00
Office	175.00
Park	127.00
Single family residential	108.00

Atmospheric stability. Turbulence throughout the boundary layer has a major effect on the rise and dispersion of air pollutants. Thus the dispersion parameters σ_y and σ_z in Eq. (3) are a function of atmospheric stability. Atmospheric stability determines the extent to which vertical mixing occurs, and consequently, the degree to which airbone pollutants are mixed. The ambient atmosphere is unstable if the buoyancy forces enhance the vertical motion of an air parcel, resulting in a peak ground-level odor concentration near an elevated emission source and low concentrations far from the source. The atmosphere is stable if the buoyancy forces resist the vertical motion. In this case, there is a low ground-level concentration near an elevated source, with comparatively higher concentrations at long distances from the source. Finally, the ambient atmosphere is said to be neutral if the buoyancy force does not resist or enhance vertical motion.

The degree of stability can be categorized into defined increments or "stability classes." The most commonly used categories are the six Pasquill-Gifford stability classes: A, B, C, D, E, and F (Pasquill, 1961). The Pasquill classification system is presented in Table 8. Class A denotes the most unstable or most turbulent conditions and Class F denotes the most stable or least turbulent conditions. In this system, wind speed measured at 10 m above ground level, and day time incoming solar radiation or the night time percentage of cloud cover are used to determine the stability class.

The dispersion parameters σ_y and σ_z in the Gaussian model are calculated using algorithms based on field studies. Table 9 summarizes some of the empirical equations that have been used to estimate the dispersion coefficients. These parameter values are most applicable for releases near the ground.

Table 8
Key to the Pasquill-Gifford stability categories (adapted from Pasquill, 1974)

Surface wind speed at 10 m (m/s)	Day incoming solar radiation			Night-time cloud cover	
	Strong	Moderate	Slight	> 50%	< 50%
< 2	A	A-B	B	E	F
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
> 6	C	D	D	D	D

Table 9
Examples of empirical models that have been used to calculate the dispersion parameters

Type source	σ_y	σ_z	Reference
Industrial source	$e^{k1+ k2\ln x+ k3 (\ln x)(\ln x)}$	$e^{k4+ k5\ln x+ k6 (\ln x)(\ln x)}$	McMullen, 1975
Industrial source	$k_1x/[1 + (x/k_2)]^{k3}$	$k_4x/[1 + (x/k_2)]^{k5}$	Green et al., 1980
Rural area $10^2 < x < 10^4$	$k_1x(1 + 0.0001x)^{-0.5}$	$k_2x(1 + k_3x)^{-0.5\,k4}$	Briggs cited by Gifford, 1976
Urban area $10^2 < x < 10^4$	$k_1x(1 + 0.0004x)^{-0.5}$	$k_2x(1 + k_3x)^{-0.5}$	Briggs cited by Gifford, 1976
Agricultural source	$0.84678x\tan(k_1 + k_2\ln x)$	k_3x^{k4}	Smith, 1993
Industrial source	$k_1x^{0.903}$	k_2x^{k3}	Koch cited by Chen et al., 1998
Agricultural source	$k_1x\,\hat{u}^{-k2}e^{-k3x}$	$k_4x\,\hat{u}^{-k5}e^{-k6x}$	Chen et al., 1998

Note: û is the average wind speed in m/s; x is downwind distance in meters; the coefficients k_1-k_6 are fitted coefficients.

The mixing layer height. The mixing layer height (also known as the mixing depth) is the thickness of the layer above the earth's surface that experiences vigorous mixing by convection and turbulence. Dispersion of pollutants is generally restricted to the mixing layer because of strong stability above the mixing layer height. The greater the mixing depth is, the more effective is dispersion at reducing pollutant concentration. Mixed layer depth is very important to pollutant concentration far from the emission source. For receptors closer to the source, the influence of the mixing layer height can be ignored without too much loss of accuracy. A few empirical parameters can be used as inputs in computer models to describe the mixing depth as well as its evolution in time. The Monin-Obukhov length is one of these parameters. It is related to the depth of the near-surface layer in which vertical wind shear is large enough to create turbulent mixing even under stable conditions.

Topography. The depth of the mixing layer is influenced on a local scale by surface characteristics such as roughness, reflectivity, and availability of moisture. These influences are quantified through the surface roughness length, albedo and Bowen ratio respectively. The albedo is the ratio of the amount of solar radiation reflected by the surface to the amount incident upon it. It varies from 0.95 over fresh snow to 0.05 over dark wet soils. The Bowen ratio is the ratio of sensible to latent heat fluxes from the earth's surface into the air. It is smaller over moist surfaces where most energy goes into evaporation and higher over dry surfaces where most of the energy goes into sensible heating. Typical values range from 6.0 over arid regions to 0.1 over the ocean. Albedo and Bowen ratio usually vary with time and weather as indicated in Tables 10 and 11.

Model Selection

Several Gaussian plume models are commercially available. The ones that have been evaluated for their effectiveness in modeling emissions from feedlot facilities include the Australian regulatory model AUSPLUME (Smith, 1995b); the sanctioned American regulatory models ISC3 (EPA, 1995b), CALPUFF (Scire et al., 2000), INPUFF-2 (Zhu et al., 2000b), and PTDIS (Janni, 1982); and the AMS/EPA Regulatory Model AERMOD (EPA, 1998b). A dispersion model, known as STINKBAK, was

Table 10
Albedo of ground covers by land-use and season (EPA, 1998a)

Land-use	Spring	Summer	Autumn	Winter
Water (fresh and sea)	0.12	0.10	0.14	0.20
Deciduous forest	0.12	0.12	0.12	0.50
Coniferous forest	0.12	0.12	0.12	0.35
Swamp	0.12	0.14	0.16	0.30
Cultivated land	0.14	0.20	0.18	0.60
Grassland	0.18	0.18	0.20	0.60
Urban	0.14	0.16	0.18	0.35
Desert shrubland	0.30	0.28	0.28	0.45

Table 11
Daytime Bowen ratio by land-use and season with average moisture conditions (EPA, 1998a)

Land-use	Spring	Summer	Autumn	Winter
Water (fresh and sea)	0.1	0.1	0.1	1.5
Deciduous forest	0.7	0.3	1.0	1.5
Coniferous forest	0.7	0.3	0.8	1.5
Swamp	0.1	0.1	0.1	1.5
Cultivated land	0.3	0.5	0.7	1.5
Grassland	0.4	0.8	1.0	1.5
Urban	1.0	2.0	2.0	1.5
Desert shrubland	3.0	4.0	6.0	6.0

designed specifically for agricultural odors (Smith, 1993). The choice of model for a particular application depends on many factors such as the source, the atmospheric conditions, the scale of dispersion studied, and the type of output desired (emission rate or concentrations). Regulatory models are designed to determine compliance with air quality standards. ISC3 is often selected because of its ease of use and because comparisons between available models show that it is the most suitable model to use for a detailed analysis (Curran et al., 2002; Koppolu et al., 2002; Sheridan et al., 2004). However, the accuracy of traditional steady-state dispersion models, such as ISC3 and AUSPLUME, has been seriously questioned (Ormerod, 2001). Gaussian puff models that are in fact non-steady Gaussian plume models, like CALPUFF or INPUFF-2, recognize the fact that odor emission occurs intermittently and not in a steady continuous stream for any length of time (Zhu et al., 2000a). Currently another model, AERMOD, has been developed to replace the 30-year-old ISC3. It has been shown that in simple terrain (without obstructions) AERMOD forecasts are more accurate than ISC3. In a study conducted by Hanna et al. (2001) on the emissions from five industrial sites and considering only the highest predicted and observed concentrations, AERMOD was found to underpredict by about 20%, on average, while ISC3 overpredicts by a factor of seven, on average.

Because of previous validation studies, AERMOD was selected as the most suitable model to use in this study in order to predict odor dispersion. Moreover, STINBAK was also chosen because it calculates the odor emission rate, a required input for AERMOD.

STINKBAK

Dr. Rod Smith from the University of Southern Queensland, Australia, created the Gaussian plume model, STINKBAK (Smith, 1993; Smith, 1995a) for his own research purposes. The program, written in FORTRAN, was designed to predict the odor emission rate from area sources of finite size and any orientation with respect to the wind direction. The basis for the computer model lies on the numerical integration of Eq. (3) over the source area. The program STINKBAK first calculates a non-dimensional concentration $\chi(x,y,z)$ at a specified point downwind of a rectangular source, given the dimensions of the source (X,Y), the location of the receptor from the center of the source (x,y), and the wind speed and direction (angle Θ to the x axis) (Fig. 6). Surface roughness length, atmospheric stability class, and the Monin-Obukhov length are the only meteorological data required to run the model. The non-dimensional concentration is determined by solving the numerical integration of Eq. (3):

$$\chi(x,y,z) = \Sigma\{1/(2\pi\sigma_{zi}) \times \exp(-z^2/2\sigma_{zi}^2) \times [\mathrm{erf}((y+0.5Y)/(2^{0.5}\sigma_{yi})) - \mathrm{erf}((y-0.5Y)/2^{0.5}\sigma_{yi}))]\ \delta X\} \quad (4)$$

where σ_{yi} and σ_{zi} are the dispersion coefficients for each strip. The non-dimensional concentration χ at the receptor is related to the actual concentration C and to the emission rate by:

$$C(x,y,z) = \chi(x,y,z) \times E_a / \hat{u} \quad (5)$$

where E_a is the spatial average emission rate per unit area from the area source ($OU.m^3/s/m^2$). Thus, the odor emission rate can be calculated from Eqs. (4) and (5).

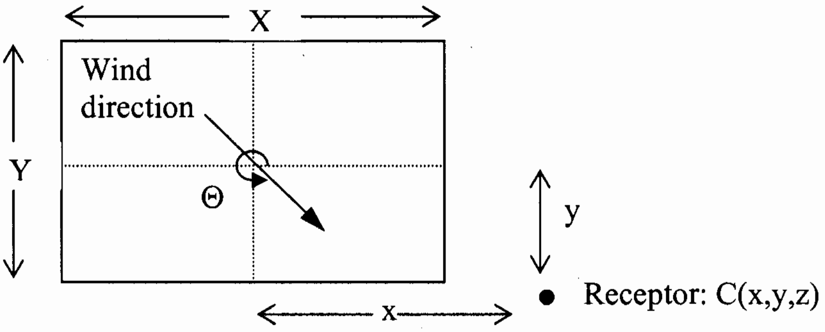

Fig. 6. Coordinate definition for a rectangular area source (adapted from Smith, 1995a).

Currently, STINKBAK is one of the only programs that was specifically written to study the dispersion of malodors from agricultural sources. However, only a few studies were carried out to evaluate the accuracy and consistency of the predicted emission rates. Moreover, the model cannot handle multiple area sources. This can be problematic if the study site is surrounded by other CAFOs.

AERMOD

The American Meteorology Society (AMS) in collaboration with the EPA developed AERMOD for regulatory purposes. The EPA (2000) proposes to include the model in the Guideline on Air Quality Models and the model has been released for public review and comment. The model is capable of handling multiple sources, including point, line, area, and volume sources. Surface and upper air observations from the closest observing sites are used to specify meteorological conditions. In addition, the user has to specify the albedo, the Bowen ratio, and the surface roughness length.

The basic types of output available with AERMOD are summaries of high values (highest, second highest, etc) at receptors for each averaging period. Model output can be imported into many graphics packages to produce contoured plots (EPA, 1998b).

CHAPTER 3

MATERIALS AND METHODS

Field Methods

Field measurements took place on 13 consecutive weeks during July/September 2003 at two different finishing hog confinements located about 10 to 20 km south of Cedar Falls, Iowa. Data were collected in the morning only, except for three days in September measurements were made also in the evening. The facility in Fig. 7 (hereafter referred to as Confinement A) is mechanically ventilated with wall and pit fans. An open gestation and breeding lot, farrowing house, nursery house, and earthen basin with manure are located approximately 100 m to the west of confinement A. Two steel bins lie directly to the west of the confinement. The surrounding field of grass is flat and covers an area of 5,000 m^2. The grass was mown to a height of 3 cm during the experiments. Farther out, cornfields replace the grass. The corn varied in height from 1 m to 2 m during the sampling. A schematic drawing and complementary information on the site (hereafter referred to as Site A) is given in Appendix A. The facility in Fig. 8 (hereafter referred to as Confinement B) is naturally ventilated through its open curtains during the summer and mechanically ventilated via its pit fans during the winter. The confinement is located in relatively smooth, homogeneous terrain consisting of soybeans that reached 60 cm high by the end of the growing season. The closest neighboring hog confinements are several hundred meters away. A schematic drawing and complementary information on the site (hereafter referred to as Site B) is given in Appendix A. Further information obtained from the owners is presented in Table 12.

Fig. 7. Mechanically ventilated confinement. Note the presence of six sidewall fans and four pit fans.

Fig. 8. Curtain-sided confinement.

Table 12
Basic information for the confinements

Description	Confinement A	Confinement B
Date of construction	1977	1990 (estimated)
Dimension		
Length (m)	43.9	73.2
Width (m)	12.3	12.5
Height (m)	3.0	3.0
Surface area (m^2)	537.7	915.0
Volume (m^3)	1621.5	2745.0
Capacity	500 hogs	1200 hogs
Ventilation System	Mechanical	Natural
Number of pit fans	8	8
Number of wall fans	14	-
Max volumetric flow rate (m^3/s)		
Pit fan	1.27	Unknown
Wall fans	2.02-1.65	-
Curtain area (m^2)	-	73.2
Manure collection		
Floor type (material)	Slatted	Slatted
Pit capacity	42.6×12.2×1.8 m deep	Unknown
Pit washing frequency	Twice a year	Unknown
Geography		
Land use around confinement	Grass and corn fields	Flat soybean fields
Closest obstruction (size)	2 circular steel bins (10 m in diameter× 5 m high)	Warehouse (40.0×10.0×3.0 m)
Closest odor source (distance)	gestation/breeding, farrowing and nursery barns, and earthen basin (100 m)	finishing barn (600 m)
Facility proximity to neighbors (m)	800	150

Work at Facility A was completed before work began at B at the request of one owner in order to minimize the risk of contamination. Sampling at Confinement A occurred on 1 July to 5 August 2003 on days when the wind was not coming from the other odor sources of the farm. Sampling at Confinement B occurred from 20 August to 30 September 2003.

Measuring Methods

The concentration of the odor was estimated in the field at various distances downwind from the hog confinement by a panel of volunteers using a Nasal Ranger® Field Olfactometer (St. Croix Sensory Incorporation, P.O. Box 313, Lake Elmo, Minnesota 55042, USA). This instrument (Fig. 9) is designed with dilution ratios of 2, 4, 7, 15, 30 and 60 parts of filtered air to one part of ambient air. Its selection results from the fact that it is currently one of the most reliable, easy to use, and cost effective means to quantify odor strength (McGinley and McGinley, 2003; Nosing around, 2003). To use, a panelist firmly places his nose inside the nasal mask and inhales at a constant rate. The correct inhalation rate is indicated via a set of recessed LED lights on the Nasal Ranger. At the beginning of each measurement, a panelist starts with the highest dilution ratio, i.e. 60, and decides if he detects the presence of an odor. If an odor is observed after inhaling two or three times, a concentration of 60 OU is recorded. Otherwise, the panelist decreases the dilution ratio until an odor is detected. If no odor is detected with a dilution ratio of 2, the concentration is below 2 OU. The locations of the measurements relative to the confinement were determined using a hand-held Global Positioning System (GPS) receiver (Trimble GeoExplorer®, 645 North Mary Avenue, P.O. Box 3642,

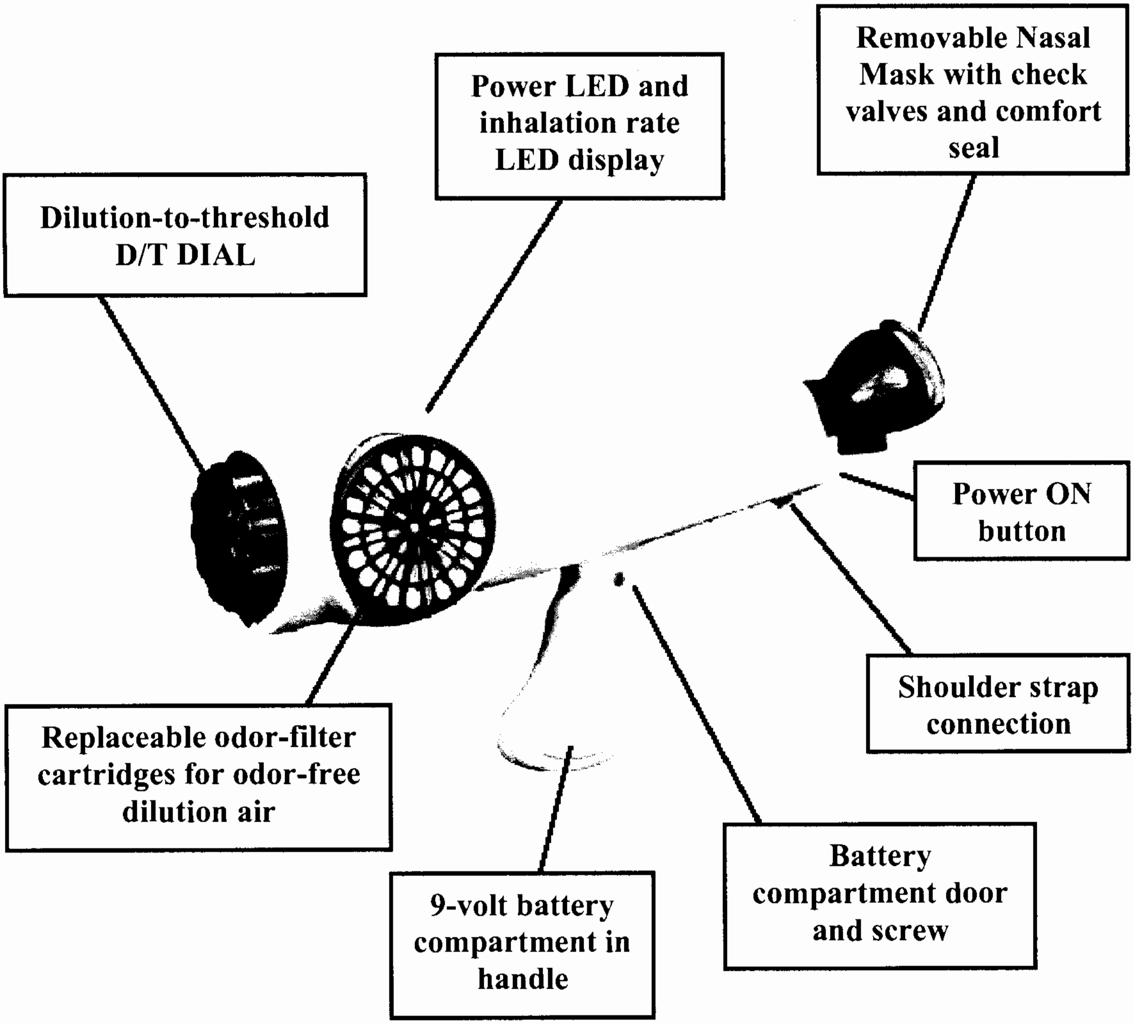

Fig. 9. The Nasal Ranger® Field Olfactometer (St. Croix Sensory, 2003).

Sunnyvale, California 94088, USA). Wind speed at 10 m was obtained from the Waterloo municipal airport (WBAN ID: 94910) and the amount of cloud cover was observed directly at the time of sampling. The stability class was determined using Table 8. Other variables required in order to run the computer models (wind speed and direction, outdoor temperature, and relative humidity) were collected with a hand-held Kestrel® 4000 anemometer (Nielsen-Kellerman, 104 West 10th street, Chester, Pennsylvania 19013, USA), which is the same instrument used by firefighters in the 2003 California wildfires (Gizmo, 2003).

All panelists (four male and five female) were either students or staff at the University of Northern Iowa (UNI) and ranged in age from 21 to 49 years. The character sketches of each panelist are presented in Appendix B. Panelists were not provided any monetary compensation for their participation. They were also asked to refrain from smoking at least 30 min before testing. Panelists first underwent an introductory session on use of the olfactometer. Five panelists (hereafter P1, P2, P3, P4 and P5) measured the odor concentration downwind from Confinement A. When sampling at Confinement B, only P1 came back. He was accompanied by a new panel of four (hereafter P6, P7, P8 and P9).

Panelists took turns recording the odor concentration. All used the same olfactometer but each used his or her own nasal mask. The measurements always started at the greatest distance from the source where no odor was observed. Measurements progressed closer to the confinement along an irregular (zigzag) track (Van Langenhove and Van Broeck, 2001). Ten to 20 sampling locations were recorded every sampling day.

Panelists were required to wear a carbon filter mask between each measurement and to limit their time on the farm to two hours per day in order to minimize odor desensitization.

Computer Analysis

Emission Calculation with STINKBAK

Emission rates were obtained by specifying the source length and width, the location of the measurement site relative to the confinement, the mean wind direction and speed, the Pasquill stability class over an averaging time of 1 hour, the surface roughness length, and the Monin-Obukhov stability length. The selection of a roughness length for Site A was complicated by non-homogeneous terrain. Different values were finally adopted depending on the location of the measurement and ranged from 0.01 m over grass to 0.74 m over the 2 m high corn. The roughness length for Site B was estimated to be 0.22 m. The Monin-Obukhov length was then determined using its relationship to Pasquill stability class and roughness length as given by Golder (1972). The values adopted for both sites are shown in the second row of Table 13 and used the roughness length for cultivated land. They were the same as the ones adopted by Smith (1995a). For each measured odor concentration, an emission rate was calculated (OU.m^3/s/m^2).

Table 13
Values of Monin-Obukhov length used as inputs for STINKBAK

Pasquill Stability Class	A	B	C	D	E	F
Adopted Monin-Obukhov length	-5	-40	-200	∞	100	5

Forecasting Odor Plume with AERMOD

Concentrations from AERMOD were calculated using its rural dispersion mode. A 30 m cartesian grid based on a 1 m resolution aerial photograph centered on the confinement was defined. The terrain and the nearby steel bins were taken into account. Digitized topographic information (30 m resolution elevation) was obtained from the United States Geological Survey (USGS). The surface parameters (surface roughness length, albedo, and Bowen ratio) were determined using the values for cultivated land given in Tables 6, 9 and 10. Confinement A was described by multiple volume sources, each representing a pit or wall fan. The odor emission rate was modified from that provided by STINKBAK according to Eq. (6), which transforms the emission rate from an area source to that of a volume source:

$$E_{AERMOD} = (E_{STINKBAK} \times A \times Q) / (n \times V) \tag{6}$$

where E_{AERMOD} is the odor emission rate of each individual fan, expressed in OU.m^3/s; $E_{STINKBAK}$ is the odor emission rate calculated by the program STINKBAK; A and V are the surface area and volume of the confinement (537.7 m^2 and 1621.5 m^3); n is the number of fans (22); and Q is the mean volumetric flow rate of each fan (1.41 m^3/s). This last value corresponds to an average of the maximum flow rates of the wall and pit fans. We assumed that during the summer the fans ran at their highest setting. Confinement B was defined as an area source when its curtains were open. No sampling occurred when curtains were closed.

Total clouds, pressure, temperature, dew point temperature, wind speed and direction, were generated by the Workstation Eta model. The BUFKIT and BUFGET programs were used to estimate the cloud ceiling height. The model was run with hourly input of meteorological data.

After running the meteorological preprocessor AERMET on the initial conditions, a 1-hour maximum odor concentration forecast was generated by the BREEZE AERMOD version 4.0.9 graphical interface (Trinity Consultants, 12801 North Central Expressway, Ste. 1200, Dallas, Texas 75243, USA). The program was run for every sampling day.

CHAPTER 4

RESULTS AND DISCUSSION

Odor Emission Rate Calculations

For each sampling location, the emission rate was calculated for each of the panelists using the computer program STINKBAK. A simple analysis of the data was performed using the statistical program SPSS 11.0 for windows (SPSS Inc. Headquarters, 233 South Wacker Drive, Chicago, Illinois 60606, USA) in order to get the means and standard deviations for each observer. The data were found to have a normal distribution. Many outliers were isolated and then deleted from the data population. Indeed, STINKBAK is a Gaussian model that is specifically design to calculate the odor emission rate downwind from an area source. Therefore, use of the program is inappropriate for locations outside of the cone shaped plume. Even if sampling locations were carefully selected on site, it was frequently found later that they were outside of the Gaussian plume. This represents a real limitation of the STINKBAK program. The final results are summarized in Table 14. Odor emission rates are reported as the geometric mean of the measured values presented in Appendix C. Confinement-average odor emission rates ranged from 13.1 to 39.5 OU.m^3/s/m^2 for Confinement A and from 15.8 to 52.5 OU.m^3/s/m^2 for Confinement B. A considerable amount of variance in odor concentration and therefore, in emission rate was observed among samples. This was probably due to inherent errors in the olfactometry procedures, and temporal and spatial variance of odor in the building. In the following sections, the effects of sampling time, outdoor temperature, wind speed, relative humidity, panelist, and barn type are discussed.

Table 14
Mean odor emission rate calculated by STINKBAK program. The first part of the table refers to Confinement A and the second part to Confinement B

Date, 2003	Wind speed (m/s)	Temperature (°C)	Relative humidity (%)	Mean odor emission rate (OU.m^3/s/m^2) for				
				P1	P2 or P6	P3 or P7	P4 or P8	P5 or P9
03-Jul	2.6	29.7	66.4	35.1	35.4	26.9	*	*
05-Jul	2.6	24.5	62.7	33.5	37.4	38.0	*	*
09-Jul	0.6	18.0	81.2	17.7	23.8	13.9	*	*
10-Jul	1.4	18.3	80.2	17.6	15.2	*	20.6	16.2
11-Jul	2.4	21.1	66.7	19.2	37.7	20.0	*	*
14-Jul	1.7	28.7	47.0	33.4	25.6	13.6	*	*
15-Jul	2.7	29.2	44.7	36.0	27.4	34.4	30.5	*
16-Jul	1.1	25.7	58.6	34.0	*	37.7	*	*
17-Jul	1.1	27.0	68.3	34.7	32.4	20.9	*	*
21-Jul	1.5	24.1	57.8	29.4	24.2	18.9	*	*
22-Jul	2.1	20.7	58.5	26.9	30.4	*	29.4	21.3
24-Jul	1.6	23.2	53.2	19.1	13.1	*	15.2	17.1
25-Jul	2.6	23.8	59.3	21.9	26.1	*	26.2	22.7
30-Jul	2.9	22.4	74.5	26.7	*	21.6	*	*
31-Jul	3.6	24.6	63.5	33.7	39.5	37.8	*	*
05-Aug	2.6	23.1	70.7	28.1	*	22.6	*	*
20-Aug	1.4	36.7	35.4	32.5	20.5	*	30.4	*
21-Aug	2.6	29.7	46.4	35.5	29.7	*	*	39.8
22-Aug	1.6	25.3	49.8	38.9	24.0	41.7	38.5	27.0
27-Aug	5.8	35.6	26.1	33.4	23.9	25.4	*	*
28-Aug	1.9	29.5	55.4	51.6	*	51.6	26.0	45.9
03-Sep	3.6	31.4	36.6	52.5	29.0	46.4	*	42.0
04-Sep	2.0	16.6	59.2	27.6	18.4	*	28.1	27.5
09-Sep	2.0	30.0	28.7	29.7	*	29.9	29.2	*
09-Sep	1.5	19.1	28.2	27.8	*	24.1	30.0	*
10-Sep	3.4	30.3	35.7	32.9	20.8	26.9	15.8	*
17-Sep	4.3	28.2	40.2	38.5	27.4	36.0	*	*
18-Sep	2.0	26.1	51.7	37.5	32.8	*	25.8	*
18-Sep	3.3	19.8	62.8	23.9	20.6	20.2	*	*
24-Sep	1.6	20.0	22.3	26.0	16.1	28.9	*	*
24-Sep	1.7	17.0	23.9	18.5	18.2	19.9	*	*
25-Sep	2.9	9.4	50.6	24.5	22.2	*	20.6	29.3

Note: * indicates that the panelist was not present on the sampling day.

Sampling Time and Meteorological Effects

Many parameters can influence odor dispersion in the atmosphere. Wood et al. (2001) observed that the season (month of collection) significantly affected odor emission rates. To better compare facilities, the period of data collection was limited in order to reduce the confounding effect of seasonal change. Figs. 10 and 11 show the temporal evolution of the relative odor emission calculated from P1's measurements. Relative odor emission is defined as the ratio of emission rate to the average of all emission rates at this site based on P1's measurements. A ratio of 1.0 means that the odor level in a given sampling day was the same as the average. Statistical analysis indicated that emissions were significantly (p-values < level of significance $\alpha = 0.05$) greater than 1.0 on the15 and 17 July and lower than 1.0 for periods 9-11 July and on 24 July for Confinement A. For Confinement B, the highest emissions occurred during the period from 28 August-3 September. No clear pattern of odor emission was observed and it appears that sampling time is not the dominant factor contributing to emission variation.

Odor measurements were usually taken in the morning. In addition, on three days in September, measurements were taken in the evening at Confinement B. It seemed that more odor was emitted from the facility in the late morning than evening (Fig. 12). Nevertheless, these differences are not statistically significant at an alpha level of 0.05. This result has been described in other studies, which usually observe an increase in odor emission from 11:00 am until 1:00 pm (Zhu et al., 2000a). The effect of time of day on odor emission rate should be studied further to validate these results.

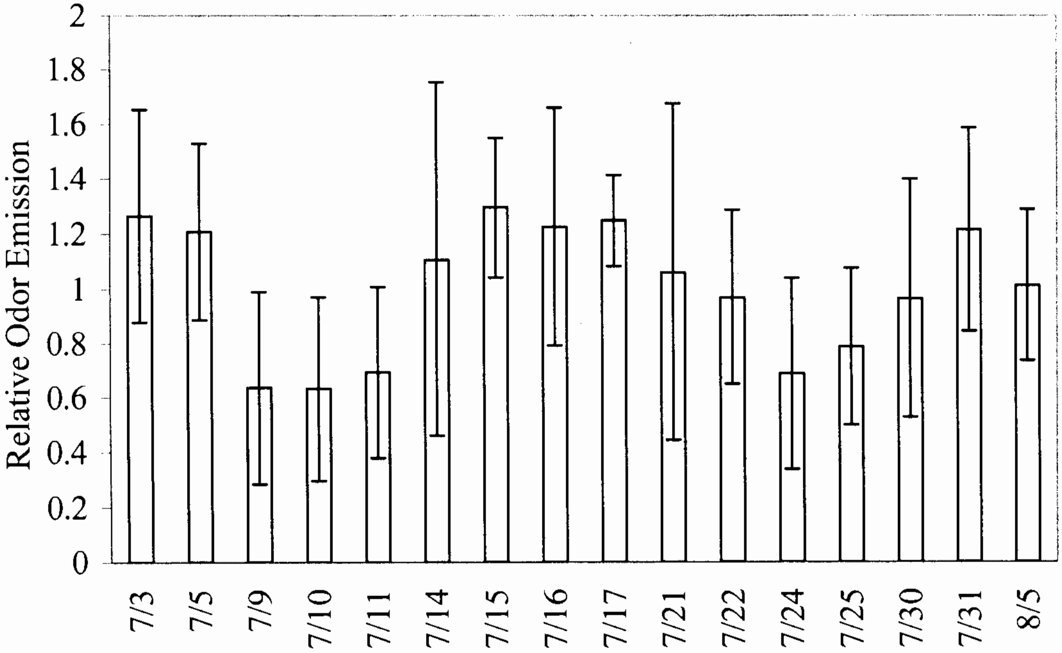

Fig. 10. Relative odor emission for Confinement A from P1's measurements. Error bars indicate the standard error at a level of significance α = 0.05.

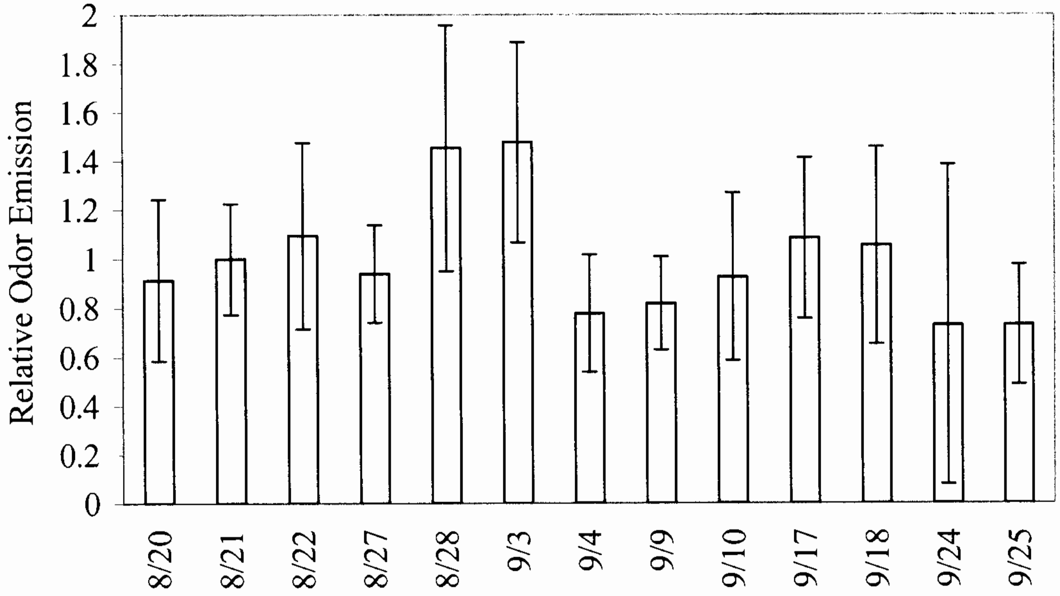

Fig. 11. Relative odor emission for Confinement B from P1's measurements. Error bars indicate the standard error at a level of significance α = 0.05.

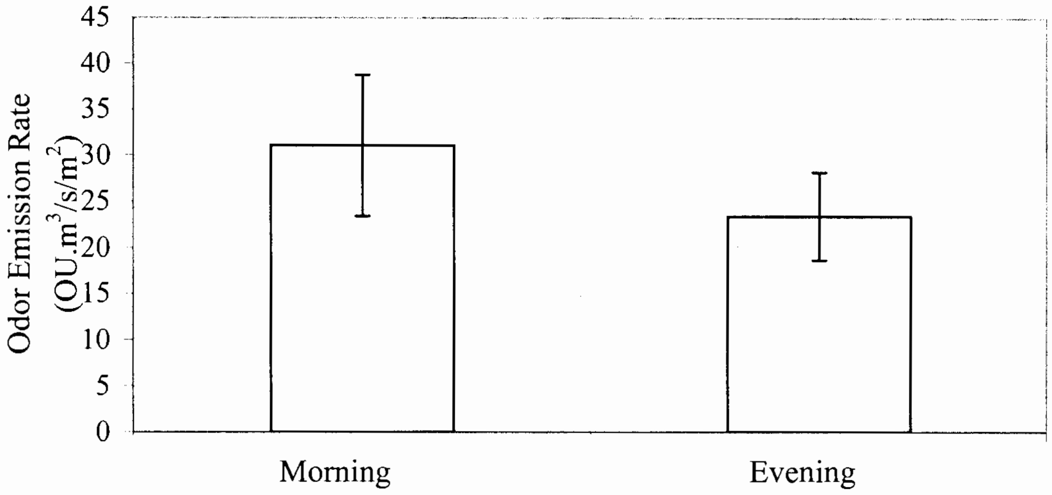

Fig. 12. Calculated odor emission rate from P1 at different times of the day in September on Confinement B. Error bars indicate the standard error at a level of significance $\alpha = 0.05$.

Linear regression analyses were performed to study the relationships between the odor emission rate and each of the wind speed, the outdoor temperature, and the relative humidity. No correlations were found for any panelist with the wind speed or the relative humidity (R^2 correlation coefficients of 0.01 for each). Outdoor temperature appeared to have an effect on emission. The correlation coefficients for Confinement A and Confinement B are summarized in Table 15. A polynomial (quadratic or cubic) regression analysis could also be applied to describe the correlation, especially for the naturally ventilated building because it significantly increased the correlation coefficients. However, the linear model was preferred because it is easier to interpret in statistical analysis. Moreover, unlike the polynomial models, the linear models in Table 15 are similar between panelists suggesting that outdoor temperature had the same effect

Table 15
Summary of the regression analysis between the odor emission rate and the outdoor temperature

	Linear model	Linear R^2	Polynomial model	Polyn R^2
Confinement A				
P1	$E = 1.6T - 11.3$	0.71	$E = -0.001T^3 + 2.9T - 31.2$	0.72
P2	$E = 0.7T + 11.4$	0.11	$E = -0.1T^2 + 6.6T - 57.7$	0.15
P3	$E = 0.8T + 4.6$	0.11	$E = -0.004T^3 + 7.7T - 104.6$	0.26
P4	$E = 0.6T + 9.2$	0.18	$E = 0.003T^3 - 0.1\ T^2 + 37.8$	0.25
P5	$E = 0.7T + 5.3$	0.27	$E = 0.2T^2 + 10.6T - 98.8$	0.34
Confinement B				
P1	$E = 0.7T + 15.4$	0.34	$E = -0.01T^3 + 0.5T^2 - 10.3T + 82.1$	0.58
P6	$E = 0.3T + 17.0$	0.17	$E = -0.006T^3 + 0.4T^2 - 7.9T + 66.2$	0.61
P7	$E = 0.8T + 10.5$	0.23	$E = -0.003T^3 + 5.8T - 69.9$	0.53
P8	$E = 0.2T + 24.4$	0.03	$E = 0.005T^3 - 0.4T^2 + 8.6T - 32.6$	0.29
P9	$E = 0.7T + 18.7$	0.55	$E = 0.003T^3 - 0.1T^2 + 0.7T + 29.7$	0.80

Note: E = emission rate ($OU.m^3/s/m^2$)
T = outdoor temperature (°C)

for all panelists. The mean slope values were 0.9 and 0.5 $OU.m^3/s/m^2/°C$ for Confinement A and Confinement B respectively. Data for P1 are presented in Figs. 13 and 14.

Higher emissions were noted with higher temperatures. This relationship was expected because higher temperatures increase the biological activity of odor-producing bacteria. Temperature accelerates the biodegradation of manure and urine. At temperatures below 5 °C the decomposition process almost comes to a stop. Very little odor is produced during the winter compared to the warmer summer months. Maximum activity occurs between 30 and 37 °C and then falls off (Zhu, 2000). The present research needs to be complimented by sampling during the winter. Moreover, it appeared that

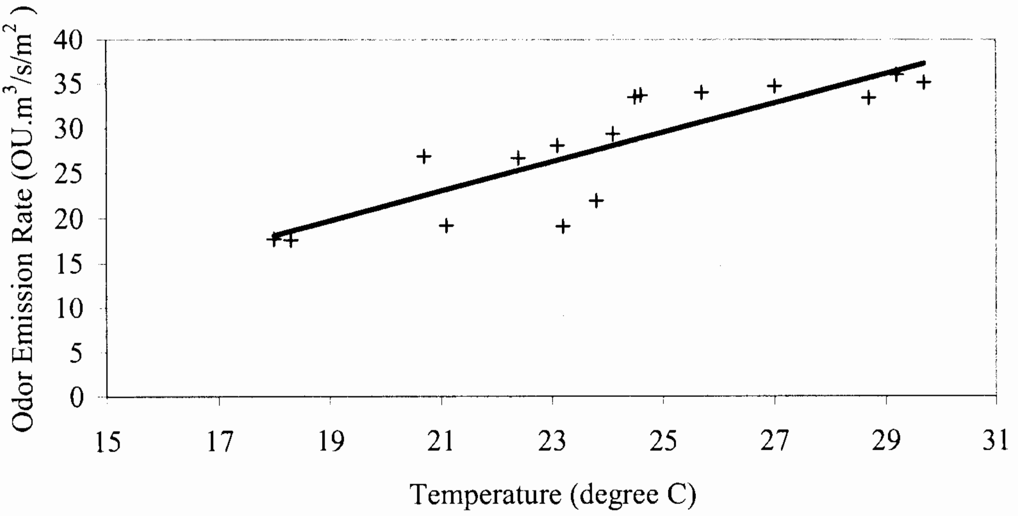

Fig. 13. Mean temperature measured downwind of Confinement A and mean odor emission rate for P1, from Table 14.

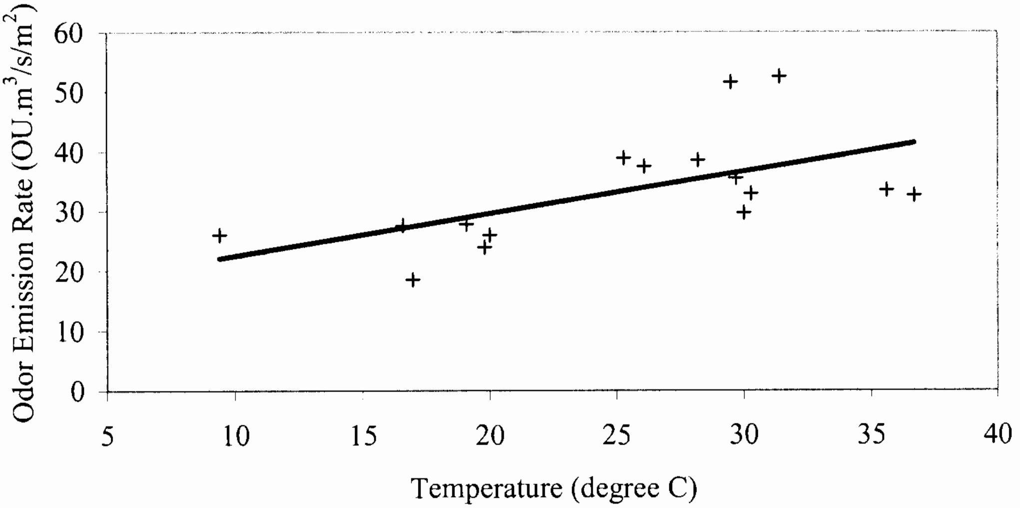

Fig. 14. Mean temperature measured downwind of Confinement B and mean odor emission rate for P1, from Table 14.

outside temperature had a weaker influence on odor emission for the naturally ventilated building. Variable speed of the exhaust fans of the mechanically ventilated confinement might have contributed to this difference. Indeed, a rise in outdoor temperature was usually associated with an increase in ventilation rates. Fans running at maximum speed increase downwind concentration. For the present study, it was concluded that the odor emission rate was linearly dependent on the outside temperature and it should be calculated as a function of the temperature.

Selection of Panelists

Odor assessment is typically conducted by a panel of volunteers. The data collected by the panelists were statistically analyzed to discern dependance of measurements on observer while taking into account the effect of outdoor temperature. A formal analysis of covariance (ANCOVA) hypothesis test was performed for each facility. The emission rates measured by panelists were considered as the dependent variable. The panelists acted as the categorical variable and the temperature was the only covariate considered. Fitting the ANCOVA model was done with the Statistical Analysis System (SAS) software purchased from SAS Institute Incorporation (100 SAS Campus Drive, Cary, North Carolina 27513, USA). Table 16 contains the respective sums of squared error (SSE) and the degrees of freedom (df) to be used in the subsequent ANCOVA hypothesis tests.

The ANCOVA formally tests whether the observed odor emission rates are similar (common regression planes), have different initial values but change at the same rate (parallel planes), or are completely different (separate planes). Because of the three

Table 16
Comparison between the panelists: ANCOVA fittings (sums of squared error = SSE; degree of freedom = df)

Facility	Model	SSE	df
Confinement A			
	Separate	151546.0	577
	Parallel	152624.9	581
	Common	159973.7	585
Confinement B	Separate	176781.7	609
	Parallel	178948.1	613
	Common	196516.5	617

possible outcomes, a formal hypothesis test first compared common (the simplest model) versus parallel planes. The F-test of significance (TS), calculated using the data from Table 16, is used to test H_0: common planes versus H_A: parallel planes, and compared to the cut off value F (found in the statistical table of F-values).

Confinement A:

$$TS = [(SSE_{common} - SSE_{parallel})/(df_{common} - df_{parallel})]/(SSE_{parallel}/df_{parallel}) = 6.99 \tag{7}$$

$$F_{df_{common} - df_{parallel},\, df_{parallel}} = 2.37 \text{ (at a significance level } \alpha = 0.05) \tag{8}$$

Confinement B:

$$TS = [(SSE_{common} - SSE_{parallel})/(df_{common} - df_{parallel})]/(SSE_{parallel}/df_{parallel}) = 14.79 \tag{9}$$

$$F_{df_{common} - df_{parallel},\, df_{parallel}} = 2.37 \text{ (at a significance level } \alpha = 0.05) \tag{10}$$

For both facilities, TS is greater than F meaning that H_0 is rejected in favor of the parallel planes model. The next step, therefore was to test H_0: parallel planes versus H_A: separate planes. The F-test of significance and cut off value for this test were

Confinement A:

$$TS = [(SSE_{parallel} - SSE_{separate})/(df_{parallel} - df_{separate})]/(SSE_{separate}/df_{separate}) = 1.02 \tag{11}$$

$$F_{df_{separate} - df_{parallel},\, df_{parallel}} = 2.37 \text{ (at a significance level } \alpha = 0.05) \quad (12)$$

Confinement B:

$$TS = [(SSE_{parallel} - SSE_{separate})/(df_{parallel} - df_{separate})]/(SSE_{separate}/df_{separate}) = 1.87 \quad (13)$$
$$F_{df_{separate} - df_{parallel},\, df_{parallel}} = 2.37 \text{ (at a significance level } \alpha = 0.05) \quad (14)$$

At this level of significance, H_0 cannot be rejected (p-value < 0.0001). Since the data best support a parallel planes model, we formally concluded that temperature had the same effect on each panelist. With higher temperature, panelists were able to detect more odor. This trend in odor sensation was found to be statistically the same for each panelist. Table 17 summarizes the equations relative to the odor emission as a function of outdoor temperature for each panelist. The significant differences between them are represented in Fig. 15 (Panel B).

Table 17
Parallel model equations for each panelist

Facility	Panelist	Parallel model equation
Confinement A		
	P1	E = T + 3.8
	P2	E = T + 4.2
	P3	E = T + 0.6
	P4	E = T + 1.9
	P5	E = T – 2.0
Confinement B		
	P1	E = 0.4T + 22.4
	P6	E = 0.4T + 12.6
	P7	E = 0.4T + 20.4
	P8	E = 0.4T + 16.3
	P9	E = 0.4T + 24.4

Note: E = odor emission rate ($OU.m^3/s/m^2$)
T = outdoor temperature (°C)

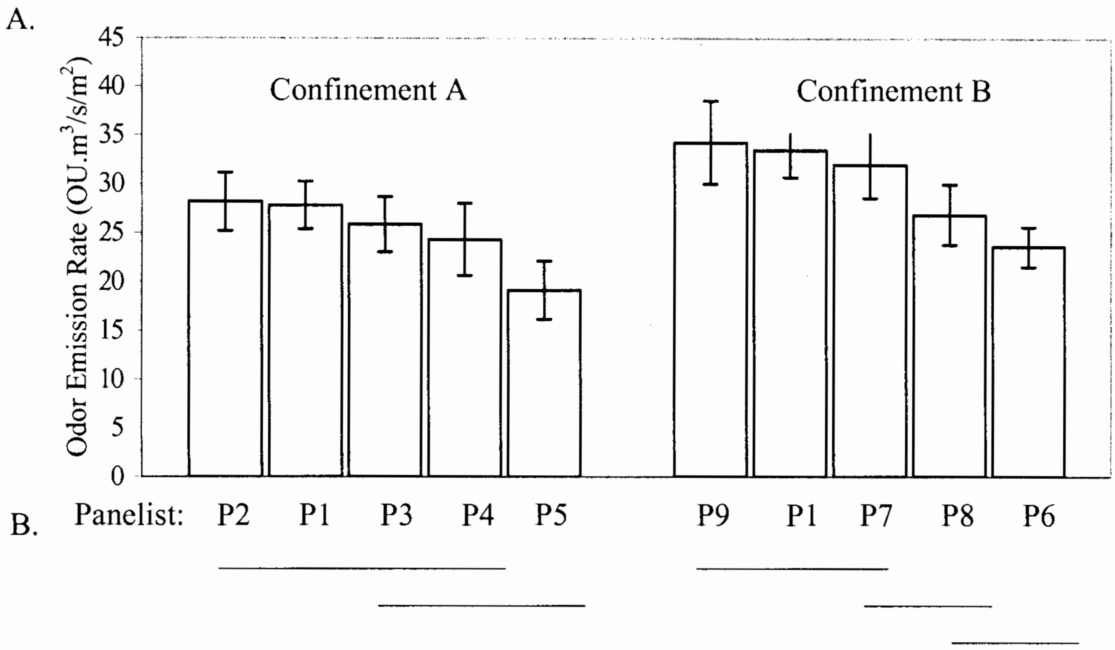

Fig. 15. Comparison between the odor emission rates of the mechanically ventilated confinement and the curtain sided confinement as a function of the panelists.

Panel A shows the mean odor emission rates which were calculated by STINKBAK program after the measurements taken by each panelist. The x-axis represents the different sniffers who sampled the mechanically ventilated confinement (on the left) and the naturally ventilated confinement (on the right). Errors bar indicate standard error at a significant level of 0.05.
Panel B. ANCOVA procedure indicated that underlined measurements are not significantly different.

For Confinement A, measurements by P5 were found to be significantly different from those of P2 and P1. For Confinement B, measurements by P6 were the lowest, indicating that P6's sense of smell is significantly different from that of P9, P1 and P7. Measurements by P9 and P1 were also significantly different from P8. P5, P6 and P8 appear to have lower odor sensitivity, although P9 and P1 may have higher odor sensitivity than the other panelists. An age-related decline in odor sensitivity has been demonstrated by a number of studies (Griep et al., 1997; Evans et al., 1995). Looking at the character sketches of the panelists presented in Appendix B, age could explain the lower measurements of P6. As far as P5 is concerned, it appeared that he might have been desensitized by animal production facilities near his home. However, no particular reason was found for P8. She was a non-smoker and was in very good health during the sampling.

In the following analysis, P5 and P6 were removed because they were hyposensitive. P8 was also eliminated because she was considered a little bit hyposensitive and inconsistent in her measurements. Indeed, unlike the other panelists, she is the only one that does not experience higher odor concentration with higher outdoor temperature. The correlation coefficient of the linear model for P8 was only 0.03 (Table 15) although it was greater than 0.17 for the others. P9 and P1 were not removed because there was not enough evidence of their supposed odor hypersensitivity. Finally, we concluded that the panelists P1, P2, P3, P4, P7 and P9 had a "normal sense of smell" (i.e., that their sense of smell is representative of the human population's sense of smell) and only their data were used to determine an average of the odor emission rate required to run AERMOD.

Odor Emission From the Confinements

The next goal of the statistical analysis was to determine the variation in odor emission for each confinement. A formal analysis of covariance (ANCOVA) hypothesis test was performed. The emission rates measured by the subset of panelists were considered as the dependent variable. The type of confinement acted as the categorical variable and the temperature was the only covariate considered. Fitting the ANCOVA model was done with SAS. Table 18 contains the respective sums of squared error (SSE) and the degrees of freedom (df) to be used in the subsequent ANCOVA hypothesis tests.

The ANCOVA formally tests whether the odor emission rates from the two confinements are similar (common regression planes), have different initial values but change at the same rate (parallel planes), or are completely different (separate planes). Using the data from Table 18, the test H_0: common planes versus H_A: parallel planes had F-test of significance of 42.2 and a cut off value F of 3.84 with a p-value less than 0.0001. Thus, H_0 was rejected in favor of the parallel planes model. The hypothesis test H_0: parallel planes versus H_A: separate planes has a F-test of significance of 2.85 and a cut off value of 3.84 ($p\text{-value} < 0.0001$). H_0 cannot be rejected using a 0.05 significance level. Thus, we cannot formally reject the common lines hypothesis. Since data best support a parallel planes model, we formally concluded that the odor emissions are dependent upon temperature. The linear relationships between the outside temperature and the odor emission rate are plotted in Fig. 16 using the following equations from the ANCOVA procedure:

$$\text{Confinement A: } E = 0.70T + 10.31 \qquad (15)$$

$$\text{Confinement B: } E = 0.70T + 15.16 \qquad (16)$$

Table 18
Comparison between the two confinements: ANCOVA fittings (sums of squared error = SSE; degree of freedom = df)

	Separate model	Parallel model	Common model
SSE	268880.5	269734.0	282395.1
df	898	899	900

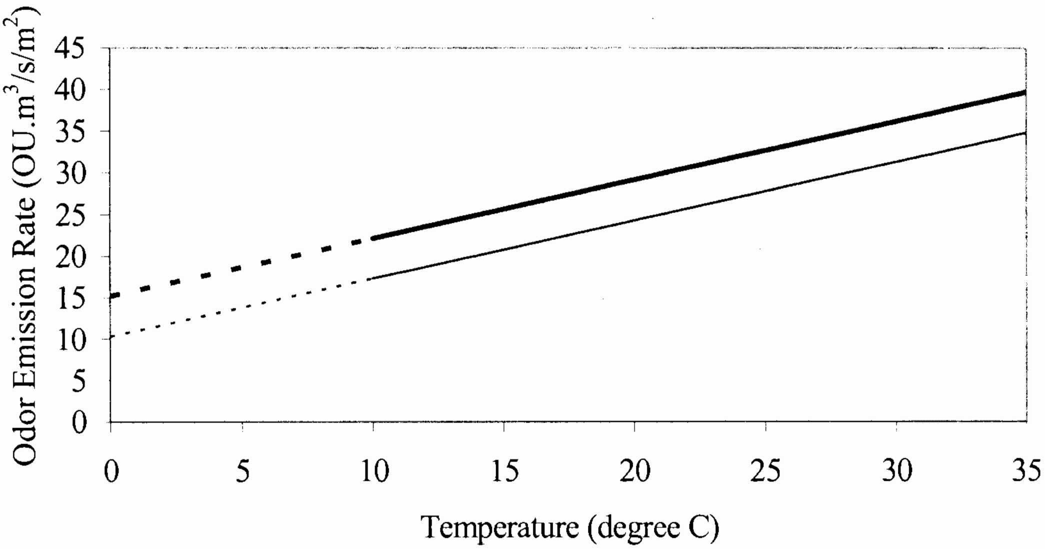

Fig. 16. Nomograph indicating the linear relationship between the temperature and the odor emission rate of the mechanically ventilated confinement (——) and the curtain-sided confinement (▬▬). The dash lines extrapolate the correlation to temperatures that were not observed.

The odor emission rate E and the outdoor temperature T are expressed in OU.m^3/s/m^2 and °C respectively. The equation is valid for temperatures from 10 to 35 °C. No sampling occurred at lower or higher temperature. According to the equations, at a fixed temperature, the curtain-sided confinement emits significantly more odor than the mechanically-ventilated facility. This is not surprising because the naturally ventilated confinement had a higher animal density than the mechanically ventilated building (1.6 animals/m^2 versus 1.1 animals/m^2). Moreover, the ventilation through the large curtain was much more effective. The wind speed is usually faster than any pit or wall fans and the large curtain area enables odors to disperse easily into the atmosphere. The "natural" volumetric flow rate was almost three times the total volumetric flow rate of the mechanical confinements (115.3 m^3/s versus 38.4 m^3/s). The difference noted in Fig. 16

is also probably related to the type of management, orientation and design of buildings, diet of the animals, and type of manure collection/storage used in the different farms. However, in the literature, Jacobson et al. (1999) reported that curtain-sided facilities often emit less odor than mechanically-ventilated buildings. Comparisons are also difficult because measurements were not taken on the same day at both facilities.

Under standard conditions (25 °C), the odor emission rate is estimated at 27.8 OU.m^3/s/m^2 for Confinement A and 32.7 OU.m^3/s/m^2 for Confinement B. These numbers are within the range given by Biosystems (1999) for different swine barns, but about two times higher than the mean emission rates given by Jacobson et al. (1999) for a mechanically-ventilated barn and about 10 times higher than a curtain-sided barn. The difference between the odor emissions can largely be explained by the fact that Jacobson et al. reported annual average emission.

Odor Plumes

Odor plume measurements on a specific day are presented in Fig. 17 for Confinement A and Fig. 18 for Confinement B. The plume footprints were plotted using the Geographic Information System (GIS) ESRI® ArcMap™ 8.3 (380 New York Street Redlands, California 92373, USA). Nineteen observations on 17 July at Site A and 14 observations on 10 September at Site B were interpolated to a 10 m grid. Geostatistical analyses using the Kriging method (Bolstad, 2002) were performed to produce the shaded contours. These days were selected because the atmospheric conditions were reasonably

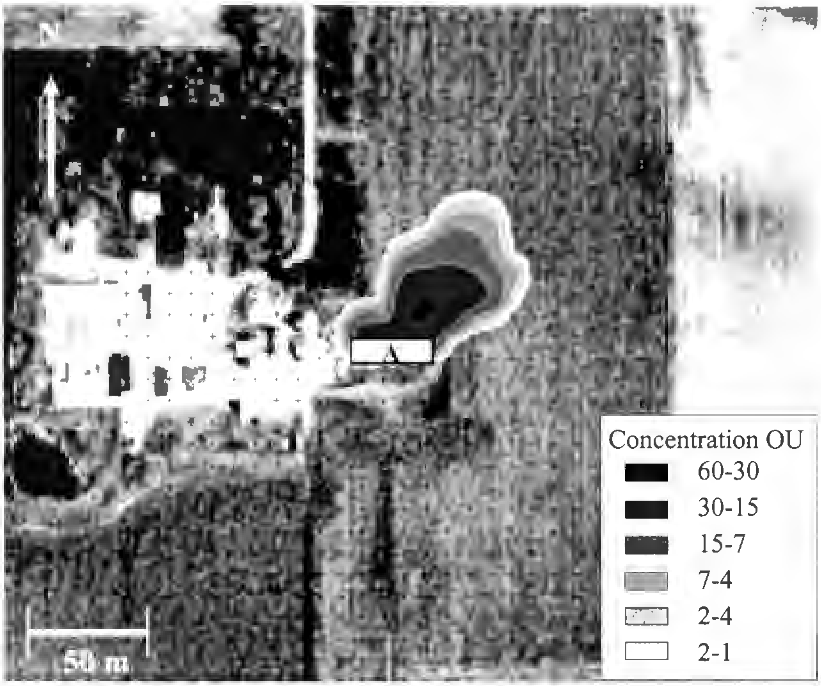

Fig. 17. Odor concentration downwind of Confinement A at 9:00 am on 17 July 2003.

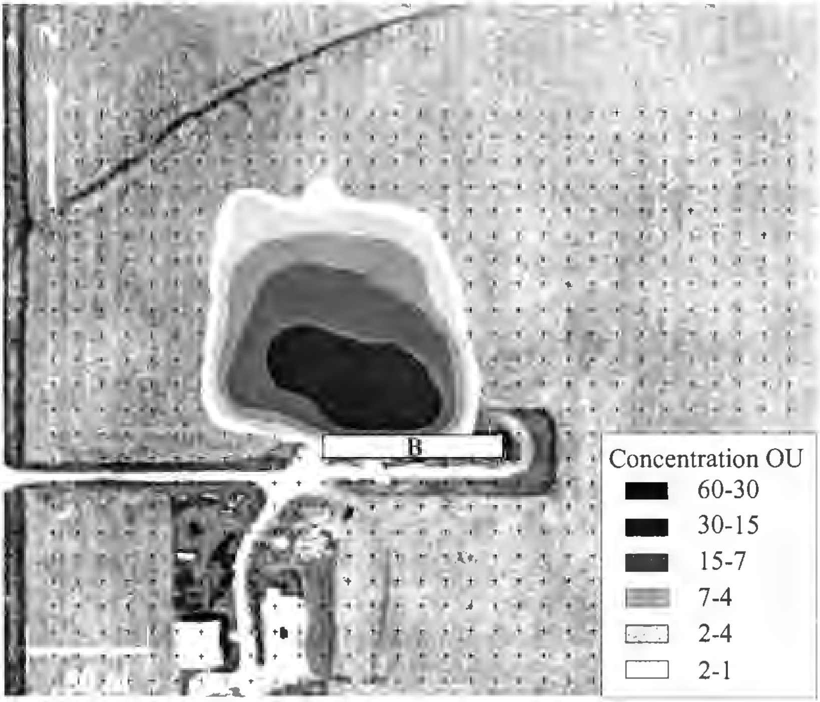

Fig. 18. Odor concentration downwind of Confinement B at 10:00 am on 10 September 2003.

similar during the sampling periods. In both cases ambient temperatures were high (greater than 27 °C) with a fairly constant south wind.

To minimize odor fatigue, panelists were kept from making measurements close to the confinement where the odor would be strong. As a result, the highest odor concentrations may not have been observed. However, comparison of the odor plume patterns is still possible. The lateral and downwind spread of the plume was less at Site A than Site B. In Fig. 17, it is shown that odor decreased from more than 30 OU near the confinement to 2 OU at 70 m downwind. Odor plume measurements at Site B on 10 September indicated that levels decreased from more than 30 OU to 2 OU in about 100 m. Odor levels at a given distance downwind from Confinement B were always higher than or equal to those of Confinement A. This can be explained by the different odor emissions, atmospheric conditions, different group of panelists, and land use around the sites. Site B was fairly homogeneous compared to Site A. Buildings and nearby cornfields appear to limit plume dispersion at Site A. The role played by the cornfields surrounding the facility is dramatic. It was observed that tall cornfields significantly reduced odor concentration. Although the odor level was very high upwind of the corn, it was not detectable only a few tens of meters into the corn. Eddies forming as the wind interacts with the corn and deposition of dust on the corn leaves may be contributing to dilution of the odor and the upward movement of the plume as it interacts with the corn would lift the odor above the panelists, preventing detection.

AERMOD Analysis

AERMOD records every exceedance of a pre-defined threshold value during a chosen 1-hour averaging period for each grid point. The threshold value used in this study was 1 OU. Data extracted from AERMOD includes the peak concentration at each grid point where exceedances were registered. Peak concentrations for times when sampling occurred were examined further. These concentrations were then plotted with ESRI® ArcMap™ 8.3. The observed plume was overlaid on the forecast for comparison. Typical examples are presented in Fig. 19 for Confinement A and Figs. 20 and 21 for Confinement B.

Overall, the AERMOD forecasts compare favorably to the observations. Predicted and observed plumes have the same lateral spread and roughly the same range of concentrations. The concentrations are maximum near the confinement and decrease downwind. However, AERMOD underpredicts odor concentration near the confinements. Similarities between predicted and observed plumes appear to be greater for Confinement B. The varied land use around Confinement A is not adequately represented by AERMOD and modeling fans as volume sources can also be a source of error. The relatively uniform land use around Confinement B allows for more realistic modeling of the roughness length.

For the two selected dates on Site B, the predicted plumes disperse about twice as far downwind as observed. The predicted plumes also cover an area about twice that of the observed plumes. Because the predicted concentrations are peak concentrations over a 1-hour period, it is expected that the observed plume is smaller than predicted. The

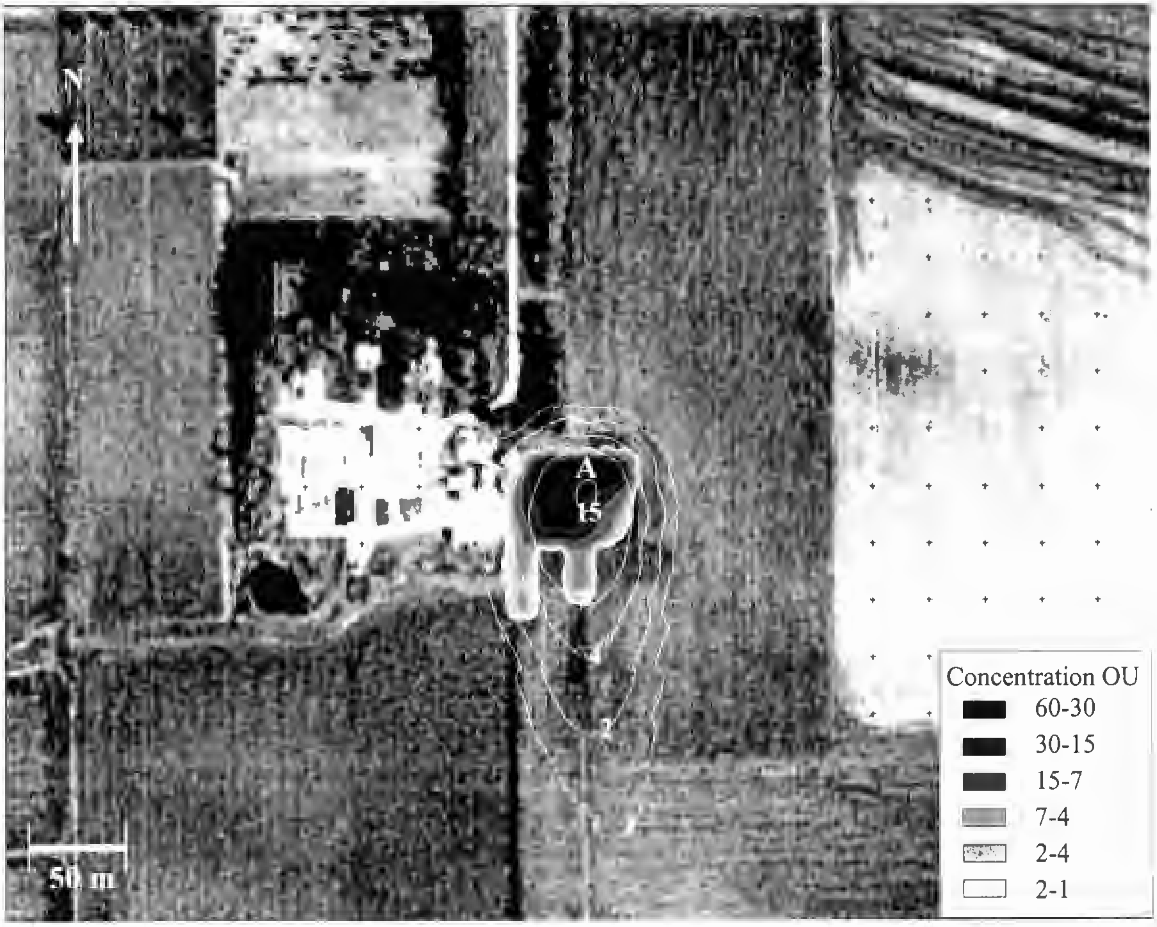

Fig. 19. Predicted (contours) and observed (shaded) odor concentration (OU) at 10:00 am on 21 July 2003 at Site A.

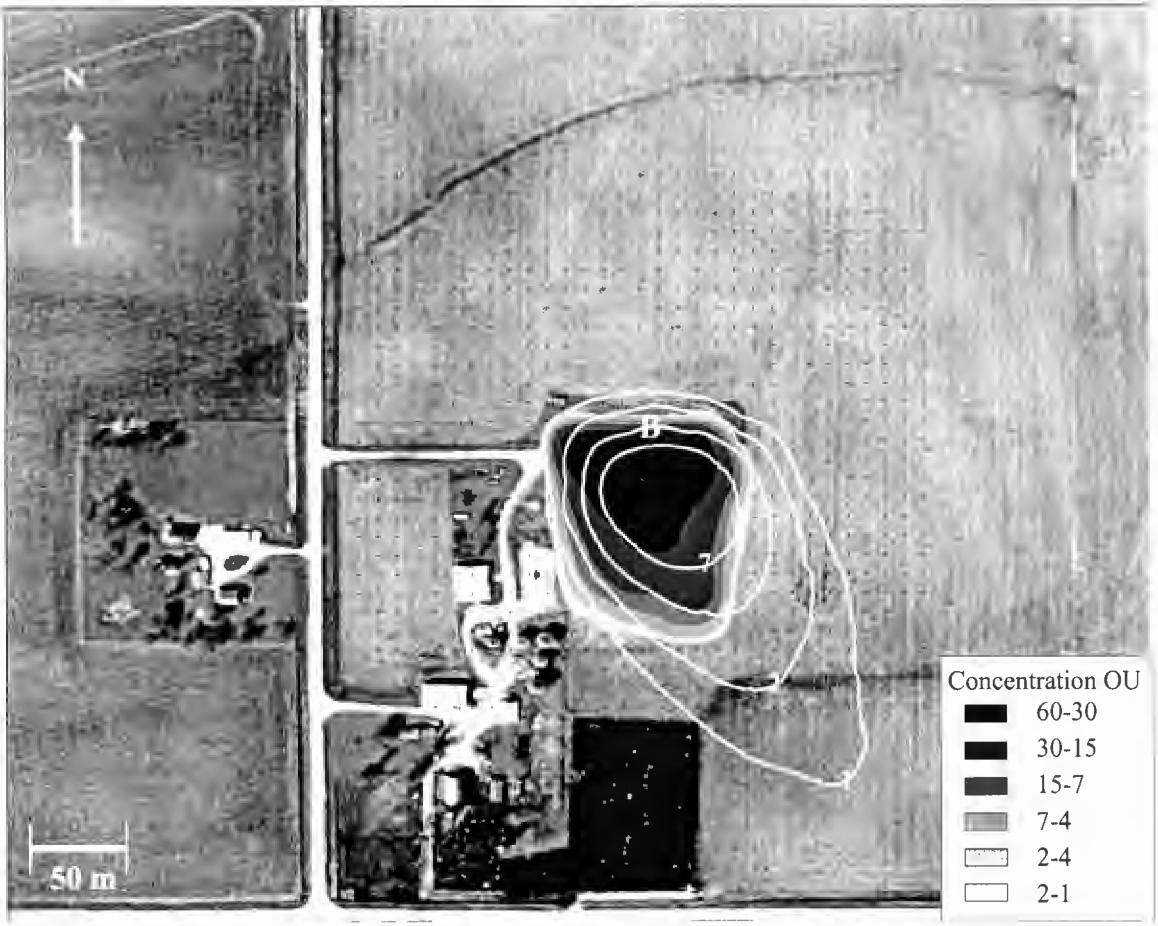

Fig. 20. Predicted (contours) and observed (shaded) odor concentration (OU) at 11:00 am on 21 August 2003 at Site B.

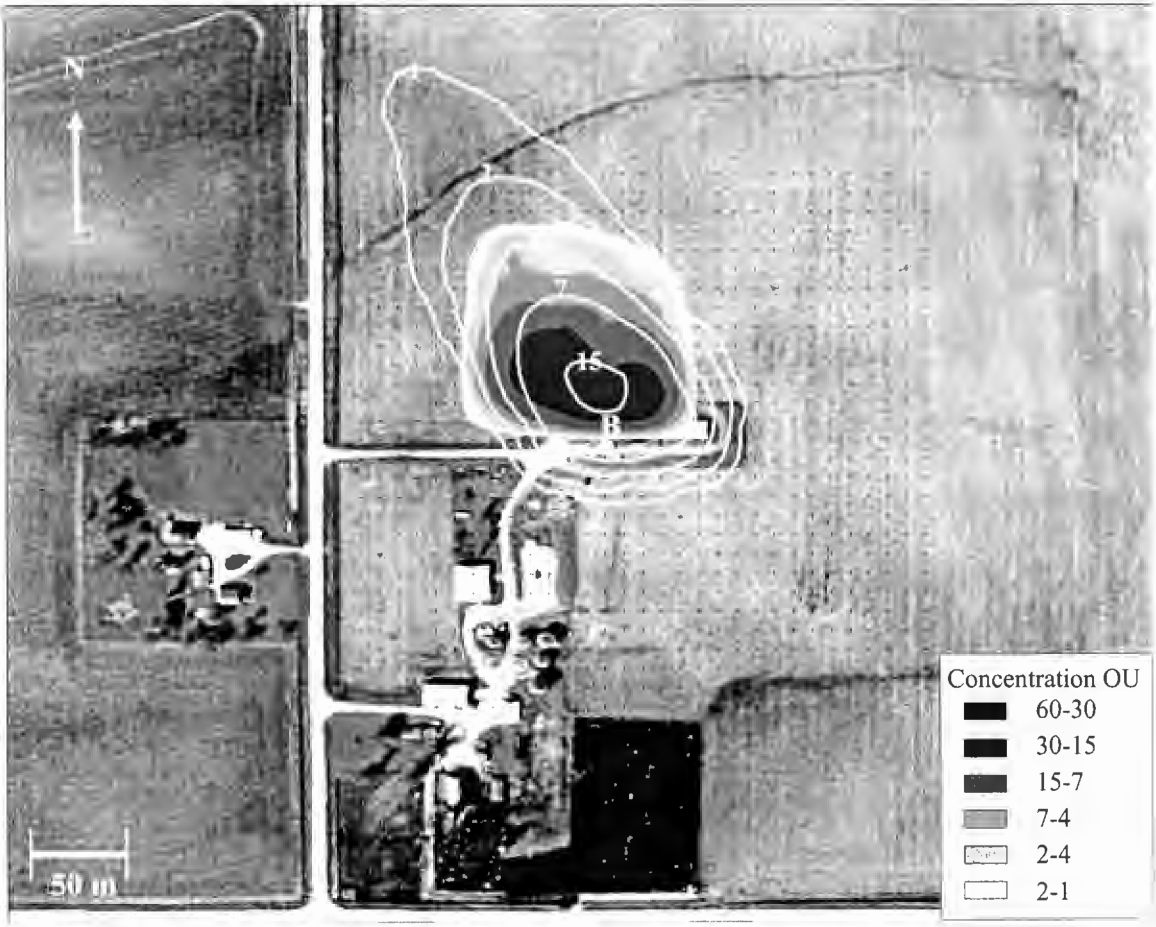

Fig. 21. Predicted (contours) and observed (shaded) odor concentration (OU) at 9:00 am on 10 September 2003 at Site B.

probability that panelists would record the maximum concentration for a given time period was very low and hence most of the observed values are smaller than predicted. Incomplete observations are also important in explaining this difference. Odor dispersion is also predicted upwind from the confinement (see Fig. 21). This was not observed. Since AERMOD's meteorological data allows for variable wind speed and direction, odor may disperse in several directions.

The meteorological data are of primary importance in plume forecast accuracy. Figs. 22 and 23 are very good illustrations. The predicted plumes are valid at 1:00 pm and 4:00 pm on 18 September. Overall, the forecast at 1:00 pm was good. However at 4:00 pm, the downwind axis of the forecast plume was offset about 45°. The Workstation Eta forecast a dramatic wind shift between 2:00 pm and 3:00 pm from 190° to 238°. In reality, the wind remained south. Between 2:00 pm and 3:00 pm, winds at the Waterloo airport varied from 170° to 190°. Looking at the surface weather conditions at 7:00 am on 18 September, a cold front located along western Iowa was moving toward eastern Iowa. The front was preceded by southerly winds. The front had not yet passed Cedar Falls at 4:00 pm (Fig. 24), unlike what Workstation Eta was expecting. The forecast wind shift had not yet occurred.

The forecast odor plumes compared well to the observations. The meteorological information was found to be of primary importance in plume forecast accuracy.

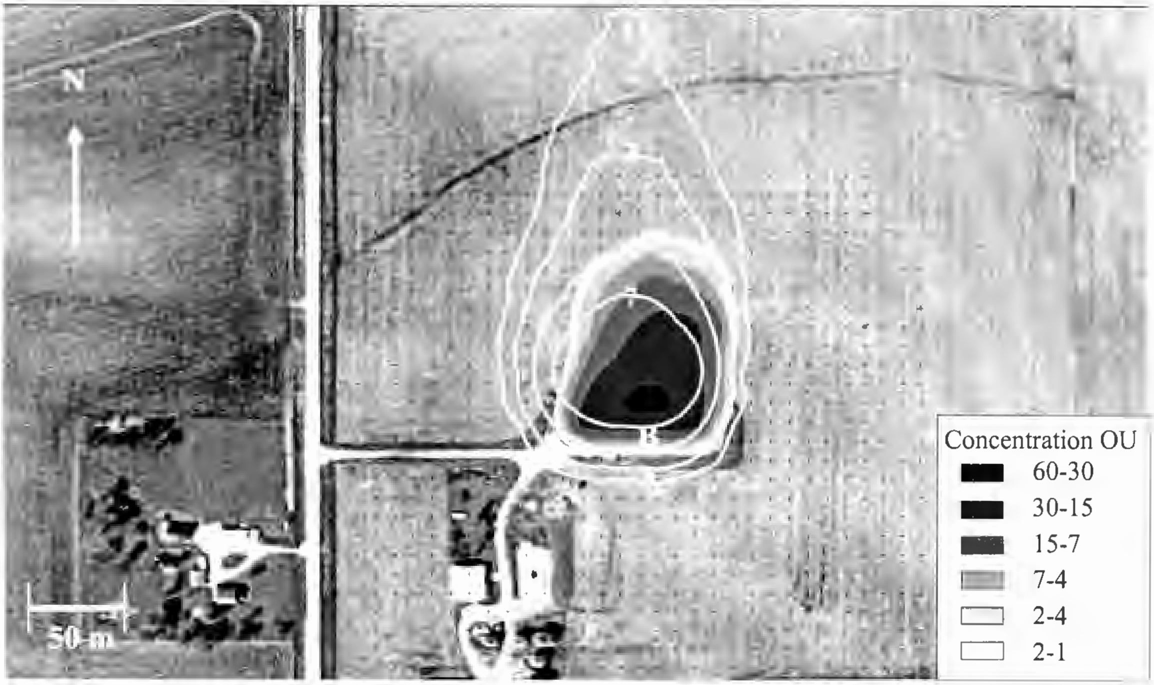

Fig. 22. Predicted (contours) and observed (shaded) odor concentration at 1:00 pm on 18 September 2003 at Site B.

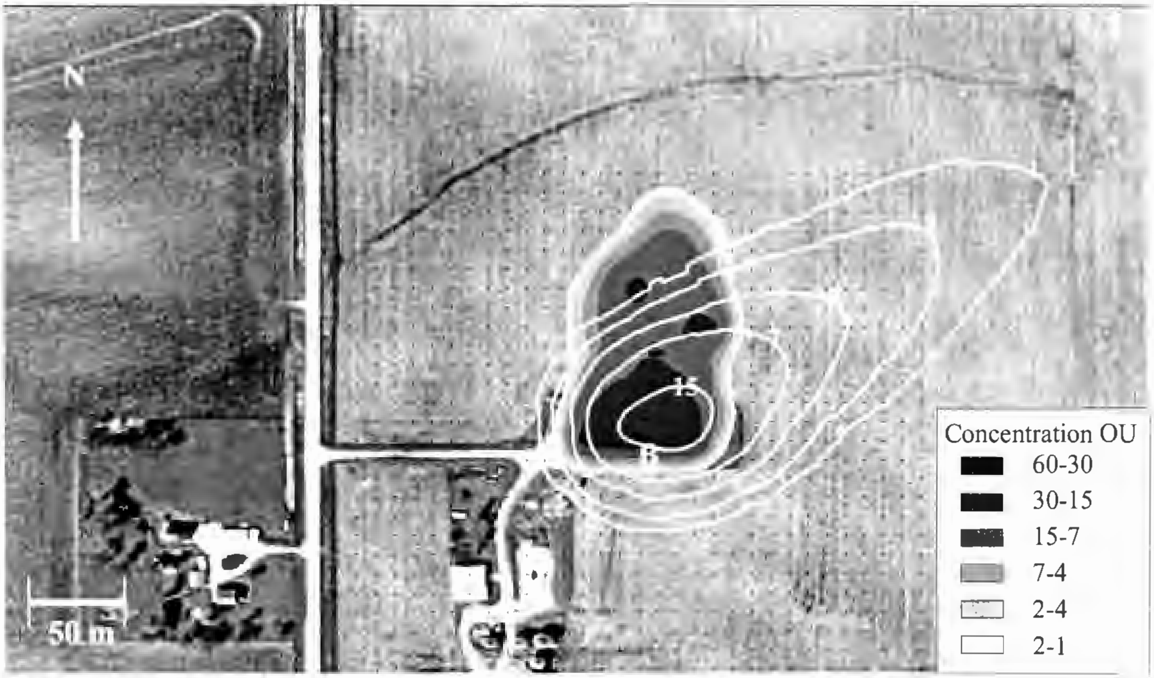

Fig. 23. Predicted (contours) and observed (shaded) odor concentration at 4:00 pm on 18 September 2003 at Site B.

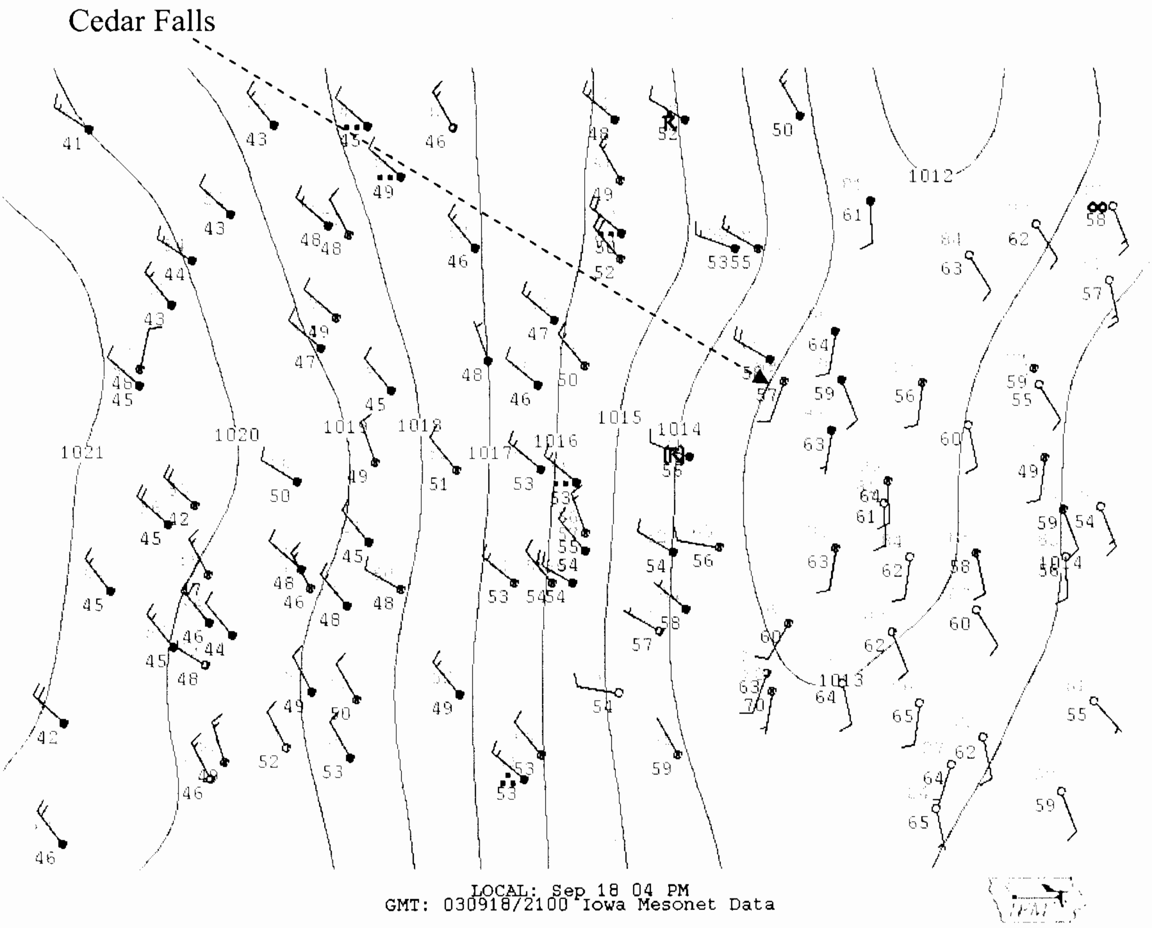

Fig. 24. Surface observations and isobars (solid; every 1 hPa) over Iowa at 4:00 pm on 18 September 2003.

CHAPTER 5

CONCLUSION

Emission rates based on odor concentrations measured with a field olfactometer downwind of two hog confinements were found to be well correlated with outdoor temperature. Temperature increases odor concentration downwind from the confinements. Panelists' odor perception (as well as confinements' odor emission) was similarly affected by temperature even when controlling for individual odor sensitivity. Results indicate the curtain-sided confinement had higher odor emission. At 25 °C, the odor emission rate was estimated at 27.8 OU.m^3/s/m^2 for Confinement A and 32.7 OU.m^3/s/m^2 for Confinement B. These numbers are slightly higher than those reported in the literature.

Odor levels at a given distance downwind from Confinement B were always higher than or equal to those of Confinement A. Odor measurements at Site A exhibited significant dispersion/dilution of odor concentration by the surrounding cornfields. Corn plants appear to serve as a natural barrier that may protect citizens from odor nuisances. The fact that different panelists sampled on the two confinements might also have influenced the results.

AERMOD odor plumes appeared to be realistic compared to observations. Shape and concentration ranges are similar. However, as reported by other studies, AERMOD underpredicts odor concentrations near the confinements. The accuracy of the meteorological data used by AERMOD is of primary importance in plume forecast accuracy. In this study, the Workstation Eta model was the source of AERMOD's meteorological data. Generally, its forecasts were reasonably accurate. However, in one instance, the passage of a cold front and an accompanying wind shift were poorly forecast by the Workstation Eta. As a result, AERMOD's forecast odor plume was significantly different from the observed plume.

Combining odor emission estimates from STINKBAK into AERMOD produced forecasts that compared well to observations. More sampling needs to be done during other seasons to validate the correlation between odor emission rates and outdoor temperature. The results are and should be confirmed by sampling more confinements using several field olfactometers with different D/Ts to improve the accuracy of the observations.

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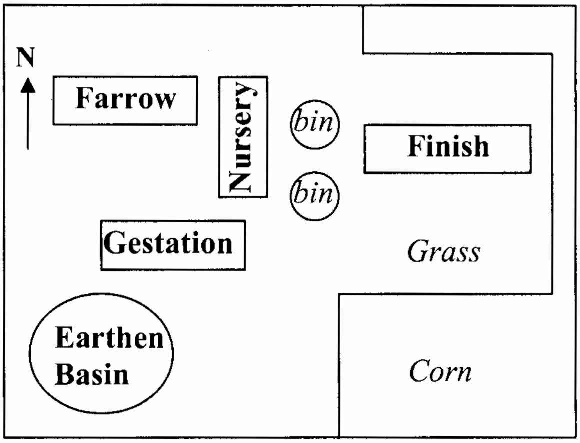
APPENDIX A

DESCRIPTION OF SITES INCLUDED IN THIS STUDY

Site A



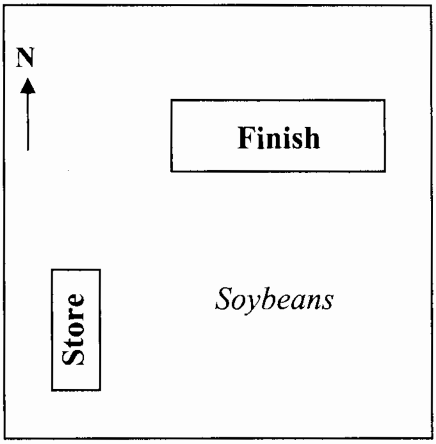
General Information
Type of operation: gestation to finish
Estimated age of operation: 25 years
Capacity: 500 hogs

Geography
Topography around operation: corn
Shelterbelt or windbreak:
    Type: mature trees
    Distance from facility: 50 m to the north

Facility and ventilation
Number of swine buildings: 3 (farrow, nursery, and finish)
Number of open lots: 1 (gestation/breeding)
Facility size: farrow: 25.9×7.3×3.0 m; finish: 43.9×12.3×3.0 m; gestation: 10.0×5.0 m; nursery: 18.3×12.2×3.0 m;
Floor type (material): farrow, nursery, and finish: slatted; gestation: cement lots
Type of ventilation: farrow, nursery, and finish: pit and wall fans; gestation: wind
Filtration for exhaust: none

Manure Management
Hog manure handled as a liquid/slurry: farrow, finish and nursery: yes; gestation: no
Confinement collection/storage systems:
    Indoor: pit
    Outdoor: tank
Gestation/breeding collection system: runoff from cement lots to the earthen basin
Barn washing frequency: farrow: ~20 times/year (manure hand scraper to a 4000 gallon pit); finish: ~2 times/year (42.6×12.2 with 1.8 m deep pit); nursery: ~2 times/year (0.6 m shallow pit and 1.7 m deep pit) and ~10 times/year (shallow pit)
Earthen basin washing frequency: ~ every 20 years
Solid manure storage: piled in a raised concrete area
Area used for spreading manure (acres): 100
Season applied: spring and fall
Facility proximity to neighbors: 800 m

Site B



General Information

Type of operation: finish
Estimated age of operation: 10 years
Capacity: 1200 hogs

Geography

Topography around operation: soybeans
Shelterbelt or windbreak:
  Type: warehouse
  Distance from facility: 60 m to the southwest

Building and ventilation

Number of swine buildings: 1 (finish)
Number of open lots: 0
Facility size: finish: 73.2×12.5×3.0 m
Floor type (material): slatted
Type of ventilation: curtains and pit fans
Filtration for exhaust: none

Manure Management

Hog manure handled as a liquid/slurry: yes
Confinement collection/storage systems:
  Indoor: pit
  Outdoor: earthen basin (not located on site)
Barn washing frequency: ~10 times/year
Solid manure storage: no
Facility proximity to neighbors: 150 m

APPENDIX B

CHARACTER SKETCHES OF THE PANELISTS

Panelist	Sex	Age	Smoker	Height	General Health	Remarks
P1	Male	23	No	1.70 m	Good	Smoking environment
P2	Male	33	No	1.90 m	Good	Nothing
P3	Female	21	No	1.70 m	No measurements after 1 August 2003 because of illness	Nothing
P4	Female	22	Sometimes	1.60 m	Good	Smoking environment
P5	Male	21	No	1.75 m	Good	Lives close to animal production units
P6	Male	49	No	1.70 m	Good	Nothing
P7	Female	21	No	1.75 m	Good	Nothing
P8	Female	22	No	1.75 m	Good	Nothing
P9	Female	23	Sometimes	1.80 m	Good	Smoking environment

APPENDIX C

ODOR EMISSION RATE CALCULATED USING STINKBAK MODEL

Confinement A

	Wind speed (m/s)	Temperature (˚C)	Relative humidity (%)	Odor emission rate (OU.m^3/s/m^2)				
				P1	P2	P3	P4	P5
03-Jul								
	1.2	28.1	69.3	9.7	9.0	9.7		
	2.5	29.3	68.5	22.7	21.0	11.4		
	2.8	28.1	68.4	26.2	24.3	45.9		
	2.4	28.9	66.3	50.6	47.0	28.9		
	2.9	29.0	66.4	30.6	61.1	17.5		
	2.3	29.7	67.0	66.4	61.9	31.0		
	2.4	30.1	65.4	29.0	27.0	29.0		
	2.9	30.2	65.4	59.1	55.5	59.1		
	3.4	31.1	65.9	43.6	40.9	20.4		
	2.6	30.9	65.4	38.8	17.0	18.1		
	2.3	29.8	65.3	24.4	25.1	24.4		
	2.6	29.7	64.5	20.4				
Avg	2.6	29.7	66.4	35.1	35.4	26.9		
05-Jul								
	1.2	24.5	66.7	35.5	35.6	35.5		
	2.6	24.6	66.5	47.3	47.7	47.3		
	2.9	24.5	65.1	13.6	14.2	13.6		
	2.5	24.7	62.3	24.9	26.4	49.7		
	3.5	24.2	64.0	38.8	44.2			
	4.2	24.2	62.1	39.1	36.5	39.1		
	3.9	24.4	60.1	49.1	45.9	49.1		
	1.5	24.3	60.4			41.0		
	2.1	24.5	61.0		47.8	50.9		
	2.2	24.4	60.2	24.0	48.5	24.0		
	2.0	24.7	60.8	29.5	27.4	29.5		
Avg	2.6	24.5	62.7	33.5	37.4	38.0		
09-Jul								
	1.1	18.2	83.1	35.2	70.8	35.2		
	0.5	18.1	83.2	21.1	37.5	21.1		
	0.8	18.1	81.2	15.7	27.9	15.7		
	1.4	18.3	81.8	10.1	10.8	10.1		
	0.4	18.0	81.0	16.4	17.9	16.4		

	0.3	17.9	80.1	40.8	36.7			
	0.5	17.8	80.3	5.4	2.6	2.5		
	0.4	18.0	80.4	4.9	5.2	2.4		
	0.4	17.7	80.1	9.5	5.1	7.8		
Avg	0.6	18.0	81.2	17.7	23.8	13.9		
10-Jul								
	1.5	18.0	83.1	58.4	61.3		58.4	58.4
	1.3	18.3	82.9	8.7	8.5		18.6	18.6
	1.5	18.2	81.4	11.9	11.7		23.8	11.9
	1.9	18.5	80.8	14.9	12.9		11.9	11.9
	1.4	18.4	79.1	11.9	5.1		14.9	6.0
	1.3	18.3	79.5	22.5	11.1		22.5	22.5
	1.0	18.5	78.1	11.9	11.7		23.8	11.9
	1.5	18.3	80.0	6.5	6.9		13.0	3.0
	1.3	18.4	79.8	6.5	6.9		6.5	13.0
	1.8	18.2	80.2	13.0	6.9		6.5	6.5
	0.7	18.1	79.4	8.8	9.4		17.6	2.4
	1.8	18.2	79.5	14.7	17.6		29.4	14.7
	0.9	18.4	80.5	24.6	14.6		12.3	24.6
	1.5	18.3	78.2	24.6	14.6		24.6	12.3
	1.4	18.3	79.8	24.6	29.3		24.6	24.6
Avg	1.4	18.3	80.2	17.6	15.2		20.6	16.2
11-Jul								
	3.4	21.3	68.5	15.9	53.8	7.9		
	2.4	20.9	68.0	18.5	16.6	18.5		
	1.8	21.2	66.9	19.9	38.4	19.9		
	2.5	21.0	66.4	38.9	74.7	39.0		
	3.1	20.8	66.1	28.7	52.3	28.7		
	1.9	20.7	66.2	11.9	46.5	25.5		
	1.5	21.3	66.4	5.0	10.8	5.0		
	2.3	21.5	65.3	15.1	16.2	15.1		
Avg	2.4	21.1	66.7	19.2	37.7	20.0		
14-Jul								
	1.8	28.5	48.9	39.3	74.9			
	2.1	28.4	48.5	17.3	8.8	4.9		
	0.9	28.6	48.4	66.4	29.4	15.5		
	1.2	28.8	47.1	21.8	19.7	21.8		
	2.4	28.8	46.1	39.4	8.4	9.2		
	1.9	29.2	46.5		22.6	24.7		
	1.5	29.0	45.5	7.9	17.4	7.9		
	2.1	28.7	45.2	23.0	23.5	11.5		

Avg	1.7	28.7	47.0	30.7	25.6	13.6	
15-Jul							
	0.9	28.6	45.1	48.1		11.2	34.9
	2.8	28.7	44.8	32.9	33.0	32.9	44.4
	3.2	28.7	44.7	38.8	19.3	38.8	26.2
	3.1	29.1	44.6	33.0	32.8	66.0	10.4
	2.9	29.2	44.5	18.9	4.1	18.9	43.5
	2.5	29.5	44.8	32.3	32.0	32.3	27.4
	2.9	29.3	44.7	49.7	21.2	39.1	49.7
	3.5	29.6	44.5	35.3	38.6	35.3	24.5
	2.1	29.7	44.2	34.8	38.0	34.8	13.3
Avg	2.7	29.2	44.7	36.0	27.4	34.4	30.5
16-Jul							
	1.9	25.2	60.4	16.7		8.4	
	1.5	25.1	59.0	64.6		64.6	
	0.9	25.4	59.2	33.5		66.9	
	1.5	25.3	58.1	47.5		47.5	
	0.5	25.5	58.4	38.2		17.8	
	0.4	25.7	58.7	24.4		24.4	
	0.9	25.6	58.6	40.4		20.2	
	0.7	25.9	58.4	21.0		42.1	
	1.1	26.1	58.2	7.0		26.2	
	1.5	26.4	58.2	58.7		58.7	
	1.6	26.1	57.9	22.4			
Avg	1.1	25.7	58.6	34.0		37.7	
17-Jul							
	2.1	26.4	71.5	10.9	20.4	10.9	
	2.0	26.5	71.5	20.4	35.7	9.5	
	0.9	26.4	71.0	22.3	19.2	6.4	
	0.4	26.7	70.5	36.7	31.7	36.7	
	2.1	26.6	70.4	14.5	54.4	7.3	
	0.6	26.8	70.0	30.0	14.7	30.0	
	0.3	26.9	69.2	39.4	19.3	39.4	
	1.5	27.1	68.0	33.1	61.1	18.9	
	0.4	27.0	67.9	25.8	23.1	14.8	
	1.4	27.3	67.4	74.8	67.8	34.9	
	1.0	27.2	68.2	62.0	13.5	31.0	
	2.0	27.1	68.1	10.3	19.5	22.2	
	1.3	27.2	67.6	9.1	9.8	9.1	
	0.8	27.1	67.4	71.7	14.5	16.7	
	1.3	27.2	67.2	75.3	69.8		

	1.1	27.1	66.0	59.8	65.9			
	1.6	27.1	66.0	34.1	35.5	34.1		
	0.4	27.3	66.6	18.7	10.1	9.4		
	1.2	27.1	66.4	34.7	52.5	34.8		
	0.5	27.3	66.0	9.2	9.9	9.2		
Avg	1.1	27.0	68.3	34.7	32.4	20.9		
21-Jul								
	2.2	23.8	58.8	73.0	65.0	19.5		
	0.6	24.1	58.0	15.0	28.6	15.0		
	2.5	24.2	57.8	13.5	11.9	28.9		
	0.3	24.0	57.8	19.0	17.1	8.9		
	1.6	23.9	57.6	34.2	15.6	17.1		
	1.8	24.1	57.4	45.8	19.7	21.4		
	1.8	24.3	57.5	7.0	2.0	6.9		
	1.6	24.0	57.6	10.0	10.2	5.1		
	0.9	24.2	57.5	47.2	47.3	47.2		
Avg	1.5	24.1	57.8	29.4	24.2	18.9		
22-Jul								
	2.3	19.9	64.1	16.3	64.9			16.3
	2.1	19.9	63.0	33.9	33.6		33.9	15.8
	0.9	20.2	60.8	27.6	41.6		48.4	27.6
	2.9	20.3	59.9	13.6	11.7		13.6	13.6
	1.6	20.5	59.8	69.9	60.0		69.9	20.0
	1.8	20.4	58.9	3.0	21.2		10.0	10.0
	1.9	20.5	58.6	61.8	30.2		61.8	35.3
	2.6	20.6	58.9	28.1	24.1		49.2	14.0
	2.4	20.9	57.5	38.9	71.7		38.9	22.3
	2.9	20.8	57.8	14.1	29.0		14.1	8.0
	3.5	20.7	57.4	16.1	31.7		16.1	32.2
	1.0	20.9	57.6	15.8	15.1		15.8	33.8
	3.7	20.6	57.4	31.9	15.7		31.9	31.9
	2.7	20.9	57.2	36.2	35.8		36.2	18.1
	2.5	21.0	57.3	12.3	13.1		12.3	5.8
	2.1	21.1	57.9	37.4	19.7		18.7	18.7
	1.4	21.0	57.0	17.3	20.2		8.7	17.3
	1.2	21.2	56.6	18.9	39.7		37.7	18.9
	2.5	20.9	56.2	19.1	20.1		19.1	19.1
	1.9	21.1	56.9	17.1	20.0		17.1	34.2
	1.2	21.0	56.9	34.8	20.3		34.8	34.8
Avg	2.1	20.7	58.5	26.9	30.4		29.4	21.3

24-Jul								
	0.6	22.9	55.2	7.3	6.4		7.3	7.3
	0.9	22.8	55.1	57.5	13.3		28.8	28.8
	0.5	22.7	54.3	10.0	9.8		10.0	10.0
	1.6	23.0	54.0	37.1	8.6		37.1	37.1
	1.9	22.8	53.9	20.3	19.8		9.5	20.3
	0.9	23.0	53.1	5.8	5.0		5.8	5.8
	2.5	23.1	53.0	17.2	27.6		30.2	30.2
	2.1	23.4	52.8	23.1	6.1		23.1	13.2
	2.1	23.4	52.7	8.7	9.2		4.1	8.7
	1.9	23.5	52.4	14.3	7.5		7.1	7.1
	2.0	23.4	52.1	6.8	14.1		6.8	13.6
	1.6	23.6	52.0	15.4	15.8		15.4	15.4
	1.8	23.4	51.2	25.0	27.4		12.5	25.0
Avg	1.6	23.2	53.2	19.1	13.1		15.2	17.1
25-Jul								
	2.9	24.0	61.3	16.9	32.5		16.9	32.5
	3.1	23.9	60.0	11.7	12.8		5.5	11.7
	4.1	23.7	59.9	10.2	4.4		5.1	10.2
	1.5	23.8	59.6	20.6	9.5		20.6	5.5
	1.9	23.6	59.3	20.7	20.5		41.5	20.7
	1.2	23.9	58.9	12.2	45.1		45.8	45.7
	2.0	23.7	58.6	32.8	34.7		32.8	18.8
	3.5	23.5	58.4	47.3	51.6		47.3	47.3
	3.0	23.4	58.2	23.1	25.2		23.1	11.6
	2.6	23.6	58.6	23.0	25.0		23.0	23.0
Avg	2.6	23.8	59.3	21.9	26.1		26.2	22.7
30-Jul								
	2.7	22.1	77.4	46.3		21.6		
	2.6	22.3	76.8	21.0		9.8		
	3.0	22.1	76.0	14.8		14.8		
	3.1	22.0	74.1	63.4		31.7		
	2.9	22.3	74.0	14.5		14.5		
	2.4	22.6	73.5	15.5		8.8		
	3.1	22.5	73.1	30.8		61.7		
	3.5	22.6	73.2	30.8		14.4		
	3.1	22.5	73.4	8.5		17.1		
	2.9	22.6	73.6	21.8		21.8		
Avg	2.9	22.4	74.5	26.7		21.6		

31-Jul						
	2.3	24.2	64.6	18.8	20.7	37.6
	3.6	24.3	64.2	18.9	8.1	18.9
	3.8	24.3	64.0	32.5	75.2	64.9
	3.7	24.6	63.9	44.4	44.6	20.7
	4.2	24.7	63.8	52.4	52.1	52.4
	4.1	24.5	62.9	22.3	44.2	44.6
	3.1	24.8	63.1	21.8	43.1	43.6
	2.9	24.9	63.2	52.8	28.6	26.4
	4.9	24.7	63.0	47.6	52.1	47.6
	5.1	24.8	62.9	46.9	51.3	46.9
	2.4	24.7	62.5	12.7	14.0	12.7
Avg	3.6	24.6	63.5	33.7	39.5	37.8
05-Aug						
	2.4	23.2	71.2	44.9		
	2.8	23.1	71.0	38.2		38.2
	1.2	23.3	70.9	21.4		12.2
	3.1	23.0	70.5	23.0		13.2
	2.3	22.9	70.8	37.9		17.7
	2.5	23.2	70.6	27.6		12.9
	1.8	23.0	70.8	25.2		25.2
	2.8	23.0	70.7	34.8		34.8
	2.9	22.9	70.9	13.4		13.4
	3.5	22.9	70.6	45.4		45.4
	3.4	23.4	70.5	10.1		20.2
	2.9	23.1	70.0	15.3		15.3
Avg	2.6	23.1	70.7	28.1		22.6

Confinement B

	Wind speed (m/s)	Temperature (˚C)	Relative humidity (%)	Odor emission rate (OU.m^3/s/m^2)				
				P1	P6	P7	P8	P9
20-Aug								
	1.5	36.3	36.9	17.2	17.2		17.2	
	0.6	36.4	36.6	33.6	33.6		33.6	
	1.1	36.5	36.4	26.6	26.5		12.4	
	2.1	36.6	36.3	37.7	17.6		37.7	
	0.8	36.5	36.2	45.3	21.1		12.1	
	1.3	36.7	35.5	16.2	16.2		60.9	
	1.8	36.8	35.5	27.5	27.5		58.8	
	1.3	36.7	35.3	18.9	33.0		18.9	
	2.2	36.8	35.2	15.8	15.8		27.7	
	1.6	36.9	35.0	19.8	19.8		11.3	
	1.2	36.8	35.1	55.8	13.0		55.8	
	2.8	36.9	35.0	75.1	5.0		18.8	
Avg	1.4	36.7	35.4	32.5	20.5		30.4	
21-Aug								
	1.5	29.3	47.6	26.3	56.4			56.4
	2.3	29.5	47.4	34.7	34.7			34.7
	3.9	29.4	47.0	22.0	38.6			38.6
	3.8	29.2	46.7	26.7	13.3			26.7
	1.8	29.8	46.7	40.8	40.8			40.8
	2.4	29.7	46.3	31.6	31.6			31.6
	1.2	29.9	46.0	56.7	26.5			56.7
	2.4	29.8	46.0	22.3	22.3			22.3
	2.7	29.8	45.9	41.0	19.1			41.0
	2.8	29.9	45.7	33.7	15.7			33.7
	3.4	29.9	45.7	54.9	27.4			54.9
Avg	2.6	29.7	46.4	35.5	29.7			39.8
22-Aug								
	0.8	24.7	51.0	21.5	37.6	76.3	10.8	21.5
	1.5	24.9	50.4	27.2	27.2	45.0	27.2	13.6
	0.2	25.0	50.2	18.9	9.5	35.7	37.8	9.5
	1.4	25.3	50.3	78.6	19.6	37.1	39.3	78.6
	2.4	25.1	50.3	63.1	63.1	59.6	36.0	63.1
	1.8	25.3	50.0	40.5	40.5	38.4	40.5	10.8
	2.3	25.2	49.7	28.4	14.2	55.0	56.9	28.4
	1.9	25.3	49.6	62.4	31.2	29.7	62.4	14.6

	1.5	25.4	49.1	21.8	10.9	21.5	21.8	21.8
	1.7	25.6	49.1	22.7	11.3	22.5	22.7	22.7
	1.8	25.6	49.0	60.0	16.0	58.1	60.0	
	2.0	25.7	48.9	22.0	6.3	20.9	47.1	12.6
Avg	1.6	25.3	49.8	38.9	24.0	41.7	38.5	27.0
27-Aug								
	5.9	35.3	27.3	30.9	30.9	30.9		
	4.3	35.3	27.3	25.7	25.7	45.0		
	6.0	35.4	27.1	15.2	7.6	15.2		
	5.4	35.4	27.1	25.0	12.5	25.0		
	5.5	35.4	26.7	21.6	21.6	21.6		
	6.9	35.4	26.5	37.8	37.8	5.4		
	6.4	35.5	26.0	37.8	18.9	9.5		
	5.9	35.5	26.2	34.7	34.7	19.8		
	5.8	35.4	26.1	57.3	26.8	57.3		
	5.4	35.7	25.4	56.0	56.0	26.1		
	5.6	35.8	25.3	47.9	22.4	22.4		
	5.8	35.8	25.1	46.8	21.8	46.8		
	6.0	35.9	25.1	27.3	15.6	27.3		
	5.9	35.9	24.9	2.7	2.7	2.7		
Avg	5.8	35.6	26.1	33.4	23.9	25.4		
28-Aug								
	1.5	29.3	56.9	77.9		77.9		77.9
	2.4	29.3	56.5	46.8		46.8	12.5	46.8
	1.8	29.1	56.0	43.2		43.2	43.2	43.2
	0.6	29.4	55.5	73.0		73.0	41.7	
	2.1	29.4	55.6	78.3		78.3	10.5	78.3
	2.4	29.6	54.5	24.7		24.7	24.7	14.1
	1.8	29.7	54.4	17.1		17.1	4.9	36.7
	1.5	29.8	54.3	36.7		36.7	36.7	36.7
	2.0	29.7	54.4	67.1		67.1	33.6	33.5
Avg	1.9	29.5	55.4	51.6		51.6	26.0	45.9
03-Sep								
	4.1	31.5	37.8	19.5	39.0	19.5		19.5
	2.5	31.6	37.4	81.9	41.0	41.0		41.0
	2.8	31.5	36.9	58.8	27.5	58.8		27.5
	3.9	31.4	37.5	70.2	18.7	32.8		70.2
	3.4	31.3	36.9	22.2	11.1	83.3		38.9
	2.9	31.3	37.0	34.3	9.8	19.6		34.3
	4.4	31.4	36.8	28.0	28.0	28.0		49.0
	2.9	31.2	36.7	39.7	39.7	39.7		22.7

	2.4	31.2	36.0	70.8	33.0	70.8		70.8
	3.9	31.1	35.9	55.1	25.7	55.1		55.1
	4.5	31.3	35.4	83.6	41.8	41.8		
	5.2	31.4	35.1	65.8	32.9	65.8		32.9
Avg	3.6	31.4	36.6	52.5	29.0	46.4		42.0
04-Sep								
	3.5	15.9	60.1	8.3	8.3		8.3	14.5
	2.0	15.9	60.4	48.0	12.8		48.0	22.4
	1.8	16.1	60.5	17.2	17.2		30.1	17.2
	1.4	16.0	60.2	29.4	8.4		16.8	29.4
	2.1	16.3	59.4	18.2	9.1		68.2	31.8
	2.0	16.5	59.6	57.0	32.6		57.0	32.6
	0.9	16.6	59.2	32.6	57.0		8.2	16.3
	2.1	16.7	59.0	28.0	14.0		48.9	48.9
	1.5	16.9	58.7	29.5	29.5		29.5	63.3
	1.4	16.8	58.9	55.0	25.7		14.7	25.7
	1.8	17.0	58.4	30.1	17.2		30.1	30.1
	2.4	16.8	58.6	13.8	6.9		24.1	24.1
	0.9	17.0	58.3	12.2	21.3		12.2	21.3
	3.1	17.1	58.7	21.3	12.2		21.3	21.3
	2.5	17.0	58.5	13.8	3.4		3.4	13.8
Avg	2.0	16.6	59.2	27.6	18.4		28.1	27.5
09-Sep AM								
	0.9	29.7	29.5	7.1		6.7	14.1	
	2.3	29.9	29.0	7.8		3.7	3.9	
	2.4	30.0	29.2	18.6		17.6	39.8	
	2.1	29.9	28.6	19.3		18.3	41.4	
	1.7	29.8	28.4	62.5		27.6	62.5	
	2.1	29.9	28.8	28.5		94.8	14.3	
	2.3	30.1	28.7	56.8		27.0	13.2	
	1.4	30.0	28.5	27.8		52.9	22.6	
	3.1	30.1	28.6	34.4		33.3	34.4	
	2.0	30.2	28.1	25.2		25.0	25.2	
	1.9	30.3	28.0	39.2		22.0	39.2	
Avg	2.0	30.0	28.7	29.7		29.9	29.2	
09-Sep PM								
	2.1	19.3	29.4	14.1		7.1	6.7	
	2.2	19.2	29.5	7.8		7.8	7.8	
	2.0	19.3	29.6	39.8		39.8	39.8	
	1.9	19.4	28.1	27.6		19.3	41.4	
	1.4	19.2	28.1	28.5		27.6	27.6	

	1.0	19.0	28.0	27.0		28.5	27.0
	2.0	19.1	28.3	52.9		27.0	52.9
	0.9	19.2	27.4	27.8		27.8	27.8
	0.3	19.0	27.6	33.3		33.3	33.3
	1.2	18.9	27.1	25.0		25.0	25.2
	1.0	18.9	27.0	22.0		22.0	39.2
Avg	1.5	19.1	28.2	27.8		24.1	30.0
10-Sep							
	3.4	30.4	38.2	14.7	14.7	31.5	14.7
	3.9	30.2	36.1	9.5	16.5	16.5	16.5
	2.5	29.9	37.6	19.2	19.2	11.0	11.0
	3.5	30.3	37.2	11.9	5.9	20.8	5.9
	2.0	30.2	36.0	33.4	15.6	33.4	8.9
	1.9	30.4	35.9	46.0	21.5	46.0	46.0
	3.8	30.3	35.5	25.9	25.9	12.1	12.1
	3.9	30.4	35.4	51.2	11.9	25.6	11.9
	3.4	30.5	35.6	23.8	23.8	11.1	23.8
	4.5	30.6	34.8	39.9	39.9	39.9	5.3
	2.9	30.4	35.1	84.4	21.1	42.2	21.1
	3.7	30.4	35.0	42.7	42.7	42.7	21.4
	4.5	30.3	34.2	48.6	22.7	22.7	13.0
	3.6	30.2	33.0	9.6	9.6	20.6	9.6
Avg	3.4	30.3	35.7	32.9	20.8	26.9	15.8
17-Sep							
	5.6	28.1	42.5	63.3	31.7	31.7	
	5.2	28.0	42.1	21.8	21.8	12.5	
	4.5	28.1	41.5	23.4	5.9	11.7	
	3.1	28.2	41.8	12.5	12.5	24.9	
	2.9	28.1	40.1	67.5	33.8	67.5	
	3.1	28.2	40.3	63.0	63.0	63.0	
	4.0	28.3	39.9	30.6	30.6	53.5	
	2.8	28.3	39.7	21.5	37.7	37.7	
	4.6	28.4	39.2	64.1	29.9	29.9	
	3.9	28.3	39.5	27.4	15.7	58.7	
	4.9	28.2	39.4	38.1	21.8	38.1	
	5.1	28.3	38.8	38.1	21.8	21.8	
	6.5	28.2	38.2	29.6	29.6	16.9	
Avg	4.3	28.2	40.2	38.5	27.4	36.0	
18-Sept AM							
	1.5	25.9	51.9	30.0	15.0		15.0
	1.9	25.9	51.8	39.3	39.3		19.7

	2.2	26.0	51.9	14.4	14.4		14.4
	1.8	26.1	51.7	19.0	19.0		19.0
	2.6	26.2	51.5	48.4	48.4		24.2
	2.8	26.0	51.8	60.0	14.0		60.0
	2.1	26.1	51.6	14.1	28.2		14.1
	1.8	26.2	51.4	64.2	64.2		36.7
	1.9	26.2	51.5	61.8	61.8		30.9
	1.7	26.1	51.6	23.8	23.8		23.8
Avg	2.0	26.1	51.7	37.5	32.8		25.8
18-Sep PM							
	4.1	19.5	64.5	27.8	55.5	27.8	
	2.9	19.6	64.1	32.9	15.3	15.3	
	2.1	19.5	64.0	11.7	11.7	11.7	
	2.8	19.5	63.5	10.5	18.3	10.5	
	3.6	19.7	62.7	18.0	10.3	18.0	
	2.8	19.8	62.1	10.6	10.6	10.6	
	2.4	19.9	62.0	15.7	15.7	15.7	
	3.5	19.9	62.3	28.2	13.2	13.2	
	3.8	20.0	62.0	13.3	28.4	28.4	
	4.0	19.9	61.8	47.6	23.8	47.6	
	4.6	20.1	61.4	46.8	23.4	23.4	
Avg	3.3	19.8	62.8	23.9	20.6	20.2	
24-Sept AM							
	2.1	19.7	22.9	13.3	3.8	28.5	
	1.2	19.9	22.8	55.7	55.7	13.0	
	2.0	19.8	22.1	53.1	13.3	26.6	
	2.5	20.0	22.2	9.6	4.5	9.6	
	1.0	20.2	21.7	14.7	14.7	58.7	
	0.7	20.3	21.9	9.5	4.4	18.9	
Avg	1.6	20.0	22.3	26.0	16.1	28.9	
24-Sept PM							
	1.2	17.0	24.2	13.3	13.3	28.5	
	2.0	17.1	24.3	13.0	26.5	26.5	
	1.5	17.0	24.0	26.6	26.6	26.6	
	1.8	16.9	24.1	18.9	18.9	18.9	
	1.6	16.8	23.6	29.6	14.7	14.7	
	1.8	16.9	23.4	9.5	9.5	4.4	
Avg	1.7	17.0	23.9	18.5	18.2	19.9	

25-Sept							
	2.1	9.5	52.8	43.2	43.2	20.2	43.2
	1.9	9.6	51.9	13.1	49.1	13.1	49.1
	2.4	9.4	51.0	19.1	19.1	19.1	40.9
	1.9	9.3	51.7	11.0	11.0	11.0	19.2
	3.4	9.4	50.4	13.4	13.4	23.4	13.4
	3.5	9.5	50.1	37.5	17.5	37.5	37.5
	3.9	9.3	50.5	6.6	23.3	3.8	3.8
	3.1	9.2	50.4	15.3	12.3	12.3	15.3
	4.0	9.3	49.8	21.5	16.9	16.9	16.9
	3.6	9.4	49.2	36.3	13.8	36.3	36.3
	2.8	9.3	49.8	29.5	23.5	29.5	29.5
	2.5	9.2	49.5	46.9	23.5	23.5	46.9
Avg	2.9	9.4	50.6	24.5	22.2	20.6	29.3