RESEARCH REPORT

ENVIRONMENT

Title: Meta-Analysis of H_2S, NH_3, VOCs, PM_{10} and $PM_{2.5}$ Emissions from Swine Production Facilities in North America– **NPB #12-022**

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Industry Summary:

Air emissions from livestock production facilities are receiving increased attention due to potential human health and environmental implications. The goal of this project was to collect currently available measured emissions data or property line concentration data and integrate the results through meta-analysis for air emissions of NH_3, H_2S, VOCs, PM_{10} and $PM_{2.5}$ from live swine production facilities in North America, including manure storage systems; and to interpret implication of these data relative to existing or potential federal regulations. Results from more than 80 studies were identified though a thorough literature search and data from these studies were extracted using standard data extraction sheet. Together with results from the 11 swine sites in the National Air Emissions Monitoring Study (NAEMS) the data are compiled. Extracted data from all studies were analyzed statistically.

The median emission rates from various studies were more robust because the mean emission rates were sensitive due to a few large values. The median emission rates from swine houses were 2.78, 0.09, 0.44, 0.09, and 0.015 kg $yr^{-1}hd^{-1}$, for NH_3, H_2S, VOCs, PM_{10} and $PM_{2.5}$, respectively. The median emission rates from swine storage facilities were 2.08, 0.20 and 0.75 kg $yr^{-1}hd^{-1}$, for NH_3, H_2S and VOCs, respectively. Large variations in emission rates among different studies were observed, resulting from different conditions in studies. The standard deviations of emission rates from the different studies were usually close to, or larger than, the values of the mean emission rates. Causes of variations or uncertainties in the emission rates were analyzed. Potential causes that may influence emission rates include: stage of production, manure system for swine houses, type of manure storage facilities, area of manure storage facilities, average pig weight, size of operation (number of pigs), air temperature, ventilation type, and measurement method. Farrowing operations had significant higher emission rates

than finishing operations on a per head basis for all the pollutants of interest (NH_3, H_2S, VOCs, PM_{10} and $PM_{2.5}$). Gestation houses had the highest NH_3 emission rate, but H_2S and VOCs emission rates were lower than farrowing houses. The manure management system was also a significant factor in determining whole farm emissions. Hoop systems had higher NH_3 emission rates than other types of manure systems. Deep pit systems produced higher H_2S emission rates than pit drain or pit recharge systems. The NH_3 emission rates from manure storage were significantly influenced by ambient air temperature and the area of storage per head. Slurry storage systems had higher H_2S emission rates compared with lagoon systems, especially when emission rates were expressed in kg $yr^{-1}m^{-2}$. The VOCs emission rates from swine housing were positively related with indoor air temperatures and were negatively related with size of operation, while the VOCs emissions from manure storages were positively related with size of operation. Regression models for emission rates were developed for each of the pollutants, which could be used for estimation of emission rates under various conditions.

Air emissions from industries are subject to permitting requirements under the Clean Air Act (CAA) as well as reporting requirements under the Emergency Planning and Community Right-to-Know Act (EPCRA) and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) if their emissions reach specified thresholds. For example, operations that exceed 100 lb/day H_2S or NH_3 emissions are required to report under EPCRA. Based on results of this study, sizes of swine farm that may trigger the need to report NH_3 and H_2S emissions were calculated for finishing, farrowing, gestation, and nursery operations respectively. For example, swine farm size that may trigger the need to report NH_3 emissions were estimated to be 1,819 to 3,074 head for finishing operations, and 885 to 1,313 head for farrowing operations (emissions exceeding 100 lb NH_3/day).

Data of measured concentrations of air pollutants in the vicinity of swine operations in literature were also collected and compiled. The Agency for Toxic Substances and Disease Registry (ATSDR) has suggested minimum risk levels (MRLs) for NH_3 and H_2S designed to protect sensitive populations. At the distances from 30 to 1185m from swine facilities, the ambient NH_3 concentrations did not vary greatly, and the average NH_3 concentration in literature was 66±66 ppb, which is 66% of the chronic minimum risk levels (MRL) for NH_3 (100 ppb). At distances of 30 to 1185m from swine facilities, the ambient H_2S concentrations in literature was 3.1±6.2 ppb, which is only 16% of the intermediate MRL for H_2S (20 ppb). The average contribution of swine operations in near-source (~15 to 50 m distances) ambient concentrations were 5.8±2.9 μg m^{-3} for PM_{10} and 1.7±1.1 μg m^{-3} for $PM_{2.5}$. There are limited data for VOCs emissions from swine operations and more science-based information is needed.

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Keywords:

Review, pigs, manure, air quality, environment

Scientific Abstract:

The goal of this project was to collect currently available measured emissions data or property line concentration data and integrate the results through meta-analysis for air emissions of NH_3, H_2S, VOCs, PM_{10} and $PM_{2.5}$ from live swine production facilities in North America, including manure storage systems; and to interpret the implication of these data relative to existing or potential federal regulations. Results from more than 80 studies were identified though a thorough literature search. Study results were compiled together with data from the reports of the 11 swine sites (IA4B, NC3B, NC4B, OK4B, IN3B, IN4A, NC4A, OK4A, IA4A, NC3A, and OK3A) in the National Air Emissions Monitoring Study (NAEMS) for the meta-analysis. The response variables were the mean emission rates at each data point in two different units (kg yr^{-1} hd^{-1} and kg yr^{-1} AU^{-1} for emissions from swine houses; kg yr^{-1} hd^{-1} and kg yr^{-1} m^{-2} for emissions from manure storage facilities). Histograms of emission rates usually show a skew-right distribution. The mean emission rates were sensitive due to a few large values while the medians were more robust. The median emission rates from swine houses were 2.78, 0.09, 0.44, 0.09, and 0.015 kg $yr^{-1}hd^{-1}$, for NH_3, H_2S, VOCs, PM_{10} and $PM_{2.5}$, respectively. The median emission rates from swine storage facilities were 2.08, 0.20, and 0.75 kg $yr^{-1}hd^{-1}$, for NH_3, H_2S and VOCs, respectively. Effect of stage of production, manure system for swine houses, area of manure storage facilities, average pig weight, size of operation (pig number), and air temperature on emission rates were investigated. Regression models for emission rates were developed for each of the pollutants. Farrowing operations had significant higher emission rates than finishing operations on a per head basis for all the pollutants of interest. Accordingly, sizes of swine farm that may trigger the need to report under the Emergency Planning and Community Right-to-Know Act (EPCRA) were estimated to be 1,819 to3,074 head for finishing operations, and 885 to1,313 head for farrowing operations (emissions exceeding 100 lb NH_3/day). At the distances from 30 to 1185m from swine facilities, the ambient NH_3 concentrations did not vary a lot, and the average NH_3 concentration in literature was 66±66 ppb, which is 66% of the chronic minimum risk levels (MRL) for NH_3. At the distances from 30 to 1185m from swine facilities, the ambient H_2S concentrations in literature was 3.1±6.2 ppb, which is only 16% of the intermediate MRL for H_2S. The average contribution of swine operations in near-source (~15 to 50 m distances) ambient concentrations were 5.8±2.9 μg m^{-3} for PM_{10} and 1.7±1.1 μg m^{-3} for $PM_{2.5}$. There are limited data on VOCs emissions from swine operations and more science-based information is needed.

Introduction:

Air emissions from livestock production facilities receive considerable attention due to human health and environmental implications. The major pollutants (or chemical species) of interest in farm emissions include: odor, hydrogen sulfide (H_2S), ammonia (NH_3), volatile organic compounds (VOCs), nitrous oxide (N_2O), methane (CH_4), and particulate matter (NRC, 2003). Emissions of different pollutants differ in the potential severity and the spatial scales of their effects. For example, the impact of H_2S is of interest mainly at a very local level because of its health concern, while impact of NH_3 has relevant impacts mainly on a regional-scale perspective because of its impact on ecosystems. Particulate matter (PM), or dust, is of interest because of both health and environmental concerns, and it is commonly classified into PM_{10} (≤10 μm in equivalent aerodynamic diameter) and $PM_{2.5}$ (≤2.5 μm in equivalent aerodynamic diameter). The VOCs can contribute to odor and also can be precursors to ozone and $PM_{2.5}$. Both N_2O and CH_4 are greenhouse gases (GHG) that contribute to climate change and the impact is mainly at a global scale.

A number of federal environmental statutes and their associated regulations may affect swine production facilities. Air emissions from industries are subject to permitting requirements under the Clean Air Act (CAA) as well as reporting requirements under the Emergency Planning and Community Right-to-Know Act (EPCRA) and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) if their emissions reach specified thresholds. For example, operations that exceed 100 lb/day

H_2S or NH_3 emissions are required to report under EPCRA. In the past, the U.S. EPA has generally not enforced the reporting requirement against concentrated animal feeding operations (CAFOs) that release hazardous air pollutants, but CERCLA includes a broad citizen suit provision and EPCRA also allows citizen suits for some violations. Large livestock operations are therefore vulnerable to citizen suits for failure to comply with reporting under these statutes (NRC, 2003). In the late 1990s, pork producers worked with U.S. EPA to develop voluntary environmental compliance programs. As air emissions from CAFOs receive increasing attention, the U.S. EPA continues to update its "CAFO rule" in recent years (regulations were revised in 2003, 2008, and 2012), which may have significant effects on the U.S. swine industry.

Accurate quantification of farm emissions is essential in order to ensure compliance with the regulatory requirements but it is not an easy task. Direct measurements of farm emissions are expensive and difficult considering the many uncontrollable factors that may affect measurements. Air emissions from individual farms can vary depending on many factors, such as species, number of animals, animal size, animal age, type of feed, manure handling and storage systems, ventilation methods, and climate. In order to improve estimation of air emissions from swine production facilities, a systematic review of the literature is desired.

There is a large volume of published studies on emissions from swine production facilities. However, these studies have not been summarized through a meta-analysis with the exception of studies that collected GHG emissions data (Liu et al., 2013). Meta-analysis is a rapidly expanding area of research that has been relatively underutilized in agricultural fields. It is a quantitative statistical analysis of a large collection of analysis results from individual previous studies for the purpose of integrating the findings. Results from a meta-analysis usually are more precise than any individual study contributing to the pooled analysis because of improved statistical power. With a clearly written protocol, they are more robust and have less bias than an unsystematic review. Meta-analysis provides a useful tool for helping to understand and quantify sources of variation in results across studies. It has the potential to investigate new hypotheses using existing data through the development of a priori hypotheses and by examination of the heterogeneity in study responses (Lean et al., 2009).

Objectives:

The goal of the study is to improve understanding on air emissions of NH_3, H_2S, VOCs, PM10 and PM2.5 from swine production facilities and provide robust emission estimations based on results of a meta-analysis of currently available measured data in literature, and to interpret implication of these data relative to existing or potential federal regulations. Review of literature includes both a qualitative review and statistical analysis (meta-analysis) that integrates results of various independent studies. The specific objectives include:

(1) Collect currently available measured emissions data or property line concentration data and integrate the results through meta-analysis for air emissions of NH_3, H_2S, VOC, PM10 and PM2.5 from live swine production facilities in North America, including manure storage systems;

(2) Analyze the uncertainty associated with the data assembled and evaluate the causes of variation;

(3) Interpret the implication of overall data relative to existing or potential federal regulatory thresholds; and

(4) Identify the research gaps in literature as well as the challenges and opportunities regarding air emissions from swine production facilities.

Materials & Methods:

Literature search strategy

Multiple strategies were undertaken to identify potentially eligible studies to be included in the meta-analysis. The inclusion criteria were that studies must be conducted in North America and must report measured emission data or concentration data in the vicinity of swine facilities for concentrations ofNH_3, H_2S, VOCs, PM_{10} or $PM_{2.5}$ from live swine production facilities, including manure storage systems. The searches in electronic bibliographic databases were started with combinations of the key words of "(swine or pig) and (NH_3 or H_2S or VOCs or PM_{10} or $PM_{2.5}$)". An iterative process was used to refine the search strategy through testing of several search terms and incorporation of new search terms as new relevant studies were identified. A manual search was carried out on the references that were cited in the identified studies and reviews. Efforts were made to check our own data and consult with experts in the field to identify unpublished studies. Two individuals independently conducted the search processes and screened the studies by reading the title and abstract in order to select studies for full review according to the inclusion criteria. For each identified study either an abstract or full article was obtained and entered into an electronic database that included all eligible studies.

Data extraction and synthesis

The included studies were distributed to a group of reviewers for data extraction. Standard data extraction sheets were developed for consistency. Emission data were extracted following the protocol presented in Table 1. Some studies provided emission data from different sites or under different settings, therefore in these cases more than one data point were used. Each study was reviewed in duplicate by two independent reviewers for quality control. Data quality was checked and disagreements were resolved by consensus between the reviewers or by the principal investigator. Duplication of data was avoided by examining the names of all authors and the institutions involved. As the result of the data review and extraction processes, a meta-analysis database was created. Emission data of each of the five pollutants (NH_3, H_2S, VOCs, PM_{10} and $PM_{2.5}$) were categorized and compiled into the two emission sources (swine buildings and manure storage facilities). Data from reports of the 11 swine sites (IA4B, NC3B, NC4B, OK4B, IN3B, IN4A, NC4A, OK4A, IA4A, NC3A, OK3A) in the NAEMS project were included in the database. Concentration data were compiled separately. For concentration data, sampling location and distances from emission sources were recorded in addition.

Table 1. Emission data extraction protocol

Categories of data		Extracted values
Information on the paper	Name of authors	Input the text
	Year of publication	Input numeric values
	Title of the study	Input the text
Information on emission sources	Emission source type	Type of swine house manure systems: select from deep pit, dry, hoop, pit drain or pit recharge with frequency recorded; type of manure storage facilities: select from lagoon or slurry storage
	Stage of production	Select from: gestation, farrowing, nursery, and finishing
	Ventilation type	Select from: mechanical and natural
	Size of operation	Input number of animals
	Average pig weight	Input numeric values (kg)
	Area of manure storage facilities	Input numeric values (m^2)
	Temperature	Input indoor temperatures for swine house, ambient temperatures for manure storage facilities (^oC)
	Treatment	Record any strategies applied that may affect emissions
Information on the measurement methods		Select from: the traditional methods[1], the OP-FTIR method[2], the micrometeorological method, the inverse dispersion modeling method, the SF6 (sulfur hexafluoride) tracer method[3], the RPM method[4] and bLS method[5]
Average emission rates and standard deviation for NH_3, H_2S, VOCs, PM_{10} and $PM_{2.5}$		Input numeric values and units

[1] Emission rate was calculated as the product of concentration and ventilation rate, with or without a chamber.
[2] The plane-integrated concentration data from open-path Fourier transform infrared spectrometry (OP-FTIR), along with wind speed and direction were analyzed using an emission flux computational method.
[3] CH_4 and SF_6 concentration were measured at downwind sites, and CH_4 emission rates were determined using the ratio of measured concentration and known source strength of $SF_{6.}$
[4] Radial Plume Mapping method that was used for determining lagoon emission rates in NAEMS sites.
[5] backward Lagrangian stochastic method that was used for determining lagoon emission rates in NAEMS sites.

Various units of emission data have been used in literature. In order to perform statistical analysis and to compare the emission data between different studies, the units of measured emission data were converted to kg yr^{-1} hd^{-1} and kg yr^{-1} AU^{-1} (AU is an animal unit corresponding to 500 kg body mass) for emissions from swine houses; and to kg yr^{-1} hd^{-1} and kg yr^{-1} m^{-2} for emissions from manure storage facilities. When unit conversion was not possible due to lack of key information, the original emission data were excluded from statistical analysis. At all stages the process used and outcomes are explicit. A full list of included studies and completed data extraction spreadsheets are available to allow for independent scrutiny of the process.

Statistical analysis

Data across studies were analyzed statistically using procedures of SAS (SAS for Windows, Version 9.3, SAS Institute, Cary, NC). In statistical analysis for emission rates, study (or each publication) was treated as a random variable since some studies contain multiple data points. The response variables were the mean emission rates at each data point in two different units (kg yr^{-1} hd^{-1} and kg yr^{-1} AU^{-1} for emissions from swine houses; kg yr^{-1} hd^{-1} and kg yr^{-1} m^{-2} for emissions from manure storage facilities). In alternative analysis, the ratios of emission rate over standard deviation were used as weighting variables such that data points that have relatively small standard deviations were given more weight in the analysis.

Potential prediction variables for emissions include: stage of production, manure system for swine houses, type of manure storage facilities, area of manure storage facilities, average pig weight, size of operation (number of pigs), air temperature, ventilation type, and measurement method (Table 1). Individual effect of each prediction variable was first estimated once at a time in turn, which provided a general idea of how each prediction variable affect the response variables regardless influence from other factors. Tukey's test was applied to compare emission rates for various effects. Significant effects were declared at P-value<0.05. Then all the candidate prediction variables were put together into one regression model. Efforts were made to remove the confounded terms and to reduce non-significant terms one by one using backward elimination process. Least squares means for various effects were obtained using a mixed model procedure in SAS.

Uncertainties of the emission data were first examined through potential measurement errors, effect of measurement method, and observed standard deviations in the studies, and then were evaluated based on the random standard errors in the analysis of variance.

Results:

NH_3

(1) Emission rates

Thirty one studies and five NAEMS sites were identified that have reported measured emission rates of NH_3 from swine houses in North America (116 data points in total). Twenty six studies and six NAEMS sites were identified that have reported measured emission rates of NH_3 from swine manure storage facilities in North America (79 data points in total). The NH_3 emission data for swine houses and manure storage facilities are listed in Appendices 1 and 2, respectively. The statistics of NH_3 emission rates are presented in Table 2. For swine houses, less variation in emission rates was observed when the unit of kg $yr^{-1}AU^{-1}$ was used. For swine manure storage facilities, less variation in emission rates was observed when the unit of kg $yr^{-1}m^{-2}$ was used. The NH_3 emission rates for swine houses were comparable with those for manure storage facilities when both were expressed in the unit of kg $yr^{-1}hd^{-1}$. Histograms of NH_3 emission rates for swine houses and manure storage facilities both show a skew-right distribution (Figure 1 and 2). The mean emission rates were sensitive due to a few large values while the medians were more robust. For swine houses, the median NH_3 emission rate was 2.78 kg $yr^{-1}hd^{-1}$ although the highest emission rate was 11 times higher. In 90% of data points, NH_3 emission rates were less than 7.17 kg $yr^{-1}hd^{-1}$. The average NH_3 emission rate for swine houses in the five NAEMS sites was 3.53±2.21 kg $yr^{-1}hd^{-1}$. For swine manure storage facilities, the median NH_3 emission rate was 2.08 kg $yr^{-1}hd^{-1}$ although the highest emission rate was 11 times higher. In 90% of data points, NH_3 emission rates were less than 9.54 kg $yr^{-1}hd^{-1}$. The average NH_3 emission rate for swine manure storage facilities in the six NAEMS sites was 11.82±7.50 kg $yr^{-1}hd^{-1}$, which was higher than the 90th percentile in Table 2. When expressed in kg $yr^{-1}m^{-2}$, the average NH_3 emission rate for swine manure storage facilities in the six NAEMS sites was 2.90±2.35 kg $yr^{-1}m^{-2}$, which is around the 77th percentile.

Table 2. Statistics of NH_3 emissions from swine houses and manure storage facilities

	Swine houses		Swine manure storage facilities	
	Emission rates in kg $yr^{-1}hd^{-1}$	Emission rates in kg $yr^{-1}AU^{-1}$	Emission rates in kg $yr^{-1}hd^{-1}$	Emission rates in kg $yr^{-1}m^{-2}$
Range	0.33 to 31.6	0.79 to 124.2	0.00 to 23.23	0.00 to 7.28
Mean	3.95±4.51	20.64±18.09	3.83±4.43	1.68±1.66
Median	2.78	16.43	2.08	1.08
75th percentile	4.49	24.61	6.27	2.75
90th percentile	7.17	39.46	9.54	4.59
Mode (rounded to nearest integer)	3	22	1	0

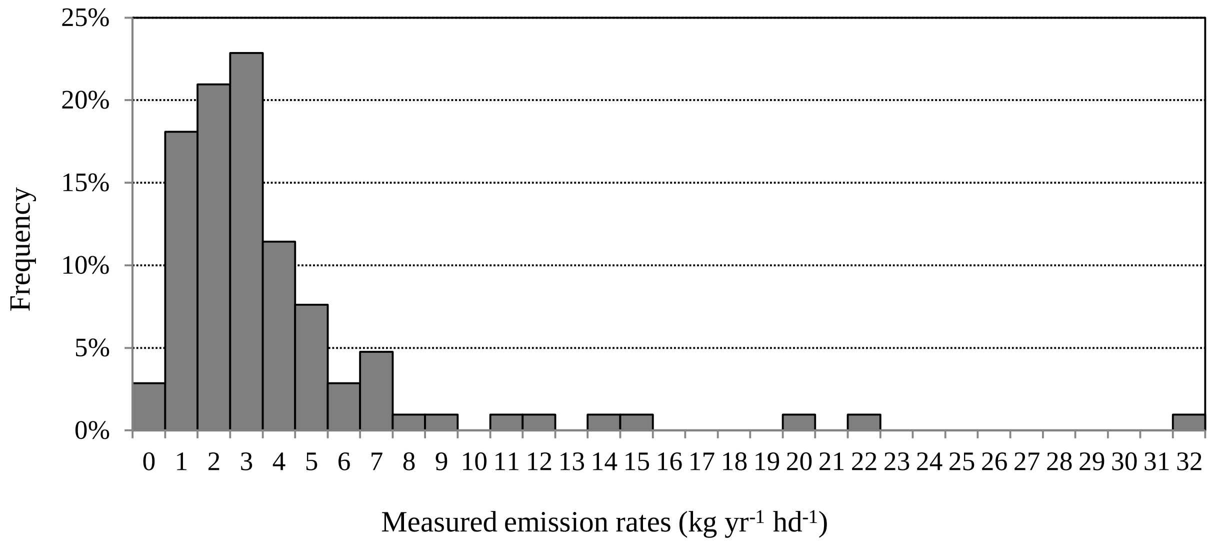

Figure 1. Histogram of measured emission rates of NH_3 from swine houses

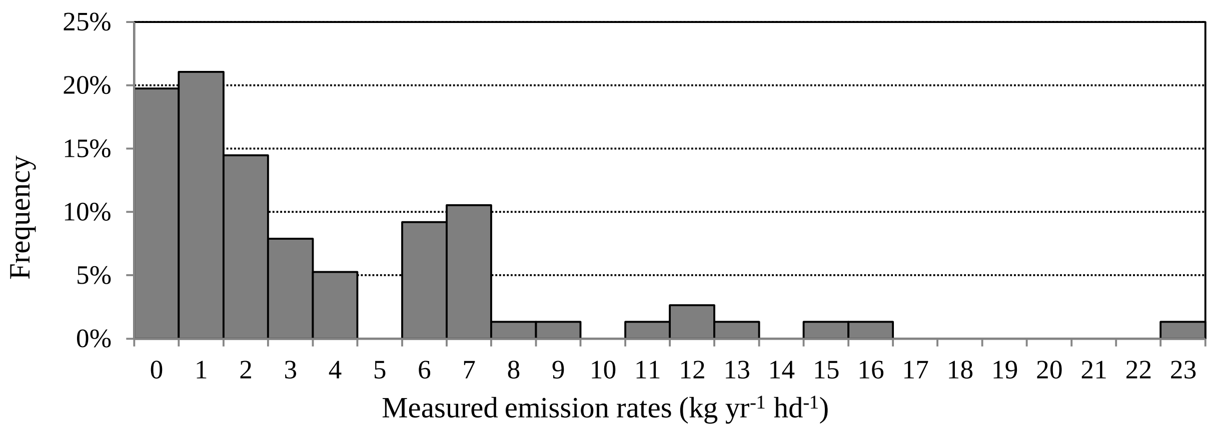

Figure 2. Histogram of measured emission rates of NH_3 from swine manure storage facilities

(2) Variations and uncertainties in emission rates

Individual effects of various prediction variables on NH_3 emission rates are presented in Table 3. For NH_3 emission rates from swine houses, the effect of manure pit type is significant regardless of NH_3 emission rates expressed in kg $yr^{-1}hd^{-1}$ or kg $yr^{-1}AU^{-1}$. The effect of stage of production is significant when NH_3 emission rates are expressed in kg $yr^{-1}hd^{-1}$ and the significance is reduced when emission rates were expressed in kg $yr^{-1}AU^{-1}$. Average pig weight and indoor air temperature also have potential significant effects at certain conditions. For manure storage facilities, when NH_3 emission rates were expressed in kg $yr^{-1}m^{-2}$, none of the potential prediction variables is significant. However, when emission rates were expressed in kg $yr^{-1}hd^{-1}$, stage of production, storage area per head, size of operation, and ambient air temperature all have potential significant effect.

Table 3. P values of individual effects of various prediction variables on NH_3 emission rates

		When each data point was treated equal		When the ratios of emission rate over standard deviation were used as weighting variables	
	Prediction variables	Emission rates in kg $yr^{-1}hd^{-1}$	Emission rates in kg $yr^{-1}AU^{-1}$	Emission rates in kg $yr^{-1}hd^{-1}$	Emission rates in kg $yr^{-1}AU^{-1}$
Swine houses	Stage of production	<0.01	0.21	0.50	0.05
	Manure system	0.03	<0.01	<0.01	<0.01
	Average pig weight	0.15	<0.03	0.06	0.03
	Size of operation	0.60	0.46	0.85	0.82
	Indoor air temperature	0.57	0.50	0.08	<0.01
	Ventilation type	0.17	1.00	0.21	0.40
	Measurement method	0.85	0.85	0.21	0.40
	Prediction variables	Emission rates in kg $yr^{-1}hd^{-1}$	Emission rates in kg $yr^{-1}m^{-2}$	Emission rates in kg $yr^{-1}hd^{-1}$	Emission rates in kg $yr^{-1}m^{-2}$
Manure storage facilities	Stage of production	<0.01	0.68	0.19	0.30
	Storage type	0.08	0.69	0.27	0.82
	Area per head	0.02	0.12	0.01	0.50
	Size of operation	0.54	0.24	0.02	0.35
	Ambient air temperature	0.01	0.10	0.10	0.19
	Area of storage facilities	0.67	0.42	0.40	0.22
	Measurement method	<0.01	0.44	0.02	0.44

Frequencies of data points in for NH_3 emission rates from swine houses with various production stages and manure systems are presented in Table 4. Frequencies of data points for NH_3 emission rates from swine manure storage with various production stages and storage types are presented in Table 5. These frequencies are considered when developing regression models for NH_3 emission rates. When stage of production, or manure system, or storage type were not provided in the original studies, these data points were accounted as “Frequency Missing” as in the table.

Table 4. Frequency of data points for NH_3 emission rates from swine houses with various production stages and manure systems

	Farrowing	Finishing	Gestation	Nursery	Total
Deep pit	1	37	7	1	46
Pit drain	6	3	2	0	11
Dry	0	7	2	0	9
Hoop	0	2	0	0	2
Pit recharge	3	32	4	1	40
Total	10	81	15	2	108
Frequency Missing = 8					

Table 5. Frequency of data points for NH_3 emission rates from swine manure storage with various production stages and storage types

	Farrowing	Finishing	Nursery	Total
Lagoon	11	47	1	59
Slurry	0	12	4	16
Total	11	59	5	75
Frequency Missing = 4				

Regression models were developed for NH_3 emission rates from swine houses in kg $yr^{-1}hd^{-1}$ and in kg $yr^{-1}AU^{-1}$, respectively (Tables 6 and 7). In both models, the remaining significant prediction variables include manure system type and average pig weight. The models are able to explain 53.7% and 52.9% of the variations in data, respectively.

Table 6. Regression model for NH_3 emissions rates from swine houses (in kg $yr^{-1}hd^{-1}$)

Parameter[1]	Estimate	Standard error	t Value	P value
Intercept	2.67277505	0.50936047	5.25	<.0001
Weight	0.01283372	0.00444462	2.89	0.005
Drain	-2.49016841	0.86073611	-2.89	0.0049
Dry	64.46222495	12.92171631	4.99	<.0001
Hoop	9.04443832	1.42866046	6.33	<.0001
Recharge	-1.43283397	0.4620824	-3.1	0.0026
Weight*Dry	-0.93080247	0.18803473	-4.95	<.0001
R-Square	Coeff Var	Root MSE[2]	Mean	DF[3]
0.537386	59.15343	1.969012	3.328652	88

Regression equation:
NH_3 emission rate from finishing swine houses in kg $yr^{-1}hd^{-1}$
= 2.6728+0.01283Weight–2.4902Drain+9.0444Hoop–1.4328Recharge+(64.4622–0.9308Weight)*Dry

[1] Weight is average weight of pigs, kg. Drain, dry, hoop, recharge, and dry are 0/1 dummy variables for type of swine house manure systems with deep pit as the baseline/reference. For example, drain is coded 1 if the manure system is pit drain system, and 0 if it is not.
[2] Root mean squared error.
[3] Corrected total degree of freedom.

Table 7. Regression model for NH_3 emissions rates from swine houses (in kg $yr^{-1}AU^{-1}$)

Parameter[1]	Estimate	Standard error	t Value	P value
Intercept	30.6097164	3.41581072	8.96	<.0001
Weight	-0.0790193	0.02980594	-2.65	0.0096
Drain	-11.1973012	5.77216296	-1.94	0.0558
Dry	550.7102836	86.65402967	6.36	<.0001
Hoop	46.0376062	9.58070762	4.81	<.0001
Recharge	-7.4777913	3.09876031	-2.41	0.018
Weight*Dry	-7.9262932	1.26097544	-6.29	<.0001
R-Square	Coeff Var	Root MSE[2]	Mean	DF[3]
0.529327	62.18413	13.20434	21.23427	75

Regression equation:

NH_3 emission rate from finishing swine houses in kg $yr^{-1}AU^{-1}$

= 36.6097–0.07902Weight–11.1973Drain+46.0376Hoop–7.4778Recharge+(550.7103–7.9263Weight)*Dry

[1] Weight is average weight of pigs, kg. Drain, dry, hoop, recharge, and dry are 0/1 dummy variables for type of swine house manure systems with deep pit as the baseline/reference. For example, drain is coded 1 if the manure system is pit drain system, and 0 if it is not.

[2] Root mean squared error.

[3] Corrected total degrees of freedom.

Regression models were developed for NH_3 emissions rates from swine manure storage facilities in kg $yr^{-1}hd^{-1}$ and in kg $yr^{-1}m^{-2}$, respectively (Tables 8 and 9). In both models, the remaining significant prediction variables include stage of production, area of storage per head and ambient air temperature. The models are able to explain 50.3% and 21.1% of the variations in data, respectively.

Table 8. Regression model for NH_3 emissions rates from manure storage facilities (in kg $yr^{-1}hd^{-1}$)

Parameter[1]	Estimate	Standard error	t Value	P value
Intercept	6.66206483	2.11555542	3.15	0.0026
T	-0.68721481	0.27023791	-2.54	0.0138
Farrowing	35.81474781	7.58959219	4.72	<.0001
Farrowing*T	-1.1467601	0.2553721	-4.49	<.0001
Farrowing*APN	-0.90927071	0.44204842	-2.06	0.0444
T*T	0.01867661	0.00791497	2.36	0.0219
APN*APN	-0.04330087	0.02161895	-2	0.0501
T*APN	0.05297998	0.02325938	2.28	0.0266
R-Square	Coeff Var	Root MSE[2]	Mean	DF[3]
0.503267	86.85046	3.502004	4.032222	62

Regression equation:

NH_3 emission rate from swine manure storage facilities in kg $yr^{-1}hd^{-1}$

= 6.6621+(35.8147–1.1468T –0.9093APN)Farrowing –0.6872T +0.01868T*T+0.05298APN*T–0.04331APN*APN

[1] Farrowing is 0/1 dummy variable for stage of production with finishing as the baseline/reference. Farrowing is coded 1 if the production stage is farrowing, and 0 if it is not. APN is area of storage per animal head, m^2. T is ambient air temperature, ^oC.

[2] Root mean squared error.

[3] Corrected total degrees of freedom.

Table 9. Regression model for NH_3 emissions rates from manure storage facilities (in kg $yr^{-1}m^{-2}$)

Parameter[1]	Estimate	Standard error	t Value	P value
Intercept	5.435139194	1.45698023	3.73	0.0004
T	-0.902585813	0.33029451	-2.73	0.0084
Farrowing	1.373030621	0.67465841	2.04	0.0465
T*T	0.05827177	0.02199241	2.65	0.0104
APN*T	-0.00925161	0.00421123	-2.2	0.0321
T*T*T	-0.001065044	0.0004357	-2.44	0.0176
R-Square	Coeff Var	Root MSE[2]	Mean	DF[3]
0.211453	91.8931	1.564662	1.702698	62

Regression equation:

NH_3 emission rate from swine manure storage facilities in kg $yr^{-1}m^{-2}$

= 5.4351+1.3730Farrowing –0.9026T +0.05827T*T–0.009252APN*T–0.001065T*T*T

[1] Farrowing is 0/1 dummy variable for stage of production with finishing as the baseline/reference. Farrowing is coded 1 if the production stage is farrowing, and 0 if it is not. APN is area of storage per animal head, m^2. T is ambient air temperature, ^oC.

[2] Root mean squared error.

[3] Corrected total degrees of freedom.

The main effect means of NH_3 emission rates are presented in Table 10 under various considerations. For NH_3 emissions from swine houses, gestation swine had the highest emission rates in kg $yr^{-1}hd^{-1}$, followed by farrowing and finishing. Nursery swine houses had significantly lower emission rates on a per head basis compared with other production stage, which could be associated with the lower weight of nursery pigs. The NH_3 emission rates from hoop system were 4 to 9 times higher than that from pit systems. Emission rates in kg $yr^{-1}hd^{-1}$ were positively related with pig weight, while emission rates in kg $yr^{-1}AU^{-1}$ were negatively related with pig weight. For NH_3 emissions from manure storage facilities, when emission rates were expressed in kg $yr^{-1}m^{-2}$, none of the potential prediction variables is significant. However, farrowing swine manure storage facilities had significantly higher emission rates on a per head basis, which could be associated with the higher weight of farrowing pigs. The NH_3 emission rates from manure storage facilities were positively related with ambient air temperature. As expected, larger storage area on a per head basis resulted in lager NH_3 emission rates on a per head basis.

In the NAEMS sites, uncertainties of NH_3 emission rates from swine houses were calculated based on measurement errors (observed bias and precision from zero/span check) of concentrations and airflows. They were 13 to 35% for gestation houses, 28 to77% for farrowing houses, and 12 to 18% for finishing houses. In literature, the average reported standard deviation for measured NH_3 emission rates from swine houses was 34% of the mean. The average reported standard deviation for measured NH_3 emission rates from manure storage facilities was 35% of the mean. However, there were larger variations among different studies. For NH_3 emissions from swine houses, the standard deviation was 114% of the mean emission rate when expressed in kg $yr^{-1}hd^{-1}$. These variations or uncertainties were results of different conditions (prediction variables) in different studies. In the regression model, because effects of significant prediction variables had been taken into account, the root mean squared error was reduced to 59% of the mean. For NH_3 emissions from manure storage facilities, the standard deviation was 116% of the mean emission rate when expressed in kg $yr^{-1}hd^{-1}$, while in the regression model, the root mean squared error was reduced to 87% of the mean.

Table 10. Main effects on NH_3 emission rates

Response variables	Effects considered in model		P value	Category	n[1]	Least squares means	Standard error
Swine houses, emission rates in kg $yr^{-1}hd^{-1}$	Individual effect of production stage		<0.01	Finishing	89	3.23[b]	0.74
				Gestation	15	9.75[c]	1.55
				Farrowing	10	6.69[b,c]	1.62
				Nursery	2	-3.21[a]	2.46
	Two effects	Manure system	<0.01	Deep pit	46	4.03[a]	0.71
				Pit drain	12	1.66[a]	0.97
				Pit recharge	40	2.10[a]	0.74
				Dry	9	6.35[a]	1.49
				Hoop	2	15.22[b]	1.46
		Average pig weight	0.03	Slope=0.01144 kg $yr^{-1}hd^{-1}$ per kg			
Swine houses, emission rates in kg $yr^{-1}AU^{-1}$	Individual effect of production stage		0.21	Finishing	89	24.42	3.81
				Gestation	15	14.22	6.80
				Farrowing	10	10.01	6.64
				Nursery	2	23.56	13.14
	Two effects	Manure system	<0.01	Deep pit	46	23.89[a]	5.40
				Pit drain	12	16.86[a]	6.58
				Pit recharge	40	15.77[a]	5.66
				Dry	9	48.21[a,b]	11.79
				Hoop	2	84.07[b]	9.40
		Average pig weight	<0.01	Slope=-0.09068 kg $yr^{-1}hd^{-1}$ per kg			
Manure storage facilities, emission rates in kg $yr^{-1}hd^{-1}$	Individual effect of production stage		<0.01	Finishing	59	3.92[a]	0.80
				Farrowing	11	8.98[b]	1.43
				Nursery	5	1.50[a]	2.08
	Three effects	Production stage	0.14	Finishing	59	4.02	1.12
				Farrowing	11	8.23	1.89
				Nursery	5	3.12	2.49
		Ambient air temperature	0.02	Slope=0.1395 kg $yr^{-1}hd^{-1}$ per ^oC			
		Area per head	0.07	Slope=0.4207 kg $yr^{-1}hd^{-1}$ per m^2			
Manure storage facilities, emission rates in kg $yr^{-1}m^{-2}$	Individual effect of production stage		0.68	Finishing	59	1.73	0.32
				Farrowing	11	2.20	0.56
				Nursery	5	1.39	0.85
	Three effects	Production stage	0.64	Finishing	59	1.76	0.36
				Farrowing	11	2.50	0.70
				Nursery	5	1.79	1.11
		Ambient air temperature	0.21	Slope=0.03396 kg $yr^{-1}m^{-2}$ per ^oC			
		Area per head	0.10	Slope=-0.1446 kg $yr^{-1}m^{-2}$ per m^2			

[1] n=number of data points.

[a,b,c] Values within the same effect section differ significantly if without common letter ($P < 0.05$).

(3) Concentrations

Ten studies were identified that report measured NH_3 concentrations in the vicinity of swine facilities in North America at various distances (40 data points in total, see Appendix 3 and Figure 3). The average NH_3 concentration at the edge of the emission sources (swine houses or lagoons) was 5.5±5.2 ppm (ranged from 0.3 to16 ppm). The ambient NH_3 concentrations in the vicinity of swine facilities decreased gradually with increasing distances. At the distances from 30 to 118 5m from emission sources, the average ambient NH_3 concentration was 66±66 ppb (ranged from 10 to 280 ppb). In comparison, the average background ambient NH_3 concentration not within swine production areas was 7.7±3.5 ppb, while the average ambient NH_3 concentration in neighborhoods within swine production areas was 11.8±5.5 ppb, based on data reported by Godbout et al (2009) and Donham et al (2006). The average ambient NH_3 concentration in the vicinity of swine facilities (66±66 ppb at distances from 30 to 1185m) was about 8 times higher than the average background ambient NH_3 concentration which was not influenced by swine productions (7.7±3.5 ppb).

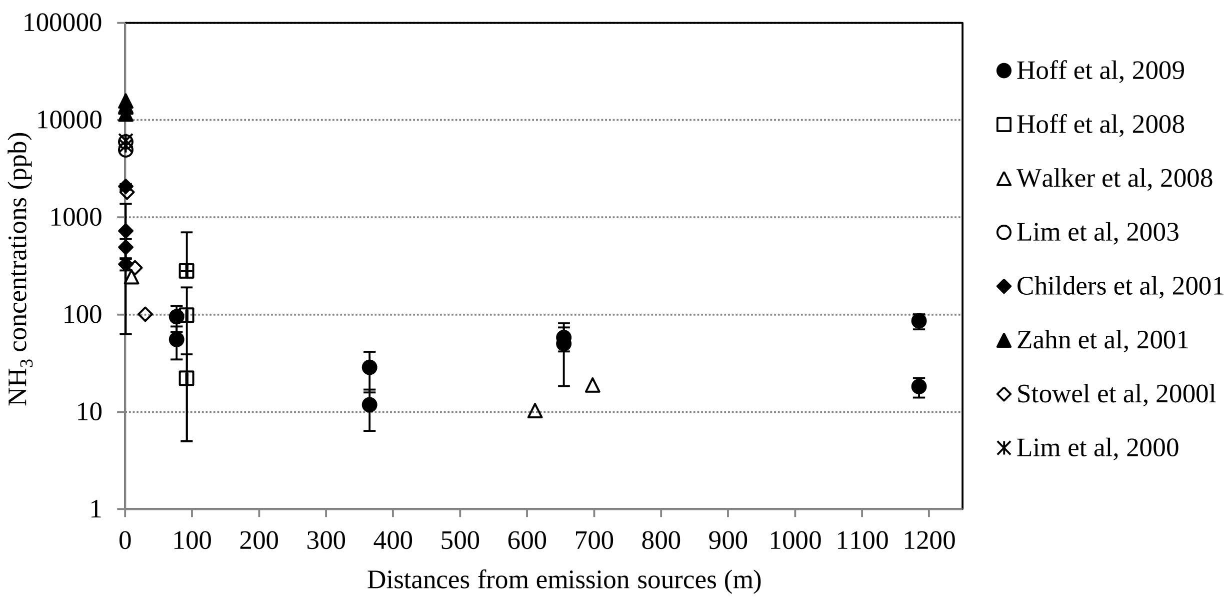

Figure 3. Measured NH_3 concentrations at various distances from swine facilities

7.2 H_2S

Twenty two studies and 5 NAEMS sites have been identified that have reported measured emission rates of H_2S from swine houses in North America (85 data points in total). Ten studies and 6 NAEMS sites have been identified that have reported measured emission rates of H_2S from swine manure storage facilities in North America (32 data points in total). The H_2S emission data for swine houses and manure storage facilities are listed in Appendices 4 and 5, respectively. The statistics of H_2S emission rates are presented in Table 11. For swine houses, less variation in emission rates was observed when the unit of kg $yr^{-1}AU^{-1}$ was used. The H_2S emission rates for swine houses were comparable, if not less than that for manure storage facilities when both were expressed in the unit of kg $yr^{-1}hd^{-1}$. Histograms of H_2S emission rates for swine houses and manure storage facilities both show a skew-right distribution (Figure 4 and 5). The mean emission rates were sensitive due to a few large values while the medians were more robust.

For swine houses, the median H_2S emission rate was only 0.09 kg $yr^{-1}hd^{-1}$ although the highest emission rate was 35 times higher. In 90% of data points, H_2S emission rates were less than 0.47 kg $yr^{-1}hd^{-1}$. The average H_2S emission rate for swine houses in the 5 NAEMS sites was 0.78±1.02 kg $yr^{-1}hd^{-1}$, which was higher than the 90th percentile in Table 11. For swine manure storage facilities, the median H_2S emission rate was only 0.20 kg $yr^{-1}hd^{-1}$ and the highest emission rate was 7 times higher. In 90% of data points, H_2S emission rates were less than 0.83 kg $yr^{-1}hd^{-1}$. The average H_2S emission rate for swine manure storage facilities in the 6 NAEMS sites was 0.39±0.44 kg $yr^{-1}hd^{-1}$.

Table 11. Statistics of H_2S emissions from swine houses and manure storage facilities

	Emission from swine houses		Emission from swine manure storage facilities	
	Emission rates in kg yr^{-1} hd^{-1}	Emission rates in kg yr^{-1} AU^{-1}	Emission rates in kg yr^{-1} hd^{-1}	Emission rates in kg yr^{-1} m^{-2}
Range	0.00 to 3.12	0.00 to 11.09	0.00 to 1.33	0.00 to 0.70
Mean	0.26±0.56	1.08±1.07	0.33±0.37	0.18±0.21
Median	0.09	0.55	0.20	0.07
75th percentile	0.20	1.25	0.63	0.31
90th percentile	0.47	2.78	0.83	0.55
Mode (rounded to nearest tenth)	0.0	0.1	0.0	0.0

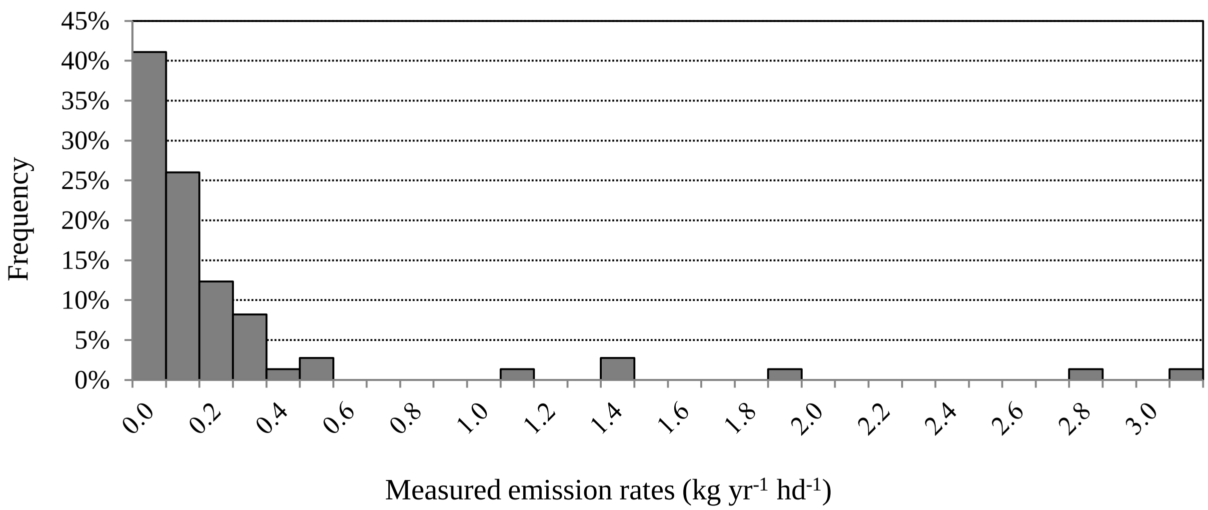

Figure 4. Histogram of measured emission rates of H_2S from swine houses

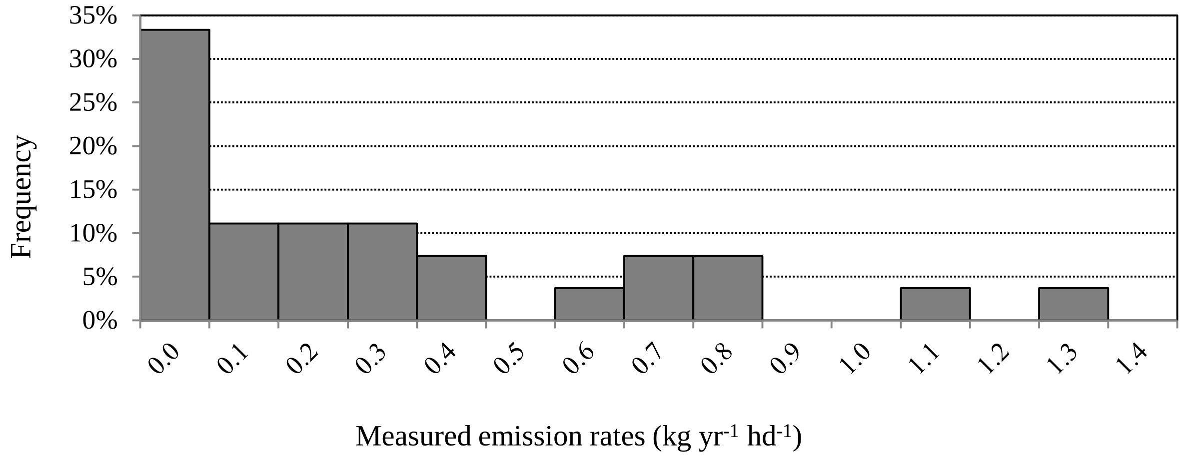

Figure 5. Histogram of measured emission rates of H_2S from swine manure storage facilities

(2) Variations and uncertainties in emission rates

Individual effects of various prediction variables on H_2S emissions are presented in Table 12. For H_2S emissions from swine houses, stage of production is significant no matter H_2S emission rates were expressed in kg $yr^{-1}hd^{-1}$ or kg $yr^{-1}AU^{-1}$. Average pig weight and size of operation have potential significant effect at certain conditions. For H_2S emission rates from slurry storage facilities, stage of production, storage type, storage area per head, and size of operation all have potential significant effect.

Table 12. P-values of individual effects of various prediction variables on H_2S emissions

		When each data point was treated equal		When the ratios of emission rate over standard deviation were used as weighting variables	
	Prediction variables	Emission rates in kg yr^{-1} hd^{-1}	Emission rates in kg yr^{-1} AU^{-1}	Emission rates in kg yr^{-1} hd^{-1}	Emission rates in kg yr^{-1} AU^{-1}
Swine houses	Stage of production	<0.01	<0.01	<0.01	0.01
	Manure system	0.87	0.46	0.90	0.37
	Average pig weight	<0.01	0.19	<0.01	0.01
	Size of operation	0.03	0.70	0.01	0.30
	Indoor air temperature	0.83	0.08	0.86	0.84
	Ventilation type	0.86	0.44	-	-
	Measurement method	-	-	-	-
	Prediction variables	Emission rates in kg yr^{-1} hd^{-1}	Emission rates in kg yr^{-1} m^{-2}	Emission rates in kg yr^{-1} hd^{-1}	Emission rates in kg yr^{-1} m^{-2}
Manure storage facilities	Stage of production	0.68	0.12	0.13	0.34
	Storage type	0.88	0.01	0.88	0.01
	Area per head	0.92	0.39	0.01	0.71
	Size of operation	0.16	0.97	0.06	0.19
	Ambient air temperature	0.90	0.80	0.72	0.81
	Area of storage facilities	0.67	0.15	0.39	0.14
	Measurement method	0.14	0.32	0.31	0.98

Frequencies of data points in for H_2S emissions from swine houses with various production stages and manure systems are presented in Table 13. Frequencies of data points for H_2S emissions from swine manure storage with various production stages and storage types are presented in Table 14. These frequencies are considered when developing regression models for H_2S emission rates.

Table 13. Frequency of data points for H_2S emissions from swine houses with various production stages and manure systems

	Farrowing	Finishing	Gestation	Nursery	Total
Deep pit	1	26	7	1	35
Dry	0	6	1	0	7
Hoop	0	2	0	0	2
Pit drain	4	3	2	0	9
Pit recharge	1	17	2	0	20
Total	6	54	12	1	73
Frequency Missing = 12					

Table 14. Frequency of data points for H_2S emissions from swine manure storage with various production stages and storage types

	Farrowing	Finishing	Nursery	Total
Lagoon	10	16	0	26
Slurry	0	5	1	6
Total	10	21	1	32

Regression models were developed for H_2S emissions rates from swine houses in kg $yr^{-1}hd^{-1}$ and in kg $yr^{-1}AU^{-1}$, respectively (Tables 15 and 16). In both models, the remaining significant prediction variables include stage of production, manure system type, indoor air temperature, and size of operation. The models are able to explain 64.6% and 41.8% of the variations in data, respectively.

Table 15. Regression model for H_2S emissions rates from swine houses (in kg $yr^{-1}hd^{-1}$)

Parameter[1]	Estimate	Standard error	t Value	P value
Intercept	-9.218987299	2.530428	-3.64	0.0007
Gestation	0.693616115	0.18625218	3.72	0.0005
Farrowing	1.404150145	0.26884649	5.22	<.0001
Drain	-0.507373248	0.19222002	-2.64	0.0112
Number	0.00742104	0.00203418	3.65	0.0007
T	0.67691436	0.18344904	3.69	0.0006
T*T	-0.01131276	0.00340236	-3.32	0.0017
Number*T	-0.00033697	0.00009256	-3.64	0.0007
R-Square	Coeff Var	Root MSE[2]	Mean	DF[3]
0.646266	128.5129	0.40554	0.315564	54

Regression equation:
H_2S emission rate from swine houses in kg $yr^{-1}hd^{-1}$
= –9.2190+0.6936Gestation+1.4042Farrowing–0.5074Drain+0.007421Number+0.6769T –0.01131T*T–0.0003370Number*T

[1] Farrowing and gestation is 0/1 dummy variable for stage of production with finishing as the baseline/reference. For example, farrowing is coded 1 if the production stage is farrowing, and 0 if it is not. Drain is 0/1 dummy variable for type of swine house manure systems with deep pit as the baseline/reference. T is indoor air temperature, ^oC. Number is number of pigs.
[2] Root mean squared error.
[3] Corrected total degrees of freedom.

Table 16. Regression model for H_2S emissions rates from swine houses (in kg $yr^{-1}AU^{-1}$)

Parameter[1]	Estimate	Standard error	t Value	P value
Intercept	-17.43129995	5.51754973	-3.16	0.0027
Farrowing	2.36559313	1.07750661	2.2	0.033
Drain	-2.3751244	0.78775349	-3.02	0.0041
Recharge	-1.41335868	0.55358598	-2.55	0.0139
Number	0.01793581	0.00569168	3.15	0.0028
T	0.85953818	0.25270051	3.4	0.0014
Number*T	-0.00077856	0.00026195	-2.97	0.0046
R-Square	Coeff Var	Root MSE[2]	Mean	DF[3]
0.417827	125.3722	1.634626	1.303818	54

Regression equation:

H_2S emission rate from finishing swine houses in kg $yr^{-1}AU^{-1}$

= –17.4313+2.3656Farrowing–2.3751Drain–0.1.4134Recharge+0.01794 Number+0.8595T –0.0007786Number*T

[1] Farrowing is 0/1 dummy variable for stage of production with finishing as the baseline/reference. Farrowing is coded 1 if the production stage is farrowing, and 0 if it is not. Drain and recharge are 0/1 dummy variables for type of swine house manure systems with deep pit as the baseline/reference. T is indoor air temperature, ^oC. Number is number of pigs.

[2] Root mean squared error.

[3] Corrected total degrees of freedom.

Regression models were developed for NH_3 emissions rates from swine manure storage facilities in kg $yr^{-1}hd^{-1}$ and in kg $yr^{-1}m^{-2}$, respectively (Tables 17 and 18). In both models, the remaining significant prediction variables include stage of production, storage type, area of storage per head, size of operation, and ambient air temperature. The models are able to explain 91.3% and 98.7% of the variations in data, respectively.

Table 17. Regression model for H_2S emissions rates from manure storage facilities (in kg $yr^{-1}hd^{-1}$)

Parameter[1]	Estimate	Standard error	t Value	P value
Intercept	-3.00964959	1.15998754	-2.59	0.041
APN	1.46719219	0.49746065	2.95	0.0256
Number	0.00083424	0.00033033	2.53	0.045
APN*Number	-0.00037382	0.00013976	-2.67	0.0368
Slurry	-61.90380747	24.60153488	-2.52	0.0455
Slurry*APN	0.77264955	0.39167333	1.97	0.096
Slurry*T	3.13501034	1.25478344	2.5	0.0466
Farrowing	3.73538713	1.19600501	3.12	0.0205
Farrowing*APN	-1.67960049	0.50128854	-3.35	0.0154
Farrowing*Number	-0.00098514	0.00033363	-2.95	0.0255
Farrowing*APN*Number	0.00047309	0.00014298	3.31	0.0162
Nursery	-3.08321449	1.45422538	-2.12	0.0783
R-Square	Coeff Var	Root MSE[2]	Mean	DF[3]
0.913494	65.65424	0.198349	0.302111	17

Regression equation:

H_2S emission rate from swine manure storage facilities in kg $yr^{-1}hd^{-1}$

= –3.0096+1.4672APN+0.0008342Number–0.0003738APN*Number+(3.7354–1.6796APN–0.0009851Number+0.0004731APN*Number)Farrowing–3.0832Nursery+(0.7726APN+3.1350T–61.9038)*Slurry

[1] Farrowing and gestation is 0/1 dummy variable for stage of production with finishing as the baseline/reference. For example, farrowing is coded 1 if the production stage is farrowing, and 0 if it is not. Slurry is 0/1 dummy variable for storage type with lagoon as the baseline/reference. APN is area of storage per animal head, m^2. Number is number of pigs. T is ambient air temperature, ^oC.

[2] Root mean squared error.

[3] Corrected total degrees of freedom.

Table 18. Regression model for H_2S emissions rates from manure storage facilities (in kg $yr^{-1}m^{-2}$)

Parameter[1]	Estimate	Standard error	t Value	P value
Intercept	-1.36453197	0.26488877	-5.15	0.0021
APN	0.66303275	0.11359755	5.84	0.0011
Number	0.0004633	0.00007543	6.14	0.0009
APN*Number	-0.00020422	0.00003191	-6.4	0.0007
Slurry	-37.1066254	5.6178796	-6.61	0.0006
Slurry*APN	0.26503562	0.0894405	2.96	0.0252
Slurry*T	1.89185391	0.28653587	6.6	0.0006
Farrowing	1.45483423	0.27311354	5.33	0.0018
Farrowing*APN	-0.68899563	0.11447166	-6.02	0.0009
Farrowing*Number	-0.00046821	0.00007619	-6.15	0.0009
Farrowing*APN*Number	0.00021508	0.00003265	6.59	0.0006
Nursery	-1.62982622	0.33207941	-4.91	0.0027
R-Square	Coeff Var	Root MSE[2]	Mean	DF[3]
0.986959	24.9248	0.045294	0.181722	17

Regression equation:
H_2S emission rate from swine manure storage facilities in kg $yr^{-1}m^{-2}$
= –1.3645+0.6630APN+0.0004633Number–0.0002042APN*Number+(1.4548–0.6890APN–0.0004682Number+0.0002151APN*Number)Farrowing–1.6298Nursery+(0.2650APN+1.8919T–37.1066)*Slurry

[1] Farrowing and gestation is 0/1 dummy variable for stage of production with finishing as the baseline/reference. For example, farrowing is coded 1 if the production stage is farrowing, and 0 if it is not. Slurry is 0/1 dummy variable for storage type with lagoon as the baseline/reference. APN is area of storage per animal head, m^2. Number is number of pigs. T is ambient air temperature, ^oC.
[2] Root mean squared error.
[3] Corrected total degrees of freedom.

The main effect means of H_2S emission rates are presented in Table 19 under various considerations. For H_2S emissions from swine houses, finishing swine has lowest emission rates, followed by gestation and farrowing. The H_2S emission rates (kg $yr^{-1}hd^{-1}$) from deep pit system were significantly higher than that from pit drain or recharge systems. The H_2S emission rates from slurry storage facilities were higher than that from lagoon, especially when emission rates were expressed in kg $yr^{-1}m^{-2}$.

Table 19. Main effects on H_2S emission rates

Response variables	Effects considered in model		P value	Category	n[1]	Least squares means	Standard error
Swine houses, emission rates in kg $yr^{-1}hd^{-1}$	Individual effect of production stage		<0.01	Finishing	64	0.108^{a}	0.076
				Gestation	12	0.787^{b}	0.175
				Farrowing	8	1.615^{c}	0.214
				Nursery	1	$0.557^{a,b,c}$	0.413
	Four effects	Production stage	0.33	Finishing	64	-0.002	0.324
				Gestation	12	-0.090	0.434
				Farrowing	8	0.863	0.596
				Nursery	1	0.296	0.574
		Manure system	<0.01	Deep pit	34	1.789^{b}	0.398
				Pit drain	9	-0.392^{a}	0.473
				Pit recharge	13	-0.255^{a}	0.433
				Dry	7	$-0.074^{a,b}$	0.935
		Indoor air temperature	0.82	Slope=-0.00764 kg $yr^{-1}hd^{-1}$ per ^{o}C			
		Size of operation	0.34	Slope=-0.00058 kg $yr^{-1}hd^{-1}$ per head			
Swine houses, emission rates in kg $yr^{-1}AU^{-1}$	Individual effect of production stage		<0.01	Finishing	64	0.738^{a}	0.235
				Gestation	12	$1.551^{a,b}$	0.419
				Farrowing	8	2.908^{b}	0.523
				Nursery	1	11.076^{c}	1.175
	Four effects	Production stage	<0.01	Finishing	64	0.609^{a}	0.391
				Gestation	12	$0.823^{a,b}$	0.684
				Farrowing	8	3.761^{b}	1.114
				Nursery	1	10.830^{c}	1.347
		Manure system	0.06	Deep pit	34	5.538	0.595
				Pit drain	9	3.148	0.825
				Pit recharge	13	3.933	0.710
				Dry	7	3.405	1.323
		Indoor air temperature	0.94	Slope=-0.00529 kg $yr^{-1}AU^{-1}$ per ^{o}C			
		Size of operation	0.86	Slope=-0.00019 kg $yr^{-1}AU^{-1}$ per head			
Manure storage facilities, emission rates in kg $yr^{-1}hd^{-1}$	Individual effect of production stage		0.68	Finishing	21	0.329	0.111
				Farrowing	9	0.388	0.146
				Nursery	1	0.059	0.342
	Four effects	Production stage	0.50	Finishing	21	0.309	0.150
				Farrowing	9	0.682	0.291
				Nursery	1	-0.026	0.456
		Storage type	0.18	Lagoon	25	0.115	0.198
				Slurry	6	0.527	0.220
		Ambient air temperature	0.60	Slope=-0.01113 kg $yr^{-1}hd^{-1}$ per ^{o}C			
		Area per head	0.77	Slope=-0.01411 kg $yr^{-1}hd^{-1}$ per m^2			
Manure storage facilities, emission rates in kg $yr^{-1}m^{-2}$	Individual effect of production stage		0.12	Finishing	21	0.183	0.052
				Farrowing	9	0.130	0.063
				Nursery	1	0.526	0.167
	Four effects	Production stage	0.36	Finishing	21	0.195	0.065
				Farrowing	9	0.327	0.127
				Nursery	1	0.461	0.198
		Storage type	0.05	Lagoon	25	0.182^{a}	0.086
				Slurry	6	0.473^{b}	0.096
		Ambient air temperature	0.69	Slope=-0.00362 kg $yr^{-1}m^{-2}$ per ^{o}C			
		Area per head	0.39	Slope=-0.01839kg $yr^{-1}m^{-2}$ per m^2			

[1] n=number of data points.

[a,b,c] Values within the same effect section differ significantly if without common letter (P < 0.05).

In the NAEMS sites, uncertainties of H_2S emission rates from swine houses were calculated to be 13 to 77% for gestation houses, 28 to 77% for farrowing houses, and 13 to 18% for finishing houses. In literature, the average reported standard deviation for measured H_2S emission rates from swine houses was 59% of the mean. The average reported standard deviation for measured H_2S emission rates from manure storage facilities was 62% of the mean. However, there were larger variations among different studies. For H_2S emissions from swine houses, the standard deviation was 215% of the mean emission rate when expressed in kg $yr^{-1}hd^{-1}$. These variations or uncertainties were results of different conditions (prediction variables) in different studies. In the regression model, since effects of significant prediction variables had been accounted, the root mean squared error was reduced to 128% of the mean. For H_2S emissions from manure storage facilities, the standard deviation was 112% of the mean emission rate when expressed in kg $yr^{-1}hd^{-1}$, while in the regression model, the root mean squared error was reduced to 64% of the mean.

(3) Concentrations

Ten studies have been identified that have reported measured H_2S concentrations in the vicinity of swine facilities in North America at various distances (63 data points in total, see Appendix 6 and Figure 6). The average H_2S concentration at the edge of the emission sources (swine houses or lagoons) was 40±48 ppb (ranged from 0.9 to146 ppb). The ambient H_2S concentrations in the vicinity of swine facilities decreased gradually with increasing distances from 5.1±4.1 ppb at 30 m to 0.55±0.21 ppb at 1185 m from emission sources. The average ambient H_2S concentration was 3.1±6.2 ppb at the distances from 30 to 1185 m from emission sources. As comparison, the average ambient H_2S concentration not within swine production areas was 1.9±1.1 ppb, based on data reported by Godbout et al (2009) and Donham et al (2006).

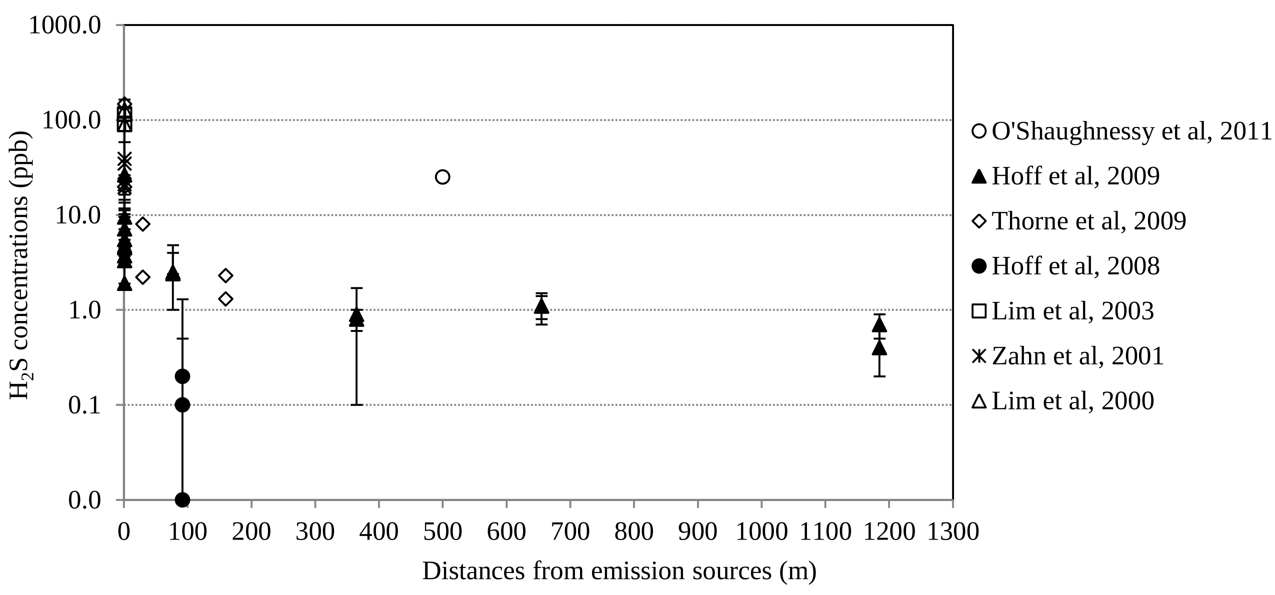

Figure 6. Measured H_2S concentrations at various distances from swine facilities

7.3 VOCs

Four studies and 5 NAEMS sites have been identified that have reported measured emission rates of VOCs from swine houses in North America (32 data points in total). Five studies have been identified that have reported measured emission rates of VOCs from swine manure storage facilities in North America (18 data points in total). The VOCs emission data for swine houses and manure storage facilities are listed in Appendices 7 and 8, respectively. The statistics of VOCs emission rates are presented in Table 20. The VOCs emission rates for swine houses were comparable, if not less than that for manure storage facilities when both were expressed in the unit of kg $yr^{-1}hd^{-1}$. Histograms of VOCs emission rates for swine houses and manure storage facilities both show a skew-right distribution (Figure 7 and 8). The mean emission rates were sensitive due to a few large values while the medians were more robust. For swine houses, the median H_2S emission rate was only 0.44 kg $yr^{-1}hd^{-1}$ although the highest emission rate was 10 times higher. In 90% of data points, VOCs emission rates were less than 3.45 kg $yr^{-1}hd^{-1}$. The average VOCs emission rate for swine houses in the 5 NAEMS sites was 1.70±1.41 kg $yr^{-1}hd^{-1}$. For swine manure storage facilities, the median VOCs emission rate was only 0.75 kg $yr^{-1}hd^{-1}$ and the highest emission rate was 8 times higher. In 90% of data points, VOCs emission rates were less than 5.69 kg $yr^{-1}hd^{-1}$.

Table 20. Statistics of VOCs emissions from swine houses and manure storage facilities

	Emission from swine houses		Emission from swine manure storage facilities	
	Emission rates in kg $yr^{-1}hd^{-1}$	Emission rates in kg $yr^{-1}AU^{-1}$	Emission rates in kg $yr^{-1}hd^{-1}$	Emission rates in kg $yr^{-1}m^{-2}$
Range	0.00 to 4.41	0.04 to 17.22	0.02 to 6.16	0.12 to 8.26
Mean	0.96±1.25	4.21±4.67	1.42±1.89	2.20±2.86
Median	0.44	2.08	0.75	0.52
75th percentile	1.10	6.31	1.69	3.24
90th percentile	3.45	11.50	5.69	7.64
Mode (rounded to nearest tenth)	0.20	1.90	0.30	0.10

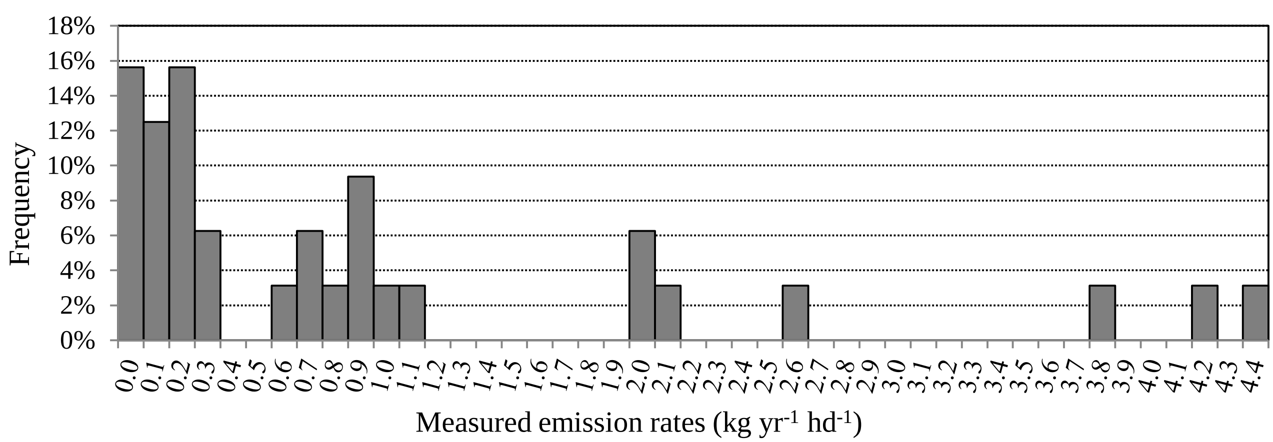

Figure 7. Histogram of measured emission rates of VOCs from swine houses

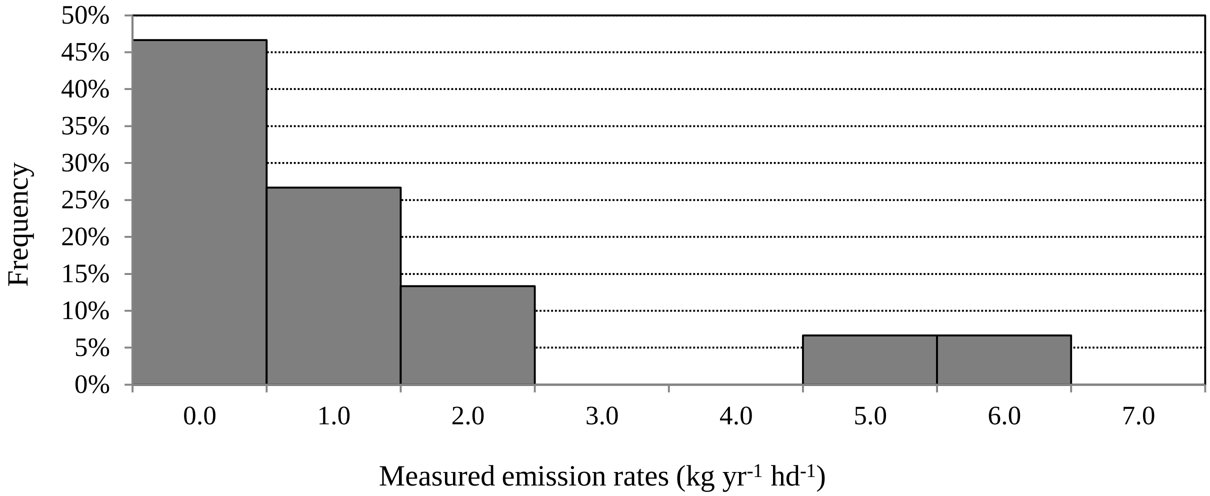

Figure 8. Histogram of measured emission rates of VOCs from swine manure storage facilities

(2) Variations and uncertainties in emission rates

Individual effects of various prediction variables on VOCs emissions are presented in Table 21. For VOCs emissions from swine houses, stage of production and size of operations show significant effects. Average pig weight has significant effect when emission rates are expressed in kg $yr^{-1}hd^{-1}$. For VOC emissions from manure storage facilities, storage type, storage area per head, and size of operation all have potential significant effect.

Table 21. P-values of individual effects of various prediction variables on VOCs emissions

		When each data point was treated equal		When the ratios of emission rate over standard deviation were used as weighting variables	
	Prediction variables	Emission rates in kg $yr^{-1}hd^{-1}$	Emission rates in kg $yr^{-1}AU^{-1}$	Emission rates in kg $yr^{-1}hd^{-1}$	Emission rates in kg $yr^{-1}AU^{-1}$
Swine houses	Stage of production	<0.01	<0.01	<0.01	0.05
	Manure system	0.14	0.30	0.43	0.01
	Average pig weight	<0.01	0.89	0.02	0.89
	Size of operation	<0.01	<0.01	<0.01	0.04
	Indoor air temperature	0.39	0.38	0.98	0.88
	Ventilation type	-	-	-	-
	Measurement method	-	-	-	-
	Prediction variables	Emission rates in kg $yr^{-1}hd^{-1}$	Emission rates in kg $yr^{-1}m^{-2}$	Emission rates in kg $yr^{-1}hd^{-1}$	Emission rates in kg $yr^{-1}m^{-2}$
Swine manure storage facilities	Stage of production	0.23	0.38	0.64	0.68
	Storage type	0.07	0.08	<0.01	<0.01
	Area per head	0.11	0.06	0.57	0.54
	Size of operation	0.23	0.02	0.35	0.35
	Ambient air temperature	0.89	0.84	0.10	0.09
	Area of storage facilities	0.02	0.01	0.33	0.34
	Measurement method	0.85	0.70	-	-

Frequencies of data points in for VOCs emissions from swine houses with various production stages and manure systems are presented in Table 22. Frequencies of data points for VOC emissions from swine manure storage with various production stages and storage types are presented in Table 23. These frequencies are considered when developing regression models for VOC emission rates.

Table 22. Frequency of data points for VOCs emissions from swine houses with various production stages and manure systems

	Farrowing	Finishing	Gestation	Total
Deep pit	0	5	2	7
Dry	0	3	0	3
Pit drain	2	0	2	4
Pit recharge	1	15	2	18
Total	3	23	6	32

Table 23. Frequency of data points for VOCs emissions from swine manure storage with various production stages and storage types

	Finishing	Nursery	Total
Lagoon	6	0	6
Slurry	8	1	9
Total	14	1	15
Frequency Missing = 3			

Regression models were developed for VOCs emissions rates from swine houses in kg $yr^{-1}hd^{-1}$ and in kg $yr^{-1}AU^{-1}$, respectively (Tables 24 and 25). In both models, the remaining significant prediction variables include average pig weight, indoor air temperature, and size of operation. The models are able to explain 90.6% and 89.1% of the variations in data, respectively.

Table 24. Regression model for VOCs emissions rates from swine houses (in kg $yr^{-1}hd^{-1}$)

Parameter[1]	Estimate	Standard error	t Value	P value
Intercept	0.057324296	0.21393314	0.27	0.7937
Weight	-0.005954128	0.00177756	-3.35	0.0065
T	0.053944617	0.00931283	5.79	0.0001
Number*Number	-0.000000638	0.00000007	-9.55	<.0001
R-Square	Coeff Var	Root MSE[2]	Mean	DF[3]
0.905841	47.74914	0.110778	0.232	14

Regression equation:
VOCs emission rate from swine houses in kg $yr^{-1}hd^{-1}$
= 0.05732–0.005954Weight+0.05394T–0.000000638Number*Number

[1] Weight is average weight of pigs, kg. T is indoor air temperature, ^{o}C. Number is number of pigs.
[2] Root mean squared error.
[3] Corrected total degrees of freedom.

Table 25. Regression model for VOCs emissions rates from swine houses (in kg $yr^{-1}AU^{-1}$)

Parameter[1]	Estimate	Standard error	t Value	P value
Intercept	0.913260656	1.58058842	0.58	0.575
Weight	-0.04727813	0.01313305	-3.6	0.0042
T	0.371614299	0.06880539	5.4	0.0002
Number*Number	-4.3655E-06	0.00000049	-8.84	<.0001
R-Square	Coeff Var	Root MSE[2]	Mean	DF[3]
0.890741	47.16408	0.818454	1.735333	14

Regression equation:
VOCs emission rate from swine houses in kg $yr^{-1}AU^{-1}$
= 0.9133–0.04728Weight+0.3716T–0.000004366Number*Number

[1] Weight is average weight of pigs, kg. T is indoor air temperature, ^{o}C. Number is number of pigs.
[2] Root mean squared error.
[3] Corrected total degrees of freedom.

Regression models were developed for VOC emissions rates from swine manure storage facilities in kg $yr^{-1}hd^{-1}$ and in kg $yr^{-1}m^{-2}$, respectively (Tables 26 and 27). In both models, the remaining significant prediction variables include stage of production, storage type, area of storage per head, and size of operation. The models are able to explain 96.9% and 98.1% of the variations in data, respectively.

Table 26. Regression model for VOCs emissions rates from manure storage facilities (in kg $yr^{-1}hd^{-1}$)

Parameter[1]	Estimate	Standard error	t Value	P value
Intercept	-4.03043322	0.47977668	-8.4	0.0002
Slurry	-41.62037308	5.7224813	-7.27	0.0003
APN	0.00070358	0.00006484	10.85	<.0001
Slurry*Number	2.25847377	0.30020057	7.52	0.0003
Nursery	-4.26979355	0.59540071	-7.17	0.0004
R-Square	Coeff Var	Root MSE[2]	Mean	DF[3]
0.969162	27.91686	0.481693	1.725455	10

Regression equation:
VOCs emission rate from finishing swine manure storage facilities in kg $yr^{-1}hd^{-1}$
= –4.0304+(2.2584Number –41.6203)Slurry–4.2698Nursery+0.0007036APN

[1] Slurry is 0/1 dummy variable for storage type with lagoon as the baseline/reference. Slurry is coded 1 if the storage is slurry system and 0 if it is not. Nursery is 0/1 dummy variable for production stage with finishing as the baseline/reference. APN is area of storage per animal head, m^2. Number is number of pigs.
[2] Root mean squared error.
[3] Corrected total degrees of freedom.

Table 27. Regression model for VOC emissions rates from manure storage facilities (in kg $yr^{-1}m^{-2}$)

Parameter[1]	Estimate	Standard error	t Value	P value
Intercept	-6.13538772	0.53166849	-11.54	<.0001
Slurry	-55.82196956	6.34141495	-8.8	0.0001
APN	0.00098483	0.00007185	13.71	<.0001
Slurry*Number	3.0403518	0.33266974	9.14	<.0001
Nursery	-5.16618285	0.65979822	-7.83	0.0002
R-Square	Coeff Var	Root MSE[2]	Mean	DF[3]
0.980752	25.32001	0.533792	2.108182	10

Regression equation:
VOCs emission rate from finishing swine manure storage facilities in kg $yr^{-1}m^{-2}$
= –6.1354+(3.0404Number –55.8220)Slurry–5.1662Nursery+0.0009848APN

[1] Slurry is 0/1 dummy variable for storage type with lagoon as the baseline/reference. Slurry is coded 1 if the storage is slurry system and 0 if it is not. Nursery is 0/1 dummy variable for production stage with finishing as the

baseline/reference. APN is area of storage per animal head, m^2. Number is number of pigs.
[2] Root mean squared error.
[3] Corrected total degrees of freedom.

The main effect means of VOCs emission rates are presented in Table 28 under various considerations. For VOCs emissions from swine houses, farrowing swine has significant higher emission rates that gestation and finishing swine. The VOCs emission rates from swine houses were positively related with indoor air temperature, and negatively related with average pig weight and size of swine operations. However, the VOCs emissions from manure storage were positively related with size of operation.

Table 28. Main effects on VOCs emission rates

Response variables	Effects considered in model		P value	Category	n[1]	Least squares means	Standard error
Swine houses, emission rates in kg $yr^{-1}hd^{-1}$	Individual effect of production stage		<0.01	Finishing	23	0.526[a]	0.223
				Gestation	6	1.358[a]	0.317
				Farrowing	3	4.137[b]	0.368
	Three effects	Average pig weight	0.03	Slope=-0.00462 kg $yr^{-1}hd^{-1}$ per kg			
		Indoor air temperature	<0.01	Slope=0.03639 kg $yr^{-1}hd^{-1}$ per ^oC			
		Size of operation	<0.01	Slope=-0.00070 kg $yr^{-1}hd^{-1}$ per head			
Swine houses, emission rates in kg $yr^{-1}AU^{-1}$	Individual effect of production stage		<0.01	Finishing	23	4.194[a,b]	1.776
				Gestation	6	3.228[a]	2.395
				Farrowing	3	10.270[b]	2.591
	Three effects	Average pig weight	0.02	Slope=-0.03813 kg $yr^{-1}AU^{-1}$ per kg			
		Indoor air temperature	<0.01	Slope=0.2515 kg $yr^{-1}AU^{-1}$ per ^oC			
		Size of operation	<0.01	Slope=-0.00481 kg $yr^{-1}AU^{-1}$ per head			
Manure storage facilities, emission rates in kg $yr^{-1}hd^{-1}$	Individual effect of production stage		0.23	Finishing	14	1.358	0.792
				Nursery	1	-0.870	1.854
	Four effects	Production stage	0.19	Finishing	14	1.789	0.668
				Nursery	1	-0.809	1.568
		Storage type	0.81	Lagoon	6	0.156	1.708
				Slurry	12	0.824	1.414
		Size of operation	0.05	Slope=0.000266 kg $yr^{-1}hd^{-1}$ per head			
		Area per head	0.73	Slope=-0.4879 kg $yr^{-1}hd^{-1}$ per m^2			
Manure storage facilities, emission rates in kg $yr^{-1}m^{-2}$	Individual effect of production stage		0.38	Finishing	14	2.241	1.291
				Nursery	1	-0.329	2.909
	Four effects	Production stage	0.14	Finishing	14	2.734	0.909
				Nursery	1	-1.375	2.134
		Storage type	0.76	Lagoon	6	1.248	2.325
				Slurry	12	0.111	1.925
		Size of operation	0.11	Slope=0.000278 kg $yr^{-1}m^{-2}$ per head			
		Area per head	0.30	Slope=-2.092 kg $yr^{-1}m^{-2}$ per m^2			

[1] n=number of data points.
[a,b,c] Values within the same effect section differ significantly if without common letter ($P < 0.05$).

In literature, the average reported standard deviation for measured VOCs emission rates from swine houses was 61% of the mean. The average reported standard deviation for measured VOCs emission rates from manure storage facilities was only 8% of the mean. However, there were larger variations among different studies. For VOCs emissions from swine houses, the standard deviation was 130% of the mean emission rate when expressed in kg $yr^{-1}hd^{-1}$. These variations or uncertainties were results of different conditions (prediction variables) in different studies. In the regression model, since effects of significant prediction variables had been accounted, the root mean squared error was reduced to 48% of the mean. For VOCs emissions from manure storage facilities, the standard deviation was 112% of the mean emission rate in literature when expressed in kg $yr^{-1}hd^{-1}$, while in the regression model, the root mean squared error was reduced to 28% of the mean.

(3) Concentrations

Five studies have been identified that have reported measured VOCs concentrations in the vicinity of swine facilities in North America at various distances (23 data points in total, see Appendix 9 and Figure 9). The reported VOCs concentrations at the edge of the emission sources (swine houses or lagoons) were in a wide range from 0.9 µg m^{-3} to 27.7 mg m^{-3} and averaged 2.6±7.9 mg m^{-3}. Hermandez et al (2012) observed VOCs concentration was 12.6±3.8 µg m^{-3} at 46to62m distances. Park et al (2012b) observed VOCs concentration was 1.9±0.5 µg m^{-3} at 10to30 m and 0.48 µg m^{-3} at 300m from barn. Zahn et al (1997) reported much higher VOCs concentrations (19.44 mg m^{-3} at 25 m and 10.67 mg m^{-3} at 100m from slurry storage basin) compared with other researchers.

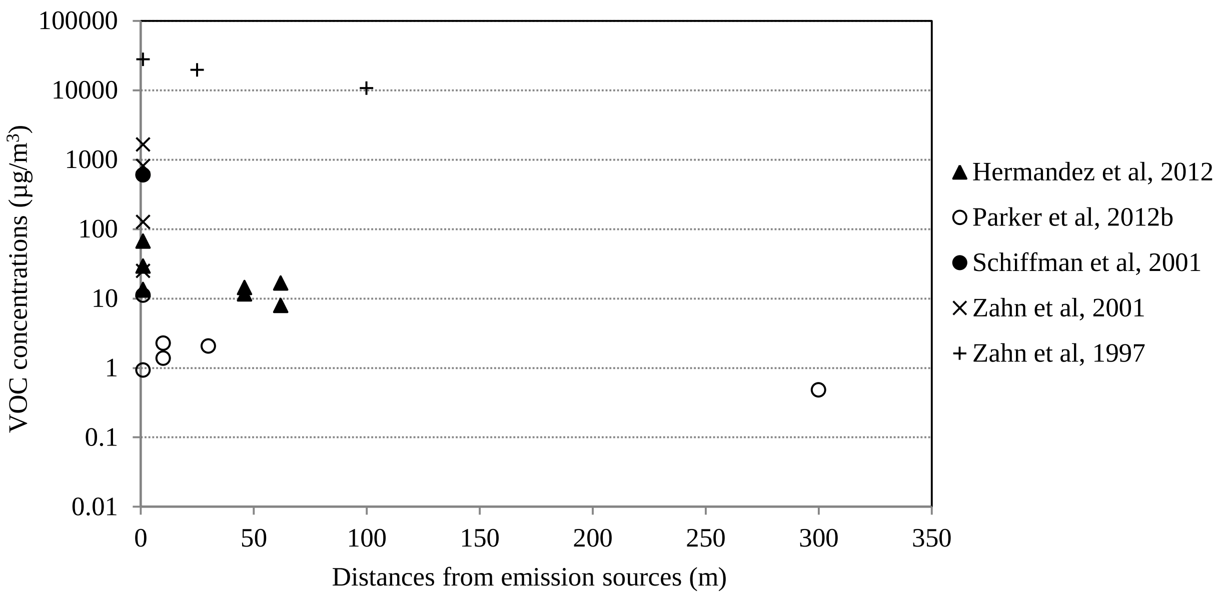

Figure 9. Measured VOCs concentrations at various distances from swine facilities

7.4 PM_{10} and $PM_{2.5}$

Seven studies and 5 NAEMS sites have been identified that have reported measured emission rates of PM_{10} from swine houses in North America (37 data points in total). One study and 5 NAEMS sites have been identified that have reported measured emission rates of $PM_{2.5}$ from swine houses in North America (17 data points in total). The PM_{10} and $PM_{2.5}$ emission data for swine houses are listed in Appendices 10 and 11, respectively. The statistics of PM_{10} and $PM_{2.5}$ emission rates are presented in Table 29. Histograms of PM_{10} and $PM_{2.5}$ emission rates for swine houses both show a skew-right distribution (Figure 10 and 11). The mean emission rates were sensitive due to a few large values while the medians were more robust. The median emission rate was 0.09 kg $yr^{-1}hd^{-1}$ for PM10 and was 0.015 kg $yr^{-1}hd^{-1}$ for $PM_{2.5}$. The average PM_{10} emission rate for swine houses in the 5 NAEMS sites was 0.20±0.18 kg $yr^{-1}hd^{-1}$.

The average $PM_{2.5}$ emission rate for swine houses in the 5 NAEMS sites was 0.021±0.023 kg $yr^{-1}hd^{-1}$, which was 11% of the average PM_{10} emission rate.

Table 29. Statistics of PM_{10} and $PM_{2.5}$ emissions from swine houses

	PM_{10} Emission from swine houses		$PM_{2.5}$ Emission from swine houses	
	Emission rates in kg $yr^{-1}hd^{-1}$	Emission rates in kg $yr^{-1}AU^{-1}$	Emission rates in kg $yr^{-1}hd^{-1}$	Emission rates in kg $yr^{-1}AU^{-1}$
Range	0.03 to 0.62	0.22 to 1.66	-0.004 to 0.079	-0.33 to 0.284
Mean	0.14±0.14	0.69±0.40	0.021±0.023	0.068±0.078
Median	0.09	0.63	0.015	0.038
75th percentile	0.17	0.76	0.034	0.100
90th percentile	0.37	1.54	0.059	0.215
Mode (rounded to nearest hundredth for PM_{10} and to nearest thousandth for $PM_{2.5}$)	0.10	0.70	0.020	0.040

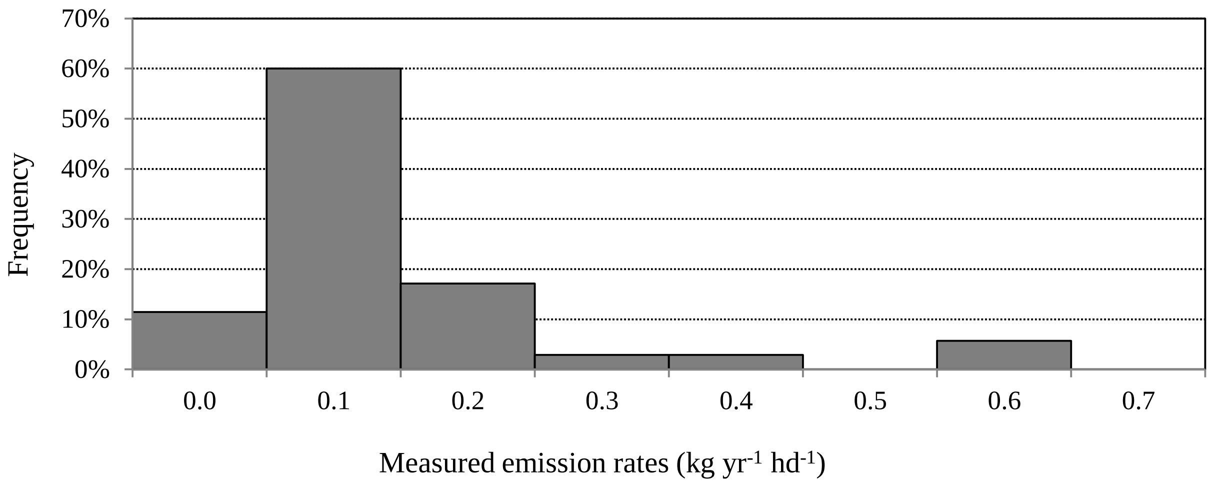

Figure 10. Histogram of measured emission rates of PM_{10} from swine houses

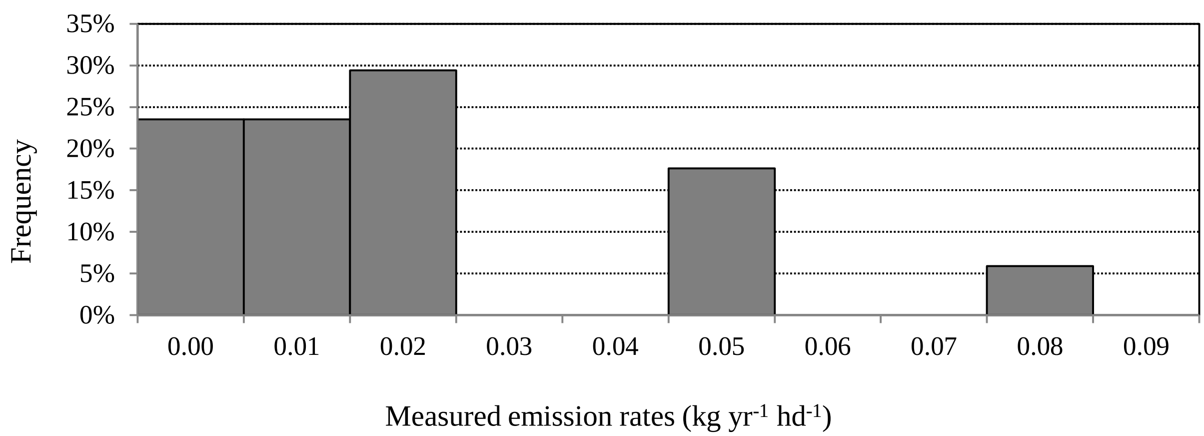

Figure 11. Histogram of measured emission rates of $PM_{2.5}$ from swine houses

(2) Variations and uncertainties in emission rates

Individual effects of various prediction variables on PM_{10} and $PM_{2.5}$ emissions are presented in Table 30. The effect of stage of production is significant for both PM_{10} and $PM_{2.5}$ no matter emission rates were expressed in kg $yr^{-1}hd^{-1}$ or kg $yr^{-1}AU^{-1}$. Average pig weight, indoor air temperature, and size of operation all have potential significant effect.

Table 30. P-values of individual effects of various prediction variables on PM_{10} and $PM_{2.5}$ emissions from swine houses

		When each data point was treated equal		When the ratios of emission rate over standard deviation were used as weighting variables	
	Prediction variables	Emission rates in kg $yr^{-1}hd^{-1}$	Emission rates in kg $yr^{-1}AU^{-1}$	Emission rates in kg $yr^{-1}hd^{-1}$	Emission rates in kg $yr^{-1}AU^{-1}$
PM_{10}	Stage of production	<0.01	<0.01	<0.01	<0.01
	Manure system	0.08	0.64	0.29	0.96
	Average pig weight	<0.01	0.98	<0.01	0.94
	Size of operation	<0.01	0.28	<0.01	0.01
	Indoor air temperature	0.01	<0.01	0.01	<0.01
	Ventilation type	0.57	0.02	0.55	0.02
	Measurement method	0.76	0.29	-	-
	Prediction variables	Emission rates in kg $yr^{-1}hd^{-1}$	Emission rates in kg $yr^{-1}AU^{-1}$	Emission rates in kg $yr^{-1}hd^{-1}$	Emission rates in kg $yr^{-1}AU^{-1}$
$PM_{2.5}$	Stage of production	<0.01	<0.01	<0.01	<0.01
	Manure system	0.37	0.73	0.39	0.34
	Average pig weight	0.07	0.75	0.11	0.87
	Size of operation	<0.01	0.24	<0.01	<0.01
	Indoor air temperature	0.05	0.06	0.08	0.07
	Ventilation type	0.21	<0.01	<0.01	<0.01
	Measurement method	0.21	<0.01	-	-

Frequencies of data points in for PM_{10} and $PM_{2.5}$ emissions from swine houses with various production stages and manure systems are presented in Tables 31 and 32, respectively. These frequencies are considered when developing regression models for PM_{10} and $PM_{2.5}$ emission rates.

Table 31. Frequency of data points for PM_{10} emissions from swine houses with various production stages and manure systems

	Farrowing	Finishing	Gestation	Total
Deep pit	0	13	2	15
Dry	0	0	1	1
Hoop	0	2	0	2
Pit drain	2	0	2	4
Pit recharge	1	11	2	14
Total	3	26	7	36

Table 32. Frequency of data points for $PM_{2.5}$ emissions from swine houses with various production stages and manure systems

	Farrowing	Finishing	Gestation	Total
Deep pit	0	5	2	7
Pit drain	2	0	2	4
Pit recharge	1	3	2	6
Total	3	8	6	17

Regression models were developed for PM_{10} emissions rates from swine houses in kg $yr^{-1}hd^{-1}$ and in kg $yr^{-1}AU^{-1}$, respectively (Tables 33 and 34). In both models, the remaining significant prediction variables include production stage, indoor air temperature, and average pig weight. The models are able to explain 95.7% and 91.4% of the variations in data, respectively.

Table 33. Regression model for PM_{10} emissions rates from swine houses (in kg $yr^{-1}hd^{-1}$)

Parameter[1]	Estimate	Standard error	t Value	P value
Intercept	0.677235667	0.25011766	2.71	0.0144
Gestation	0.199680964	0.06924624	2.88	0.0099
Farrowing	0.541963337	0.0899816	6.02	<.0001
T	-0.020371867	0.0093622	-2.18	0.0431
Number	-0.000128599	0.00005873	-2.19	0.042
Weight*Weight	-0.000003756	0.0000019	-1.98	0.0633
R-Square	Coeff Var	Root MSE[2]	Mean	DF[3]
0.956764	24.97861	0.037988	0.152083	23

Regression equation:
PM_{10} emission rate from swine houses in kg $yr^{-1}hd^{-1}$
= 0.6772+0.1997Gestation+0.5420Farrowing–0.02037T–0.0001286Number–0.000003756Weight*Weight

[1] Farrowing and gestation are 0/1 dummy variables for stage of production with finishing as the baseline/reference. For example, farrowing is coded 1 if the production stage is farrowing, and 0 if it is not. T is indoor air temperature, ^oC. Number is number of pigs. Weight is average weight of pigs, kg.
[2] Root mean squared error.
[3] Corrected total degrees of freedom.

Table 34. Regression model for PM_{10} emissions rates from swine houses (in kg $yr^{-1}AU^{-1}$)

Parameter[1]	Estimate	Standard error	t Value	P value
Intercept	-2.80474115	0.86982249	-3.22	0.005
T	0.15004742	0.03836065	3.91	0.0011
Gestation	-2.90428685	0.78426486	-3.7	0.0018
Gestation*Weight	0.0138438	0.00399199	3.47	0.0029
Farrowing	10.10245899	2.94469352	3.43	0.0032
Farrowing*Weight	-0.01489627	0.00327962	-4.54	0.0003
Farrowing*T	-0.26540011	0.11528959	-2.3	0.0342
R-Square	Coeff Var	Root MSE[2]	Mean	DF[3]
0.914424	19.29488	0.12196	0.632083	23

Regression equation:
PM_{10} emission rate from swine houses in kg $yr^{-1}AU^{-1}$
= –2.8047+0.1500T+(0.01384Weight–2.9043)Gestation+(10.1025–0.01490Weight–0.2654T)Farrowing

[1] Farrowing and gestation are 0/1 dummy variables for stage of production with finishing as the baseline/reference. For example, farrowing is coded 1 if the production stage is farrowing, and 0 if it is not. T is indoor air temperature, ^oC. Weight is average weight of pigs, kg.
[2] Root mean squared error.
[3] Corrected total degrees of freedom.

Regression models were developed for $PM_{2.5}$ emissions rates from swine houses in kg $yr^{-1}hd^{-1}$ and in kg $yr^{-1}AU^{-1}$, respectively (Tables 35 and 36). In both models, the remaining significant prediction variables include production stage, manure system type, size of operation, and average pig weight. The models are able to explain 96.9% and 81.3% of the variations in data, respectively.

Table 35. Regression model for $PM_{2.5}$ emissions rates from swine houses (in kg $yr^{-1}hd^{-1}$)

Parameter[1]	Estimate	Standard error	t Value	P value
Intercept	0.22242	0.05327	4.17	0.0024
Gestation	0.09874	0.02289	4.31	0.002
Farrowing	0.04626	0.01978	2.34	0.0441
Recharge	-0.0239	0.00774	-3.09	0.013
T	-0.0037	0.00135	-2.76	0.022
Number	-0.0001	2.7E-05	-3.99	0.0031
Weight	-0.0005	0.00015	-3.53	0.0064
R-Square	Coeff Var	Root MSE[2]	Mean	DF[3]
0.969204	26.98856	0.005094	0.018875	15

Regression equation:
$PM_{2.5}$ emission rate from swine houses in kg $yr^{-1}hd^{-1}$
= 0.6772+0.1997Gestation+0.5420Farrowing–0.02037T–0.0001286Number–0.000003756Weight*Weight

[1] Farrowing and gestation are 0/1 dummy variables for stage of production with finishing as the baseline/reference. For example, farrowing is coded 1 if the production stage is farrowing, and 0 if it is not. Recharge is 0/1 dummy variable for type of swine house manure systems with deep pit as the baseline/reference. T is indoor air temperature, ^oC. Number is number of pigs. Weight is average weight of pigs, kg.
[2] Root mean squared error.
[3] Corrected total degrees of freedom.

Table 36. Regression model for $PM_{2.5}$ emissions rates from swine houses (in kg $yr^{-1}AU^{-1}$)

Parameter[1]	Estimate	Standard error	t Value	P value
Intercept	-0.142276465	0.03587967	-3.97	0.0019
Gestation	-0.189283458	0.03014161	-6.28	<.0001
Recharge	0.071320667	0.02215574	3.22	0.0074
Number	8.09221E-05	0.00001416	5.71	<.0001
Weight	0.001248524	0.00020636	6.05	<.0001
R-Square	Coeff Var	Root MSE[2]	Mean	DF[3]
0.813399	56.92814	0.038946	0.068412	15

Regression equation:
$PM_{2.5}$ emission rate from swine houses in kg $yr^{-1}AU^{-1}$
= –0.1423–0.1893Gestation+0.07132Recharge+0.00008092Number–+0.001248Weight

[1] Farrowing and gestation are 0/1 dummy variables for stage of production with finishing as the baseline/reference. For example, farrowing is coded 1 if the production stage is farrowing, and 0 if it is not. Recharge is 0/1 dummy variable for type of swine house manure systems with deep pit as the baseline/reference. T is indoor air temperature, ^oC. Number is number of pigs. Weight is average weight of pigs, kg.
[2] Root mean squared error.
[3] Corrected total degrees of freedom.

The main effect means of VOCs emission rates are presented in Table 37 under various considerations. It can be seen that farrowing houses have significantly higher PM_{10} and $PM_{2.5}$ emission rates than finishing houses and nursery houses.

Table 37. Main effects on PM_{10} and $PM_{2.5}$ emission rates from swine houses

Response variables	Effects considered in model		P value	Category	n[1]	Least squares means	Standard error
PM_{10} emission rates in kg $yr^{-1}hd^{-1}$	Individual effect of production stage		<0.01	Finishing	26	0.102^{a}	0.016
				Gestation	7	0.147^{a}	0.028
				Farrowing	3	0.550^{b}	0.037
	Three effects	Production stage	<0.01	Finishing	26	0.041^{a}	0.085
				Gestation	7	0.196^{a}	0.066
				Farrowing	3	0.638^{b}	0.086
		Indoor air temperature	0.20	Slope=-0.001115 kg $yr^{-1}hd^{-1}$ per ^{o}C			
		Average pig weight	0.37	Slope=-0.00071 kg $yr^{-1}hd^{-1}$ per kg			
PM_{10} emission rates in kg $yr^{-1}AU^{-1}$	Individual effect of production stage		<0.01	Finishing	26	0.732^{a}	0.082
				Gestation	7	0.352^{a}	0.138
				Farrowing	3	1.377^{b}	0.183
	Three effects	Production stage	<0.01	Finishing	26	0.392^{a}	0.201
				Gestation	7	0.714^{a}	0.309
				Farrowing	3	1.806^{b}	0.393
		Indoor air temperature	0.55	Slope=-0.02334 kg $yr^{-1}AU^{-1}$ per ^{o}C			
		Average pig weight	0.25	Slope=-0.00430 kg $yr^{-1}AU^{-1}$ per kg			
$PM_{2.5}$ emission rates in kg $yr^{-1}hd^{-1}$	Individual effect of production stage		<0.01	Finishing	8	0.0185^{a}	0.0107
				Gestation	6	0.0158^{a}	0.0107
				Farrowing	3	0.0603^{b}	0.0111
	Four effects	Production stage	<0.01	Finishing	8	0.0073^{a,b}	0.0386
				Gestation	6	0.0127^{a}	0.0338
				Farrowing	3	0.0732^{b}	0.0364
		Manure system	0.39	Deep pit	7	0.0388	0.0201
				Drain	4	0.0209	0.0150
				Recharge	6	0.0335	0.0159
		Size of operation	0.33	Slope=0.000009767 kg $yr^{-1}hd^{-1}$ per head			
		Average pig weight	0.95	Slope=0.000031 kg $yr^{-1}hd^{-1}$ per kg			
$PM_{2.5}$ emission rates in kg $yr^{-1}AU^{-1}$	Individual effect of production stage		<0.01	Finishing	8	0.113^{a,b}	0.060
				Gestation	6	0.038^{a}	0.060
				Farrowing	3	0.150^{b}	0.061
	Four effects	Production stage	<0.01	Finishing	8	0.027^{a,b}	0.140
				Gestation	6	0.037^{a}	0.123
				Farrowing	3	0.242^{b}	0.132
		Manure system	0.44	Deep pit	7	0.116	0.073
				Drain	4	0.061	0.055
				Recharge	6	0.128	0.057
		Size of operation	0.06	Slope=0.000074 kg $yr^{-1}AU^{-1}$ per head			
		Average pig weight	0.96	Slope=-0.00009 kg $yr^{-1}AU^{-1}$ per kg			

[1] n=number of data points.

[a,b,c] Values within the same effect section differ significantly if without common letter ($P < 0.05$).

In the NAEMS sites, uncertainties of PM_{10} emission rates from swine houses were calculated to be 16 to 35% for gestation houses, 30 to 67% for farrowing houses, and 12 to 17% for finishing houses. In literature, the average reported standard deviation for measured PM_{10} emission rates from swine houses was 49% of the mean. The average reported standard deviation for measured $PM_{2.5}$ emission rates from swine houses was 110% of the mean. However, there were larger variations among different studies. For PM_{10} emissions from swine houses, the standard deviation was 100% of the mean emission rate when expressed in kg $yr^{-1}hd^{-1}$. These variations or uncertainties were results of different conditions (prediction variables) in different studies. In the regression model, since effects of significant prediction variables had been accounted, the root mean squared error was reduced to 48% of the mean. For $PM_{2.5}$ emissions from swine houses, the standard deviation was 110% of the mean emission rate when expressed in kg $yr^{-1}hd^{-1}$, while in the regression model, the root mean squared error was reduced to 57% of the mean.

(3) Concentrations

Four studies have been identified that have reported measured PM_{10} concentrations in the vicinity of swine facilities in North America (see Appendix 12). Wing et al (2008) reported the average PM_{10} concentration in 16 neighborhoods within swine production areas was 20.9±5.9 µg m^{-3}. Donham et al (2005) reported PM_{10} concentration (42.25 µg m^{-3}) in the hoop structure area where animals were housed with a medium density level (about 150 head per building) were higher than that in the swine CAFO area (30.28 µg m^{-3}). Martin et al (2006) showed background, non-barn influenced PM_{10} concentrations were around 35 µg m^{-3}, while in-plume values were 40 to 60 µg m^{-3}. Martin et al (2008) showed average near-source increases (~15 to 50 m from swine operation) in ambient PM_{10} concentration was 5.8±2.9 µg m^{-3}, adding ~15% to the prevailing background levels (~37 µg m^{-3}).

Two studies have been identified that have reported measured $PM_{2.5}$ concentrations in the vicinity of swine facilities in North America (see Appendix 12). Martin et al (2006) showed background, non-barn influenced $PM_{2.5}$ concentrations were around 10 µg m^{-3}, while in-plume values were 10 to 15 µg m^{-3}. Martin et al (2008) showed average near-source increases (15 to 50m from swine operation) in ambient $PM_{2.5}$ concentration was 1.7±1.1 µg m^{-3}, adding ~12% to the prevailing background levels (~14 µg m^{-3}).

I. Discussion

Large variations in emission rates among different studies were observed. These variations or uncertainties were results of different conditions (prediction variables) in different studies. The standard deviations of emission rates from different studies were usually close to, or larger than the values of the mean emission rates. Farrowing operations had significant higher emission rates than finishing operations on a per head basis for all the pollutants of interest (NH_3, H_2S, VOCs, PM_{10} and $PM_{2.5}$). Gestation houses had highest NH_3 emission, but their H_2S and VOCs emissions were lower than that from farrowing houses. Manure system in swine house was also a significant factor. Hoop system resulted in higher NH_3 emission rates than other manure systems. Deep pit system resulted in higher H_2S emission rates than pit drain or pit recharge systems. The NH_3 emissions from manure storage were significantly influenced by ambient air temperature and the area of storage per head. Slurry storage had higher H_2S emissions compared with lagoon, especially when emission rates were expressed in kg $yr^{-1}m^{-2}$. The VOCs emissions from swine house were positively related with indoor air temperatures and were negatively related with size of operation, while the VOCs emissions from manure storage were positively related with size of operation.

The EPCRA and CERCLA require reporting of NH_3 and H_2S emissions that exceed 100 lb/day. Efforts to regulate air emissions from agricultural sources have been confounded by a lack of scientific information. Based on results of meta-analysis, sizes of swine farm that may trigger the need to report NH_3 and H_2S emissions under EPCRA and CERCLA were calculated and presented in Tables 38 and 39. Stage of production had significant effects on both NH_3 and H_2S emissions. Based on the main effect means at difference production stages, the sizes that may trigger the need for a farm to report emissions were calculated for finishing, farrowing, gestation, and nursery operations respectively.

Table 38. Sizes of swine farm that may trigger the need to report NH_3 under EPCRA and CERCLA

Scenarios	NH_3 emission rates (kg $yr^{-1}hd^{-1}$)			Sizes that may reach the 100lb NH_3/day threshold
	Swine houses	Manure storage	Total	
Finishing operation	3.23±0.74	4.02±1.12	7.25±1.86	1,819 to 3,074 head
Farrowing operation	6.69±1.62	8.98±1.43	15.67±3.05	885 to 1,313 head
Gestation operation	9.75±1.55	-	-	1,466 to 2,021 head (House only)
Nursery operation	-	3.12±2.49	-	2,954 to 26,303 head (Storage only)
Based on the average emission rates in the NAEMS sites	3.53±2.21	11.82±7.50	15.35±9.71	661 to 2,938 head
Based on the median emission rates in literature	2.78	2.08	4.86	3,410 head
Based on the 75th percentile emission rates in literature	4.49	6.27	10.76	1,540 head
Based on the 90th percentile emission rates in literature	7.17	9.54	16.71	992 head

Table 39. Sizes of swine farm that may trigger the need to report H_2S under EPCRA and CERCLA

Scenarios	H_2S emission rates (kg $yr^{-1}hd^{-1}$)			Sizes that may reach the 100lb H_2S/day threshold
	Swine houses	Manure storage	Total	
Finishing operation	0.108±0.076	0.329±0.111	0.437±0.187	26,556 to 66,284 head
Farrowing operation	1.165±0.214	0.388±0.146	1.553±0.360	8,662 to 13,890 head
Gestation operation	0.787±0.175	-	-	17,226 to 27,077 head (House only)
Nursery operation	0.557±0.413	0.059±0.342	0.616±0.755	>12,087 head
Based on the average emission rates in the NAEMS sites	0.78±1.02	0.39±0.44	1.17±1.46	>6,301 head
Based on the median emission rates in literature	0.09	0.20	0.29	57,141
Based on the 75th percentile emission rates in literature	0.20	0.63	0.83	19,965
Based on the 90th percentile emission rates in literature	0.47	0.83	1.30	12,747

Based on the median NH_3 emission rates in literature, a 3,000 head swine site will normally emit 88 lb/day NH_3, including 50 lb/day from swine houses and 38 lb/day from manure storage facilities. Considering the uncertainties of the data, it should be noted that a 3,000 head swine site has 25% chance to emit NH_3 higher than 195 lb/day and 10% chance to emit NH_3 higher than 302 lb/day. At 90% confidence level, the size that may trigger the need for a farm to report NH_3 emissions under EPCRA is as less as 992 head.

Based on the median H_2S emission rates in literature, a 3,000 head swine site will normally emit 5.2 lb/day H_2S, including 1.6 lb/day from swine houses and 3.6 lb/day from manure storage facilities. Considering the uncertainties of the data, it should be noted that a 3,000 head swine site has 25% chance to emit H_2S higher than 15 lb/day and 10% chance to emit H_2S higher than 24 lb/day. At 90% confidence level, the size that may trigger the need for a farm to report H_2S emissions under EPCRA is 12,747 head.

The Agency for Toxic Substances and Disease Registry (ATSDR) has suggested minimum risk levels (MRLs) for NH_3 and H_2S designed to protect sensitive populations (ATSDR, 2008). The MRLs for NH_3 are 1700 ppb and 100 ppb for an acute (1-14 days continuous) and chronic (>365 days continuous) exposure, respectively. The MRLs for H_2S are 70 ppb and 20 ppb for an acute and intermediate (15-365 days continuous) exposure, respectively.

The average NH_3 concentration at the edge of swine houses or lagoons (5.5±5.2 ppm) is higher than the acute MRL (1700 ppb) for NH_3. But the ambient NH_3 concentrations can decrease quickly to be less than the chronic MRL (100 ppb) as distances from emission sources increase. Stowell et al (2000) reported NH_3 concentration was 100ppb at 30m distance. Hoff et al (2009) reported NH_3 concentration were 55 and 95 ppb at 77 m distance. At the distances from 30 to 1185m from emission sources, the ambient NH_3 concentrations had small variations (Figure 3), and the average NH_3 concentration in literature was 66±66 ppb, which is 66% of the chronic MRL for NH_3. There was only one report of NH_3 concentration higher than 100 ppb in the vicinity of swine facilities (280 ppb at 92 m distance in Hoff et al, 2008).

The average H_2S concentration at the edge of swine houses or lagoons (40±48 ppb) is less than the acute MRL (100 ppb) but higher than the intermediate MRL (20 ppb) for H_2S. But the ambient H_2S concentrations can decrease quickly to be less than 20 ppb as distances from emission sources increase. At the distances from 30 to 1185m from emission sources, the ambient H_2S concentrations decreased gradually (Figure 4), and the average H_2S concentration in literature was 3.1±6.2 ppb, which is only 16% of the intermediate MRL for H_2S. There was only one report of H_2S concentration higher than 20ppb in the vicinity of swine facilities (25 ppb at 500 m distance in O'Shaughnessy et al, 2011).

There are limited data on VOCs emissions from swine operations compared with NH_3 and H_2S. Research on VOCs at swine facilities has demonstrated that it (quantification of VOCs) is technically challenging to measure because of the large number of VOCs compounds and their inherent variation in physicochemical properties (Ni, et al., 2012). At present, safety standard (OSHA, NIOSH) for VOCs are based on exposure to a single compound rather than simultaneous exposure to 300 or more compounds (Schiffman, 2001). More science-based information developed on solid data is needed to support unbiased regulations.

EPA has set National Ambient Air Quality Standards for six criteria pollutants, which include PM10 and PM2.5. Primary standards provide public health protection, including protecting the health of "sensitive" populations such as asthmatics, children, and the elderly. Secondary standards provide public welfare protection, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings. The primary and secondary 24-hour average standards for PM_{10} are both 150 µg m^{-3}. It was reported that average contribution of swine operations in near-source (~15 to 50 m distances) ambient PM_{10} concentration was 5.8±2.9 µg m^{-3}, adding ~15% to the prevailing background levels (~37 µg m^{-3}) (Martin, et al, 2008). The measured ambient PM10 concentrations under influences of swine facilities were only around 14 to 28% of the 24-hour average PM_{10} standard. The primary and secondary 24-hour average standards for $PM_{2.5}$ are both 35 μg m^{-3}. It was reported that average contribution of swine operations in near-source (~15 to 50 m distances) ambient $PM_{2.5}$ concentration was 1.7±1.1 μg m^{-3}, adding ~12% to the prevailing background levels (~14 μg m^{-3}) (Martin, et al, 2008). The measured ambient $PM_{2.5}$ concentrations under influences of swine facilities were only around 28 to 43% of the 24-hour average $PM_{2.5}$ standard. However, the primary and secondary annual average standards for $PM_{2.5}$ are 12 and 15μg m^{-3}, respectively. And the background, non-barn influenced $PM_{2.5}$ concentrations were around 10 μg m^{-3} (Martin et al, 2006). There will be occurrences for ambient $PM_{2.5}$ concentrations to be over the annual average $PM_{2.5}$ standards under constant influences of emissions from swine facilities.

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Appendix

Appendix 1. NH_3 emissions from swine houses

Study	Manure system	Production stage	Pig weight (kg)	Number of pigs	Indoor temperature (^oC)	Ventilation	Measurement Method	Emission rates in kg $yr^{-1}hd^{-1}$		Emission rates in kg $yr^{-1}AU^{-1}$	
								Mean	Std[1]	Mean	Std[1]
IA4B[2]	Deep pit	Gestation	249	1004	17.4	Mechanical	Traditional	10.73	8.43	21.55	16.93
	Deep pit	Gestation	249	1084	17.3	Mechanical	Traditional	6.31	2.85	12.67	5.72
	Pit drain, 3 weeks	Farrowing	233	24	25.2	Mechanical	Traditional	3.65	3.03	7.83	6.50
NC4B[2]	Pit recharge, 2 weeks	Gestation	181	912	22.8	Mechanical	Traditional	2.36	0.92	6.52	2.54
	Pit recharge, 2 weeks	Gestation	181	884	24.6	Mechanical	Traditional	2.99	1.08	8.26	2.98
	Pit recharge, 3 weeks	Farrowing	181	19	25.5	Mechanical	Traditional	2.67	1.51	7.38	4.17
OK4B[2]	Pit drain, 1 week	Gestation	200	1169	22	Mechanical	Traditional	3.38	0.68	8.45	1.70
	Pit drain, 1 week	Gestation	200	1170	22	Mechanical	Traditional	3.51	0.47	8.78	1.18
	Pit drain, 3 weeks	Farrowing	200	24	24	Mechanical	Traditional	0.70	2.19	1.75	5.48
IN3B[2]	Deep pit	Finishing	62.5	902	23	Mechanical	Traditional	3.03	2.37	24.24	18.96
	Deep pit	Finishing	60	974	23	Mechanical	Traditional	2.92	1.64	24.33	13.67
	Deep pit	Finishing	60	1011	22	Mechanical	Traditional	2.45	1.72	20.42	14.33
	Deep pit	Finishing	58.5	1000	24	Mechanical	Traditional	2.63	2.04	22.48	17.44
NC3B[2]	Pit recharge, 1 week	Finishing	62.5	655	23.3	Mechanical	Traditional	2.95	1.94	23.60	15.52
	Pit recharge, 1 week	Finishing	69.5	654	23	Mechanical	Traditional	2.92	0.14	21.01	1.01
	Pit recharge, 1 week	Finishing	69	650	24	Mechanical	Traditional	3.07	0.14	22.25	1.01
James, et al, 2012	Pit recharge, 1 week	Finishing	48.7	885	28	Mechanical	Traditional	1.32	0.32	13.55	3.29
	Pit recharge, 1 week	Finishing	34.6	995	20.7	Mechanical	Traditional	0.78	0.49	11.27	7.08
	Pit recharge, 1 week	Finishing	116.6	476	18.5	Mechanical	Traditional	1.55	1.40	6.65	6.00
	Pit recharge, 1 week	Finishing	50.6	875	25.5	Mechanical	Traditional	1.35	0.61	13.34	6.03
Rahman et al, 2012	Deep pit	Gestation	.	2200	.	Mechanical	Traditional	.	.	4.18	3.54
	Deep pit	Gestation	.	2100	.	Mechanical	Traditional	.	.	11.83	6.52
	Pit drain, 3 weeks	Farrowing	.	416	.	Mechanical	Traditional	.	.	1.96	1.04
	Pit drain, 3 weeks	Farrowing	.	900	.	Mechanical	Traditional	.	.	1.19	0.56
Li, et al, 2011	Dry	Finishing	72	6	22	Mechanical	Traditional	2.69	0.09	18.67	0.63
	Dry	Finishing	72	6	22	Mechanical	Traditional	2.90	0.09	20.15	0.63
	Dry	Finishing	72	6	22	Mechanical	Traditional	3.22	0.09	22.39	0.63
Rahman, et al, 2011	Deep pit	Gestation	.	2100	.	Mechanical	Traditional	.	.	10.57	7.55
	Deep pit	Gestation	.	2100	.	Mechanical	Traditional	.	.	12.08	5.20
	Pit drain, 3 weeks	Farrowing	.	900	.	Mechanical	Traditional	.	.	1.28	0.61
	Pit drain, 3 weeks	Farrowing	.	900	.	Mechanical	Traditional	.	.	1.04	0.47

Lemay, et al., 2010	EDA[3]	Finishing	105	54	20	Mechanical	Traditional	3.71	1.21	17.67	5.76
Pepple, et al, 2010	Deep pit	Finishing	37.1	1858	.	Mechanical	Traditional	1.13	0.06	15.25	0.79
	Deep pit	Finishing	34	1662	.	Mechanical	Traditional	1.68	0.08	24.69	1.23
Sun, et al, 2010	.	Finishing	34.7	512	18.2	Mechanical	Traditional	1.76	0.80	25.29	11.53
	.	Finishing	36.7	512	18.8	Mechanical	Traditional	2.78	0.83	37.89	11.32
Aneja, et al, 2008a	Pit recharge, 1 week	Finishing	104	4392	.	Natural	OP-FTIR	1.64	.	7.89	.
	Pit recharge, 1 week	Finishing	52	7611	.	Mechanical	OP-FTIR	3.45	.	33.15	.
	Pit recharge, 1 week	Finishing	67	5784	.	Mechanical	OP-FTIR	3.77	.	28.10	.
Blunden et al, 2008a	Pit recharge, 1 week	Finishing	57.6	851	19.7	Mechanical	Traditional	1.71	1.12	14.87	9.69
	Pit recharge, 1 week	Finishing	87.8	842	22.3	Mechanical	Traditional	2.38	0.86	13.55	4.91
	Pit recharge, 1 week	Finishing	37.9	896	26	Mechanical	Traditional	0.82	0.42	10.79	5.48
	Pit recharge, 1 week	Finishing	43.2	889	19	Mechanical	Traditional	0.45	0.28	5.22	3.28
Janni, et al, 2008	Deep pit	Finishing	.	2400	.	Mechanical	Traditional	2.60	0.74	.	.
Sun, et al, 2008	.	Finishing	70.9	261	23.1	Mechanical	Traditional	4.50	1.42	31.72	10.04
	.	Finishing	78.3	246	23	Mechanical	Traditional	8.84	1.94	56.47	12.37
	.	Finishing	53.9	257	18.8	Mechanical	Traditional	1.59	0.60	14.78	5.58
	.	Finishing	59.5	240	17.9	Mechanical	Traditional	4.48	0.63	37.67	5.29
	.	Finishing	66.3	264	16.4	Mechanical	Traditional	3.94	0.67	29.71	5.04
	.	Finishing	69.4	257	16.7	Mechanical	Traditional	4.42	0.43	31.83	3.07
Jacobson, et al, 2007a	Deep pit	Finishing	.	2400	.	Mechanical	Traditional	3.23	0.26	.	.
Hoff, et al, 2006	Deep pit	Finishing	58.9	1000	8	Mechanical	Traditional	1.73	0.69	14.69	5.83
	Deep pit	Finishing	58.9	1000	8	Mechanical	Traditional	2.12	1.21	18.04	10.29
	Deep pit	Finishing	52.5	1000	8	Mechanical	Traditional	1.44	0.41	13.67	3.90
	Deep pit	Finishing	52.5	1000	8	Mechanical	Traditional	2.56	1.24	24.36	11.81
	Deep pit	Finishing	103.5	1000	8	Mechanical	Traditional	3.38	0.95	16.34	4.59
	Deep pit	Finishing	103.5	1000	8	Mechanical	Traditional	4.64	2.41	22.41	11.65
	Deep pit	Finishing	83.25	1000	8	Mechanical	Traditional	4.98	2.52	29.91	15.12
	Deep pit	Finishing	83.25	1000	8	Mechanical	Traditional	7.39	3.07	44.40	18.42
Martin, et al, 2006	Deep pit	Finishing	90	3750	.	Natural	Inverse-dispersion	6.29	2.63	34.92	14.60
Powers, et al, 2005	Dry	Finishing	68	6	22	Mechanical	Traditional	2.41	0.08	17.71	0.58
	Dry	Finishing	68	6	22	Mechanical	Traditional	1.89	0.08	13.91	0.58
	Dry	Finishing	68	6	22	Mechanical	Traditional	1.31	0.08	9.66	0.58
Jacobson, et al, 2005	Dry	Gestation	.	.	.	.	Traditional	.	.	7.30	.
	Dry	Gestation	.	.	.	.	Traditional	.	.	10.04	.
Heber, et al,	Pit recharge, daily	Finishing	82	1051	22.7	Mechanical	Traditional	3.73	0.53	22.74	3.24

2004	Pit recharge, daily	Finishing	78.3	1062	21.7	Mechanical	Traditional	2.81	0.31	17.92	1.98
	Pit recharge, daily	Finishing	55.1	1133	22.7	Mechanical	Traditional	2.40	0.32	21.79	2.93
	Pit recharge, daily	Finishing	57	1128	21.7	Mechanical	Traditional	1.91	0.28	16.79	2.48
	Pit recharge, daily	Finishing	55.1	1091	22.7	Mechanical	Traditional	1.77	0.14	16.10	1.31
	Pit recharge, daily	Finishing	57	1105	21.7	Mechanical	Traditional	1.45	0.18	12.70	1.56
	Pit recharge, daily	Finishing	61	1130	22.7	Mechanical	Traditional	2.04	0.17	16.72	1.41
	Pit recharge, daily	Finishing	60.8	1116	21.7	Mechanical	Traditional	1.65	0.15	13.54	1.20
	Pit recharge, daily	Finishing	90.8	779	15	Mechanical	Traditional	1.20	.	6.63	.
	Pit recharge, daily	Finishing	59.7	881	15	Mechanical	Traditional	2.56	.	21.40	.
Harper, et al, 2004a	Pit recharge, 1 week	Farrowing	208.8	884	25	Mechanical	Traditional	0.33	.	0.79	.
Lim, et al, 2004	Pit drain, daily	Finishing	78	25	22	Mechanical	Traditional	0.86	0.18	5.52	1.12
	Pit drain, 1 week	Finishing	85	25	24	Mechanical	Traditional	1.59	0.16	9.36	0.94
	Pit drain, 2 weeks	Finishing	88	25	24	Mechanical	Traditional	1.50	0.10	8.54	0.58
	Pit recharge, 1 week	Finishing	83	25	20	Mechanical	Traditional	0.63	0.20	3.78	1.23
	Pit recharge, 2 weeks	Finishing	86	25	21	Mechanical	Traditional	0.79	0.12	4.58	0.68
	Pit recharge, 6 weeks	Finishing	97	25	21	Mechanical	Traditional	0.82	0.07	4.21	0.38
Jacobson, et al, 2003	Hoop	Finishing	82	180	.	Mechanical	Traditional	12.30	6.31	74.99	38.46
	Deep pit	Finishing	105	950	.	Mechanical	Traditional	0.63	0.19	3.00	0.90
	Hoop	Finishing	107	180	.	Mechanical	Traditional	13.56	14.19	63.37	66.31
	Deep pit	Finishing	68	1000	.	Mechanical	Traditional	1.89	1.89	13.91	13.91
Schmidt et al, 2002	Deep pit	Finishing	102	1000	.	Mechanical	Traditional	0.49	.	2.39	.
	Deep pit	Finishing	70	1033	.	Natural	Traditional	3.37	.	24.10	.
Harris et al, 2002	Pit recharge	Finishing	32	949		Mechanical	Traditional	4.80	1.46	75.01	22.84
	Pit recharge	Finishing	75.6	920		Mechanical	Traditional	3.44	0.83	22.77	5.48
	Pit recharge	Finishing	103.6	631		Mechanical	Traditional	6.87	4.22	33.15	20.37
Zahn et al, 2001a	Deep pit	Finishing		13680		.	.	2.71	.	.	.
Heber, et al, 2000a	Deep pit	Finishing	72.5	865	8.4	Mechanical	Traditional	5.10	0.30	35.19	2.04
	Deep pit	Finishing	73.2	872	8.4	Mechanical	Traditional	6.94	0.69	47.41	4.75
	Deep pit	Finishing	78.2	868	12	Mechanical	Traditional	4.22	0.14	27.01	0.91
	Deep pit	Finishing	79	866	12	Mechanical	Traditional	5.44	0.21	34.42	1.31
	Deep pit	Finishing	72.5	892	21.9	Mechanical	Traditional	5.64	0.33	38.91	2.26
	Deep pit	Finishing	73.2	887	21.9	Mechanical	Traditional	7.84	0.53	53.55	3.65
	Deep pit	Finishing	78.2	876	20	Mechanical	Traditional	5.31	0.58	33.95	3.69
	Deep pit	Finishing	79	867	20	Mechanical	Traditional	7.02	0.70	44.46	4.45
Ni et al, 2000a	Deep pit	Finishing	47.3	881	25.2	Mechanical	Traditional	5.01	0.35	52.93	3.65

Stowell, et al, 2000	Dry	Finishing	60	960	21.6	Mechanical	Traditional	14.90	.	124.20	.
Zhu, et al, 2000	Deep pit	Finishing	109.1	400	18.1	Natural	Traditional	3.60	.	16.52	.
	Deep pit	Finishing	81.8	550	14.4	Mechanical	Traditional	0.81	.	4.96	.
	Deep pit	Gestation	204.5	550	22.2	Mechanical	Traditional	0.51	.	1.25	.
	Deep pit	Farrowing	204.5	26	22.1	Mechanical	Traditional	7.03	.	17.18	.
	Deep pit	Nursery	20.5	475	27.3	Mechanical	Traditional	0.66	.	16.04	.
Ni et al, 2000b	Deep pit	Finishing	88.1	858	19.9	Mechanical	Traditional	2.60	0.07	14.78	0.41
	Deep pit	Finishing	84.2	870	19.9	Mechanical	Traditional	1.87	0.05	11.12	0.30
Harris et al, 1998	Pit recharge	Finishing	.	.	.	Mechanical	Traditional	3.69	1.03	.	.
Heber et al, 1997	Deep pit	Finishing	.	.	.	Natural	Traditional	.	.	12.41	.
Collins, 1990	Pit recharge	Gestation	.	366	.	Mechanical	Traditional	31.60	.	.	.
	Pit recharge	Gestation	.	450	.	Natural	Traditional	21.50	.	.	.
	Pit recharge	Farrowing	.	20	.	Mechanical	Traditional	20.40	.	.	.
	Pit recharge	Nursery	.	380	.	Mechanical	Traditional	0.86	.	.	.
	Pit recharge	Finishing	126	380	.	Mechanical	Traditional	5.40	.	21.43	.

[1] Standard deviation.
[2] Codes of NAEMS sites. Data was adapted from the NAEMS report (2007-2009). Available at http://www.epa.gov/airquality/agmonitoring/data.html.
[3] Enclosed dunging area.

Appendix 2. NH_3 emissions from swine manure storage facilities

Study	Storage type	Production stage	Area (m^2)	Number of pigs	Ambient temperature (°C)	Measurement method	Emission rates in kg $yr^{-1}hd^{-1}$		Emission rates in kg $yr^{-1}m^{-2}$	
							Mean	Std[1]	Mean	Std[1]
IN4A[2]	Lagoon	Farrowing	11240	1400	11.33	RPM	15.23	.	1.90	.
NC4A[2]	Lagoon	Farrowing	29193	2000	18.07	RPM	12.92	.	0.89	.
OK4A[2]	Lagoon	Farrowing	22486	2784	12.88	RPM	23.23	.	2.88	.
IA3A[2]	Lagoon	Finishing	2363	3840	9.72	RPM	4.48	.	7.28	.
NC3A[2]	Lagoon	Finishing	18986	8000	15.1	RPM	2.66	.	1.12	.
OK3A[2]	Lagoon	Finishing	11203	3024	13.05	RPM	12.41	.	3.35	.
James, et al, 2012	Lagoon	Finishing	17150	7000	21.6	Chamber	6.17	.	2.52	.
	Lagoon	Finishing	17150	7000	14.8	Chamber	2.16	.	0.88	.
	Lagoon	Finishing	17150	7000	8.4	Chamber	1.53	0.33	0.63	0.13
	Lagoon	Finishing	17150	7000	16.2	Chamber	2.57	0.57	1.05	0.23
Aneja, et al, 2008b	Slurry	Finishing	307.7	3519	17.2	Chamber	0.13	.	1.46	.
	Slurry	Finishing	307.7	3138	14.2	Chamber	0.03	.	0.29	.
	Slurry	Finishing	17.4	2390	14.9	Chamber	0.01	.	1.60	.
	Slurry	Finishing	17.4	3113	31.6	Chamber	0.00	.	0.47	.
Aneja, et al, 2008a	Lagoon	Finishing	17150	4392	26.5	Chamber	5.86	2.46	1.50	0.63
	Lagoon	Finishing	17150	3727	7.2	Chamber	0.45	0.15	0.10	0.03
	Lagoon	Finishing	17150	7611	25	Chamber	2.42	0.74	1.08	0.33
	Lagoon	Finishing	17150	5784	7.2	Chamber	0.70	0.28	0.24	0.09
Blunden and Aneja, 2008a	Lagoon	Finishing	17150	7000	18.2	Chamber	2.56	0.79	1.04	0.32
	Lagoon	Finishing	17150	7000	11.5	Chamber	2.02	0.38	0.82	0.16
	Lagoon	Finishing	17150	7000	15.1	Chamber	3.90	.	1.59	.
	Lagoon	Finishing	17150	7000	29.7	Chamber	6.71	.	2.74	.
Szögi and Vanotti, 2007	Lagoon	Finishing	9200	4360	26	Micrometeorological	7.38	1.33	3.50	0.63
	Lagoon	Finishing	9300	4360	26	Micrometeorological	2.10	0.88	0.98	0.41
	Lagoon	Finishing	9200	4359	6	Micrometeorological	0.91	0.60	0.43	0.28
	Lagoon	Finishing	9300	4359	4	Micrometeorological	0.63	0.51	0.30	0.24
Szögi et al, 2006	Lagoon	Finishing	9200	4360	6.6	Micrometeorological	0.22	0.14	0.11	0.07
	Lagoon	Finishing	9000	4360	6.2	Micrometeorological	0.66	0.48	0.32	0.23
	Lagoon	Finishing	9200	4360	23.6	Micrometeorological	0.73	0.48	0.35	0.23
	Lagoon	Finishing	9000	4360	23.6	Micrometeorological	5.75	0.99	2.78	0.48
Pelletier, et al, 2006	Slurry	Finishing	731	800	15	Chamber	0.48	.	0.53	.
Shore, et al, 2005	Lagoon	Finishing	3000	980	28	OP-FTIR	16.09	0.80	5.26	0.26
	Lagoon	Finishing	3000	980	24	OP-FTIR	4.18	0.37	1.37	0.12

	Lagoon	Finishing	3000	980	10	OP-FTIR	1.38	0.11	0.45	0.04
	Lagoon	Finishing	3000	980	26	OP-FTIR	0.93	.	0.30	.
	Lagoon	Finishing	3000	980	28	OP-FTIR	1.93	0.12	0.63	0.04
Bicudo, et al, 2004	Slurry	Nursery	2482	8000	19.7	Chamber	1.02	0.01	3.28	0.03
	Slurry	Finishing	3772	2000	19.7	Chamber	5.95	0.07	3.15	0.04
	Slurry	Finishing	3431	3000	19.7	Chamber	3.50	0.04	3.06	0.04
	Slurry	Finishing	9685	13000	17.1	Chamber	2.51	0.03	3.37	0.03
	Slurry	Finishing	9685	13000	17.1	Chamber	1.79	0.03	2.40	0.03
	Slurry	Finishing	9685	13000	18.7	Chamber	0.99	0.03	1.32	0.03
	Slurry	Finishing	9685	13000	18.7	Chamber	0.54	0.03	0.73	0.03
Funk, et al, 2004	Lagoon	Finishing	1131	560	19.6	Chamber	0.00	0.00	0.00	0.00
Harper, et al, 2004b	Lagoon	Finishing	21760	1200	15	Micrometeorological	1.10	.	0.06	.
	Lagoon	Farrowing	25650	2000	17.5	Micrometeorological	0.80	.	0.06	.
Smith, et al., 2004	Slurry	Nursery	2.28	6	.	Chamber	0.36	.	0.95	.
	Slurry	Nursery	2.28	6	.	Chamber	0.17	.	0.46	.
	Slurry	Nursery	2.28	6	.	Chamber	0.27	.	0.71	.
Lim, et al, 2003	Lagoon	Farrowing	30735	20000	27	Chamber	7.12	0.68	4.64	0.44
	Lagoon	Farrowing	12310	2900	29	Chamber	7.36	5.01	1.73	1.18
Liang, et al, 2002	Lagoon	.	.	10102	.	Chamber	2.42	.	.	.
Miner, et al, 2002	Lagoon	Finishing	2000	1224	24	OP-FTIR	9.02	.	5.52	.
	Lagoon	Finishing	2000	1224	24	OP-FTIR	2.06	.	1.26	.
	Lagoon	Finishing	2000	1224	24	OP-FTIR	0.26	.	0.16	.
Zahn, et al, 2002	Lagoon	Finishing	7800	3747	.	Micrometeorological	8.12	5.30	3.90	2.55
Harris et al, 2002	Lagoon	Finishing	3000	2500	.	OP-FTIR	1.96	1.69	1.63	1.40
Aneja, et al, 2001	Lagoon	Nursery	1214	1450	12.5	Chamber	0.02	.	0.03	.
	Lagoon	Finishing	4905	4400	17.8	Chamber	0.09	.	0.08	.
Zahn, et al, 2001a	Slurry	Finishing	.	8200	.	Chamber	6.31	.	.	.
	Lagoon	Finishing	.	14170	.	Chamber	6.00	.	.	.
	Lagoon	Finishing	.	18500	.	Chamber	7.28	.	.	.
Zahn et al, 2001b	Lagoon	Finishing	7800	3747	2.2	Micrometeorological	11.82	0.46	5.68	0.22
	Lagoon	Finishing	7800	3747	2.2	Micrometeorological	10.77	0.39	5.17	0.19
Todd et al, 2001	Lagoon	.	.	.	.	OP-FTIR	.	.	1.22	.
	Lagoon	.	.	.	.	OP-FTIR	.	.	3.05	.
Aneja, et al, 2000	Lagoon	Finishing	25000	10000	30	Chamber	6.41	1.57	2.56	0.63
	Lagoon	Finishing	25000	10000	11.6	Chamber	1.35	0.64	0.54	0.26

	Lagoon	Finishing	25000	10000	12.1	Chamber	0.49	0.25	0.19	0.10
	Lagoon	Finishing	25000	10000	24.7	Chamber	2.72	0.88	1.09	0.35
Harper, et al, 2000	Lagoon	Finishing	96000	12000	21.4	Micrometeorological	3.52	4.91	0.44	0.61
Heber et al, 2000b	Lagoon	Farrowing	30735	20000	27	Chamber	7.14	2.58	4.65	1.68
	Lagoon	Farrowing	12310	2900	29	Chamber	7.30	4.48	1.72	1.06
Lim, et al, 2000	Lagoon	Farrowing	.	5800	24.7	Chamber	.	.	4.54	.
	Lagoon	Farrowing	12130	2900	28	Chamber	6.86	.	1.64	.
McCulloch et al, 1999	Lagoon	.	.	.	.	Inverse-dispersion	1.70	.	.	.
Harper and Sharpe, 1998	Lagoon	Finishing	26700	13685	.	Micrometeorological	0.75	.	0.47	.
	Lagoon	Farrowing	23700	4304	.	Micrometeorological	1.25	.	0.27	.
	Lagoon	Finishing	97600	12036	.	Micrometeorological	0.86	.	0.13	.

[1] Standard deviation.

[2] Codes of NAEMS sites. Data was adapted from the NAEMS report (2007-2009). Available at http://www.epa.gov/airquality/agmonitoring/data.html.

Appendix 3. NH_3 concentrations in the vicinity of swine facilities

Study	Production stage	Number of pigs	Ambient temperature (°C)	Location	Distance (m)	Concentration (ppb) Mean	Concentration (ppb) Std[1]
Godbout et al, 2009	.	.	.	Background not within swine production areas	.	7.1	.
	.	.	.	Background not within swine production areas	.	6.9	.
	.	.	.	Background not within swine production areas	.	12.6	.
	.	.	.	Neighborhood within swine production areas	.	8.9	.
	.	.	.	Neighborhood within swine production areas	.	11.1	.
	.	.	.	Neighborhood within swine production areas	.	18.3	.
Hoff et al, 2009	Finishing	1800-4000	.	Residence	365	28.6	12.8
	Finishing	1800-4000	.	Ambient	365	11.7	5.3
	Finishing	1800-4000	.	Residence	1185	85.7	15.3
	Finishing	1800-4000	.	Ambient	1185	18.1	4.1
	Finishing	1800-4000	.	Residence	655	57.8	16
	Finishing	1800-4000	.	Ambient	655	49.8	31.4
	Finishing	1800-4000	.	Residence	77	94.7	28.1
	Finishing	1800-4000	.	Ambient	77	55.1	20.6
	Finishing	1800-4000	.	Residence	>8000	36	6.9
	Finishing	1800-4000	.	Ambient	>8000	24.1	4
	Finishing	1200	.	Driveway of the residence	92	22	17
	Finishing	1200	.	Basement	92	280	421
	Finishing	1200	.	Living room	92	98	93
Walker et al, 2008	Finishing	4900	25.1	.	10	244	.
	Finishing	4900	25.1	.	612	10.2	.
	Finishing	4900	25.1	.	698	18.7	.
Donham et al, 2006	.	.	.	Neighborhood in CAFO area	.	5.01	.
	.	.	.	Neighborhood in hoop structure area	.	12.78	.
	.	.	.	Background	.	4.27	.
Lim et al, 2003	Farrowing	20000	27	Lagoon berm	1	5909	865
	Farrowing	2900	29	Lagoon berm	1	4900	1009
Childers et al, 2001	Farrowing	7920	12.8	Around the barn	1	328	44
	Farrowing	7920	12.8	Downwind of fan	1	2063	140
	Farrowing	7920	12.8	Besides the lagoon	1	488	110
	Farrowing	7920	12.8	Besides the lagoon	1	722	659
Zahn et al, 2001a	Finishing	13680	.	.	1	13868	.
	Finishing	8200	.	.	1	11418	.
	Finishing	14170	.	.	1	13492	.
	Finishing	18500	.	.	1	15626	.

Stowell et al, 2000	Finishing	960	16.5±9.1	Downwind	3	1800	.
	Finishing	960	16.5±9.1	Downwind	15.2	300	.
	Finishing	960	16.5±9.1	Downwind	30.5	100	.
Lim et al, 2000	.	5800	.	Besides the lagoon	1	6100	.
	.	2900	.	Besides the lagoon	1	5400	.

[1] Standard deviation.

Appendix 4. H_2S emissions from swine houses

Study	Manure system	Production stage	Pig weight (kg)	Number of pigs	Indoor temperature (°C)	Ventilation	Measurement Method	Emission rates in kg $yr^{-1}hd^{-1}$		Emission rates in kg $yr^{-1}AU^{-1}$	
								Mean	Std[1]	Mean	Std[1]
IA4B[2]	deep pit	Gestation	249	1004	17.4	Mechanical	Traditional	3.120	2.060	6.265	4.137
	deep pit	Gestation	249	1084	17.3	Mechanical	Traditional	1.880	1.180	3.775	2.369
	Pit drain, 3 weeks	Farrowing	233	24	25.2	Mechanical	Traditional	1.370	2.570	2.940	5.515
NC4B[2]	Pit recharge, 2 weeks	Gestation	181	912	22.8	Mechanical	Traditional	0.120	0.100	0.331	0.276
	Pit recharge, 2 weeks	Gestation	181	884	24.6	Mechanical	Traditional	0.100	0.090	0.276	0.249
	Pit recharge, 3 weeks	Farrowing	181	19	25.5	Mechanical	Traditional	2.790	1.880	7.707	5.193
OK4B[2]	Pit drain, 1 week	Gestation	200	1169	22	Mechanical	Traditional	0.270	0.070	0.675	0.175
	Pit drain, 1 week	Gestation	200	1170	22	Mechanical	Traditional	0.280	0.060	0.700	0.150
	Pit drain, 3 weeks	Farrowing	200	24	24	Mechanical	Traditional	1.380	1.140	3.450	2.850
IN3B[2]	deep pit	Finishing	62.5	902	23	Mechanical	Traditional	0.190	0.380	1.520	3.040
	deep pit	Finishing	60	974	23	Mechanical	Traditional	0.250	0.380	2.083	3.167
	deep pit	Finishing	60	1011	22	Mechanical	Traditional	0.150	0.210	1.250	1.750
	deep pit	Finishing	58.5	1000	24	Mechanical	Traditional	0.310	0.430	2.650	3.675
NC3B[2]	Pit recharge, 1 week	Finishing	62.5	655	23.3	Mechanical	Traditional	0.090	0.090	0.720	0.720
	Pit recharge, 1 week	Finishing	69.5	654	23	Mechanical	Traditional	0.100	0.100	0.719	0.719
	Pit recharge, 1 week	Finishing	69	650	24	Mechanical	Traditional	0.110	0.090	0.797	0.652
Rahman et al., 2012	Deep pit	Gestation	.	2200	.	Mechanical	Traditional	.	.	0.866	1.000
	Deep pit	Gestation	.	2100	.	Mechanical	Traditional	.	.	1.721	1.095
	Pit drain, 3 weeks	Farrowing	.	416	.	Mechanical	Traditional	.	.	0.271	0.142
	Pit drain, 3 weeks	Farrowing	.	900	.	Mechanical	Traditional	.	.	0.149	0.073
Li, et al., 2011	Dry	Finishing	72	24	22.0	Mechanical	Traditional	0.022	0.003	0.150	0.022
	Dry	Finishing	72	24	22.0	Mechanical	Traditional	0.028	0.003	0.195	0.022
	Dry	Finishing	72	24	22.0	Mechanical	Traditional	0.020	0.003	0.136	0.022
Rahman, et al., 2011	Deep pit	Gestation	.	2100	.	Mechanical	Traditional	.	.	1.186	.
	Deep pit	Gestation	.	2100	.	Mechanical	Traditional	.	.	2.040	.
	.	Farrowing	.	900	.	Mechanical	Traditional	.	.	0.157	.
	.	Farrowing	.	900	.	Mechanical	Traditional	.	.	0.131	.
Pepple, et al., 2010	Deep pit	Finishing	37	1858	.	Mechanical	Traditional	0.037	0.002	0.502	0.025
	Deep pit	Finishing	34	1662	.	Mechanical	Traditional	0.068	0.003	1.004	0.043
Sun, et al., 2010		Finishing	35	512	18.2	Mechanical	Traditional	0.038	0.053	0.548	0.767
		Finishing	37	512	18.8	Mechanical	Traditional	0.043	0.048	0.584	0.657
Blunden et al., 2008a	Pit recharge, 1 week	Finishing	58	851	19.7	Mechanical	Traditional	0.177	0.089	1.534	0.774
	Pit recharge, 1 week	Finishing	88	842	22.3	Mechanical	Traditional	0.209	0.062	1.187	0.351
	Pit recharge, 1 week	Finishing	38	896	26.0	Mechanical	Traditional	0.033	0.020	0.441	0.263

	Pit recharge, 1 week	Finishing	43	889	19.0	Mechanical	Traditional	0.055	0.017	0.632	0.200
Sun et al, 2008	.	Finishing	71	261	23.1	Mechanical	Traditional	0.201	0.068	1.416	0.482
	.	Finishing	78	246	23.0	Mechanical	Traditional	0.292	0.126	1.865	0.807
	.	Finishing	58	257	18.8	Mechanical	Traditional	0.028	0.014	0.245	0.124
	.	Finishing	63	240	17.9	Mechanical	Traditional	0.089	0.029	0.701	0.230
	.	Finishing	66	264	16.4	Mechanical	Traditional	0.116	0.031	0.876	0.234
	.	Finishing	69	257	16.7	Mechanical	Traditional	0.161	0.042	1.157	0.299
Janni, et al., 2008	Deep pit	Finishing	.	2400	.	Mechanical	Traditional	0.091	0.013	.	.
Jacobson, et al., 2007a	Deep pit	Finishing	.	2400	.	Mechanical	Traditional	0.089	.	.	.
Hoff, et al., 2006	Deep pit	Finishing	59	1000	8.0	Mechanical	Traditional	0.088	0.069	0.750	0.583
	Deep pit	Finishing	59	1000	8.0	Mechanical	Traditional	0.024	0.042	0.200	0.356
	Deep pit	Finishing	53	1000	8.0	Mechanical	Traditional	0.168	0.099	1.595	0.941
	Deep pit	Finishing	53	1000	8.0	Mechanical	Traditional	0.009	0.005	0.081	0.050
	Deep pit	Finishing	104	1000	8.0	Mechanical	Traditional	0.185	0.213	0.895	1.027
	Deep pit	Finishing	104	1000	8.0	Mechanical	Traditional	0.028	0.014	0.136	0.066
	Deep pit	Finishing	83	1000	8.0	Mechanical	Traditional	0.477	0.232	2.865	1.395
	Deep pit	Finishing	83	1000	8.0	Mechanical	Traditional	0.039	0.020	0.236	0.122
Powers, et al., 2005	Dry	Finishing	68	6	22.0	Mechanical	Traditional	0.010	0.002	0.070	0.013
	Dry	Finishing	68	6	22.0	Mechanical	Traditional	0.011	0.002	0.080	0.013
	Dry	Finishing	68	6	22.0	Mechanical	Traditional	0.013	0.002	0.094	0.013
Jacobson, et al., 2005	dry	Gestation	.	.	.	.	Traditional	.	.	0.730	.
Heber, et al., 2004	Pit recharge, daily	Finishing	82	1051	22.7	Mechanical	Traditional	0.080	0.010	0.489	0.058
	Pit recharge, daily	Finishing	78	1062	21.7	Mechanical	Traditional	0.072	0.009	0.460	0.058
	Pit recharge, daily	Finishing	55	1133	22.7	Mechanical	Traditional	0.014	0.007	0.128	0.062
	Pit recharge, daily	Finishing	57	1128	21.7	Mechanical	Traditional	0.020	0.007	0.179	0.066
	Pit recharge, daily	Finishing	55	1091	22.7	Mechanical	Traditional	0.032	0.014	0.292	0.124
	Pit recharge, daily	Finishing	57	1105	21.7	Mechanical	Traditional	0.038	0.008	0.332	0.073
	Pit recharge, daily	Finishing	61	1130	22.7	Mechanical	Traditional	0.032	.	0.263	.
Lim, et al., 2004	Pit drain, daily	Finishing	78	25	22.0	Mechanical	Traditional	0.026	0.004	0.168	0.028
	Pit drain, 1 week	Finishing	85	25	24.0	Mechanical	Traditional	0.016	0.004	0.094	0.026
	Pit drain, 2 weeks	Finishing	88	25	24.0	Mechanical	Traditional	0.026	0.004	0.149	0.025
	Pit recharge, 1 week	Finishing	83	25	20.0	Mechanical	Traditional	0.010	0.009	0.062	0.053
	Pit recharge, 2 weeks	Finishing	86	25	21.0	Mechanical	Traditional	0.022	0.007	0.127	0.042
	Pit recharge, 6 weeks	Finishing	97	25	21.0	Mechanical	Traditional	0.108	0.028	0.557	0.143
Jacobson, et al., 2003	Hoop	Finishing	82	180	.	Mechanical	Traditional	0.012	0.012	0.075	0.071
	Deep pit	Finishing	105	950	.	Mechanical	Traditional	0.007	0.003	0.032	0.015

	Hoop	Finishing	107	180	.	Mechanical	Traditional	0.017	0.025	0.081	0.116
	Deep pit	Finishing	68	1000	.	Mechanical	Traditional	0.061	0.069	0.448	0.506
Ni, et al., 2002	Deep pit	Finishing	51	887	21.8	Mechanical	Traditional	0.308	0.041	3.015	0.402
Schmidt, 2002	Deep pit	Finishing	102	1000	.	Mechanical	Traditional	0.001	.	0.003	.
Zahn et al, 2001a	Deep pit	Finishing	.	13680	.	.	.	0.016	.	0.621	.
Zhu et al, 2000	Deep pit	Finishing	109	400	18.1	Natural	Traditional	0.360	.	1.652	.
	Deep pit	Finishing	82	550	14.4	Mechanical	Traditional	0.239	.	1.459	.
	Deep pit	Gestation	205	550	22.2	Mechanical	Traditional	0.128	.	0.313	.
	Deep pit	Farrowing	205	26	22.1	Mechanical	Traditional	1.065	.	2.604	.
	Deep pit	Nursery	21	475	27.3	Mechanical	Traditional	0.455	.	11.089	.
Ni et al, 2000b	Deep pit	Finishing	88	858	19.9	Mechanical	Traditional	0.123	0.019	0.695	0.110
	Deep pit	Finishing	84	870	19.9	Mechanical	Traditional	0.076	0.006	0.448	0.036
Ni et al, 1998	.	Finishing	.	.	.	Natural	Traditional	.	.	0.214	0.021
	.	Finishing	.	.	.	Natural	Traditional	.	.	0.003	.
Heber et al, 1997	Deep pit	Finishing	.	.	.	Natural	Traditional	.	.	0.307	.

[1] Standard deviation.

[2] Codes of NAEMS sites. Data was adapted from the NAEMS report (2007-2009). Available at http://www.epa.gov/airquality/agmonitoring/data.html.

Appendix 5. H_2S emissions from swine manure storage facilities

Study	Storage type	Production stage	Area (m^2)	Number of pigs	Ambient temperature (^oC)	Measurement method	Emission rates in kg $yr^{-1}hd^{-1}$		Emission rates in kg $yr^{-1}m^{-2}$	
							Mean	Std[1]	Mean	Std[1]
IN4A[2]	Lagoon	Farrowing	11240	1400	11.33	bLS	0.104	.	0.013	.
NC4A[2]	Lagoon	Farrowing	29193	2000	18.07	bLS	0.055	.	0.004	.
OK4A[2]	Lagoon	Farrowing	22486	2784	12.88	bLS	1.101	.	0.136	.
IA3A[2]	Lagoon	Finishing	2363	3840	9.72	bLS	0.209	.	0.340	.
NC3A[2]	Lagoon	Finishing	18986	8000	15.1	bLS	0.091	.	0.038	.
OK3A[2]	Lagoon	Finishing	11203	3024	13.05	bLS	0.760	.	0.205	.
O'Shaughnessy and Altmaier, 2011	Lagoon	Finishing	.	.	.	Inverse-dispersion	.	.	0.017	.
	Lagoon	Finishing	.	.	.	Inverse-dispersion	.	.	0.015	.
	Lagoon	Finishing	.	.	.	Inverse-dispersion	.	.	0.009	.
	Lagoon	Farrowing	.	.	.	Inverse-dispersion	.	.	0.032	.
Blunden and Aneja, 2008a	Lagoon	Finishing	17150	7000	18.2	Chamber	0.000	0.000	0.000	0.000
	Lagoon	Finishing	17150	7000	11.5	Chamber	0.000	0.000	0.000	0.000
	Lagoon	Finishing	17150	7000	15.1	Chamber	0.001	0.001	0.000	0.001
	Lagoon	Finishing	17150	7000	29.7	Chamber	0.007	0.004	0.003	0.002
Bicudo, et al., 2004	Slurry	Nursery	2482	8000	19.7	Chamber	0.204	0.013	0.656	0.041
	Slurry	Finishing	3772	2000	19.7	Chamber	1.329	0.080	0.705	0.043
	Slurry	Finishing	3431	3000	19.7	Chamber	0.628	0.050	0.549	0.044
	Slurry	Finishing	9685	13000	17.9	Chamber	0.150	0.028	0.202	0.038
	Slurry	Finishing	9685	13000	17.9	Chamber	0.043	0.030	0.057	0.040
Funk, et al, 2004	Lagoon	Finishing	1131	560	19.6	Chamber	0.007	0.003	0.003	0.002
Lim, et al, 2003	Lagoon	Farrowing	30735	20000	27	Chamber	0.441	0.039	0.287	0.025
	Lagoon	Farrowing	12310	2900	29	Chamber	0.308	0.535	0.073	0.126
Zahn et al, 2002	Lagoon	Finishing	7800	3747	.	Micrometeorological	0.709	0.361	0.341	0.173
Zahn, et al, 2001a	Slurry	Finishing	.	8200	.	Chamber	0.040	.	.	.
	Lagoon	Finishing	.	14170	.	Chamber	0.018	.	.	.
	Lagoon	Finishing	.	18500	.	Chamber	0.020	.	.	.
Zahn et al, 2001b	Lagoon	Finishing	7800	3747		Micrometeorological	0.762	0.020	0.366	0.009
	Lagoon	Finishing	7800	3747	.	Micrometeorological	0.748	0.020	0.360	0.009
Heber et al, 2000b	Lagoon	Farrowing	30735	20000	.	Chamber	0.444	0.136	0.289	0.088
	Lagoon	Farrowing	12310	2900	.	Chamber	0.312	0.867	0.074	0.204
Lim, et al, 2000	Lagoon	Farrowing	.	5800	24.7	Chamber	.	.	0.290	.
	Lagoon	Farrowing	12310	2900	28	Chamber	0.330	.	0.079	.

[1] Standard deviation.
[2] Codes of NAEMS sites. Data was adapted from the NAEMS report (2007-2009). Available at http://www.epa.gov/airquality/agmonitoring/data.html.

Appendix 6. H_2S concentrations in the vicinity of swine facilities

Study	Production stage	Number of pigs	Ambient temperature (^oC)	Location	Distance (m)	Concentration (ppb)	
						Mean	Std[1]
O'Shaughnessy et al, 2011	Finishing	.	.	Downwind	6000	2.0	.
	Finishing	.	.	Downwind	500	25.0	.
Godbout et al, 2009	.	.	.	Background not within swine production areas	.	1.1	.
	.	.	.	Background not within swine production areas	.	1.4	.
	.	.	.	Background not within swine production areas	.	1.5	.
	.	.	.	Neighborhood within swine production areas	.	1.1	.
	.	.	.	Neighborhood within swine production areas	.	1.3	.
	.	.	.	Neighborhood within swine production areas	.	1.6	.
Hoff et al, 2009	Finishing	3176	.	deep-pit	1	9.5	15.1
	Finishing	1929	.	earthen basin	1	7.1	9.3
	Finishing	2894	.	concrete basin + earthen basin	1	26.3	32.3
	Finishing	1882	.	deep-pit + concrete basin	1	3.7	4.9
	Finishing	3812	.	concrete basin	1	4.7	6.5
	Finishing	2510	.	deep-pit	1	4.5	7.2
	Finishing	1976	.	deep-pit	1	1.9	2.7
	Finishing	3953	.	deep-pit	1	3.3	6.9
	Finishing	3953	.	deep-pit	1	5.5	8.0
	Finishing	1800-4000	.	Residence	365	0.8	0.2
	Finishing	1800-4000	.	Ambient	365	0.9	0.8
	Finishing	1800-4000	.	Residence	1185	0.7	0.2
	Finishing	1800-4000	.	Ambient	1185	0.4	0.2
	Finishing	1800-4000	.	Residence	655	1.1	0.3
	Finishing	1800-4000	.	Ambient	655	1.1	0.4
	Finishing	1800-4000	.	Residence	77	2.5	1.5
	Finishing	1800-4000	.	Ambient	77	2.4	2.4
	Finishing	1800-4000	.	Residence	>8000	0.7	0.2
	Finishing	1800-4000	.	Ambient	>8000	4.0	0.2
Thorne et al, 2009	.	.	.	In barn	1	19.6	.
	.	.	.	Downwind	30	2.2	.
	.	.	.	Downwind	160	1.3	.
	.	.	.	In barn	1	146.0	.
	.	.	.	Downwind	30	8.0	.
	.	.	.	Downwind	160	2.3	.
Hoff et al, 2008	Finishing	1200	.	Driveway of the residence	92	0.2	1.1
	Finishing	1200	.	Basement	92	0.0	0.2

	Finishing	1200	.	Living room	92	0.1	0.4
Wing et al, 2008	.	.	8.3	Neighborhood	.	0.0	.
	.	.	10.0	Neighborhood	.	0.1	.
	.	.	15.6	Neighborhood	.	1.5	.
	.	.	15.0	Neighborhood	.	0.4	.
	.	.	25.0	Neighborhood	.	0.0	.
	.	.	25.0	Neighborhood	.	0.2	.
	.	.	10.6	Neighborhood	.	0.1	.
	.	.	17.2	Neighborhood	.	0.0	.
	.	.	26.7	Neighborhood	.	0.4	.
	.	.	26.1	Neighborhood	.	0.4	.
	.	.	27.8	Neighborhood	.	0.3	.
	.	.	21.7	Neighborhood	.	0.1	.
	.	.	23.9	Neighborhood	.	0.1	.
	.	.	15.0	Neighborhood	.	0.0	.
	.	.	25.0	Neighborhood	.	1.0	.
	.	.	15.0	Neighborhood	.	0.1	.
Donham et al, 2006	.	.	.	Neighborhood in CAFO area	.	8.4	.
	.	.	.	Neighborhood in hoop structure area	.	3.7	.
	.	.	.	Background	.	3.5	.
Lim et al, 2003	Farrowing	20000	27	Lagoon berm	1	115.3	18.0
	Farrowing	2900	29	Lagoon berm	1	89.4	74.9
Zahn et al, 2001a	Finishing	13680	.	.	1	38.9	.
	Finishing	8200	.	.	1	34.6	.
	Finishing	14170	.	.	1	19.5	.
	Finishing	18500	.	.	1	20.9	.
Lim et al, 2000	.	5800	.	Besides the lagoon	1	127	.
	.	2900	.	Besides the lagoon	1	90	.

[1] Standard deviation.

Appendix 7. VOC emissions from swine houses

Study	Manure system	Production stage	Pig weight (kg)	Number of pigs	Indoor temperature (°C)	Ventilation	Measurement Method	Emission rates in kg $yr^{-1}hd^{-1}$		Emission rates in kg $yr^{-1}AU^{-1}$	
								Mean	Std[1]	Mean	Std[1]
IA4B[2]	Deep pit	Gestation	249.0	1004	.	Mechanical	Traditional	2.62	4.14	5.27	8.32
	Deep pit	Gestation	249.0	1084	.	Mechanical	Traditional	0.95	0.83	1.91	1.66
	Pit drain, 3 weeks	Farrowing	233.0	24	.	Mechanical	Traditional	3.80	4.87	8.16	10.44
NC4B[2]	Pit recharge, 2 weeks	Gestation	181.0	912	.	Mechanical	Traditional	2.08	2.63	5.76	7.27
	Pit recharge, 2 weeks	Gestation	181.0	884	.	Mechanical	Traditional	0.67	0.34	1.86	0.95
	Pit recharge, 3 weeks	Farrowing	181.0	19	.	Mechanical	Traditional	4.20	4.13	11.62	11.40
OK4B[2]	Pit drain, 1 week	Gestation	200.0	1169	.	Mechanical	Traditional	0.70	0.31	1.74	0.77
	Pit drain, 1 week	Gestation	200.0	1170	.	Mechanical	Traditional	1.13	0.27	2.83	0.68
	Pit drain, 3 weeks	Farrowing	200.0	24	.	Mechanical	Traditional	4.41	2.74	11.03	6.84
IN3B[2]	Deep pit	Finishing	62.5	902	.	Mechanical	Traditional	0.79	0.35	6.31	2.80
	Deep pit	Finishing	60.0	974	.	Mechanical	Traditional	2.00	2.28	16.67	18.98
	Deep pit	Finishing	60.0	1011	.	Mechanical	Traditional	0.92	0.43	7.70	3.59
	Deep pit	Finishing	58.5	1000	.	Mechanical	Traditional	2.01	2.82	17.22	24.11
NC3B[2]	Pit recharge, 1 week	Finishing	62.5	655	.	Mechanical	Traditional	0.23	0.14	1.84	1.11
	Pit recharge, 1 week	Finishing	69.5	654	.	Mechanical	Traditional	0.33	0.35	2.36	2.52
	Pit recharge, 1 week	Finishing	69.0	650	.	Mechanical	Traditional	0.29	0.22	2.09	1.56
Rumsey et al, 2012	Pit recharge, 1 week	Finishing	48.7	884	15.0	Mechanical	Traditional	0.05	.	0.50	.
	Pit recharge, 1 week	Finishing	34.6	994	15.0	Mechanical	Traditional	0.05	.	0.68	.
	Pit recharge, 1 week	Finishing	116.6	476	15.0	Mechanical	Traditional	0.03	.	0.12	.
	Pit recharge, 1 week	Finishing	50.6	874	15.0	Mechanical	Traditional	0.08	.	0.75	.
Li et al, 2011	Dry	Finishing	72.0	24	22.0	Mechanical	Traditional	0.55	0.01	3.82	0.09
	Dry	Finishing	72.0	24	22.0	Mechanical	Traditional	0.88	0.01	6.13	0.09
	Dry	Finishing	72.0	24	22.0	Mechanical	Traditional	1.01	0.01	7.01	0.09
Heber et al, 2004	Pit recharge, daily	Finishing	82.0	1051	22.7	Mechanical	Traditional	0.11	0.02	0.66	0.11
	Pit recharge, daily	Finishing	78.3	1062	21.7	Mechanical	Traditional	0.06	0.01	0.40	0.08
	Pit recharge, daily	Finishing	55.1	1133	22.7	Mechanical	Traditional	0.15	0.02	1.39	0.20
	Pit recharge, daily	Finishing	57.0	1128	21.7	Mechanical	Traditional	0.09	0.02	0.79	0.20
	Pit recharge, daily	Finishing	55.1	1091	22.7	Mechanical	Traditional	0.23	0.03	2.08	0.28
	Pit recharge, daily	Finishing	57.0	1105	21.7	Mechanical	Traditional	0.18	0.09	1.59	0.79
	Pit recharge, daily	Finishing	61.0	1130	22.7	Mechanical	Traditional	0.01	0.00	0.07	0.04
	Pit recharge, daily	Finishing	60.8	1116	21.7	Mechanical	Traditional	0.00	0.00	0.04	0.03
Zahn et al, 2001a	Deep pit	Finishing	.	13680	.	.	.	0.23	.	.	.

[1] Standard deviation.
[2] Codes of NAEMS sites. Data was adapted from the NAEMS report (2007-2009). Available at http://www.epa.gov/airquality/agmonitoring/data.html.

Appendix 8. VOC emissions from swine manure storage facilities

Study	Storage type	Production stage	Area (m^2)	Number of pigs	Ambient temperature (^oC)	Measurement method	Emission rates in kg $yr^{-1}hd^{-1}$		Emission rates in kg $yr^{-1}m^{-2}$	
							Mean	Std[1]	Mean	Std[1]
Parker et al, 2012a	Slurry	.	.	.	21.0	Chamber	.	.	0.05	.
	Slurry	.	.	.	21.0	Chamber	.	.	0.13	.
	Slurry	.	.	.	21.0	Chamber	.	.	0.04	.
Rumsey et al, 2012	Lagoon	Finishing	18145	6400	26.7	Chamber	0.85	.	0.30	.
	Lagoon	Finishing	18145	6400	25.5	Chamber	0.33	.	0.12	.
	Lagoon	Finishing	18145	6400	8.6	Chamber	0.38	.	0.13	.
	Lagoon	Finishing	18145	6400	18.3	Chamber	0.33	.	0.12	.
Bicudo et al, 2004	Slurry	Nursery	2482	8000	19.7	Chamber	0.20	0.05	0.65	0.15
	Slurry	Finishing	3772	2000	19.7	Chamber	0.75	0.10	0.40	0.05
	Slurry	Finishing	3431	3000	19.7	Chamber	0.40	0.06	0.35	0.05
	Slurry	Finishing	9685	13000	17.1	Chamber	1.69	0.03	2.27	0.03
	Slurry	Finishing	9685	13000	17.1	Chamber	2.51	0.03	3.37	0.04
	Slurry	Finishing	9685	13000	18.7	Chamber	5.38	0.03	7.22	0.03
	Slurry	Finishing	9685	13000	18.7	Chamber	6.16	0.03	8.26	0.03
Zahn et al, 2001a	Slurry	Finishing	.	8200	.	Chamber	1.03	.	.	.
	Lagoon	Finishing	.	14170	.	Chamber	0.09	.	.	.
	Lagoon	Finishing	.	18500	.	Chamber	0.02	.	.	.
Zahn et al, 1997	Slurry	Finishing	468	1230		Micrometeorological	1.23	.	3.24	.

[1] Standard deviation.

Appendix 9. VOC concentrations in the vicinity of swine facilities

Study	Production stage	Number of pigs	Ambient temperature (°C)	Location	Distance (m)	Concentration (µg m^{-3})	
						Mean	Std[1]
Hermandez et al, 2012	Finishing	.	.	Swine building (ground level)	1	67.16	.
	Finishing	.	.	Swine building (tower)	1	13.24	.
	Finishing	.	.	46 m downwind before buffer	46	14.4	.
	Finishing	.	.	62 m downwind corn field	62	16.66	.
	Finishing	.	.	Swine building (ground level)	1	29.09	.
	Finishing	.	.	Swine building (tower)	1	13.53	.
	Finishing			46 m downwind before buffer	46	11.55	.
	Finishing	.	.	62 m downwind corn field	62	7.93	.
Parker et al, 2012b	.	45600		Upwind background	.	1.23	.
	.	45600		Downwind from lagoon	1	0.93	.
	.	45600		Exhaust fan	1	11.12	.
	.	45600		Downwind from fan	10	2.26	.
	.	45600		Downwind from fan	10	1.37	.
	.	45600		Downwind from barn	30	2.06	.
	.	45600		300m downwind of barn	300	0.48	.
Schiffman et al, 2001	.	.	.	.	1	602	.
Zahn et al, 2001a	Finishing	13680	.	.	1	806	.
	Finishing	8200	.	.	1	1647	.
	Finishing	14170	.	.	1	126	.
	Finishing	18500	.	.	1	25	.
Zahnet al, 1997	Finishing	1230	.	Downwind of slurry storage basin	1	27700	.
	Finishing	1230		Downwind of slurry storage basin	25	19440	.
	Finishing	1230	.	Downwind of slurry storage basin	100	10670	.

[1] Standard deviation.

Appendix 10. PM10 emissions from swine houses

Study	Manure system	Production stage	Pig weight (kg)	Number of pigs	Indoor temperature (^oC)	Ventilation	Measurement Method	Emission rates in kg $yr^{-1}hd^{-1}$		Emission rates in kg $yr^{-1}AU^{-1}$	
								Mean	Std[1]	Mean	Std[1]
IA4B[2]	Deep pit	Gestation	249	1004	17.4	Mechanical	Traditional	0.17	0.08	0.34	0.16
	Deep pit	Gestation	249	1084	17.3	Mechanical	Traditional	0.18	0.08	0.36	0.16
	Pit drain, 3 weeks	Farrowing	233	24	25.2	Mechanical	Traditional	0.43	0.26	0.92	0.56
NC4B[2]	Pit recharge, 2 weeks	Gestation	181	912	22.8	Mechanical	Traditional	0.10	0.05	0.28	0.14
	Pit recharge, 2 weeks	Gestation	181	884	24.6	Mechanical	Traditional	0.17	0.08	0.47	0.22
	Pit recharge, 3 weeks	Farrowing	181	19	25.5	Mechanical	Traditional	0.60	0.31	1.66	0.86
OK4B[2]	Pit drain, 1 week	Gestation	200	1169	22.0	Mechanical	Traditional	0.11	0.04	0.28	0.10
	Pit drain, 1 week	Gestation	200	1170	22.0	Mechanical	Traditional	0.15	0.05	0.38	0.13
	Pit drain, 3 weeks	Farrowing	200	24	24.0	Natural	Inverse-dispersion	0.62	0.38	1.55	0.95
IN3B[2]	Deep pit	Finishing	62.5	902	23.0	.	.	0.09	0.07	0.72	0.56
	Deep pit	Finishing	60	974	23.0	.	Traditional	0.08	0.05	0.67	0.42
	Deep pit	Finishing	60	1011	22.0	Mechanical	Traditional	0.07	0.04	0.58	0.33
	Deep pit	Finishing	58.5	1000	24.0	Mechanical	Traditional	0.09	0.18	0.77	1.54
NC3B[2]	Pit recharge, 1 week	Finishing	62.5	655	23.3	Mechanical	Traditional	0.10	0.07	0.80	0.56
	Pit recharge, 1 week	Finishing	69.5	654	23.0	Mechanical	Traditional	0.10	0.06	0.72	0.43
	Pit recharge, 1 week	Finishing	69	650	24.0	Mechanical	Traditional	0.09	0.05	0.65	0.36
Jacobson et al, 2007b	Deep pit	Finishing	.	2400	.	Mechanical	Traditional	0.08	.	.	.
	Deep pit	Finishing	.	2400	.	Mechanical	Traditional	0.04	.	.	.
	Deep pit	Finishing	.	2400	.	Mechanical	Traditional	0.05	.	.	.
Martin et al, 2006	Deep pit	Finishing	90	3750	.	Mechanical	Traditional	0.20	.	1.12	.
Hoff et al, 2005	Deep pit	Finishing	.	.	.	Mechanical	Traditional	0.04	.	.	.
Jacobson et al, 2005	Dry	Gestation	.	.	.	Mechanical	Traditional	.	.	0.44	.
Heber et al, 2004	Pit recharge, daily	Finishing	82.0	1051	22.7	Mechanical	Traditional	0.11	0.01	0.68	0.06
	Pit recharge, daily	Finishing	78.3	1062	21.7	Mechanical	Traditional	0.03	0.01	0.22	0.04
	Pit recharge, daily	Finishing	55.1	1133	22.7	Natural	Traditional	0.08	0.02	0.74	0.15
	Pit recharge, daily	Finishing	57.0	1128	21.7	Mechanical	Traditional	0.03	0.01	0.23	0.08
	Pit recharge, daily	Finishing	55.1	1091	22.7	Mechanical	Traditional	0.07	0.01	0.62	0.11
	Pit recharge, daily	Finishing	57.0	1105	21.7	Mechanical	Traditional	0.07	0.04	0.61	0.32
	Pit recharge, daily	Finishing	61.0	1130	22.7	Mechanical	Traditional	0.05	0.01	0.42	0.08
	Pit recharge, daily	Finishing	60.8	1116	21.7	Mechanical	Traditional	0.06	0.01	0.50	0.07
Jacobson et al,	Hoop	Finishing	82	180	.	Mechanical	Traditional	0.08	0.01	0.46	0.07

2003	Deep pit	Finishing	105	950	.	Mechanical	Traditional	0.06	0.01	0.30	0.06
	Hoop	Finishing	107	180	.	Mechanical	Traditional	0.32	0.36	1.51	1.67
	Deep pit	Finishing	68	1000	.	Natural	inverse-dispersion technique	0.10	0.06	0.72	0.44
Schmidt et al, 2002	Deep pit	Finishing	102	1000		.	.	0.13	0.01	0.65	0.02
	Deep pit	Finishing	70	1033		.	Traditional	0.22	0.11	1.56	0.79

[1] Standard deviation.

[2] Codes of NAEMS sites. Data was adapted from the NAEMS report (2007-2009). Available at http://www.epa.gov/airquality/agmonitoring/data.html.

Appendix 11. PM2.5 emissions from swine houses

Study	Manure system	Production stage	Pig weight (kg)	Number of pigs	Indoor temperature (°C)	Ventilation	Measurement Method	Emission rates in kg $yr^{-1}hd^{-1}$		Emission rates in kg $yr^{-1}AU^{-1}$	
								Mean	Std[1]	Mean	Std[1]
IA4B[2]	Deep pit	Gestation	249	1004	17.4	Mechanical	Traditional	0.017	0.006	0.034	0.012
	Deep pit	Gestation	249	1084	17.3	Mechanical	Traditional	0.018	0.011	0.036	0.022
	Pit drain, 3 weeks	Farrowing	233	24	25.2	Mechanical	Traditional	0.048	0.041	0.103	0.088
NC4B[2]	Pit recharge, 2 weeks	Gestation	181	912	22.8	Mechanical	Traditional	0.016	0.005	0.044	0.014
	Pit recharge, 2 weeks	Gestation	181	884	24.6	Mechanical	Traditional	0.020	0.009	0.055	0.025
	Pit recharge, 3 weeks	Farrowing	181	19	25.5	Mechanical	Traditional	0.054	0.020	0.149	0.055
OK4B[2]	Pit drain, 1 week	Gestation	200	1169	22.0	Mechanical	Traditional	0.009	0.006	0.023	0.015
	Pit drain, 1 week	Gestation	200	1170	22.0	Mechanical	Traditional	0.015	0.012	0.038	0.030
	Pit drain, 3 weeks	Farrowing	200	24	24.0	Mechanical	Traditional	0.079	0.068	0.198	0.170
IN3B[2]	Deep pit	Finishing	62.5	902	23.0	Mechanical	Traditional	0.003	0.005	0.024	0.040
	Deep pit	Finishing	60	974	23.0	Mechanical	Traditional	0.002	0.006	0.017	0.050
	Deep pit	Finishing	60	1011	22.0	Mechanical	Traditional	-0.004	0.016	-0.033	0.133
	Deep pit	Finishing	58.5	1000	24.0	Mechanical	Traditional	0.001	0.002	0.009	0.017
NC3B[2]	Pit recharge, 1 week	Finishing	62.5	655	23.3	Mechanical	Traditional	0.012	0.004	0.096	0.032
	Pit recharge, 1 week	Finishing	69.5	654	23.0	Mechanical	Traditional	0.007	0.003	0.050	0.022
	Pit recharge, 1 week	Finishing	69	650	24.0	Mechanical	Traditional	0.005	0.002	0.036	0.014
Martin et al, 2006	Deep pit	Finishing	90	3750	.	Natural	Inverse-dispersion	0.051	.	0.284	.

[1] Standard deviation.

[2] Codes of NAEMS sites. Data was adapted from the NAEMS report (2007-2009). Available at http://www.epa.gov/airquality/agmonitoring/data.html.

Appendix 12. PM10 and PM2.5 concentrations in the vicinity of swine facilities

Pollutants	Study	Production stage	Number of pigs	Ambient temperature (^oC)	Location	Distance (m)	Concentration ($\mu g\ m^{-3}$)	
							Mean	Std[1]
PM10	Wing et al, 2008	.	.	8.3	Neighborhood	.	10.8	.
		.	.	10.0	Neighborhood	.	13.6	.
		.	.	15.6	Neighborhood	.	28.7	.
		.	.	15.0	Neighborhood	.	13.7	.
		.	.	25.0	Neighborhood	.	28.7	.
		.	.	25.0	Neighborhood	.	28.4	.
		.	.	10.6	Neighborhood	.	17.5	.
		.	.	17.2	Neighborhood	.	16.8	.
		.	.	26.7	Neighborhood	.	27	.
		.	.	26.1	Neighborhood	.	21.7	.
		.	.	27.8	Neighborhood	.	22.8	.
		.	.	21.7	Neighborhood	.	23	.
		.	.	23.9	Neighborhood	.	17.1	.
		.	.	15.0	Neighborhood	.	27.3	.
		.	.	25.0	Neighborhood	.	18.7	.
		.	.	15.0	Neighborhood	.	19.1	.
	Martin et al, 2008	Finishing	1250	.	Upwind background	.	37	.
		Finishing	1250	.	Facility-derived concentration (upwind-background)	.	5.8	2.9
	Donham et al, 2006	.	.	.	Neighborhood in CAFO area	.	30.28	.
		.	.	.	Neighborhood in hoop structure area	.	42.25	.
		.	.	.	Background	.	34.26	.
	Martin et al, 2006	Finishing	3750	.	Upwind background	.	35	.
		Finishing	3750	.	Downwind from barn	40	40 to 60	.
PM2.5	Martin et al, 2008	Finishing	1250		Upwind background	.	14	.
		Finishing	1250	.	Facility-derived concentration (upwind-background)	.	1.7	1.1
	Martin et al, 2006	Finishing	3750	.	Upwind background	.	10	.
		Finishing	3750	.	Downwind from barn	40	10 to 15	.

[1] Standard deviation.