Ammonia and Hydrogen Sulfide Emissions from Swine Production Facilities in North America: a Meta-Analysis[1]

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Summary

Ammonia (NH_3) and hydrogen sulfide (H_2S) emissions from swine production facilities receive considerable attention due to human health and environmental implications. Accurate quantification of farm emissions is essential to ensure compliance with regulatory requirements. The objectives of this study were to provide a review of the literature on NH_3 and H_2S emissions from swine production facilities in North America with a meta-analysis that integrates results of independent studies, including measured emissions data from both swine houses and manure storage facilities as well as concentration data in the vicinity of swine production facilities. Results from more than 80 studies were identified through a thorough literature search, and the data were compiled together with results from the 11 swine sites in the National Air Emissions Monitoring Study (NAEMS). Data across studies were analyzed statistically using the MIXED procedures of SAS.

Median emissions rates from swine houses were 2.78 and 0.09 kg/year per pig for NH_3 and H_2S, respectively. Median emissions rates from swine storage facilities were 2.08 and 0.20 kg/year per pig for NH_3 and H_2S, respectively. The Emergency Planning and Community Right-to-Know Act (EPCRA) require reporting of NH_3 and H_2S emissions that exceed 100 lb/d. The size that may trigger the need for a farm to report NH_3 emissions is 3,410 pigs based on median NH_3 emissions rates in the literature, but the threshold can be as low as 992 pigs based on 90th-percentile emissions rates. Swine hoop houses had significantly higher NH_3 emission rates than other manure-handling systems ($P < 0.01$), whereas deep pit houses had the highest H_2S emission rates ($P = 0.03$). Farrowing houses had the highest H_2S emission rates, followed by gestation houses, and finishing houses had lowest H_2S emission rates ($P < 0.01$). Regression models for NH_3 and H_2S emission rates were developed for finishing houses with deep pits, recharge pits, and lagoons. The NH_3 emission rates increased with increasing air temperature, but effects of air temperature on H_2S emission rates were not significant. The recharge interval of manure pits significantly affected H_2S but not NH_3 emission rates. The H_2S emission rates were also influenced by the size of the operation. Although NH_3 and H_2S concentrations at the edge of swine houses or lagoons were often higher than corresponding acute or intermediate minimum risk levels (MRLs), they decreased quickly to be less than corresponding chronic or intermediate MRLs as distances from emission sources increase. At distances 30 to 1,185 m from emission sources, the average ambient concentrations for NH_3 and H_2S were 66 ± 66 ppb and 3.1 ± 6.2 ppb, respectively.

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Introduction

Air emissions from swine production facilities receive considerable attention due to human health and environmental implications. Major farm emissions of interest include ammonia (NH_3) and hydrogen sulfide (H_2S). The H_2S is of interest mainly at the local level because of health concerns, whereas NH_3 has regional-scale impacts on ecosystems. Air emissions from industries are subject to permit 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 emissions reach specified thresholds; for example, operations that exceed 100 lb/d NH_3 or H_2S emissions are required to report under EPCRA. Accurate quantification of farm emissions is essential to ensure compliance with the regulatory requirements, but direct measurements of farm emissions are expensive and difficult. Fortunately, a large volume of published studies on NH_3 and H_2S emissions from swine production facilities are available for a meta-analysis. Meta-analysis is a quantitative statistical analysis of a collection of results from individual previous studies for the purpose of integrating the findings. Results from meta-analyses are usually more robust and have less bias than individual studies because of improved statistical power.

The objectives of this study were to provide a review of the literature on NH_3 and H_2S emissions from swine production facilities in North America, with a meta-analysis that integrates results of independent studies, including measured emissions data from both swine houses and manure storage facilities as well as concentration data in the vicinity of swine production facilities.

Procedures

Literature search and data extraction

Multiple strategies were undertaken to identify potentially eligible studies to be included in the meta-analysis. The inclusion criteria were that studies must have been conducted in North America and must have reported measured NH_3 or H_2S emissions data from swine production facilities, including manure storage systems, or concentration data in the vicinity of swine facilities. Data from reports of the 11 swine sites in the National Air Emissions Monitoring Study (NAEMS) were included in the database. Two individuals independently conducted the search processes and screened the studies by reading the title and abstract to select studies for full review according to the inclusion criteria.

The included studies were distributed to a group of reviewers for data extraction. Standard data extraction sheets were developed for consistency. Some studies provided emissions data from different sites or settings; in these cases, more than one data point was extracted from one study. Each study was reviewed in duplicate by two independent reviewers for quality control. After the data review and extraction processes, a meta-analysis database was created. Emissions data for NH_3 and H_2S were compiled into the two emission sources (swine houses and manure storage facilities). Concentration data were compiled separately and included sampling locations and distances from emission sources.

Data analysis

Various units of emissions data have been used in the literature. To perform statistical analysis and compare emissions data between different studies, the units of measured emissions data were converted to kg/year per pig and kg/year per AU (AU is an animal unit corresponding to 500 kg of body mass) for emissions from swine houses and to kg/year per pig and kg/year per m^2 for emissions from manure storage facilities. When unit conversion was not possible due to lack of key information, the original emissions data were excluded from statistical analysis. A full list of included studies and completed data extraction spreadsheets are available to allow for independent scrutiny of the process.

Data across studies were analyzed statistically using the MIXED procedures of SAS (SAS for Windows, Version 9.3, SAS Institute, Inc., Cary, NC). Study (or each publication) was treated as a random variable because some studies contain multiple data points. The ratios of emissions rate over SD were used as a weighting variable such that data points with relatively small SDs were given more weight in the analysis. Effects of production stage and manure handling/storage system on emissions rates were examined using Tukey's test. Significant effects were declared at $P < 0.05$. Multi-linear regression models were developed for certain emission sources to reflect the effects of indoor or ambient air temperature, average pig weight, size of operation (number of pigs), area of manure storage, recharging interval of manure pits, etc. A backward-elimination process was used to remove the confounded terms and to reduce non-significant terms one by one. When a regression model failed to pass normality tests, a natural log transformation was applied to the response variable (emission rate).

Results and Discussion

Statistics of NH_3 and H_2S emissions from swine houses and manure storage facilities

The ranges, means, and medians of NH_3 and H_2S emission rates for swine houses and manure storage facilities are presented in Table 1. Large variations in emission rates were observed. Histograms of NH_3 and H_2S emission rates for swine houses and manure storage facilities all showed a positively skewed distribution. The median emission rates were believed more robust, and the means were all larger than the medians due to a few large values. For swine houses, the median NH_3 emission rate was 2.78 kg/year per pig, whereas the highest emission rate was 11 times higher; the median H_2S emission rate was only 0.09 kg/year per pig, but the highest emission rate was 35 times higher. For swine manure storage facilities, the median NH_3 emission rate was 2.08 kg/year per pig, whereas the highest emission rate was 11 times higher; the median H_2S emission rate was only 0.20 kg/year per pig, but the highest emission rate was 7 times higher.

Emission rates from swine houses: Effects of production stage and manure-handling system

Means and least squares means of NH_3 and H_2S emission rates from swine houses for various production stages and manure-handling systems are presented in Table 2. Swine hoop houses had significantly higher NH_3 emission rates than other manure handling systems ($P < 0.01$ for NH_3 emission rates in both kg/year per pig and kg/year per AU). Effects of production stages (gestation, farrowing, nursery, or finishing) were not significant for NH_3 emission rates from swine houses ($P = 0.23$ and 0.15 for NH_3 emission rates in kg/year per pig and kg/year per AU, respectively). Deep-pit houses had higher H_2S emission rates than other manure-handling systems ($P = 0.03$ and <0.01 for H_2S emission rates in kg/year per pig and kg/year per AU, respectively). Farrowing houses had the highest H_2S emission rates, followed by gestation houses, and finishing houses had lowest H_2S emission rates, regardless of whether emission rates were expressed in kg/year per pig or kg/year per AU ($P < 0.01$ in both cases).

Emission rates from manure storage facilities: Effects of production stage and storage type

Means and least squares means of NH_3 and H_2S emission rates from manure storage facilities for various production stages and storage types are presented in Table 3. No storage type or production stage effects were observed for NH_3 emission rates (in kg/year per pig, $P = 0.45$ and 0.24, respectively; or in kg/year per m^2, $P = 0.75$ and 0.30, respectively), or H_2S emission rates (in kg/year per pig, $P = 0.47$ and 0.13, respectively; or in kg/year per m^2, $P = 0.06$ and 0.60, respectively).

Regression models for NH_3 and H_2S emission rates

Regression models for NH_3 and H_2S emission rates were developed for deep-pit finishing houses, finishing houses with recharge pits, and lagoons for finishing operations (Table 4) to reflect the effects of indoor or ambient air temperature, average pig weight, size of operation (number of pigs), area of manure storage, recharging interval of manure pits, etc. The indoor air temperatures ranged from 8 to 28°C; average pig weights ranged from 21 to 249 kg; number of pigs ranged from 6 to 13,680; recharge interval of manure pits ranged from 1 to 42 d; ambient air temperatures ranged from 2 to 32°C; and areas of lagoons ranged from 1,131 to 97,600 m^2.

For finishing houses with deep pits or recharge pits, NH_3 emission rates were positively related to indoor air temperature. Finishing operation lagoons had NH_3 emission rates that were positively related to ambient air temperature ($P < 0.01$). Effects of temperature on H_2S emission rates were not significant. The recharge interval of manure pits in finishing houses significantly affected H_2S but not NH_3 emission rates. Swine houses with pits that had longer recharge intervals emitted more H_2S ($P < 0.01$). The NH_3 and H_2S emission rates from swine houses in kg/year per pig increased with increasing pig weights. When expressed in kg/year per AU, NH_3 emission rates were no longer influenced by pig weight, but for finishing houses with recharge pits, H_2S emission rates in kg/year per AU remained positively related with pig weight ($P = 0.01$). The H_2S emission rates were also influenced by size of operation. Deep-pit finishing houses with larger pig numbers tend to have higher H_2S emission rates in kg/year per AU ($P = 0.02$).

Swine farm sizes that may trigger the need to report NH_3 or H_2S emissions

The EPCRA and CERCLA require reporting of NH_3 and H_2S emissions that exceed 100 lb/d. Swine farm sizes that may trigger the need to report NH_3 and H_2S emissions under EPCRA and CERCLA were calculated and are presented in Table 5.

NH_3 concentrations in the vicinity of swine facilities

The average NH_3 concentration at the edge of the emission sources (swine houses or lagoons) was 5.5 ± 5.2 ppm (ranging from 0.3 to16 ppm), which is higher than the acute minimum risk levels (MRL) for NH_3 (1700 ppb[4]). The ambient NH_3 concentrations in the vicinity of swine facilities decreased quickly to be less than the chronic MRL (100 ppb) as distances from emission source increased (Figure 1). At distances of 30 to 1,185 m from emissions sources, the average ambient NH_3 concentration was 66 ± 66 ppb (ranging from 10 to 280 ppb). In comparison, the average background ambient NH_3 concentration outside swine production areas was 7.7 ± 3.5 ppb, whereas Godbout et al. (2009[5]) and Donham et al. (2006[6]) reported the average ambient NH_3 concentration within swine production areas was 11.8 ± 5.5 ppb. The average ambient NH_3 concentration in the vicinity of swine facilities (66 ± 66 ppb at distances from 30 to 1,185 m) was about 8 times higher than the average background ambient NH_3 concentration in areas not influenced by swine production facilities (7.7 ± 3.5 ppb).

H_2S concentrations in the vicinity of swine facilities

The average H_2S concentration at the edge of the emission sources (swine houses or lagoons) was 40 ± 48 ppb (ranging from 0.9 to146 ppb), which is less than the acute MRL (100 ppb) but higher than the intermediate MRL (20 ppb) for H_2S[7]. The ambient H_2S concentrations in the vicinity of swine facilities decrease quickly to be less than 20 ppb as distances from emission sources increase (Figure 2). The average ambient H_2S concentration was 3.1 ± 6.2 ppb at the distances of 30 to 1,185 m from emission sources. In comparison, Godbout et al. (2009[8]) and Donham et al. (2006[9]) reported average ambient H_2S concentrations of 1.9 ± 1.1 ppb in areas not influenced by swine production facilities.

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[4] 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 d continuous) and chronic (>365 d continuous) exposure, respectively.

[5] Godbout, S., S.P. Lemay, C. Duchaine, F. Pelletier, J.P. Larouch, M. Belzile, and J.J.R. Feddes. 2009. Swine Production Impact on Residential Ambient Air Quality, J. Agromed. 14:3, 291–98.

[6] Donham, K.J., J.A. Lee, K. Thu, and S.J. Reynolds. 2006. Assessment of air quality at neighbor residences in the vicinity of swine production facilities. J. Agromed. 11(3/4):15–24.

[7] 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 H_2S are 70 ppb and 20 ppb for an acute and intermediate (15–365 d continuous) exposure, respectively.

[8] Godbout, S., S.P. Lemay, C. Duchaine, F. Pelletier, J.P. Larouch, M. Belzile, and J.J.R. Feddes. 2009. Swine Production Impact on Residential Ambient Air Quality, J. Agromed. 14:3, 291–298.

[9] Donham, K.J., J.A. Lee, K. Thu, and S.J. Reynolds. 2006. Assessment of air quality at neighbor residences in the vicinity of swine production facilities. J. Agromed. 11(3/4):15–24.

Table 1. Statistics of NH_3 and H_2S emissions from swine houses and manure storage facilities

	NH_3			H_2S		
	Range	Mean	Median	Range	Mean	Median
Swine houses						
Emissions rates in kg/year per pig	0.33 to 31.6 (97)[1]	3.95 ± 4.51	2.78	0.00 to 3.12 (65)	0.26 ± 0.56	0.09
Emissions rates in kg/year per AU[2]	0.79 to 124.2 (101)	20.64 ± 18.09	16.43	0.00 to 11.09 (70)	1.08 ± 1.07	0.55
Manure storage facilities						
Emissions rates in kg/year per pig	0.00 to 23.23 (74)	3.83 ± 4.43	2.08	0.00 to 1.33 (27)	0.33 ± 0.37	0.20
Emissions rates in kg/year per m^2	0.00 to 7.28 (72)	1.68 ± 1.66	1.08	0.00 to 0.70 (30)	0.18 ± 0.21	0.07

[1] Number of data points in each category were presented in parentheses.
[2] AU = animal unit corresponding to 500 kg body mass.

Table 2. Means and least squares means of NH_3 and H_2S emission rates from swine houses by various production stages and manure handling systems

	Gestation	Farrowing	Finishing	Nursery	Least squares mean
NH_3 emission rates (in kg/year per pig)					
Hoop	(0)[1]	(0)	12.93 ± 0.89 (2)	(0)	14.80 ± 1.97[b] (2)
Dry	(0)	(0)	4.19 ± 4.77 (7)	(0)	3.26 ± 1.22[a] (7)
Deep pit	5.85 ± 5.13 (3)	7.030 (1)	3.57 ± 2.00 (36)	0.66 (1)	4.30 ± 0.90[a] (41)
Recharge pit	14.61 ± 14.39 (4)	7.80 ± 10.97 (3)	2.38 ± 1.48 (32)	0.860 (1)	2.90 ± 0.80[a] (40)
Drain pit	3.44 ± 0.09 (2)	2.18 ± 2.09 (2)	1.32 ± 0.40 (3)	(0)	3.13 ± 0.84[a] (7)
Least squares mean	6.69 ± 1.06 (9)	5.46 ± 1.74 (6)	4.89 ± 0.49 (80)	(2)	
NH_3 emission rates (in kg/year per AU[2])					
Hoop	(0)	(0)	69.18 ± 8.22 (2)	(0)	73.62 ± 13.69[b] (2)
Dry	8.67 ± 1.94 (2)	(0)	32.38 ± 40.70 (7)	(0)	8.05 ± 9.13[a] (9)
Deep pit	10.59 ± 6.54 (7)	17.18 (1)	24.67 ± 13.52 (34)	16.04 (1)	16.03 ± 5.60[a] (43)
Recharge pit	7.39 ± 1.23 (2)	4.08 ± 4.66 (2)	17.95 ± 13.26 (32)	(0)	8.77 ± 4.99[a] (36)
Drain pit	8.61 ± 0.23 (2)	2.51 ± 2.63 (6)	7.81 ± 2.02 (3)	(0)	10.83 ± 4.96[a] (11)
Least squares mean	20.53 ± 6.88 (13)	16.90 ± 9.13 (9)	32.95 ± 3.83 (78)	(1)	
H_2S emission rates (in kg/year per pig)					
Hoop	(0)	(0)	0.015 ± 0.004 (2)	(0)	1.457 ± 0.378[a,b] (2)
Dry	(0)	(0)	0.017 ± 0.007 (6)	(0)	1.224 ± 0.309[a,b] (6)
Deep pit	1.709 ± 1.503 (3)	1.065 (1)	0.136 ± 0.127 (25)	0.455(1)	1.545 ± 0.205[b] (30)
Recharge pit	0.110 ± 0.014 (2)	2.790 (1)	0.071 ± 0.057 (17)	(0)	0.970 ± 0.183[a,b] (20)
Drain pit	0.275 ± 0.007 (2)	1.375 ± 0.007 (2)	0.023 ± 0.006 (3)	(0)	0.778 ± 0.190[a] (7)
Least squares mean	1.098 ± 0.245[b] (7)	2.499 ± 0.309[c] (4)	-0.012 ± 0.121[a] (53)	(1)	
H_2S emission rates (in kg/year per AU)					
Hoop	(0)	(0)	0.078 ± 0.004 (2)	(0)	3.690 ± 1.173[a,b] (2)
Dry	0.730 (1)	(0)	0.121 ± 0.048(6)	(0)	2.132 ± 1.186[a,b] (6)
Deep pit	2.309 ± 2.063 (7)	2.604 (1)	1.019 ± 0.912 (24)	11.089 (1)	4.068 ± 0.686[b] (33)
Recharge pit	0.304 ± 0.039 (2)	7.707 (1)	0.525 ± 0.391 (17)	(0)	1.450 ± 0.620[a] (20)
Drain pit	0.688 ± 0.675 (2)	1.703 ± 1.737 (4)	0.137 ± 0.038 (3)	(0)	0.754 ± 0.601[a] (9)
Least squares mean	1.791 ± 0.822[a] (12)	5.056 ± 0.960[b] (6)	0.410 ± 0.460[a] (52)	(1)	

[a,b,c] Values within the same effect section differ significantly if without common letter ($P < 0.05$).
[1] Number of data points in each category is in parentheses.
[2] AU = animal unit corresponding to 500 kg body mass.

Table 3. Means and least squares means of NH_3 and H_2S emission rates from swine manure storage facilities by various production stages and storage systems

	Gestation	Farrowing	Finishing	Nursery	Least squares mean
NH_3 emission rates (in kg/year per pig)					
Lagoon	(0)[1]	8.92 ± 6.68 (10)	3.70 ± 3.74 (47)	0.020 (1)	5.35 ± 1.53 (58)
Slurry tank	(0)	(0)	1.85 ± 2.28 (12)	0.45 ± 0.38 (4)	3.01 ± 2.96 (16)
Least squares mean	(0)	6.00 ± 3.79 (10)	4.36 ± 1.51 (59)	2.19 ± 1.89 (5)	
NH_3 emission rates (in kg/year per m^2)					
Lagoon	(0)	2.26 ± 1.69 (11)	1.59 ± 1.81 (45)	0.030 (1)	3.02 ± 0.68 (57)
Slurry tank	(0)	(0)	1.67 ± 1.15 (11)	1.35 ± 1.30 (4)	3.50 ± 1.49 (15)
Least squares mean	(0)	4.27 ± 1.71 (11)	2.47 ± 0.76 (56)	3.04 ± 0.88 (5)	
H_2S emission rates (in kg/year per pig)					
Lagoon	(0)	0.387 ± 0.321 (8)	0.256 ± 0.344 (13)	(0)	0.388 ± 0.155 (21)
Slurry tank	(0)	(0)	0.438 ± 0.554 (5)	0.204 (1)	0.554 ± 0.181 (6)
Least squares mean	(0)	0.516 ± 0.278 (8)	0.774 ± 0.109 (18)	0.121 ± 0.271 (1)	
H_2S emission rates (in kg/year per m^2)					
Lagoon	(0)	0.128 ± 0.117 (10)	0.121 ± 0.160 (14)	(0)	0.360 ± 0.063 (24)
Slurry tank	(0)	(0)	0.378 ± 0.300 (5)	0.656 (1)	0.660 ± 0.071 (6)
Least squares mean	(0)	0.374 ± 0.115 (10)	0.450 ± 0.042 (19)	0.556 ± 0.114 (1)	

[1] Number of data points in each category is in parentheses.

Table 4. Regression models for NH_3 and H_2S emission rates from various emission sources

Emission sources	Regression model
Finishing houses with deep pits	NH_3 emission rates in kg/year per pig = EXP (-0.6284+0.01854W+0.02495T_i)
	NH_3 emission rates in kg/year per AU = EXP (2.6859+0.02569T_i)
	H_2S emission rates in kg/year per pig = EXP (-3.4502+0.002431W+0.000382N)
	H_2S emission rates in kg/year per AU = EXP (-1.0983+0.000061N)
Finishing houses with recharge pits	NH_3 emission rates in kg/year per pig = EXP (-1.4247+0.01333W+0.05562T_i)
	NH_3 emission rates in kg/year per AU = EXP (1.5524+0.05484T_i)
	H_2S emission rates in kg/year per pig = EXP (-5.9333+0.03780W+0.04709R)
	H_2S emission rates in kg/year per AU = EXP (-2.8309+0.02183W+0.04877R)
Lagoons for finishing operations	NH_3 emission rates in kg/year per pig = EXP (-0.3782+0.07017T_a)
	NH_3 emission rates in kg/year per m^2 = EXP (-1.3843+0.07373T_a)

Note: AU = animal unit corresponding to 500 kg body mass; T_i = indoor air temperature in swine houses, °C; T_a = ambient air temperature, °C; W = average weight of pigs, kg; N = number of pigs in the farm; R = recharge interval of manure pits, in days.

Table 5. Sizes of swine farm that may trigger the need to report NH_3 or H_2S emissions

Scenarios		Emission rates (kg/year per pig)			Sizes that may reach the 100-lb NH_3 or H_2S/d threshold
		Swine houses	Manure storage	Total	
Based on the median emission rates in literature	NH_3	2.78	2.08	4.86	3,410 pigs
	H_2S	0.09	0.20	0.29	57,141 pigs
Based on the 75th-percentile emission rates in literature	NH_3	4.49	6.27	10.76	1,540 pigs
	H_2S	0.20	0.63	0.83	19,965 pigs
Based on the 90th-percentile emission rates in literature	NH_3	7.17	9.54	16.71	992 pigs
	H_2S	0.47	0.83	1.30	12,747 pigs

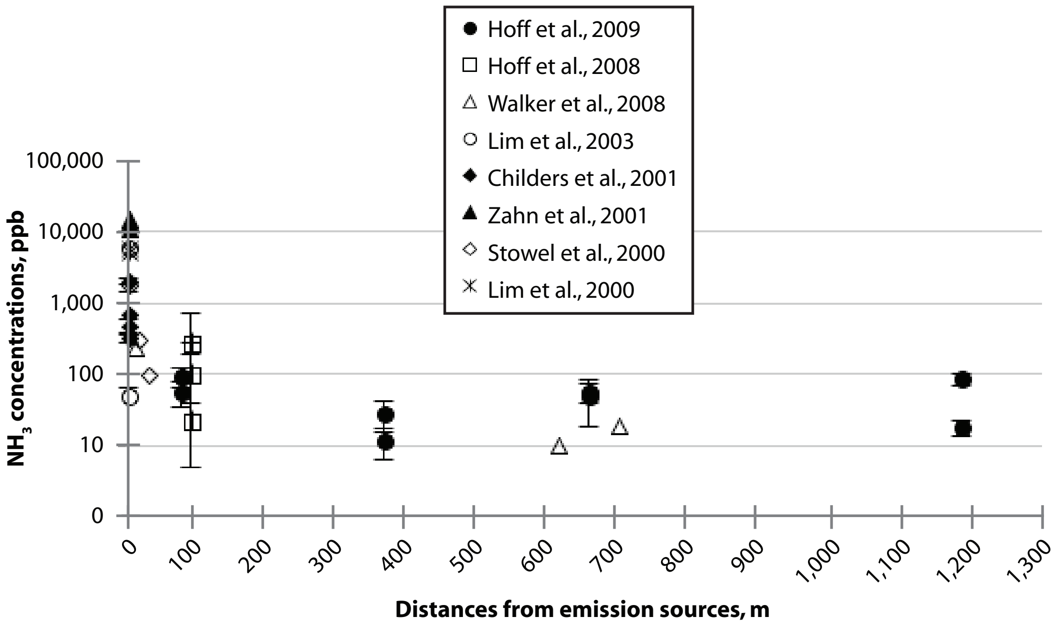

Figure 1. Measured NH_3 concentrations at various distances from swine facilities[10]

[10] References in Figure 1: Hoff, S.J., J.D. Harmon, D.S. Bundy, and B.C. Zelle. 2009. Source and receptor ammonia and hydrogen sulfide concentrations in communities with and without swine emission sources: follow-up study. Appl. Eng. Agric. 25(6):975–986.
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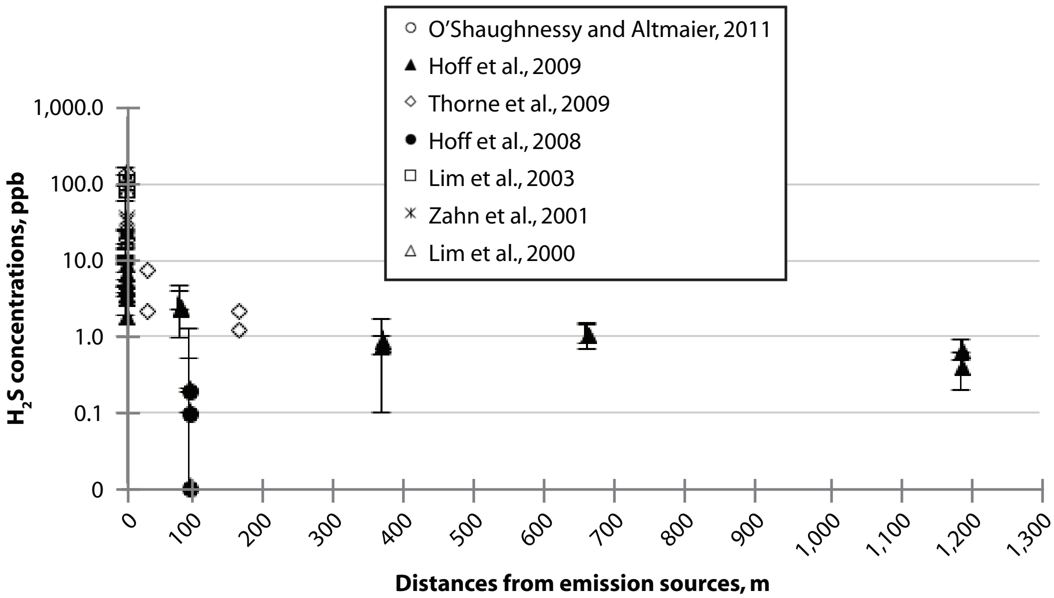

Figure 2. Measured H_2S concentrations at various distances from swine facilities[11]

[11] References in Figure 2: O'Shaughnessy, P.T. and R. Altmaier. 2011. Use of AERMOD to determine a hydrogen sulfide emission factor for swine operations by inverse modeling. Atmos. Environ. 45:4617–4625.
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