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Development of an emission factor for ammonia emissions from US swine farms based on field tests and application of a mass balance method

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Abstract

This paper discusses and summarizes post-1994 US and European information on ammonia (NH_3) emissions from swine farms and assesses the applicability for general use in the United States. The emission rates for the houses calculated by various methods show good agreement and suggest that the houses are a more significant source than previously thought. A general emission factor for houses of 3.7 ± 1.0 kg NH_3/year/finisher pig or 59 ± 10 g NH_3/kg live weight/year is recommended. For lagoons, it was found that there is good similarity between the field test results and the number calculated by a mass balance method. The suggested annual NH_3 emission factor for lagoons based on field tests at one swine farm lagoon in North Carolina is 2.4 kg/year/pig. Emission rates from sprayfields were estimated using a total mass balance approach, while subtracting the house and lagoon emissions.

The total emission rates for finishing pigs at the test farm compared well to the total rate established by a mass balance approach based on nitrogen intake and volatilization. Therefore, it was concluded that a mass balance approach can be helpful in estimating NH_3 emissions from swine farms. A general emission factor of 7 ± 2 kg NH_3/pig/year could be developed, which is comparable to general European emission factors, which varied from 4.8 to 6.4 kg NH_3/pig/year.

Keywords: Ammonia; Swine; Farms; Emissions; CAFOs

1. Introduction

In addition to direct leaching, the atmospheric deposition of ammonia (NH_3) and nitrogen oxides, as well as their associated reaction products has received renewed attention as a major route of entry into watersheds in the eastern United States (Walker et al., 2000). These nitrogen compounds, particularly the reduced forms such as NH_3, are available as plant nutrients and add to the eutrophication problems already of concern in these coastal areas (Paerl, 1997). Also, the State of Iowa has recently commissioned research into air emissions from concentrated animal feeding operations (CAFOs) (Iowa State University and The University of Iowa Study Group, 2002). Atmospheric NH_3 furthermore contributes to the formation of fine particulate matter by reacting with acid gases from combustion sources (Harris et al., 2001; Aneja et al., 2000).

The most significant source of NH_3 emissions (about 80%) in the United States is livestock waste (Battye et al., 1994). An increasing tendency towards industrialization of farming practices in the United States over

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Table 1
Comparison of ammonia emission factors (in kg NH_3/animal/year)

	Asman (1992) as quoted in Battye et al. (1994)				Bouwman and Van Der Hoek (1997)[a]	EMEP/CORINAIR (AEIG, 1998)[b]
	Stable and storage	Land application	Grazing	Total	Total	Total
Cattle (dairy)	7.4	12.2	3.4	23	25	28
Cattle (other)	7.4	12.2	3.4	23	9.5	14
Swine	2.5	2.8		5.4	4.8	6
Poultry (layers)	0.1	0.15		0.25	0.22	0.37
Poultry (broilers)	0.1	0.15		0.25	0.22	0.28

[a] For developed countries. Calculated from Table 4 in paper.
[b] For Europe.
Note: Decimals have been added for the purpose of tracking the source of the data and should not be construed as representing accuracy.

the last two decades has resulted in increased farm size and confinement of animals. For example, in 1991, the average swine population in North Carolina was about 4.5 million and by 1997, the number had increased to about 10 million. To better understand NH_3 emissions from large swine farms, the State of North Carolina coordinated a significant test effort during the late 90s. Initially, this program focused on waste storage lagoons because these were believed to be the major source of NH_3. Later, the focus shifted towards emissions from houses. In this paper, field test results and supporting information from the European and US scientific literature are summarized, and improved emission factors for houses and lagoons are presented. Also an emission factor for sprayfields is suggested based on a mass balance approach. The comprehensive study is documented in a report published jointly by the US Environmental Protection Agency (USEPA) and the North Carolina Department of Environment and Natural Resources (Doorn et al., 2002).

In 1994, an USEPA report was published that provided a comprehensive overview of NH_3 sources and associated emission factors (Battye et al., 1994). One of the conclusions of the report was that most research on NH_3 air emissions was concentrated in the Netherlands, Great Britain, and Denmark. The Battye report also recommended that European animal waste NH_3 emission factors, which were developed by Asman around 1990, be used in the United States.

Bouwman et al. (1997) estimate global NH_3 emissions from domestic animal waste at 21.6 teragrams nitrogen per year (Tg N/year); whereas, total global emissions from all sources were estimated at 54 Tg N/year. The overall uncertainty in the global estimate is stated to be 25%, while the uncertainty in regional emissions is much greater. The calculation of NH_3 emissions from domestic animal waste is based upon a mass balance method that uses average nitrogen excretion for different domestic animal categories and subsequent NH_3 losses during housing, storage, and land application, or grazing. Another major effort to estimate European and country-specific NH_3 emissions was undertaken under auspices of the European Union and is part of the EMEP/CORINAIR inventory (AEIG, 1998). The European Union default emission factors are based on nitrogen excretions and volatilization percentages.

As Table 1 indicates, the Asman emission factors are comparable to those of Bouwman et al. (1997) and those used in EMEP/CORINAIR. Only for beef cattle is there a major difference among the three data sets, which may be due to differences in feed.

Dutch and Danish NH_3 emission methodologies follow a mass balance approach based on the average yearly nitrogen excretion per animal type and the different emission or volatilization factors from specific emission sources; i.e., house, storage/treatment, and land application. The nitrogen excretion is the difference between the nitrogen that is ingested by the animal and the nitrogen that is ultimately bound in the agricultural product (meat, eggs, dairy). This approach takes the entire waste management pathway into account. Example calculations are provided in the Discussion section.

2. Field tests in North Carolina

Comprehensive field tests were conducted in the mid to late 90s at a swine operation in eastern North Carolina, "Farm 10" (located at approximately 76°00′W and 35°00′N). The test program at Farm 10 was coordinated by the North Carolina Department of Environment and Natural Resources (NCDENR) and included research teams from or funded by NCDENR, the US Department of Agriculture (USDA), USEPA's Air Pollution Prevention and Control Division (APPCD), North Carolina State University, and the University of North Carolina at Chapel Hill. Farm 10 is an integrated farrow-to-finish farm with nine finishing houses and four farrowing houses. The waste management system is "flush-type" with a pit under each side of the house running the length of the house. Each pit (per half house) is flushed every week (assumed) for several hours with water from the lagoon. After flushing, no water remains behind in the pits. This type of waste removal system is uncommon, because most farms now have a pull-plug system. A house with a pull-plug system has a basin under the entire house floor filled with approximately 70 cm of lagoon water. Typically, once per week this basin is drained by gravity by "pulling the plug". At the time of the tests, the total swine population at Farm 10 consisted of 7,480 finishers, 1,212 sows and boars, and 1,410 piglets; average weights were 61 kg (135 lb), 182 kg (400 lb), and 11 kg (25 lb), respectively; whereas, the average animal weight was 69 kg (151 lb).

2.1. Houses

Harris and Thompson (1998) reported seasonal NH_3 emission factors for several swine houses at the Farm 10 site in North Carolina: 7.5 g/pig/day for November 1997; 13.0 g/pig/day for January 1998; and 9.2 g/pig/day for May 1998, as well as an average emission factor of 9.9 g/pig/day. On an annual basis, these emissions are presented as 3.69 kg/pig/year with an individual seasonal range of 2.74–4.75 kg/pig/year. It should be noted that the values presented for Farm 10 are described as an "upper bound", since data were collected only during the daytime, when ambient temperatures and animal activity are highest.

Follow-up field tests were conducted at four separate feeder-to-finish farms in southern North Carolina in 2000. Each farm consisted of 10 tunnel-ventilated barns with a pull-plug waste removal system. Three barns at each farm were tested, representing young, middle, and older age groups within the production cycle. Preliminary conclusions indicate that there is no statistically significant variation in the emission factor as a function of age or weight. The most likely explanation for this is that the recycled lagoon water used to flush the pit below the barn floor provides a baseline emission source that contributes a significant portion of the barn emissions. Also, it was noted that there is a significant diurnal cycle. Based on these field tests, a preliminary emission factor of 4.31 kg/pig/year is suggested for emissions in the summer from pull-plug, feeder-to-finish operations. Seasonal work continued by this group in 2001 (Harris et al., 2001).

2.2. Lagoons

Several research groups sampled the lagoon at Farm 10 over a period of a year using different techniques (see Table 2). Aneja et al. (2000) used a flux chamber method to measure NH_3 emissions from the lagoon surface. The NH_3 was converted to nitric oxide which, in turn, was measured using a chemiluminescence technique. A micrometeorology method was used by Harper and Sharpe (1998). This technique uses a vertical array of wind speed and temperature sensors operated with the air sampling occurring in parallel. During testing, this vertical array is floated to the middle of the lagoon. Ammonia concentrations were obtained by drawing unfiltered air through gas washing bottles containing sulfuric acid at a known rate for 4 h. The resulting ammonium (NH_4^+) concentrations were analyzed using colorimetry. A third group employed a tomographic open-path Fourier transform infrared spectroscopy method to measure emissions from the lagoon. Unpublished results from this group were not used, because these were higher than theoretical emissions for the whole farm (based on a mass balance). The average emissions measured by the flux chamber method were 2.42 kg NH_3/animal/year; whereas, the average results from the micrometeorology method were 1.06 NH_3/animal/year. Both methods are considered to be established, routine techniques. As such, there is no reason to prefer one method over the other, and both were given equal weight in the ensuing analyses.

Harper and Sharpe (1998) report results for one additional field test that was conducted in 1997 at an unspecified swine farm in North Carolina (Farm 20). This farm was a farrow to wean facility, using a pull-plug waste removal system; the lagoon surface was $27,000\ m^2$. At the time of the test, Farm 20 housed 2352 piglets and 1940 sows.

2.3. Spraying operations

Effluent from the lagoon is sprayed on surrounding crop fields. Unfortunately, no NH_3 emissions from spraying operations were measured for Farm 10; however, one Georgia field study was found that pertains to NH_3 emissions from sprayfields (Sharpe and Harper, 1997). A micrometeorology method was used to determine NH_3 emissions from a sprayed oats field of $120,000\ m^2$ in Georgia. To this field, 4.5 g total N per m^2 was applied, of which 4.7 and 20.3 kg volatilized during application and post-application, respectively. This translates into a volatilization factor of 56%. Ammonia volatilization from land application of pig slurry in France (Moal et al., 1995) was estimated to be between 37% and 63% of ammoniacal nitrogen. Lorimor (1999) reports an even greater range for NH_3

Table 2
Results from ammonia emissions field tests at lagoons at two north Carolina swine farms

Field test method	Farm #	Study period	NH_3 per lagoon (kg/day)	NH_3 per animal (kg/animal/yr)	NH_3 per standard live weight (kg/kg/yr)
Flux chamber (Aneja et al., 2000)	10	August 1997	156.2	5.64	0.0821
	10	December 1997	32.8	1.19	0.0172
	10	February 1998	11.9	0.43	0.0062
	10	May 1998	66.3	2.40	0.0349
	10	Average	66.8	2.42	0.0351
Micro-meteorology (Harper and Sharpe, 1998)	10	Spring 1997 to winter 1998	28.1	0.75	0.0133
	10	Spring 1997	26.0	0.94	0.0137
	10	Summer 1997	50.5	1.82	0.0265
	10	Winter 1998	20.5	0.74	0.0107
	10	Average	31.3	1.06	0.0161
	20	Spring 1997 to winter 1998	14.7	1.25	0.0137
	20	Spring 1997	11.8	1.00	0.0112
	20	Summer 1997	13.8	1.17	0.0132
	20	Winter 1998	19.0	1.61	0.0182
	20	Average	14.8	1.26	0.0141

Notes: Decimals have been added for the purpose of tracking the source of the data and should not be construed as representing accuracy. The average weight of the pigs at farm 10 is approximately 69 kg. The different research groups used slightly different average weights to calculate emissions per live weight.

losses from land application of pig waste, 11–78% ammoniacal nitrogen.

3. Discussion

To date, the most complete US data set of NH_3 emissions based on field measurements from a full-scale swine farm is that of North Carolina Farm 10. The Farm 10 emission estimates can be compared with theoretical estimates based on the mass balance method. Because finishing pigs are the most significant sub-source category, and only emissions from finishing pig houses were collected at Farm 10, the finisher pig population was used as a base for the comparisons. No field tests were conducted at the farm's sprayfields, but an attempt was made to estimate these emissions based on volatilization percentages from the literature. Emission factors based on Farm 10 field test results are further compared to emission factors from the literature.

3.1. Mass balance

A simple estimate of total Farm 10 NH_3 emissions can be based on average manure production values, manure nitrogen content, and number of pigs. Barker (1998) provides values for average manure production by finishing pigs and the ammoniated nitrogen content thereof. Using a mean value of 5.05 kg of fresh manure per 61-kg (135-lb) finishing pig per day, 6.11 kg total Kjeldahl nitrogen (TKN) per 1000 kg of manure, ammoniated nitrogen of 62% of TKN, and a farm population of 7480 finishing pigs, we can arrive at an ammoniated nitrogen value of 143 kg per day for this finishing operation.

Doorn et al. (2002) includes a comprehensive mass balance approach that was used to estimate NH_3 emission rates for houses and the lagoon for Farm 10. These emission rates are compared to those from the field tests and the literature in Table 3. The emission rates for the houses in Table 3 show good agreement and suggest that the houses are a more significant source than previously thought. The emission rate for houses from the mass balance approach is somewhat lower than those of the field tests, but this may be due to the low-volatilization percentage that was used in the mass balance computation (15%). It is believed that there is enough evidence to recommend an emission factor for average finisher pigs based on the Harris and Thompson (1998) number, which is 3.7 ± 1.0 kg NH_3/year/finisher pig (59 ± 10 g NH_3/kg live weight/year). This value is supported by the 4.3 kg NH_3/year/finisher pig reported for summer by Harris et al. (2001).

Table 3
Summary of farm 10 emissions data[a]

Source	Activity basis	Emissions (kg/day)	Method
Entire farm	Finishers only	143	Mass balance
Houses	All pigs	64	Mass balance
Houses	Finishers only	43	Mass balance
Houses	Finishers only	76	OPFTIR[b] field test
Houses	Finishers only	56	Field test
Houses	Finishers only	33–69	European literature
Houses	Generic pigs	64	Canadian literature
Lagoon	All pigs	52	Mass balance
Lagoon	All pigs	67	Flux chamber field test
Lagoon	All pigs	31	Micrometeorology field test
Lagoon	All pigs	49	Average of 2 field tests
Lagoon	Finishers only	33	Average of 2 field tests
Sprayfields	Finishers only	19	Simple mass balance

[a] From Doorn et al. (2002, pp. 40–47).
[b] Open-path Fourier transform infrared spectroscopy.

There is surprising similarity between the field test results for the lagoon (average 49 kg/day) with the number (52 kg/day) calculated by the mass balance method in Doorn et al. (2002). Consequently, the suggested annual emission factor for NH_3 emissions from a swine farm lagoon in North Carolina becomes 26 g/kg live weight/year. This lagoon emission factor does not take vacancy and mortality into account, nor does it address differences in lagoon characteristics, such as pH, or climatological factors, such as temperature, rain, and wind. Models of emissions from lagoons as a function of these variables may be found in Aneja et al. (2000) and Harper and Sharpe (1998). Additional study of lagoons aimed at enhancing understanding of nitrogen pathways (e.g., to sludge or to N_2) will assist in further developing a comprehensive mass balance.

We may approach the spray field emissions as the difference between the total Farm 10 NH_3 simple mass balance and the emission rates determined during the studies for the house and lagoon operations. Using the simple mass balance emissions rate for the finisher population of 143 kg/day, a house rate of 76 kg per day, and the lagoon rate of 33 kg per day, we arrive at a residue of: $143 - 76 - 33 = 34$ kg applied NH_3 per day or 12,410 kg/year. Assuming that the Georgia emission factor of 56% is representative of the Farm 10 situation, we can estimate spray field emissions at 19 kg/day or 6950 kg per year. It must be recognized that spraying operations happen as relatively few events per year. As such, spraying events could be very significant during the actual spraying operations and the several days following.

There are general limitations to a nitrogen mass balance approach. Inaccuracies in the determination of the nitrogen content of manure or litter can lead to inaccuracies in estimates of NH_3 losses. Another limitation of the mass balance method is that it cannot be easily adapted to address the loop that is induced by the use of NH_3-laden lagoon water to flush and fill the pit under houses, as occurs in North Carolina pull-plug houses. However, the approach may be appropriate for a flush-type farm. The method may also be useful as an emission estimation tool in discussions regarding the closing of lagoons and alternative waste treatment methods.

4. Conclusion

The total of emissions for finishing pigs from houses (76 kg/day), lagoon (33 kg/day), and estimated spray application (19 kg/day) is 128 kg/day or 102 g NH_3/kg live weight/year. The 128 kg/day number compares well to the number from the simple total mass balance (143 kg/day). Therefore, it can be concluded that a mass balance approach can be useful in estimating NH_3 emissions from swine farms, especially those that do not employ pull-plug waste flushing technology.

The average weight of the swine at Farm 10 is 69 kg. If we assume that this swine population reflects a self-sustaining population (in other words, is similar to the average swine population in North Carolina), we can arrive at an emission factor of 7 kg NH_3/animal/year (using the 102 g NH_3/kg live weight/year number). This emission factor is a generic emission factor mainly based on field data for two farms in North Carolina for houses and one farm for lagoons. The sprayfield component was calculated using a simple mass balance approach based on nitrogen feed intake.

This emission factor is comparable to other generic European emission factors from the literature (see Table 4). This is surprising, because one would expect

Table 4
Comparison of ammonia emission factors for swine

	NH_3 emission factor (kg per animal per year)
Battye et al. (1994)	9.21[a]
Asman (1992)	5.4
Bouwman and Van Der Hoek (1997)	4.8[b]
Emission factor recommended by European Community (AEIG, 1998)	6.39
This study, based on limited field tests and theoretical sprayfield emissions estimation	7

[a] This number is now believed to be biased high, apparently due to an earlier interpretation error.
[b] Calculated from data in paper.
Note: Decimals have been added for the purpose of tracking the source of the data and should not be construed as representing accuracy.

large differences as a result of differences in climatological conditions (temperature and humidity) and in waste handling practices (use of lagoons and flushing with lagoon water as opposed to pits). The three European emission factors in Table 4 are all somewhat lower than the North Carolina emission factor. If we take the Bouwman and Van Der Hoek (1997) emission factor (5 kg/animal/year) as a lower boundary, we may suggest a range for the North Carolina emission factor of ± 2 kg/animal/year. Finally, because of the general similarity between the European and the North Carolina emission factors, it is probably acceptable to use this North Carolina factor for swine for other regions in the United States that have conditions comparable to North Carolina. However, the authors caution against adopting European emission factors for other animal categories in the United States, without making comparisons to factors developed from field tests in the United States.

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References

AEIG, 1998. Atmospheric Emission Inventory Guidebook. 1st Edition. Chapter: "Agriculture and Forestry, Manure Management". McInnes ed. EMEP/CORINAIR. European Environment Agency, Copenhagen, Denmark.

Aneja, V.P., Chauhan, J.P, Walker, J.T., 2000. Characterization of atmospheric ammonia emissions from swine waste storage and treatment lagoons. Journal of Geophysical Research 105 (D9), 11,535–11,545.

Asman, W.A.H., 1992. Ammonia emissions in Europe: updated emission and emission variations. Report No. 228471008, National Institute of Public Health and Environmental Protection. Bilthoven, The Netherlands. May 1992.

Barker, J.C., 1998. Personal communication with M. Doorn and D. Liles of ARCADIS, Inc, NCSU, Biological and Agricultural Engineering Department.

Battye, R., Battye, W., Overcash, C., Fudge, S., 1994. Development and selection of ammonia emission factors. Prepared for W.G. Benjey, U.S. Environmental Protection Agency, AREAL, Research Triangle Park, NC, EC/R, Inc., Durham, NC. Website: http://www.epa.gov//ttn/chief/efdocs/ammonia.pdf.

Bouwman, A.F., Van Der Hoek, K.W., 1997. Scenarios of animal waste production and fertilizer use and associated ammonia emission for the developing countries. Atmospheric Environment 31 (24), 4095–4102.

Bouwman, A.F., Lee, D.S., Asman, W.A.H., Dentener, F.J., Van Der Hoek, K.W., Olivier, G.J., 1997. A global high-resolution emissions inventory for ammonia. Global Biochemical Cycles 11 (4), 561–587.

Doorn, M.R.J., Natschke, D.F., Meeuwissen, P.C., 2002. Review of emission factors and methodologies to estimate ammonia emissions from animal waste handling. EPA-600/R-02-017, Office of Research and Development, United States Environmental Protection Agency, Washington, DC 20460. Website: http://www.epa.gov/appcdwww/apb/EPA-600-R-02-017.pdf.

Harper, L.A., Sharpe, R.R., 1998. Ammonia emissions from swine lagoons in the southeastern U.S. coastal plains. Final Report. Southern Piedmont Conservation Agricultural Research Center, Watkinsville, GA. Submitted to Division of Air Quality, North Carolina Department of Environment and Natural Resources, Raleigh, NC, December 1998.

Harris, D.B., Thompson Jr., E.L., 1998. Evaluation of Ammonia Emissions from Swine Operations in North Carolina. U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Research Triangle Park, NC. Presented at Emission Inventory: Living in a Global Environment Symposium. New Orleans, LA, 8–10 December 1998.

Harris, D.B., Shores, R.C., Jones, L.G., 2001. Ammonia emission factors from swine finishing operations.

International Emissions Inventory Conference, "One Atmosphere, One Inventory, Many Challenges", 10th International Emission Inventory Conference, Denver, CO. Website: http://www.epa.gov/ttn/chief/conference/ei10/index.html\#ses-1

Iowa State University and The University of Iowa Study Group, 2002. Iowa concentrated animal feeding operation air quality study. Final Report. Environmental Health Sciences Research Center, Iowa City, IA. February 2002. Website: http://www.public-health.uiowa.edu/ehsrc/CAFOstudy.htm

Lorimor, J., 1999. Ammonia Losses from Broadcast Liquid Manure. Bulletin ASL-R 1597. Agricultural and Biosystems Engineering, Iowa State University, Ames, IA.

Moal, J.F., Martinez, J., Guiziou, F., Coste, C.M., 1995. Ammonia volatilization following surface applied pig and cattle slurry in France. Journal of Agricultural Science 125, 245–252.

Paerl, H.W., 1997. Coastal eutrophication and harmful algal blooms: importance of atmospheric deposition and groundwater as "new" nitrogen and other nutrient sources. Limnology and Oceanography 42, 1154–1165.

Sharpe, R.R., Harper, L.A., 1997. Ammonia and nitrous oxide emissions from sprinkler irrigation applications of swine effluent. Journal of Environmental Quality 26, 1703–1706.

Walker, J.T., Nelson, D., Aneja, V.P., 2000. Trends in ammonium concentration in precipitation and atmospheric ammonia emissions at a Coastal Plain Site in North Carolina, USA. Environmental Science and Technology 34, 3527–3534.