Evaluation of Alternative Approaches for Developing Growth-Stage-Specific Ammonia Emission Factors for Swine Feeding Operations

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ABSTRACT

Concentrated animal feeding operations (CAFOs) are potentially significant sources of ammonia emissions. Because of the number and proximity of swine CAFOs in North Carolina, the emissions and subsequent deposition of ammonia from these operations may lead to the eutrophication of North Carolina streams and estuaries. Accurate emission inventories are needed to assess the environmental impact of these swine CAFOs. In efforts to improve ammonia emission inventories in North Carolina, a mass-balanced emission inventory was developed based on growth-stage-specific nitrogen excretion rates. This paper addresses the ammonia data available from monitoring studies of CAFOs and methods of selecting growth-stage-specific emission factors from the data set. Three approaches for developing emission inventories for North Carolina swine CAFOs are then presented and compared. For each approach, ammonia emissions are evaluated for five model CAFOs: three single growth-stage CAFOs (farrow-to-wean, wean-to-feed, and feed-to-finish) and two multiple growth-stage CAFOs (farrow-to-feed and farrow-to-finish). The results of the different emission inventories are compared and evaluated, and the advantages and limitations of the different emission factor approaches are discussed.

INTRODUCTION

The purpose of this paper is to develop a technique to estimate CAFO-specific ammonia emission estimates. The need for this technique arose from using the information available in North Carolina's database of swine CAFOs. The state conducted a survey, collecting general information about the size and locations of CAFOs actively operating in North Carolina. For each CAFO, this information included location; growth stage(s) raised; and size of the CAFO. The information collected did not include site-specific data on the type of confinement house or the types of waste management units or disposal systems. The two primary pieces of information available in the database from which to develop site-specific emission inventories are growth stages raised at each CAFO and the size of the CAFO (in number of head of swine and steady-state live weight). Therefore, an emission inventory methodology was sought to take advantage of these two pieces of data.

A process-specific emissions model is the best approach to predict emissions from the wide variety of confinement housing and waste management systems used at the CAFOs, especially where various growth stages are produced. However, the detailed site-specific data needed to apply a growth-stage- and process-specific emissions model are not currently available. To fill this gap, RTI developed an approach to derive emission factors based on growth stage and waste management process. We assessed the relative magnitude of CAFO emissions by evaluating the three primary emission sources for North Carolina swine operations: the animal confinement house, the lagoon waste storage/treatment unit, and the sprayfield (or land application area). These emission sources occur in series, so that ammonia released at one source is not available for release from downstream sources.

* RTI International is a trade name of Research Triangle Institute.

Most monitoring studies investigate only specific emission sources at a CAFO rather than characterizing all emission source at a CAFO. The utility of these one-source monitoring data are further limited by a variety of site-specific factors, including animal type and growth stage, confinement housing type, waste management system configuration, and meteorological conditions present during the study. As a result, considerable uncertainty is associated with the emission factors available for CAFOs, and indiscriminate use of reported emission factors developed from different CAFO studies can lead to inaccurate emission inventories. RTI carefully assessed emission factors reported for various one-source monitoring studies before using those in its emission inventory.

A mass-balanced emission inventory approach was desired to facilitate the evaluation of alternative waste management or control techniques for reducing CAFO emissions. Synthetic membrane covers, for example, may reduce ammonia emissions effectively from a waste storage/treatment lagoon but this suppression control technique will tend to cause higher ammonia emissions during subsequent spray application. The net ammonia emission reduction achieved by the waste management or control technique, considering all CAFO processes (i.e., the life cycle of the waste material), is needed to properly assess the environmental impacts and benefits achieved by emission reduction strategies. Mass-balance approaches have been proposed by Doorn et al. (2002) and Webb and Misselbook (2004), but none were found that specifically addressed differences in growth stage.

This paper presents RTI's approach to filling the gap in growth-stage-specific emission factors while incorporating a technique that includes a mass balance evaluation of the entire operation from point of waste generation to final disposal. The approach consists of three steps:

- Develop model CAFOs
- Review literature data on emissions specific to waste management process and growth stage
- Fill data gaps.

The results are presented as a comparison of three emission estimating techniques: by live weight, by head of swine, and by percentage ammonia loss across waste management unit. Discussion then follows on the benefits of RTI's technique to emission estimation.

APPROACH

Swine CAFOs can be characterized based on the age range of the animals raised. "Farrows" are newborn piglets that initially nurse from their mother. After about 3 weeks, the piglets are weaned from their mothers and nursed using mechanical milk dispensers; these piglets are termed "weans." After 7 to 8 weks, the young pigs can eat solid food and are called "feeder" pigs. "Finish" pigs are grown pigs ready for market. A CAFO that breeds sows to produce new litters of piglets are termed farrow-to-wean operations (i.e., they raise farrow piglets until they are weaned from their mothers). CAFOs that take newly weaned piglets and raise them until they can eat solid food are termed wean-to-feed operations. Some CAFOs may raise the piglets from birth until they can eat solid food; these are termed farrow-to-feed operations. CAFOs that take feeder pigs and raise them until they are ready to market are termed feed-to-finish operations. Some CAFOs may raise pigs from birth to market; these are termed farrow-to-finish operations.

Develop Model CAFOs

RTI classified the swine CAFOs from the state survey database into one of five growth stage categories based on the growth stages reported by each CAFO:

- Farrow-to-Wean
- Wean-to-Feed
- Farrow-to-Feed
- Farrow-to-Finish
- Feed-to-Finish.

Although wean-to-finish operations exist, they are much less common than these five types of operations. Weaned piglets contribute very little to the total mass of pigs grown (or steady-state live weight) because of their small size and the relatively short duration of this growth stage; therefore, wean-to-finish operations were included in the feed-to-finish category.

The State of North Carolina uses certain average hog weights and production assumptions to estimate the steady-state live weight on a per sow basis for operations with multiple growth stages (see http://www.soil.ncsu.edu/certification/Manual/a/chapter3A.htm#table3-1). Table 1 presents the NC average steady-state live weight values for various growth stages and for operations with multiple growth stages. Table 1 also summarizes nitrogen excretion rates developed by U.S. EPA (2001). Together, these data are used to calculate the amount of nitrogen excreted, which RTI assumes to be 100 percent ammonia or ammonium for emission estimating purposes.

Table 1. Summary of relevant swine information.

1a. Data for specific growth stages		
Swine Type	**Average Live Weight (lb/pig)[a]**	**Nitrogen Excretion Rate (lb/yr/1,000 lb)[b]**
Sows (gestating)	400[c]	70
Sows (lactating)	400[c]	171
Farrow-to-Wean	10[d]	219
Wean-to-Feed	30	219
Feed-to-Finish	135	153
Boars	400	55
1b. Assumptions and data for operations with multiple growth stages		
Parameter/CAFO Type	**Average Live Weight (lb/sow)[a]**	**Parameter Value[a]**
Number of farrow/litter		10
Number of litters/year		2
Weanling age, days		21
Farrow-to-Wean	433	
Farrow-to-Feed	522	
Farrow-to-Finish	1,417	

[a]Values used by NC in the NC hog CAFO survey, unless otherwise noted.

[b]U.S. EPA (2001), Table 8-8.

[c]NC does not distinguish between gestating and lactating sows.

[d]Not reported by NC; used value reported in U.S. EPA (2001), Table 8-9.

To perform the nitrogen mass balance for CAFOs with multiple growth stages, we needed to estimate a time-weighted average mixture of pigs in each growth stage. These values can be back-calculated from the data in Table 1. Also, because lactating sows have much higher nitrogen excretion rates than other swine, we needed to estimate the number of lactating sows relative to the total number of sows on the CAFO. Table 2 summarizes the assumptions and calculations used to estimate the average number of pigs in a given growth stage per 100 sows. The mixture of pigs presented in Table 2 yields the NC average steady-state live weights for multiple growth stage CAFOs presented in Table 1. The data in Tables 1 and 2 can be used together to calculate nitrogen excretion rates for each of the various CAFO types on a per pig or per steady-state live weight basis, as summarized in Table 3.

Table 2. Average number of swine onsite for a farrow-to-finish operation.

Animal Type	Days/Event	Average Number of Head per 100 Sows
Gestating sows	305[a]	84[b]
Lactating sows	60[a]	16[b]
Boars	365[a]	5[c]
Farrow (to Wean)	21	115[d]
Wean (to Feed)	55[c]	301[d]
Feed (to Finish)	121[c]	663[d]

[a]Days/year. Sows and boars are assumed to remain on the CAFO year-round. Sows are assumed to be lactating (or have nitrogen excretion rates equivalent to lactating sows) for 35 days/litter, with 2 litters per year.

[B]On average, 60/365 or 16% of sows are lactating.

[c]Values selected to achieve NC steady-state live weight values for multiple growth stage CAFOs.

[d]Calculated based on 2 litters/year, 10 farrows/litter, and relative duration of growth stage on the CAFO (e.g., 20 farrows/sow/year x 100 sows x 21 days to weaning/365 days/year = 115 farrows on average).

Table 3. Nitrogen and ammonia generation rates by type of swine operation.

Model Operation	Ammonia Generation Rate[a] (kg/yr/500 kg SSLW)	Ammonia Generation Rate[a] (kg NH_3/yr/pig)
Farrow-to-Wean	54	9.55
Wean-to-Feed	133	3.63
Farrow-to-Feed	113	6.13
Farrow-to-Finish	83	9.08
Feed-to-Finish	93	11.4

[a]Assumes 100 percent of the nitrogen excreted is converted to ammonia and accounts for increased molecular weight of ammonia compared to elemental nitrogen. SSLW = steady-state live weight.

Development of Emission Factors

This section presents three approaches to estimating emissions:

- Emission factors expressed on a steady-state live-weight basis (kg NH3/yr/500 kg live weight)
- Emission factors expressed on a per pig basis (kg NH3/yr/pig)
- Percent ammonia loss per source: confinement housing, lagoon, and sprayfield.

All three approaches required a review of the literature, which is described in "Data Resources" below. The data were then used for each of the three approaches to develop emission factors and percent losses. The development of these values is presented in the context of each emission source: housing, lagoon, and sprayfield.

Data Resources

The information available on swine CAFOs and reported emission studies was reviewed to identify and develop a mass-balanced emission inventory approach that accounts for growth-stage differences. A 2002 EPA publication that provides a comprehensive compilation of available emissions data (U.S. EPA, 2002) was used as the predominant literature source for this analysis. These data were supplemented by additional peer-reviewed literature.

The units of measure used for emission factors in the literature vary considerably. In attempts to put the emission factors on a common basis, original references were consulted, when available, to report emission factors both on a per animal basis and a per live-weight basis. The average animal weight during the study was also recorded, when reported. Occasionally, emission factors were reported on one basis without supporting documentation to convert the emission factor to the other basis. When this occurred, RTI used North Carolina's average pig weight per growth stage to convert the emission factor into the desired units. The following sections summarize the ammonia emissions data review by emission source: confinement housing, lagoon, and sprayfield.

Confinement Housing Emission Factors

The emission factors collected for confinement housing from the literature review for sows (farrow-to-wean CAFOs) and farrows (wean-to-feed CAFOs) are summarized in Table 4. There are very limited data to distinguish the emissions of gestating sows from those of farrowing (lactating) sows. The data from Steernvoorden et al. (1999) suggest that confinement houses containing farrowing sows may have higher emissions than similar houses containing gestating sows. However, based on tests conducted at similar confinement houses that house gestating and farrowing sows at Barham Farm (Aneja et al., 2003) there is little difference in emission factors for gestating versus farrowing sows. The differences observed in gestating and farrowing sow confinement houses are as likely to be attributed to differences in the houses or ambient conditions during the testing program as they are to actual differences in the sows. The emission factors reported for confinement houses for farrow piglets (without sows) are very similar to the emission factors reported for sow confinement houses on a per live-weight basis.

Table 5 provides confinement housing emissions factors for finishing operations. Most of these data are for feed-to-finish CAFOs, but a few of the CAFOs include sows and piglets (i.e., farrow-to-finish operations). It is interesting to note that the per pig emission factors developed from the measurements of Harris et al. (2001) were much more similar than the per live-weight emission factors. The younger feeders tend to excrete more nitrogen than older, heavier pigs on a pound-per-pound basis, suggesting that, at least for feed-to-finish operations, emissions factors developed on a per pig basis may be more appropriate. The results from Demmers et al. (1999) appear to support this hypothesis, as does a comparison of the relative standard deviations for the two different forms of the emission factors; however, the variability is considerable with either form of the emission factor.

The individual season data from Aneja et al. (2003) were included separately in Tables 4 and 5 to intentionally weight the average emission factors toward North Carolina data. Note that the emission factors developed are averaged across different building types and seasons. Therefore, these emission factors are expected to generate emission estimates that are reasonably accurate for long-term (annual) emission projections for a large number of CAFOs. The emission estimates do not take into account site-specific factors (other that growth stage), such as temperature, wind speed, or dimensions of the waste storage/treatment units. A process-specific emission model would be needed to accurately assess an individual CAFO.

In general, very few studies reported the ammonia emissions as a fraction of the nitrogen excreted within these buildings. Recent studies in North Carolina (Aneja et al., 2003) evaluated animal feed nitrogen content and feed rates as a means to estimate the nitrogen excretion rates for specific CAFOs. Consequently, for a limited number of CAFOs, confinement housing emission factors could also be assessed as a percentage of nitrogen excreted. These data are summarized in Table 6.

Table 4. Confinement housing emission factors for sows and farrows.

Researcher	Swine Type/House Type/ Location (if not U.S.)		kg NH_3/ yr/500 kg l.w.	kg NH_3/ yr/pig	Average Weight (lb/pig)
Farrow-to-Wean (based on sows)					
Groot Koerkamp et al. (1998)	Sows, litter	England	6.5	2.7	449[a]
		Germany	28.5	11.4	441[a]
	Sows, slats	England	9.2	4.4	529[a]
		Netherlands	11.2	4.7	460[a]
		Denmark	14.9	6.4	473[a]
		Germany	10.6	2.8	295[a]
Steenvoorden et al. (1999)	Gestating sows—std individual confinement	Netherlands	11.6[b]	4.2	
	Gestating sows—narrow gutter, metal slatted floor	Netherlands	6.6[b]	2.4	
	Farrowing sows—std fully slatted floor	Netherlands	21.1[c]	8.3	
	Farrowing sows—shallow manure pit with gutter	Netherlands	10.2[c]	4.0	
Aneja et al. (2003)	Gestating sows—manure pit, Barham Farm (April)		9.7	4.6	525
	Gestating sows—manure pit, Barham Farm (Nov.)		17.4	8.3	525
	Farrowing sows—manure pit, Barham Farm (April)		12.7	6.0	525
	Farrowing sows—manure pit, Barham Farm (Nov.)		11.9	5.7	525
Mean			13.0	5.4	
Wean-to-Feed (farrows without sows)					
Groot Koerkamp et al. (1998)	Farrows, slats	England	9.2	0.23	27[a]
		Netherlands	6.9	0.24	38[a]
		Denmark	13.7	0.40	32[a]
		Germany	5.7	0.19	37[b]
Mean			8.9	0.26	34

l.w. = live weight

[a]Calculated from the reported emission factors per live-weight and per pig.

[b]Converted to a mass basis using 400 lbs/pig, the average sow weight used by the State of North Carolina.

[c]Converted to a mass basis using 433 lbs/sow, the average farrow-to-wean weight used by the State of North Carolina.

Table 5. Confinement housing emission factors for finishing swine CAFOs.

Researcher	Swine Type/House Type/ Location (if not U.S.)		kg NH_3/ yr/500 kg l.w.	kg NH_3/ yr/pig	Average Weight (lb/pig)
Groot Koerkamp et al. (1998)	Finishers, litter	England	12.5	0.95	83[a]
		Denmark	32.9	3.5	116[a]
	Finishers, slats	England	22.7	1.6	79[a]
		Netherlands	18.2	3.4	204[a]
		Denmark	22.5	2.8	137[a]
		Germany	21.0	2.7	141[a]
Demmers et al. (1999)	Finishing	U.K.	47.0	2.4	55[a]
Ni et al. (2000a)	Finishing, slats with deep pits—summer		52.9	4.6	104
Ni et al. (2000b)	Finishing, slats with deep pits—spring "tranquil times"; avg. Bldg A&B		12.6	2.2	190
Steenvoorden et al. (1999)	Finishing, 50% slatted	Netherlands	20.4[b]	2.5	
	Finishing, 100% slatted	Netherlands	25.3[b]	3.1	
	Finishing, separate manure gutters	Netherlands	14.6[b]	1.8	
	Finishing, slopping floors	Netherlands	8.2[b]	1.0	
Harris and Thompson (1998)	Finishing—Nov. 1997 ventilated		22.4[b]	2.7	
	Finishing—Jan 1998 ventilated		38.7[b]	4.7	
	Finishing—May 1998 ventilated		27.5[b]	3.4	
Harris (2001)	Farrow to Finish—Summer		39.2[b]	4.8	
	Farrow to Finish—Annual		30.1[b]	3.7	
Warn et al. (1990)			15.9[b]	2.0	
Asman (1992)	Annual	Europe	20.6[b]	2.5	
Battye et al. (1994)	Annual		32.8[b]	4.0	
Van der Hoek (1998)	Annual	Europe	30.1[b]	3.7	
Harris et al. (2001)	Finishing—multiple ventilated farms, young pigs (avg. 14 wk old)		76.8	4.8	71
	Finishing—multiple ventilated farms, medium pigs (22 wk old)		22.7	3.4	167
	Finishing—multiple ventilated farms, old pigs (avg. 28 wk old)		31.4	3.9	230
Hendricks (1998) (as reported in U.S. EPA, 2002)	Finishing, ventilated, partial slats	Belgium—late summer (8/95-9/95)	31.5	4.4	165
	Finishing, ventilated, partial slats	Belgium—winter (12/94-3/95)	27.6	3.8	134
	Finishing, ventilated, partial slats	Belgium—fall to winter (9/96-2/97)	28.9	4.0	169
	Finishing, ventilated, partial slats	Belgium—fall to winter (9/96-1/97)	17.5[c]	2.5[c]	57[c]
Aneja et al. (2003)[d]	Finishing, Stokes Farm—natural ventilation (Oct. 2002)		2.1	0.45	230
	Finishing, Stokes Farm—natural ventilation (Jan. 2003)		7.7	1.4	195
	Finishing, Corbett #2 Farm—natural ventilation (March 2003)		3.8	0.75	217
	Finishing, Corbett #2 Farm—natural ventilation (June 2003)		15.6	2.2	155
	Finishing, Moore Farm—ventilated (Oct. 2002)		33.1	3.5	115
	Finishing, Moore Farm—ventilated (Febr. 2003)		28.1	3.8	148
	Finishing, Grinnell's Lab—ventilated (April 2002)		40.0	3.9	107
	Finishing, Grinnell's Lab—ventilated (Nov. 2002)		20.9	2.1	113
	Finishing, Howard Farm—ventilated (June 2002)		44.8	5.8	142
	Finishing, Howard Farm—ventilated (Dec. 2002)		26.7	5.2	213
Mean			21.0	3.2	146

[a]Calculated from the reported emission factor per live-weight and per pig.

[b]Converted to a mass basis using 135 lbs/pig, the average finishing pig weight used by the State of North Carolina.

[c]There appears to be some discrepancy in the reported emission factors based on the reported average pig weight.

[d]Converted nitrogen emission factors to ammonia emission factors by multiplying by 17/14.

Table 6. Emissions factors for confinement housing as a percent of nitrogen excreted.

Researcher	Swine Type/House Type/ Location (if not U.S.)	kg N excreted/ yr/500 kg l.w.	kg N emitted/ yr/500 kg l.w.	Emissions as a % of N excreted
Farrow-to-Wean (based on sows)				
Aneja et al. (2003)	Gestating sows—manure pit, Barham Farm (April)	34	8.0	23.5%
	Gestating sows—manure pit, Barham Farm (Nov.)	36	14.4	39.9%
	Farrowing sows—manure pit, Barham Farm (April)	89	10.4	11.7%
	Farrowing sows—manure pit, Barham Farm (Nov.)	99	9.9	10.0%
Poulson and Kristensen (1998)	Gestating sows—various housing designs			14 to 20%
	Farrowing sows—various housing designs			10 to 15%
Wean-to-Feed (farrows without sows)				
Poulson and Kristensen (1998)	Piglets—various housing designs			15 to 25%
Farrow-to-Finish, Feed-to-Finish (finishing farms)				
Aneja et al. (2003)	Finishing, Stokes Farm—natural ventilation (Oct. 2002)	70.4	1.75	2.5%
	Finishing, Stokes Farm—natural ventilation (Jan. 2003)	66.6	6.4	9.6%
	Finishing, Corbett #2 Farm—natural ventilation (March 2003)	83.0	3.15	3.8%
	Finishing, Corbett #2 Farm—natural ventilation (June 2003)	117	12.9	11.0%
	Finishing, Moore Farm—ventilated (Oct. 2002)	114	27.2	23.9%
	Finishing, Moore Farm—ventilated (Febr. 2003)	101	23.1	22.9%
	Finishing, Grinnell's Lab—ventilated (April 2002)	88.0	32.9	37.4%
	Finishing, Grinnell's Lab—ventilated (Nov. 2002)	135	17.3	12.8%
	Finishing, Howard Farm—ventilated (June 2002)	97.0	36.9	38.0%
	Finishing, Howard Farm—ventilated (Dec. 2002)	65.9	22.0	33.4%
Poulson and Kristensen (1998)	Finishing—various housing designs			15 to 18%

l.v. = live weight.

Lagoon Emission Factors

Table 7 summarizes the emission factors available for lagoons. Because of the influence of temperature on lagoon emissions, the literature review focused on emissions data reported for North Carolina lagoons. The best data available for lagoon emission factors were for finishing operations, where two independent researchers conducted lagoon emission measurements over the course of a year. One of these studies (Harper and Sharpe, 1998) also reported measurements made for a lagoon at a farrow-to-wean operation. Although other lagoon emission measurements were made during recent studies in North Carolina (Aneja et al., 2003), these other operations use innovative technologies that are expected to alter the emissions from the lagoons. Consequently, only data from the "conventional" operations were used.

Reviewing Harper and Sharpe's (1998) results, there appears to be no significant difference in lagoon emission factors developed for the farrow-to-wean and finishing operations when expressed on a per pig basis. Furthermore, there is surprising agreement in emission factors developed for different finishing operations when expressed on a per pig basis. For two of the CAFOs, nitrogen excretion rates were estimated (based on nitrogen content in the feed and feed rates), and confinement housing emission rates were measured. After accounting for nitrogen loss from the confinement houses, the amount of ammonia entering the lagoon was calculated assuming that all of the nitrogen entering the lagoon is

Table 7. Lagoon emission factors.

Researcher	Swine Type	kg NH_3/ CAFO/day	kg NH_3/ pig/yr	kg NH_3/ 500 kg l.w./yr	% NH_3 Emitted
Farrow-to-Wean					
Harper & Sharpe (1998), NC Farm 20	Farrow-to-Wean	14.8	2.8	7.1[a]	
Farrows Without Sows (Wean-to-Feed)					
No data					
Finishing (Farrow-to-Finish, Feed-to-Finish)					
Aneja et al. (2000), NC Farm 10	Farrow-to-Finish	66.8	2.8	18[b]	
Harper and Sharpe (1998), NC Farm 10	Farrow-to-Finish	31.3	1.3	8.4[b]	
Aneja et al. (2003), Moore Farm—Sept.	Feed-to-Finish	92.7[c]	4.4	42.5	40%
Aneja et al. (2003), Moore Farm—Jan.	Feed-to-Finish	21.4[c]	1.35	10	10.6%
Average for Moore Farm			2.9	26	25%
Aneja et al. (2003), Stokes Farm—Sept.	Feed-to-Finish	60.0[c]	5.0	24	29%
Aneja et al. (2003), Stokes Farm—Jan.	Feed-to-Finish	5.8[c]	0.57	3.2	4.4%
Average for Stokes Farm			2.8	14	17%
Mean			**2.5**[d]	**17**[d]	**21%**

l.v. = live weight.

[a]Emission rate converted to a per pig basis based on the number of sows and to a live-weight basis based on 2,352 piglets (25 lbs) + 1,940 sows (400 lbs) = 834,800 lbs or 378,660 kg live-weight. Also assumes emissions occur 365 days/yr.

[b]Emission rate converted to a per pig basis based on the number of finishing pigs plus sows and to a live-weight basis based on 7,480 finishing pigs (135 lbs) + 1,212 sows (400 lbs) = 1,494,600 lbs or 678,000 kg live-weight. Also assumes emissions occur 365 days/yr.

[c]Estimated from area adjusted graph in appendix of cited reference and the number and weight of pigs reported in the cited reference.

[d]Mean emission factors for finishing operations were calculated using the average Moore Farm, the average Stokes Farm, and the two independent measurements for Farm 10.

available for ammonia volatilization. For these lagoons, emission factors are also presented as a percent of ammonia (nitrogen × 17/14) entering the lagoon.

Sprayfield Emission Factors

Most North Carolina swine CAFOs practice spray irrigation of the lagoon effluent as their final waste management stage. This method does not physically incorporate the effluent into the soil. Only a limited number of emission studies have been conducted for these types of sprayfields. Table 8 provides a summary of the sprayfield emission factors reported in the literature. The ammonia emission factors exhibit significant variability and are highly dependent on the meteorological conditions at the time of application. Cure et al. (1999) assumed that 25 percent of the ammonia remaining in the lagoon effluent is emitted during spray application and that an additional 30 percent of the ammonia that reaches the ground subsequently volatilizes from the soil surface (rather than being taken up by the vegetation), but provided no measurement data to support these assumptions. The data of Sharpe and Harper (1997) and Al-Kaisi and Waskom (2002) suggest that more of the losses occur postapplication; however, the overall spray application emission factor used by Cure et al. (47.5 percent of the ammonia in the lagoon effluent) compares well with the measured emissions for sprayfields.

Unlike the housing and lagoon emission factors, all of the sprayfield emission factors are reported in terms of percent of nitrogen (or ammonia-nitrogen). Within the lagoon, there may be losses of ammonia other than volatilization, such as seepage (leaching) and solids settling. RTI assumed in this analysis that these other loss mechanisms were minimal and that 100 percent of the nitrogen that enters

Table 8. Emissions factors for swine lagoon effluent spray application.

Researcher	% N loss during spraying	% N loss post-application	Total Sprayfield %N loss
Sharpe and Harper (1997)	10%	45%	55%
Sullivan et al. (2000)			9 to 28%
Al-Kaisi and Waskom (2002)	8 to 27%	24 to 56%	32 to 83% (avg. 58%)
Safely et al. (1992)			15 to 43%
Lockyer et al. (1989)			36 to 78%
Sharpe and Harper (2002)	12%	23%	35%

the lagoon is available for release as ammonia (being converted to ammonium at some point during collection, storage, and treatment).

Fill Data Gaps

Due to the general lack of emissions data for farrow-to-feed operations, emission factors for farrow-to-wean and wean-to-feed CAFOs were used to estimate the emissions factors for farrow-to-feed CAFOs. The factors were weighted by the relative proportion of live weight, number of animals, or nitrogen excreted for the mixed growth-stage, farrow-to-feed model CAFO. For the lagoon, no data were available for either wean-to-feed or farrow-to-feed operations. The lagoon emission factors for these model CAFOs were estimated by assuming that the lagoon emission factors on a per live-weight (or per pig basis) were proportional to the farrow-to-wean lagoon emission factor and the ratio of corresponding confinement housing emission factors. Since no data were available for any farrowing farm on a percent loss basis, all growth stages were assigned the same percent loss emission factor for lagoons.

RESULTS

Based on the literature review, the emission factors in Table 9 were selected for the model evaluation. Three different approaches were used:

- Emission factors on a mass live-weight basis
- Emission factors on a per pig (or head) basis
- Percent ammonia loss across the waste management unit.

In developing the per pig emission factors, unweaned farrows were not included in the head count, but weaned farrows (“weans”) and finishing pigs were included in the head count (if present for that model CAFO).

The three growth-stage-specific emission inventory approaches were compared to two generalized emission inventory methods currently used by the U.S. Environmental Protection Agency (EPA). The first of these (U.S. EPA, 2001) uses emission factors based on EPA’s Office of Water definition of an animal unit (AU). An animal unit equals 2.5 swine weighing over 55 pounds or 10 swine weighing 55 pounds or less; there is no special consideration for sows in this approach. The U.S. EPA (2001) approach provides slightly different emission factors based on housing type, but the average value for the different housing types are reasonably similar.

Table 9. Selected growth-stage-specific emission factors compared to other inventory factors.

Swine Animal Type	Selected Growth-Stage Specific Emission Factors			U.S. EPA (2001) Emission Factor (kg/yr/AU)[b]	U.S. EPA (2004) Emission Factors[c]
	Emission Factor (kg NH_3/yr per 500 kg l.w.)	Emission Factor (kg NH_3/yr/pig)[a]	% NH_3 loss across unit		
Confinement Housing					
Farrow-to-Wean	13.0	5.4	24%	6.2	2.7 (kg/yr/head)
Wean-to-Feed	8.9	0.26	20%		
Farrow-to-Feed	12.3	1.5	22%		
Farrow-to-Finish	21	3.2	19%		
Feed-to-Finish	21	3.2	19%		
Lagoon					
Farrow-to-Wean	7.1	2.8	21%	8.3	71%
Wean-to-Feed	4.9	0.13	21%		
Farrow-to-Feed	6.7	0.78	21%		
Farrow-to-Finish	17	2.5	21%		
Feed-to-Finish	17	2.5	21%		
Sprayfield					
All growth stages	50%	50%	50%	13.2	27.5%

l.w. = live weight.

[a]Number of pigs (head) present at CAFO, excluding unweaned farrows.

[b]Emission factor reported in U.S. EPA (2001); animal unit (AU) is based of EPA's Office of Water definition = 2.5 swine weighing over 55 pounds or 10 swine weighing 55 pounds or less; housing factor based on house with pull-plug pit.

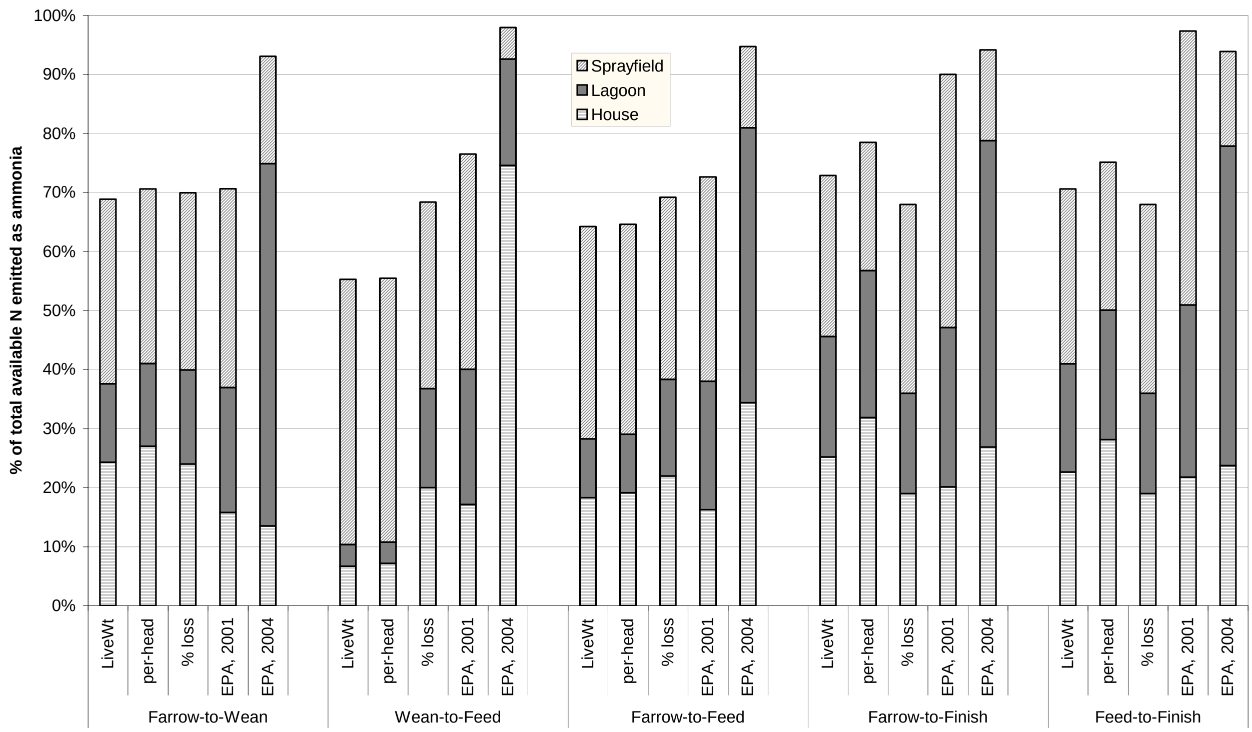
[c]Number of pigs (head) present at CAFO excluding unweaned farrows.

The second of these approaches (U.S. EPA, 2004), which is used in the National Emissions Inventory (NEI), uses a housing emission factor reported on a per head basis and then derives a percent loss emission factor for the lagoon and sprayfield. The NEI has two separate model swine CAFOs: one for deep-pit confinement houses (no separate lagoon) and one for other confinement houses used in conjunction with an anaerobic lagoon. Comparison is made to the emission factors developed for the latter of these two NEI model swine CAFOs. The emission factors used for these generalized emission inventory methods are also presented in Table 9.

Each emission factor approach presented in Table 9 was used to project the emissions from each of the five model CAFOs described previously (see Tables 1 through 3). Consistent with the development of the per pig emission factors, unweaned farrows were not counted toward the total number of head; however, unweaned farrows were included in the animal unit count. This was done primarily as a means to offset the lack of a separate sow distinction in the animal unit paradigm, and also because no direct instructions were given in the animal unit paradigm not to count farrows.

The results of the modeling efforts are illustrated in Figure 1. The results are all normalized to the total potential ammonia emissions (assuming all excreted nitrogen converts to ammonia) for each model CAFO.

Figure 1. Comparison of alternative modeling approaches by growth stage.



DISCUSSION

All of the growth-stage-specific modeling approaches yielded comparable results for all of the growth stages, except for wean-to-feed operations. In that case, the lack of data and the assumptions used to fill the data gaps significantly impact the wean-to-feed emissions results.

Of the three growth-stage-specific models, the percent nitrogen loss approach provides the best means to account for emissions, especially those that affect the confinement houses. This is because percent emissions can accommodate changes in nitrogen mass. The fixed emission factors for the confinement building and lagoon do not lend themselves as easily to changes in excretion rate based on dietary changes. Hayes et al. (2004) demonstrated that increasing the crude protein level in the diet (i.e., using higher nitrogen feed rates) increased the emissions from finishing pig confinement houses. Only the percent loss approach would yield higher confinement house emissions given higher nitrogen feed/excretion rates. The other approaches would only show increases in the sprayfield (or lagoon and sprayfield for the NEI approach). Also, it is interesting how similar the percent loss emission factors are across growth stages. Although this may be a result of limited data, the processes for which emissions occur in these confinement buildings and lagoons are expected to be kinetically first-order with respect to ammonia concentrations. As such, the percent loss approach is primarily dependent on the nitrogen excretion rates (which are growth-stage specific) and the percent loss emission factors themselves can be considered insensitive to growth stage.

The animal unit approach (U.S. EPA, 2001) compares reasonably well with the growth-stage-specific emission factor approach, except for feed-to-finish pigs. Because the animal unit approach uses fixed emission factors for all process units, the emission projections are not a function of nitrogen excretion rates or availability. If we had assumed that 5 percent of the nitrogen was not available for ammonia emissions (because it was either emitted as nitrogen oxides or fixed in solids), this approach would project ammonia emissions that violate mass balance.

The NEI approach (U.S. EPA, 2004) appears to overestimate the ammonia emissions, especially for farrow-to wean, wean-to-feed, and farrow-to-feed model CAFOs. Usually, the high emissions estimated by this approach are a result of the 71 percent loss from the anaerobic lagoon; however, the fixed per-head housing emission factor significantly overestimates the confinement house losses for wean-to-feed CAFOs.

CONCLUSIONS

Several conclusions can be drawn from this analysis:

- The mass balance, growth-stage approach provides an accurate and versatile tool for developing emission inventories on a state or national level.

- Depending on the format of the emission factors used, emission factors may differ by growth stage. Therefore, emission estimators should not assume that an emission factor for one growth stage fits all growth stages, but instead should preferentially develop growth-stage-specific emission factors.

- Significant gaps exist in emission measurement data by growth stage, especially for wean-to-feed and farrow-to-feed CAFOs.

- Using percent loss emission factors based on a nitrogen/ammonia mass balance appears to yield very consistent emission factors for different growth stages. This approach of using a nitrogen/ammonia mass balance coupled with unit-specific percent loss factors is a versatile way to account for growth-stage-specific emission differences and to assess the impacts of alternative emission reduction techniques, as well as nitrogen feed control.

- The approaches developed by RTI for estimating growth-stage-specific ammonia emissions are primarily applicable to large-scale, annual average emission inventories. Given the dependence of the emissions on ventilation rate, lagoon dimensions, temperature, and other variables, a process-specific model is needed to more accurately assess site-specific or short-term emissions. WATER9 is a process-specific model that was originally developed to predict volatile organic emissions from comparable waste management technologies. RTI is currently expanding the WATER9 modeling system, under contract to EPA, to include ammonia and CAFO-related processes.

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