PREDICTING NH_3 EMISSIONS FROM MANURE N FOR CAGED LAYER FACILITIES. A MODIFIED MASS BALANCE APPROACH.

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ABSTRACT. *NH_3 levels and resulting emissions during the handling of manure within animal-production facilities have significant health, safety, odor-generation, and environmental impacts. Determining such emissions is costly using current approaches of monitoring ammonia concentrations and airflow from facilities. This paper looks at using N-balances to bound the upper limit on emissions. The analysis uses a controlled volume approach for inputs and outputs from the system and N/ash ratios. It does not require measuring total masses of materials into and from the system. Generalized equations for predicting emissions from all classes of livestock operations was presented. Research using this N-balance method was simply, low cost, and accurate (based on results and reported literature values) in predicting upper limits on NH_3 emissions in the air leaving a 1.6 million caged layer poultry facility using two types of manure management: belt/composting and deep pit. Specific results based on the study showed clear advantages of belt/composting over conventional deep-pit systems, with N retention in compost of 0.559 kg bird^{-1} yr^{-1} versus 0.265 kg bird^{-1} yr^{-1} in deep-pit manure. Total emissions were half that of the conventional caged layer systems.*

Keywords. *Composting, ammonia, emissions, poultry manure, nitrogen balance, odor.*

During the past decade, emissions from concentrated feeding livestock facilities have become a significant environmental issue as it relates to odors and greenhouse gases, in particular NH_3. Already, in Western Europe, legislation is in place to require the reduction of NH_3 emissions by up to 50% (Groot Koerkamp, 1994). This issue is a major constraint to the profitability and growth of livestock industries and mandate new approaches to livestock housing and manure management. Evaluating the effects of these new methods on emissions from livestock buildings for full scale operations can be quite expensive and labor intensive using current methodologies of continuous monitoring of airflows and emission levels (Heber et al., 2001; NRC 2003).

Battye et al. (1994) developed a report for the U.S. Environmental Protection Agency on ammonia emission factors from livestock and cites values of 0.305 kg NH_3 animal^{-1} year^{-1} for laying hens >18 weeks of age (pullets) and 0.598 kg NH_3 animal^{-1} year^{-1} for hens >6 months of age. The problem with using results in the Battye report for decision making at the farm level was its generality, i.e., it was not specific to individual styles of management.

Groot Koerkamp (1994) reviewed poultry housing systems and ammonia emissions from them. Results of those studies on yearly emissions gave values for caged layer deep-pit systems of 0.386 kg NH_3 bird^{-1} and for belt systems 0.034 kg NH_3 bird^{-1}. No data were given on losses during drying or composting used in combination with the manure belt system. Yang et al. (2000) looked at nitrogen losses from four deep-pit caged layer facilities in Iowa using a mass balance approach and measured 25% to 41% losses of nitrogen from the system. Emissions were 0.279 ±0.040 kg NH_3 bird^{-1} yr^{-1}. Again, no studies were conducted on manure handling systems with composting.

The goal of this study was to develop the theory for a modified mass balance approach to predicting NH_3-N emissions and apply this method to a 1.6 million bird poultry facility in Ohio using two types of manure management: belt/composting and deep pit.

THEORY

N BALANCES TO PREDICT AMMONIA EMISSIONS

Figure 1 is a schematic of an animal production system showing inputs and outputs, generalized for the case of body growth, milk and egg production. It also includes morality and leachate as materials leaving the system. Analysis of this production system for NH_3-N assumes no other gaseous losses of N.

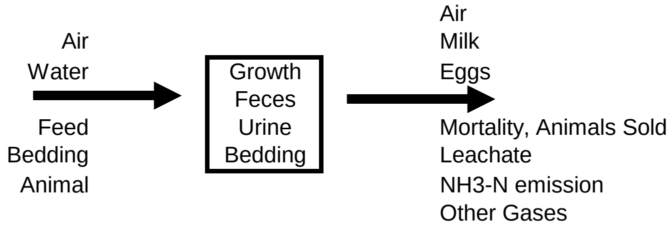

Figure 1. Flow diagram of animal production system showing inputs, storage and output variables.

To simplified the presentation of equations used in the analysis the notations presented in Table 1 were adopted. The nitrogen balance for the system based on ($N_{storage} = N_{in} - N_{out}$) is given by

$$\sum_{i=6}^{9} x_{Ni} \frac{dm_i}{d\theta} \cong \sum_{i=1}^{5} x_{Ni} m_i' - \sum_{i=10}^{14} x_{Ni} m_i' - N_{15} \qquad (1)$$

For an ash balance on the system the equation is

$$\sum_{i=6}^{9} x_{Ai} \frac{dm_i}{d\theta} = \sum_{i=1}^{5} x_{Ai} m_i' - \sum_{i=10}^{14} x_{Ai} m_i' \qquad (2)$$

Table 1. Variables and nomenclature used in mass balance equations for prediction NH_3-N emissions from livestock facilities.

Variables
θ = time, day
m_i = mass of i, kg
mi' = mass flow rate, kg/day
dmi/dθ = rate of change, kg/day
x_{Ni} = nitrogen content, dec
x_{Ai} = ash content, dec.
Ri - x_{Ni}/x_{Ai}, nitrogen to ash ratio, dec
Ni = total nitrogen in i, kg/day
Subscript
i = …….
1, air in
2, water in
3, feed in
4, bedding in
5, animals in

Subscript
i =
6, growth of animals in system
7, feces in system
8, urine in system
9, bedding in system
10, air out of system
11, milk out of system
12, eggs out of system
13, mortality, animals sold out of system
….14, leachate
….15, NH3-N emission
A, ash
N, nitrogen
M, manure

Solving equation 1 for N_{15} (the nitrogen emitted as NH_3-N gives

$$N_{15} \le \sum_{i=1}^{5} x_{Ni} m_i' - \sum_{i=6}^{9} x_{Ni} \frac{dm_i}{d\theta} - \sum_{i=10}^{14} x_{Ni} m_i' \qquad (3)$$

$$= \sum_{i=3}^{5} x_{Ni} m_i' - x_{N6} \frac{dm_6}{d\theta} - \sum_{i=7}^{9} x_{Ni} \frac{dm_i}{d\theta} - \sum_{i=11}^{14} x_{Ni} m_i'$$

The final form of (3) assumes N in the air entering the system passes through the system and no N is in the water entering the system. The term $\sum_{i=7}^{9} x_{Ni} \frac{dm_i}{d\theta}$ is the total nitrogen in the manure.

Using equation 2, the total ash in the manure is given by

$$\sum_{i=7}^{9} x_{Ai} \frac{dm_i}{d\theta} = \sum_{i=3}^{5} x_{Ai} m_i' - x_{A6} \frac{dm_6}{d\theta} - \sum_{i=11}^{14} x_{Ai} m_i' \qquad (4)$$

Now from sampling the manure and laboratory analysis the manure N/A ratio, R_M, can be evaluate. But it is also true that

$$R_M = \sum_{i=7}^{9} x_{Ni} \frac{dm_i}{d\theta} \Big/ \sum_{i=7}^{9} x_{Ai} \frac{dm_i}{d\theta} \qquad (5)$$

Substituting (5) and (4) into (3) gives

$$N_{15} \leq \sum_{i=3}^{5} x_{Ni} m_i' - x_{N6} \frac{dm_6}{d\theta} - \sum_{i=11}^{14} x_{Ni} m_i' - R_m \left[\sum_{i=3}^{5} x_{Ai} m_i' - x_{A6} \frac{dm_6}{d\theta} - \sum_{i=11}^{14} x_{Ai} m_i' \right] \qquad (6)$$

The advantage of (6) over (1) for doing N mass balance and estimating NH_3-N losses is no weighting of the manure is required. A second advantage of (6) compared to the conventional method of continuous sampling of airflow rates and NH_3-N concentration for exhausting air is avoidance of the high equipment cost, maintenance and labor to operate continuous monitoring equipment. However, this method does not distinguished for losses of N as N_2 or NO_x's. Also, it would not predict daily cycles in emissions or maximum concentrations. It can however, provide an accurate estimate of the maximum theoretical levels for NH_3-N emissions over long production cycles (several days to months) if sampling gives good precision. As such, results are to be interpreted as daily, weekly or yearly averages.

Keener et al., (2002) used this method for analysis of two types of caged layer facilities. Information from that paper are presented here to illustrate how the method can be applied. In that study, results using the modified mass balance approach were compared with measured emissions based on airflows and exhaust NH_3-N concentrations and with published literature. For analysis purposes, it was assumed the terms $\frac{dm_6}{d\theta}$, m_4', m_5', m_{11}', m_{13}' and m_{14}' were ≅ zero. Because the birds were mature, the assumption on $\frac{dm_6}{d\theta}$ (i.e. changes in their body composition, storage or release of ash and nitrogen) could be justified. Also, no bedding was used, no animals were placed, no milk was produced, mortality was very low, and no leachate was observed during the analysis periods. The following equation for yearly emission was used in presenting their results, where n_b was the number of birds in the building.

$$EM_{NH3\text{-}N} = 365\ N_{15}/n_b \quad (\text{kg } NH_3\text{-N bird}^{-1}\ \text{yr}^{-1}), \qquad (7)$$

EXPERIMENTAL FACILITIES

The Mad River facility of the Daylay Egg Farm, located near West Mansfield, Ohio, is a modern, 1.6 million bird, caged layer facility for the production of chicken eggs (fig. 2). The birds are housed in a total of eight buildings. Four buildings are of the deep-pit design and house 150,000 birds each. Manure is removed yearly from these buildings and directly land applied. The other four buildings were built in a 1997 expansion and house 250,000 birds each. They incorporate a belt conveyor system for manure removal. Manure on the belt is delivered to two separate buildings (12 lanes and 6 lanes, respectively) where it is composted, using Salmet composters, into a dry product suitable for fertilizer applications.

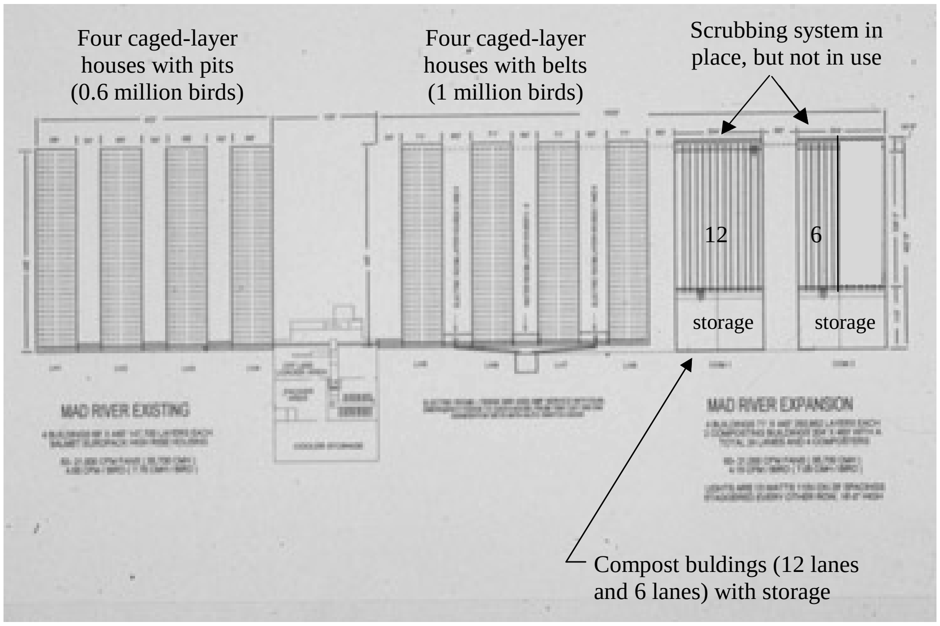

Figure 2. Schematic of the Daylay Mad River facility (Keener, et al., 2002).

All of the buildings have significant ventilation. The deep-pit caged layer houses each have 36 side-mounted hooded fans (18 per side) located in the pit area, which draw air down across the birds (maximum rate 0.13 m^3 min^{-1} $bird^{-1}$, 4.7 cfm $bird^{-1}$) and out. The new layer buildings are vented through the roof using a bank of nine large computer-controlled fans on each house (0.119 m^3 min^{-1} $bird^{-1}$, 4.2 cfm $bird^{-1}$). Inlets are located along the entire sidewall length. The composting buildings are vented at one end using eight fans on one building and four fans on the other, each with a capacity of 566 m^3 min^{-1} (20,000 cfm).

EXPERIMENTAL PROCEDURE

Sampling data on ammonia measurements were made on 22-23 March and 17-18 July 2000 in cooperation with the Wisconsin Department of Natural Resources (Keener, et al., 2002). Instantaneous ammonia concentration measurements were made from deep-pit caged layer houses 1 and 4 at the exit of the hooded exhaust fans using colorimetric stain tubes with ranges of 0.25 to 3 ppm, 2 to 30 ppm, or 5 to 70 ppm, ±15% error (National Dräger Inc., Pittsburgh, Pa.). These measurements were also made for belt caged layer house 8 at the entrance to the exhaust fans and for the two compost buildings at the exit from the shuttered fans. Airflows from fans were based on rated capacity and no verification of accuracy was attempted, as random operation of fans was a much greater source of error. Results from calculations using airflows were used only as a gauge of the range for NH_3 emissions and not a prediction of absolute amounts lost.

On day 2 of each test, manure and compost samples were collected. Eight manure samples were collected from the four deep-pit caged layer houses, two from each house. Each sample was a composite of grab samples from the top or the middle of the manure windrows at four or five different locations. For the four caged layer houses using manure belts, five manure samples were collected randomly over a 30-minute interval from the cross conveyor belt transferring manure to the compost building. For the compost buildings, five samples of finished compost were collected, one each from lanes 2, 6, and 10 in building 1 and from lanes 2 and 4 in building 2. All samples were sent to the OARDC/OSU analytical laboratory for analysis of pH, solids, ash, total carbon, inorganic carbon, NH_3-N, NO_3-N, and total N. The feed was analyzed for moisture, ash, and nitrogen. Values used for egg composition were estimated from general literature. Solution of the mass balance made use of the fact that feeding rate was known on a per bird basis and that ash per bird could be defined at all points in the system.

RESULTS

Table 2 gives chemical composition of feed, eggs, deep-pit manure (buildings 1-4), belt manure (buildings 5-8) and compost (compost buildings). The deep-pit manure had an N content of 2.94% ±0.81 and 4.02% ±0.77 for March and July, respectively. Belt manure was 1 to 3 days old and had an N content of 5.66% ±0.99 in March and 5.87% ±0.48 in July. The compost had an N content of 6.22% ±0.24 for March and 5.58% ±0.57 for July.

Table 2. Mean (µ) and standard deviation (sd) of chemical analysis of feed, egg, manures, and compost used in nitrogen balances for Daylay facilities on 22 March and 18 July 2000 (Keener et al., 2002)

Description		pH	DM (%)	Ash (%)	TC (%)	IC (%)	N (%)	NH_3-N ($\mu g\ g^{-1}$)	NO_3-N ($\mu g\ g^{-1}$)	C/N
Feed input	µ		89.60	13.73			2.82			
	sd		0.15	0.65			0.31			
Eggs	--		34.10	10.00			2.05			
22 March 2000										
Deep-pit manure	µ	8.48	40.20	48.42	26.91	3.39	2.94	19038	81.1	9.51
(buildings 1-4)	sd	0.19	10.05	9.09	3.83	0.67	0.81	11295	23.9	1.88
Belt manure	µ	7.48	46.99	30.26	33.37	1.94	5.66	6810.9	232.4	6.03
(buildings 5-8)	sd	0.29	6.65	1.96	1.06	0.31	0.99	2631.4	57.3	0.94
Compost buildings	µ	8.43	82.02	37.18	31.11	2.14	6.22	8150.2	256.1	5.00
	sd	0.11	0.97	1.80	1.07	0.23	0.24	763.3	38.7	0.15
18 July 2000										
Deep-pit manure	µ	8.47	70.81	43.97	28.96	2.78	4.02	4782.9	93.8	7.41
(buildings 1-4)	sd	0.16	12.19	5.08	1.76	0.44	0.77	1551.6	14.1	1.33
Belt manure	µ	7.98	51.71	30.74	33.85	1.68	5.87	6566.3	211.9	5.79
(buildings 5-8)	sd	0.24	8.07	3.41	2.25	0.38	0.48	2578.1	24.7	0.56
Compost buildings	µ	7.87	90.20	34.08	32.28	1.92	5.58	4846.6	213.1	5.83
	sd	0.08	0.91	1.32	1.11	0.14	0.57	1245.4	37.4	0.59

Table 3 summarizes the nitrogen balances for two caged layer manure management systems based on N fed to the animal, N in the eggs produced, and N retained in the manure or compost. Results showed that the average N retained for the March and July studies was 0.559 kg bird^{-1} yr^{-1} and 0.265 kg bird^{-1} yr^{-1} for the belt/compost system compost and conventional deep-pit manure, respectively. This represented 81.1% and 38.5% of N excreted by the birds, respectively.

Table 3. Nitrogen balance (kg bird^{-1} yr^{-1}) for Daylay operation, March and July 2000 (Keener et al., 2002)

System[a]	Measured Variable	Feed N	Egg N	N, DP or CB	NH_3-N, DP or CLB	NH_3-N, CB	NH_3-N Emissions
March							
CLDP	Manure N	0.821	0.132	0.217			0.472[b]
CLDP	NH_3 loss	0.821	0.132		0.550		0.550
CLB-CB	Compost N	0.821	0.132	0.564	0.054[b]	0.071[b]	0.125[b]
CLB-CB	NH_3 loss	0.821	0.132		0.179[c]	0.258[c]	0.437[c]
July							
CLDP	Manure N	0.821	0.132	0.313			0.376[b]
CLDP	NH_3 loss	0.821	0.132		0.513		0.513
CLB-CB	Compost N	0.821	0.132	0.553	0.038[b]	0.098[b]	0.136[b]
CLB-CB	NH_3 loss	0.821	0.132		0.039	0.186	0.225

[a] CLDP = caged layer deep-pit manure storage, CLB = caged layer manure belt, and CB = compost building.

[b] Remainder term using (feed N - egg N - manure N) or (feed N - egg N - compost N).

[c] Values believed to be high. Caged layer fans were being modulated. Compost building fans were not in full operation.

Table 3 also lists the nitrogen emissions results for March and July. Nitrogen emission during March, based on manure N levels, for a conventional caged layer deep-pit system (CLDP) was 0.472 kg (1.040 lb) N bird^{-1} yr^{-1}. This would be 0.573 kg NH_3 bird^{-1} yr^{-1} and is very similar to the value that Battye et al. (1994) reported of 0.598 kg NH_3 bird^{-1} yr^{-1} for laying hens >6 months of age. Nitrogen emission during March, based on compost N level, for the belt/compost caged layer system (CLB-CB) was calculated to be 0.125 kg (0.276 lb) N bird^{-1} yr^{-1}. This would be 0.152 kg NH_3 bird^{-1} yr^{-1} and is 25% of the value for the deep-pit system. For the CLDP and CLB-CB systems, the calculated NH_3-N loss using estimated airflow rates and measured ammonia concentrations in the exhaust air were 0.550 and 0.437 kg (1.213 and 0.963 lb) N bird^{-1} yr^{-1}, respectively. Losses of NH_3 only from the layer building for the CLB-CB system were estimated at 0.217 kg bird^{-1} yr^{-1}, compared to 0.034 kg bird^{-1} yr^{-1} cited by Groot Koerkamp (1994). Results using airflows and NH_3 concentrations were approximate because airflows were varying during the data collection period. For the conventional deep-pit caged layer system, the exhaust streams measured 5 to 60 ppm NH_3 v/v when all exhaust fans (32 per building) were running, while the belt caged layer system had 5 to 10 ppm NH_3 v/v.

Losses of NH_3-N, using manure or compost N levels, for the July test showed (table 3) similar values to the March study, with 0.376 kg (0.830 lb) N bird^{-1} yr^{-1} for CLDP and 0.136 kg (0.300 lb) N bird^{-1} yr^{-1} for the CLB-CB. Thus, NH_3 losses for the CLB-CB system were 36% of the deep-pit system in the July study. The NH_3 losses from the laying house in July for the CLB-CB system were estimated at 0.048 kg bird^{-1} yr^{-1}, compared to 0.034 kg bird^{-1} yr^{-1} cited by Groot Koerkamp (1994). These results show that the belt/compost system has a major advantage over the deep-pit system in terms of ammonia emissions. For the CLDP and CLB-CB systems, the calculated NH_3-N losses in July using airflow rates and ammonia concentrations in the exhaust air were 0.513 and 0.225 kg (1.129 and 0.495 lb) N bird^{-1} yr^{-1}, respectively. Again, results using airflows and NH_3 concentrations were approximate because airflows were varying during the data collection period. For the conventional deep-pit caged layer system, the exhaust streams measured 7 to 25 ppm NH_3 v/v when all exhaust fans (32 per building) were running, while the belt caged layer system had 1 to 1.5 ppm NH_3 v/v.

DISCUSSION

Results using nitrogen and ash levels for determining upper limits for NH_3 emissions gave values similar to those reported in the literature. The N/ash method was straightforward to implement and appears to be reasonably accurate. Values for July were similar to those for March, namely 0.125 and 0.136 kg NH_3-N bird^{-1} yr^{-1} for CLB-CB and 0.472 and 0.377 kg NH_3-N bird^{-1} yr^{-1} for the CLDP systems, respectively. Emission values calculated using airflow rates and gas concentrations were 20% to 250% higher and were subject to much greater uncertainty. The problem was that airflows were non-steady state in the March tests for the CLB-CB, and this precluded accurate measurements both for airflows and gas concentrations. With variable airflow rates, NH_3 levels in the pit increased with low airflow and decreased with high airflow and were dependent on previous airflow rates. This is because NH_3 emission from manure is affected by pit air and manure NH_3 levels, which in turn are affected by prior events. In July, airflow rates were essentially constant with all fans running at maximum output; thus, the resulting emission rates using airflow were much closer to the values based on manure nitrogen. The results clearly showed that the CLB-CB system would have 25% to 35% less emissions than the CLDP system. In addition, from the standpoint of N conservation, the CLB-CB compost retained twice as much nitrogen as the CLDP manure while being a dry product at 82% to 90% dry matter and 5.6% to 6.2% N.

CONCLUSIONS

The CLB-CB system had 25% to 35% lower total emissions than the CLDP system. The method of using ash as a reference value was an accurate and straightforward way to determine the upper limits of emissions on a per bird basis.

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