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Abstract

Ammonia (NH₃) emissions from poultry animal feeding operations (AFOs) have caused health and environmental concerns. Current NH₃ emission measurement methods are accurate and reliable but also time-consuming, expensive, and impractical for most animal facilities. In this study, an alternative mass balance method was developed to effectively predict NH₃ emissions from manure belt (MB) poultry layer facilities. This method can eliminate the need for tracking manure flow rates in traditional mass balance analyses for estimation of ammonia nitrogen (NH₃-N) emissions. It was applied to three MB layer poultry houses in Ohio, with approximately 160,000 hens in each house, and validated using continuous NH₃ emission measurement data. Feed, manure, and egg samples were collected from the three houses in different months over a year to evaluate possible seasonal variation in NH₃ emissions from the poultry houses. The estimated NH₃-N emissions from houses 1, 2, and 3 were 0.394 $\hat{\pm}$ 0.143, 0.293 $\hat{\pm}$ 0.1, and 0.284 $\hat{\pm}$ 0.129 g NH₃-N hen⁻¹ d⁻¹, respectively, and the measured NH₃-N emission rates were 0.200 $\hat{\pm}$ 0.067, 0.220 $\hat{\pm}$ 0.036, and 0.237 $\hat{\pm}$ 0.211 g NH₃-N hen⁻¹ d⁻¹, respectively. These results are comparable with NH₃-N emission rates published in the literature (0.024 to 0.592 g NH₃-N hen⁻¹ d⁻¹). A statistical comparison of the measured and estimated NH₃-N emissions showed that the root mean square error (RMSE), normalized mean square error (NMSE), and fractional bias (FB) were 0.179 g NH₃-N hen⁻¹ d⁻¹, 0.426, and 0.457, respectively. These statistical parameters indicated that the estimations were acceptable according to the criteria of NMSE < 0.5 and FB < 0.5. The results showed that this alternative mass balance method could be used to estimate NH₃-N emissions from MB poultry layer houses. However, the method estimates total nitrogen gas emissions, which is an upper limit of NH₃-N emissions. A minimum of 22 sampling and modeling events is suggested for reliable estimation of NH₃-N emission factors for MB poultry layer houses using the alternative mass balance method with a 90% confidence level ($\hat{I} \pm = 0.1$) and a maximum error of 15%.

Keywords

Air quality, Alternative mass balance, Ammonia emission, Mass balance analysis, Poultry facilities

Disciplines

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Comments

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ESTIMATION OF AMMONIA EMISSION FROM MANURE BELT POULTRY LAYER HOUSES USING AN ALTERNATIVE MASS BALANCE METHOD

S. Wang, L. Y. Zhao, X. Wang, R. Manuzon, M. Darr, H. Li, H. M. Keener

ABSTRACT. Ammonia (NH_3) emissions from poultry animal feeding operations (AFOs) have caused health and environmental concerns. Current NH_3 emission measurement methods are accurate and reliable but also time-consuming, expensive, and impractical for most animal facilities. In this study, an alternative mass balance method was developed to effectively predict NH_3 emissions from manure belt (MB) poultry layer facilities. This method can eliminate the need for tracking manure flow rates in traditional mass balance analyses for estimation of ammonia nitrogen ($\text{NH}_3\text{-N}$) emissions. It was applied to three MB layer poultry houses in Ohio, with approximately 160,000 hens in each house, and validated using continuous NH_3 emission measurement data. Feed, manure, and egg samples were collected from the three houses in different months over a year to evaluate possible seasonal variation in NH_3 emissions from the poultry houses. The estimated $\text{NH}_3\text{-N}$ emissions from houses 1, 2, and 3 were 0.394 ± 0.143 , 0.293 ± 0.1 , and 0.284 ± 0.129 g $\text{NH}_3\text{-N}$ hen⁻¹ d⁻¹, respectively, and the measured $\text{NH}_3\text{-N}$ emission rates were 0.200 ± 0.067 , 0.220 ± 0.036 , and 0.237 ± 0.211 g $\text{NH}_3\text{-N}$ hen⁻¹ d⁻¹, respectively. These results are comparable with $\text{NH}_3\text{-N}$ emission rates published in the literature (0.024 to 0.592 g $\text{NH}_3\text{-N}$ hen⁻¹ d⁻¹). A statistical comparison of the measured and estimated $\text{NH}_3\text{-N}$ emissions showed that the root mean square error (RMSE), normalized mean square error (NMSE), and fractional bias (FB) were 0.179 g $\text{NH}_3\text{-N}$ hen⁻¹ d⁻¹, 0.426, and 0.457, respectively. These statistical parameters indicated that the estimations were acceptable according to the criteria of $\text{NMSE} < 0.5$ and $\text{FB} < 0.5$. The results showed that this alternative mass balance method could be used to estimate $\text{NH}_3\text{-N}$ emissions from MB poultry layer houses. However, the method estimates total nitrogen gas emissions, which is an upper limit of $\text{NH}_3\text{-N}$ emissions. A minimum of 22 sampling and modeling events is suggested for reliable estimation of $\text{NH}_3\text{-N}$ emission factors for MB poultry layer houses using the alternative mass balance method with a 90% confidence level ($\alpha = 0.1$) and a maximum error of 15%.

Keywords. Air quality, Alternative mass balance, Ammonia emission, Mass balance analysis, Poultry facilities.

Ammonia (NH_3) emissions from poultry animal feeding operations (AFOs) have caused health and environmental concerns (NRC, 2003). In poultry houses, NH_3 is regarded as a harmful gas for bird health (Carter, 1967). Ammonia and dust particles jointly contribute to the occurrence of ascites, gastrointestinal irritation, respiratory disease, and higher chick mortality (Leeson and Summers, 2001; Estevez, 2002). In the environment, NH_3 can cause acidification and eutrophica-

tion. For example, 45% of total acid deposition in 1989 in the Netherlands was caused by NH_3 emissions (Groot Koerkamp et al., 1998). Ammonia also contributes to the formation of fine particulate matter ($\text{PM}_{2.5}$) (Baek and Aneja, 2004), which causes visibility degradation. The amount of NH_3 emissions from poultry farms in the U.S. was projected to increase from 660,000 ton year⁻¹ in 2002 to an estimated 870,000 ton year⁻¹ in 2030 (USEPA, 2004). Therefore, it is imperative to understand and manage NH_3 emissions from poultry houses to mitigate their adverse environmental and health impacts.

Currently, the most accurate measurement method for NH_3 emissions from animal facilities is continuous monitoring of the ventilation airflow rates and NH_3 concentrations of the facilities using NH_3 gas analyzers and fan operation sensors (Ni and Heber, 2001). However, this method is difficult for farmers to use to evaluate and manage NH_3 emissions from their facilities because it is costly, complicated, and time-consuming. A simple, accurate, and cost-effective method is needed to help farmers evaluate and manage the NH_3 emissions from their specific operations.

Previous researchers have used the nitrogen balance method to estimate nitrogen losses from commercial layer houses (Yang et al., 2000; Liang et al., 2005). However, this method requires accurate measurement of feed con-

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sumption, animal production, and manure generation rates. Commercial egg operations do not closely track manure production due to its relative low value in comparison with feed and eggs. An alternative mass balance method uses the ratio of nitrogen to ash content (N/ash) of feed, animal products, and manure to avoid quantifying the manure production rate (Keener et al., 2002; Keener and Zhao, 2008). This new mass balance method needs to be further developed into practical models and sampling strategies for commercial farm operations, and its accuracy needs to be verified with NH₃ emission data obtained using the state-of-the-art measurement methods (Heber et al., 2006).

The objectives of this study were to develop practical sampling methods and an alternative mass balance method for estimation of NH₃ emissions from commercial manure belt (MB) layer facilities, and verify the accuracy of the method using NH₃ measurement data acquired using the state-of-the-art air emission measurement method approved by the U.S. EPA for the National Air Emission Monitoring Study (Heber et al., 2006; Wang-Li et al., 2013).

MATERIALS AND METHODOLOGY

MASS BALANCE ANALYSIS USING N/ASH RATIO

The nutrient mass balance in animal production facilities denotes that the input nutrient mass flow of an animal production system is equal to the output nutrient flow. In a poultry egg production system, the inputs include air, water, feed, and hens entering the production system. The outputs include air, eggs, manure, mortalities, possible leachate, and gas emissions leaving the facility (fig. 1) (Keener and Zhao, 2008). Nitrogen in the air entering and leaving the system does not participate in the nitrogen conversion process, and the nitrogen in drinking water is negligible. The change in laying hen body weight over a short production period is also negligible. Mortality is also very low in a short period (about 20 mortalities per day in a layer house with 0.15 to 0.2 million chickens). Leachate is not a problem for MB layer houses with concrete floors. Nitrogen gas emissions from a poultry house include N₂O, NO_x, N₂ and NH₃ and are primarily in the form of NH₃ gas emissions. According to the above assumptions, the relevant input, storage, and output variables of an egg production system for the alternative mass balance analysis are shown schematically in figure 1.

According to the simplified schematic in figure 1, the nitrogen balance for the MB layer system is mathematically described by equation 1 (variables are defined in table 1):

$$x_{N1}m'_1 \cong x_{N3}m'_3 + x_{N2}m'_2 + N_4 \quad (1)$$

The ash balance for the system is described by equation 2:

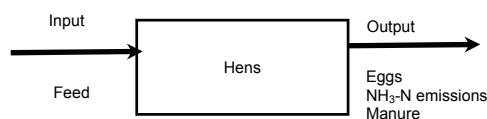


Figure 1. Simplified schematic of an egg production system with relevant input, storage, and output variables for the alternative mass balance analysis.

Table 1. Variables used in mass balance equation for poultry houses.

Variable ^[a]	Definition
m'_i	Mass flow rate of i (kg d ⁻¹)
x_{Ni}	Nitrogen content (dec)
x_{Ai}	Ash content (dec)
N_4	NH ₃ -N emission
R_3	N to ash ratio in manure (x_{N3}/x_{A3})

^[a] Subscript i : 1 = feed input, 2 = eggs output, and 3 = manure output.

$$x_{A1}m'_1 \cong x_{A3}m'_3 + x_{A2}m'_2 \quad (2)$$

The manure flow rate can be calculated from the ash contents and the feed and egg flow rates using equation 3:

$$m'_3 \cong (x_{A1}m'_1 - x_{A2}m'_2) / x_{A3} \quad (3)$$

The NH₃ nitrogen (NH₃-N) emission can be calculated using equation 4 or 5:

$$N_4 \leq x_{N1}m'_1 - x_{N2}m'_2 - x_{N3}m'_3 \\ = x_{N1}m'_1 - x_{N2}m'_2 - x_{N3}(x_{A1}m'_1 - x_{A2}m'_2) / x_{A3} \quad (4)$$

$$N_4 \leq x_{N1}m'_1 - x_{N2}m'_2 - R_3(x_{A1}m'_1 - x_{A2}m'_2) \quad (5)$$

In the traditional nitrogen mass balance method (Yang et al., 2000; Liang et al., 2005), manure flow rate quantification was necessary to accurately estimate NH₃-N emissions. However, acquiring accurate manure flow rates is challenging in an animal production system. The alternative mass balance method presented here avoids direct monitoring of manure flow rates by using the system's ash balance for estimating NH₃ emissions with parameters that are easier to measure or obtain.

This mass balance method can only determine the total nitrogen loss in the whole production process. Since the nitrogen loss from nitrogenous gases other than NH₃ is very limited, the total nitrogen loss can be approximated by the NH₃-N emissions (Wathes et al., 1997; Coufal et al., 2005). Therefore, NH₃-N will be used in the following discussions to represent the maximum total nitrogen loss defined in equations 4 and 5.

LAYER HOUSING AND MANAGEMENT PRACTICES

Three MB poultry layer houses on two poultry farms in Ohio were selected for this study. At farm 1, two poultry houses were selected (fig. 2a). The houses were 121.9 m long, 19.5 m wide, and 7.7 m high at the ridge (table 2) and equipped with mechanical tunnel ventilation systems. In each house, laying hens were kept in eight rows and eight tiers of cages with manure belts underneath the cages. Each row of cages was about 100 m long. Laying hens lived in the cages from 20 to 109 weeks old. Each house had approximately 160,000 Lohmann white hens with an initial average weight of about 1.5 kg at the beginning of each production period. Automatic feeding, watering, egg, and manure collecting systems were installed in the houses. Manure fell onto the manure belts and was removed from the building twice a week by the manure belt conveyor system.

At farm 2, the selected house was 161.6 m long, 15.9 m wide, and 7 m high (fig. 2b). Laying hens were kept in six rows with seven tiers of cages for each row. The cage rows

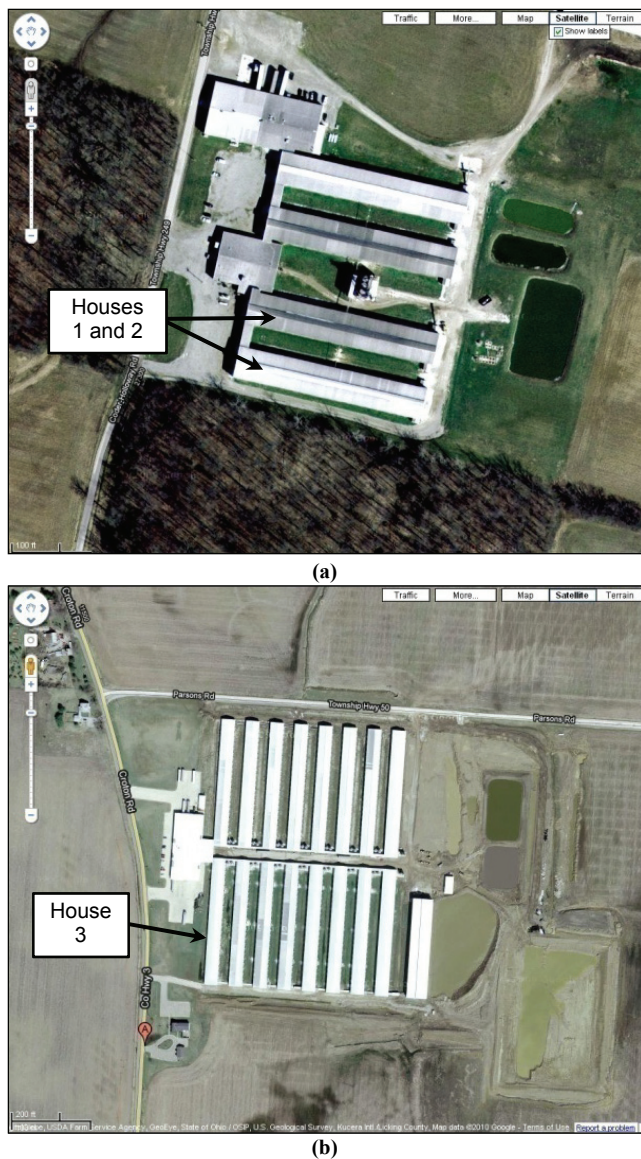


Figure 2. Satellite images of layer houses (from Google Earth).

were 154 m long. The age of the hens ranged from 20 to 75 weeks during the study period. The house had about 154,500 Lohmann white hens with an average hen weight of 1.25 kg at the time of study. Drinking nipples supplied water, and feed chains and troughs provided feed to the hens. Eggs produced in the cages rolled onto egg collection belts from the bottoms of the cages. Cross-ventilation with fifty 123 cm (48 in.) fans on two sidewalls of the building was automatically controlled according to temperature settings of the layer house. Manure was removed by manure belts under the cages to a manure storage/semi-composting building near the layer house. In this layer house, the manure belt was operated for 9 min each day, and one-fifth of

the total manure on the belt was removed daily. The characteristics of the layer houses and management data are summarized in table 2.

SAMPLING METHODS AND SAMPLE SIZE

The objective of the sampling plan was to obtain representative samples at each poultry house to estimate the $\text{NH}_3\text{-N}$ emissions in different seasons. Manure, feed, and egg samples were preliminarily collected and analyzed. Initially, eight manure samples and three feed samples were collected in houses 1 and 2; six manure samples, three feed samples, and three egg samples were collected in house 3.

During each sampling event in houses 1 and 2, three 500 g feed samples were collected from the feeder randomly. Manure samples were collected at the end of each manure belt for 5 to 6 min using a 250 mL polyethylene sampler as the manure fell down to the manure transporter from the manure belt. The sampling interval was determined by the manure belt's moving speed and total length in order to collect five samples from each belt. The manure belt conveyors under the cages moved simultaneously with constant speed. A total of five manure samples were obtained from the terminal ends of each of the five manure belt conveyors at each sampling event. The five 250 mL manure subsamples were mixed to form one sample for each belt. In house 3, in addition to six manure samples collected from six rows of manure belts, respectively, and three feed samples collected at the feeder, three egg samples, in which each sample contained four eggs, were picked randomly in the house on each sampling day.

The sample means and standard deviations were used to determine the sufficient sample size for determining the chemical compositions of the manure, feed, and eggs using equation 6:

$$n = \left(\frac{t_{\alpha/2} s}{0.15\bar{x}} \right)^2 \quad (6)$$

where

n = sampling size

$t_{\alpha/2}$ = critical value of t distribution with a type-I error of $\alpha = 0.1$

\bar{x} = sample mean

s = sample standard deviation.

This equation is derived from the formula for sample size where a t distribution is used instead of a normal distribution due to the small sample size in this study (Israel, 2013).

According to the typical climate of Ohio, December, January, and February are defined as winter; March, April, and May are spring; June, July, and August are summer; and September, October, and November are autumn in this study. Sampling events occurred on the days that manure

Table 2. Characteristics and management data of three layer houses in this study.

House	Dimensions (W × L, m)	Manure Removal Interval	Ventilation System	No of Hens	No. of Cage Rows	No. of Cage Tiers	Mass Balance Sampling Period
1	121.9 × 19.5	3.5 days	Mixed tunnel and cross	164,136	8	8	12 Apr. 2007 to 10 Dec. 2007
2	121.9 × 19.5	3.5 days	Mixed tunnel and cross	168,416	8	8	12 Apr. 2007 to 10 Dec. 2007
3	161.6 × 15.9	5 days	Cross	154,692	6	7	21 Apr. 2008 to 11 Dec. 2008

was removed. At farm 1, samples of feed and manure were collected from both houses in April, June, July, September, and December 2007. The total number of sampling events was seven at house 1 and six at house 2. At farm 2, three sampling events were conducted in April, three in August, and one each in September, October, and December 2008.

In addition to feed sampling and analysis, feed compositions were obtained from feed formulas provided by the producer and feed consultant. Feed compositions analyzed from feed samples are denoted “feed sample,” and those obtained from the producer and feed consultant are denoted “feed formula, producer” and “feed formula, consultant,” respectively.

Daily feed consumption, egg production, weekly hen mortality, hen age, and body weight for the three poultry houses were recorded by and obtained from the producers.

ANALYSIS OF FEED, EGG, AND MANURE SAMPLES

All samples were collected on site, shipped in ice coolers to the OARDC Service Testing and Research (STAR) laboratory, and stored in freezers until analysis. The ash, total nitrogen, and total solids contents of the samples are needed for the N/ash mass balance calculations. The ash content of all samples was tested using TMECC Method 03.02-A, i.e., unmilled material was ignited at 550°C without inert removal (USCC, 2002). Total nitrogen in the feed, eggs, and manure samples was determined using the combustion method described in AOAC Method 990.03 (AOAC, 2005). The mass of total solids was determined using TMECC Method 03.09, i.e., fresh material was dried at 70°C ±5°C for 72 h (USCC, 2002). The pH was tested using TMECC Method 04.11-A (USCC, 2002).

NH₃ EMISSION MEASUREMENTS

The NH₃ emission rates at farm 1 were monitored from February 2007 to February 2008 using the state-of-the-art air emission monitoring method (Heber et al., 2006). The NH₃ emission rates from the poultry houses were calculated by multiplying the house ventilation rate and the difference between the NH₃ concentrations at each building’s air exhausts and inlets (eq. 7). The calculated emission rates were converted to g NH₃-N hen⁻¹ d⁻¹ for comparison with the emissions estimated using the alternative mass balance method:

$$E = \sum_{k=1}^N [Q_{o,k} (C_{o,k} - C_i)] \quad (7)$$

where

E = NH₃ emission rate from a poultry house (g s⁻¹)

$C_{o,k}$ = NH₃ concentration of ventilation exhaust air stream k of a poultry house (g m⁻³)

C_i = NH₃ concentration of ventilation inlet air stream (g m⁻³)

$Q_{o,k}$ = Airflow rate of exhaust air stream k of a poultry house (m³ s⁻¹).

A mobile air emission laboratory was used to monitor the emission concentrations, fan operation status, and building static pressures of houses 1 and 2. The NH₃ concentrations were measured quasi-continuously at the air

inlet and at six representative exhaust fans of the layer houses for 12 months using a photoacoustic NH₃ analyzer (Chilgard RT, MSA, Inc., Pittsburgh, Pa.) connected with a gas sampling system and a computer data acquisition system (Heber et al., 2006). The ventilation rates of the houses were determined by the house static pressure, fan operation status, and fan performance curves calibrated using a portable fan tester (FANS; Gates et al., 2004).

TEMPERATURE MEASUREMENTS

To examine possible temperature effects on NH₃ emission rates, the indoor temperatures were monitored continuously in houses 1 and 2 and measured during each sampling event at several locations in house 3. For houses 1 and 2, indoor air temperatures were measured with twelve thermocouples and an electronic RH/temp transmitter (model HMW61, Vaisala, Woburn, Mass.) housed in a NEMA 4 (National Electrical Manufacturers Association rating for protective enclosures of electrical sensors and equipment) enclosure, which protected the sensors from water and dust damage, at the representative exhaust locations shown in figure 3. For house 3, a portable temperature and relative humidity meter (model HM70, Vaisala, Woburn, Mass.) was used to monitor air temperature and relative humidity at the 15 locations shown in figure 3. The ambient temperature and relative humidity were obtained from local weather station records (Wunderground, 2012).

STATISTICAL COMPARISON OF MEASURED AND ESTIMATED NH₃ EMISSIONS

The t-test/ANOVA analysis or nonparametric test was used to compare the statistical difference between measured and estimated NH₃-N emissions and the seasonal differences in measured NH₃-N emissions in houses 1 and 2 using JMP Pro 10 software. If the sample size used in the comparison was more than 30, ANOVA and t-test were used; if the sample size used in the comparison was less than 30 and the sample distribution did not follow a normal distribution, the nonparametric test was used (Wilson Van

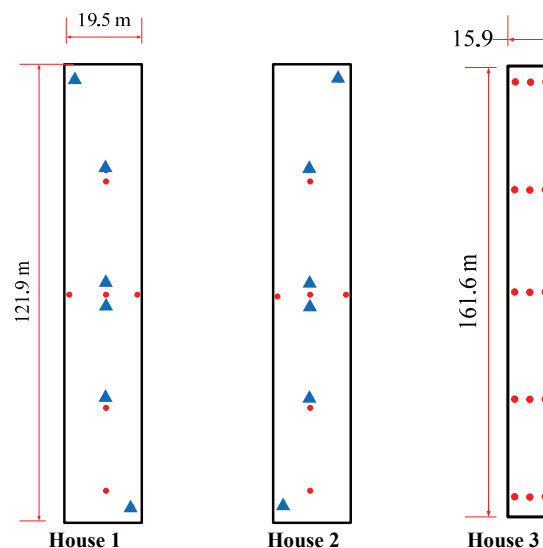


Figure 3. Measurement points of indoor temperature and relative humidity in three houses (● = bottom floor and ▲ = top floor).

Voorhis and Morgan, 2007; Fagerland, 2012).

The root mean square error (RMSE), normalized mean square error (NMSE), and fractional bias (FB) were computed using equations 8 through 10 to statistically evaluate the estimated NH₃-N emissions against measured values. Acceptability criteria of NMSE < 0.5 and FB < 0.5 were used (Kumar et al., 1993; Ahuja and Kumar, 1996):

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^N (C_{pi} - C_{oi})^2 \right]^{\frac{1}{2}} \quad (8)$$

$$NMSE = \frac{N \sum_{i=1}^N (C_{pi} - C_{oi})^2}{\sum_{i=1}^N C_{pi} \times \sum_{i=1}^N C_{oi}} \quad (9)$$

$$FB = 2 \times \left(\frac{\sum_{i=1}^N C_{pi} - \sum_{i=1}^N C_{oi}}{\sum_{i=1}^N C_{pi} + \sum_{i=1}^N C_{oi}} \right) \quad (10)$$

where

C_{pi} = NH₃-N estimation value (g hen⁻¹ d⁻¹)
 C_{oi} = NH₃-N measurement value (g hen⁻¹ d⁻¹)
 N = number of corresponding estimation and measurement values.

RESULTS AND DISCUSSION

ENVIRONMENTAL CONDITIONS

The annual ambient temperature ranged from -8°C to 22°C with a mean of 10°C at farm 1 and from -17°C to 32°C with a mean of 14°C at farm 2. Ambient RH ranged from 30% to 85% with a mean of 54% at farm 1, and from 17% to 100% with a mean of 76% at farm 2. The average indoor air temperature of houses 1 and 2 ranged from 19°C to 29°C, and the indoor air temperature of house 3 ranged from 18°C to 31°C during the monitoring period. The three houses showed typical seasonal variations in indoor air temperature and relative humidity for MB layer houses in the Midwest region. They are very similar to the indoor air temperatures (15°C to 30°C) of poultry houses in northern Iowa (Liang et al., 2003).

SAMPLE SIZES FOR FEED, EGGS, AND MANURE

The sample sizes for feed, eggs, and manure from the three houses were determined according to the nitrogen and ash contents of the preliminary samples. Table 3 shows the feed, egg, and manure sample analyses and sample size calculation according to equation 6. The results showed that maximum sample sizes of 3.1 for feed, 1.2 for eggs, 4.3 for manure are sufficient to obtain representative samples covering the variation in ash and nitrogen contents with a 90% confidence level and a maximum error level of 15%. Based on practical limitations and minimum statistical replication requirements, the sample size was deter-

Table 3. Size determination for feed, egg, and manure samples.

House	Sample Type	Ash ^[a] (% dry basis)	Total N (% dry basis)
1	Feed	N/A	0.2
	Manure	0.6	2.6
2	Feed	N/A	3.1
	Manure	0.3	4.3
3	Egg	0.7	1.2
	Feed	0.1	2.7
	Manure	0.8	1.2

^[a] Ash content was not available in houses 1 and 2 because sampling of feed in the feed trough resulted in biased ash values.

mined as 3 for feed samples, 3 for egg samples, and 4 for manure samples.

ASH AND NITROGEN CONTENTS IN FEED, EGG, AND MANURE SAMPLES

Table 4 summarizes a statistical analysis of the ash and nitrogen compositions of feed, egg, and manure samples from the three MB poultry layer houses. Except for pH, all composition values in table 4 are dry basis.

The feed samples from houses 1 and 2 were collected directly from the feed troughs and found to have unreasonably high ash contents of 19.19% to 22.7%. These high ash contents resulted from the feed being sampled after the birds' selection of feed and therefore were likely not representative of the birds' actual feed intake. Therefore, the feed ash values for houses 1 and 2 were determined to be invalid and were not used for the mass balance analyses. After revising the feed sampling strategy to direct sampling from the feed bins, the ash content of the feed samples from house 3 was analyzed as 14.98%, which was very close to the 15.32% feed ash value reported by Keener and Zhao (2008) and the feed ash values of 14.38% to 15.98% reported by Latshaw and Zhao (2011) for layer hens. The mean total nitrogen of the sampled feed varied from 2.51% to 3.31% for the three houses. These values are comparable to the 3.15% feed nitrogen value reported by Keener and Zhao (2008) and the values of 2.67% to 3.04% reported by Latshaw and Zhao (2011).

The ash and nitrogen contents of the eggs had very low sample variance. Eggs were initially sampled and analyzed in a laboratory study (Latshaw and Zhao, 2011) and then in

Table 4. Ash and nitrogen contents of the feed, egg, and manure samples from the three MB poultry layer houses.^[a]

Sample Type	House	No. of Samples	pH	Ash (%)	Total N (%)	N/Ash
Feed	1	21	N/A	N/A ^[b]	3.07	N/A
					±0.52	
	2	15	N/A	N/A ^[b]	2.51	N/A
					±0.28	
	3	30	6.25	14.98	3.31	0.23
					±0.15	±2.31
Eggs	3	21	8.08	33.29	5.78	0.17
					±0.20	±1.35
Manure	1	38	7.16	33.35	5.86	0.18
					±0.50	±2.61
	2	33	7.55	33.91	4.74	0.14
					±0.56	±2.13
	3	60	8.13	33.17	5.97	0.18
					±0.70	±2.30

^[a] Values are means ± standard deviations (SD).

^[b] Ash content of sampled feed was biased due to improper sampling.

house 3 using Lohmann white hens. Because of the stable ash and total nitrogen contents of the eggs ($33.29\% \pm 1.35\%$ and $5.78\% \pm 0.29\%$, respectively), the values for house 3 were also used for houses 1 and 2. These sampled values are comparable to the ash and nitrogen contents of 29.33% and 6.02%, respectively, reported by Keener and Zhao (2008).

The mean ash content of the manure ranged from 33.17% to 33.91%, and the mean nitrogen content ranged from 4.74% to 5.97%, similar to the values of 30.26% and 5.66% for ash and nitrogen contents, respectively, reported by Keener and Zhao (2008). The total manure nitrogen was also comparable to the value of 4.36% reported by Liang et al. (2003). Although houses 1 and 2 were identical in their structure and management, their manure nitrogen contents differed significantly ($p < 0.05$). This was caused by the varied nitrogen content of the feed given to hens at different ages. The higher feed nitrogen content was strongly related to the higher nitrogen content of the manure in house 1 for younger hens. Because of the similar nitrogen contents of the feed, the manure samples from houses 1 and 3 did not differ significantly in nitrogen content ($p > 0.05$). Poultry manure is alkaline, with a pH range of 7.16 to 8.13, which is one of the main factors triggering NH_3 emissions from the manure. The manure from the three houses was 3.5 to 5 days old, and the average N/ash value was 0.14 to 0.18 in the manure from all three houses, comparable to the value of 0.19 reported by Keener and Zhao (2008) and the values of 0.18 to 0.21 reported by Latshaw and Zhao (2011).

FEED CONSUMPTION AND EGG PRODUCTION RATES

Feed consumption and egg production rates varied seasonally because of the hens' age and the indoor environmental management of the poultry houses (table 5). The daily feed consumption and egg production rates of the houses were recorded by the producer as 73.89 to 91.44 and 8.22 to 17.35 $\text{g hen}^{-1} \text{d}^{-1}$, respectively, which were comparable to the values of 85.5 and 18.1 $\text{g hen}^{-1} \text{d}^{-1}$ for feed consumption and egg production, respectively, reported by Keener and Zhao (2008). The lower egg production rate in house 3 was likely due to the difference in bird age and housing environment.

MEASURED NH_3 EMISSIONS FROM POULTRY HOUSES

NH_3 -N emissions from houses 1 and 2 were semi-continuously measured using the air emission mobile laboratory measurement method (Heber et al., 2006) from 1 March 2007 to 27 February 2008. Hourly and daily averages of NH_3 emission rates from the two poultry houses were analyzed. The annual averages of the daily average NH_3 -N emission rates of houses 1 and 2 were $0.19 \pm 0.16 \text{ g}$

Table 5. Bird number, feed consumption, and egg production rate of the MB poultry layer houses during the study period.

House	Number of Hens	Feed	Egg
		Consumption ($\text{g hen}^{-1} \text{d}^{-1}$) ^[a]	Production ($\text{g hen}^{-1} \text{d}^{-1}$) ^[a]
1	164,300 to 156,501	73.89 to 91.44	14.28 to 17.35
2	164,615 to 145,055	91.44	14.87 to 16.72
3	154,692 to 146,598	77.18 to 91.41	8.22 to 15.29

^[a] Dry mass flow rate.

Table 6. Seasonal NH_3 -N emissions ($\text{g hen}^{-1} \text{d}^{-1}$) from houses 1 and 2 (Zhao et al., 2010).

House	Statistic	Season				Annual
		Spring	Summer	Fall	Winter	
1	No. of data	44	50	48	53	195
	Mean	0.17	0.27	0.13	0.18	0.19
	SD	0.23	0.15	0.09	0.12	0.16
2	No. of data	65	51	47	54	217
	Mean	0.24	0.21	0.18	0.20	0.21
	SD	0.23	0.09	0.09	0.14	0.16

$\text{hen}^{-1} \text{d}^{-1}$ ($n = 195$) and $0.21 \pm 0.16 \text{ g hen}^{-1} \text{d}^{-1}$ ($n = 217$), respectively (Zhao et al., 2010).

According to the measurement data (table 6), the NH_3 -N emissions from houses 1 and 2 were not significantly different ($p > 0.05$). The NH_3 -N emissions from house 1 showed significant seasonal differences ($p < 0.05$); however, those of house 2 showed no significant seasonal differences ($p > 0.05$). In house 1, the emissions showed a significant difference between summer and other seasons ($p < 0.05$). New hens at 20 weeks old were introduced into house 1 on 3 June 2007. The nitrogen content in the feed for the young hens in house 1 was higher and resulted in higher NH_3 -N emissions. Except for the higher NH_3 -N emissions caused by the younger hens and higher feed nitrogen content, the NH_3 -N emissions from house 1 in all other seasons showed no significant differences ($p > 0.05$). Overall, the NH_3 -N emissions from houses 1 and 2 were not significantly different in most seasons ($p > 0.05$). These findings agree with those of Li (2006), which showed that NH_3 emissions from MB layer houses do not display significant seasonal differences. Even though the poultry houses had significantly different ventilation rates in cold, mild, and hot seasons, the ammonia concentrations in the poultry houses varied in response to the ventilation rate changes. Consequently, the emission rate, which is the product of the ammonia concentration and the ventilation rate, did not vary significantly.

ESTIMATION OF NH_3 -N EMISSIONS USING THE ALTERNATIVE MASS BALANCE METHOD

Table 7 summarizes the ash and nitrogen contents and mass flow rates of feed and manure used for NH_3 -N estimation in houses 1 and 2. The ash and nitrogen contents of the feed were analyzed using feed samples and calculated from the feed formulas provided by the producer and the feed consultant.

The ash values of feed samples were found to be abnormally high. Improper feed sampling likely caused these errors. The high ash values resulted in lower than normal nitrogen content values, such as 2.27% and 2.26%, which are significantly lower than the formula values. They are also below the lower bound of feed nitrogen values of 2.67% to 3.04% reported by Latshaw and Zhao (2011). The nitrogen contents from the producer formula decreased with the increase of hens' ages. The feed ash and nitrogen contents calculated from both formulas did not show a significant difference ($p > 0.05$) during 13 sampling events in different months. Therefore, either of the feed formulas can be used to reliably estimate the ash and nitrogen contents for the mass balance analysis.

Table 7. Feed compositions, manure compositions, and mass flow rates used to estimate NH₃-N emissions from houses 1 and 2.

Sampling Month	House	Hen Age (weeks)	Feed Sample ^[a] (%)		Feed Formula (%) ^[a]				Manure (%)			Mass Flow (g hen ⁻¹ d ⁻¹)	
			N	Ash ^[b]	Producer		Consultant		N	Ash	N/A	Feed	Eggs
					N	Ash	N	Ash					
April	1	108	2.27	20.96	2.80	15.58	2.62	15.94	5.26	36.99	0.14	85.72	15.43
	2	55	2.37	18.29	2.68	14.94	2.76	15.50	5.09	33.51	0.15	91.44	16.72
June	1	22	2.88	26.89	3.56	15.71	3.16	13.61	6.01	31.94	0.19	73.89	14.28
	2	64	2.61	22.91	2.65	15.20	2.62	15.94	4.20	32.21	0.13	91.44	16.39
July	1	26	3.76	20.63	3.33	14.96	3.16	13.61	6.15	30.24	0.20	82.87	16.23
		27	3.02	24.00	3.30	14.91	3.16	13.61	6.17	32.77	0.19	83.69	16.22
		29	3.28	18.65	3.17	14.55	3.16	13.61	6.17	33.97	0.18	86.95	16.55
	2	68	2.75	18.19	2.65	15.33	2.62	15.94	4.28	35.12	0.12	91.44	15.69
		69	2.26	21.31	2.65	15.36	2.62	15.94	5.00	35.90	0.14	91.44	15.55
September	1	35	3.45	21.21	2.96	14.40	3.16	15.58	5.75	33.13	0.17	90.63	17.35
	2	77	2.58	15.23	2.65	15.61	2.62	15.94	4.96	35.02	0.14	91.44	14.87
December	1	48	2.86	26.59	2.76	14.77	2.87	15.74	5.86	32.23	0.18	91.44	16.71
	2	90	2.58	15.23	2.65	15.70	2.62	15.94	4.72	31.95	0.15	91.44	16.36
Mean			2.82	20.78	2.91	15.16	2.86	15.15	5.36	33.46	0.16	87.99	16.03
SD			0.46	3.71	0.32	0.44	0.26	1.08	0.71	1.88	0.03	5.32	0.84

^[a] Ash and nitrogen contents are dry basis.

^[b] Ash contents tested in the sampled feed are biased due to the improper sampling.

The daily feed intake and egg production were 87.99 ±5.32 and 16.03 ±0.84 g hen⁻¹ d⁻¹, respectively, comparable to the values of 85.31 ±4.89 and 15.98 ±0.44 g hen⁻¹ d⁻¹, respectively, reported by Latshaw and Zhao (2011) and the 83.61 g hen⁻¹ d⁻¹ feed intake reported by Fournel et al. (2012). In house 1, the feed intake increased from 73.89 to 91.44 g hen⁻¹ d⁻¹ as the hens grew from weeks 22 to 48. In house 2, the feed intake was 91.44 g hen⁻¹ d⁻¹ as the hens grew from weeks 55 to 90. The egg production ranged from 14.28 to 17.35 g hen⁻¹ d⁻¹ in house 1 and from 16.72 to 16.36 g hen⁻¹ d⁻¹ in house 2. The egg production had a stronger linear relation with feed intake from weeks 22 to 35 (R² = 0.98). After week 35, the egg production decreased slightly with a stable feed intake of 91.44 g hen⁻¹ d⁻¹.

The nitrogen and ash contents of the egg samples from houses 1 and 2 were not available. The nitrogen and ash contents for eggs produced by the Lohmann white hens were relatively stable; therefore, the values were obtained from the egg samples from house 3, which were analyzed as 5.78% nitrogen and 33.29% ash (table 4).

Table 8 summarizes the measured NH₃-N emissions and the estimated values using the alternative mass balance method (eq. 5) and different sources of feed content information for houses 1 and 2. The estimated NH₃-N emissions

using the sampled feed composition ranged from -0.125 to 0.858 g hen⁻¹ d⁻¹ (n = 7) in house 1 and from -0.03 to 0.536 g hen⁻¹ d⁻¹ (n = 6) in house 2. Since the feed samples were biased due to improper sampling, the NH₃-N emissions estimated were biased as well. Three negative NH₃-N emission values were obtained, and overall the estimated emissions were much different from the measured values.

The estimated NH₃-N emissions using the feed formula from the producer ranged from 0.106 to 0.520 g hen⁻¹ d⁻¹ (n = 7) in house 1 and from 0.159 to 0.442 g hen⁻¹ d⁻¹ (n = 6) in house 2. The estimated NH₃-N emissions using the feed formula from the consultant ranged from 0.048 to 0.641 g hen⁻¹ d⁻¹ (n = 7) in house 1 and from 0.098 to 0.345 g hen⁻¹ d⁻¹ (n = 6) in house 2. The estimated NH₃-N emissions from house 1 using the feed sample data, the producer formula, and the consultant formula were 0.365 ±0.379, 0.394 ±0.143, and 0.401 ±0.022 g NH₃-N hen⁻¹ d⁻¹, respectively, which does not show a significant difference (p > 0.05). The estimated NH₃-N emissions from house 2 using the feed sample data, the producer formula, and the consultant formula were 0.174 ±0.228, 0.293 ±0.1, and 0.217 ±0.085 g NH₃-N hen⁻¹ d⁻¹, respectively, which also does not show a significant difference (p > 0.05). However, the standard errors for the NH₃-N emission estimation using

Table 8. Estimated and measured NH₃-N emissions from houses 1 and 2.

House	Sampling Month	Estimated NH ₃ -N Emissions (g hen ⁻¹ d ⁻¹)			Measured NH ₃ -N Emissions (g hen ⁻¹ d ⁻¹)
		Feed Sample	Feed Formula, Producer	Feed Formula, Consultant	
House 1	April	-0.125	0.333	0.134	0.085 ±0.044 (n = 14)
	June	0.018	0.520	0.514	0.237 ±0.101 (n = 16)
	July	0.753	0.398	0.485	0.254 ±0.132 (n = 27)
		0.253	0.485	0.575	
		0.597	0.505	0.641	
	September	0.858	0.411	0.409	0.207 ±0.088 (n = 18)
	December	0.202	0.106	0.048	0.212 ±0.138 (n = 17)
	Mean ±SD	0.365 ±0.376	0.394 ±0.143	0.401 ±0.225	0.200 ±0.067
House 2	April	-0.030	0.253	0.251	0.160 ±0.069 (n = 27)
	June	0.329	0.368	0.251	0.216 ±0.074 (n = 16)
	July	0.536	0.442	0.345	0.233 ±0.087 (n = 27)
		-0.066	0.291	0.189	
	September	0.180	0.242	0.170	0.239 ±0.099 (n = 18)
	December	0.097	0.159	0.098	0.251 ±0.140 (n = 17)
	Mean ±SD	0.174 ±0.228	0.293 ±0.1	0.217 ±0.085	0.220 ±0.036

the feed sample data are much higher than the standard errors using the feed formulas.

The measured NH₃-N emissions for the sampling months are listed in table 8 to compare the estimated and measured NH₃-N emissions from houses 1 and 2. Because the manure was removed from the houses twice a week, the estimated emission rates are the average NH₃ emission rates over 3.5 days. For the measured ammonia data, monthly average emissions were shown to reduce the errors caused by data unavailability on some sampling days. There was no significant difference between the measured monthly averaged NH₃-N emissions and the estimated NH₃-N emissions during the sampling months ($p > 0.05$).

Table 9 summarizes the estimated NH₃-N emissions using the alternative mass balance method for house 3 and a limited comparison with the measured NH₃-N emissions from the same house in a previous study (Sun et al., 2005). The emissions estimated using the sampled feed composition ranged from 0.174 to 0.819 g NH₃-N hen⁻¹ d⁻¹, and the emissions estimated using the producer feed formula ranged from 0.116 to 0.490 g NH₃-N hen⁻¹ d⁻¹. The results calculated with the sampled feed composition (0.505 ± 0.201 g NH₃-N hen⁻¹ d⁻¹) were significantly higher ($p < 0.05$) than those calculated with the producer feed formula (0.284 ± 0.129 g NH₃-N hen⁻¹ d⁻¹).

The measured NH₃-N emissions were not available for a direct comparison of measured and estimated emission values for the sampling events (April to December 2008). However, the NH₃ emissions from this house were measured from August 2004 to January 2005 in a previous study (Sun et al., 2005), and those measured NH₃-N emissions can be used as a reference. The measured average daily mean NH₃-N emissions ranged from 0.03 to 1.09 g NH₃-N hen⁻¹ d⁻¹ with a mean of 0.237 and standard deviation of 0.211 ($n = 159$) (Sun et al., 2005). The estimated NH₃-N emissions using the producer feed formula appear to be closer to the referenced emission measurements than those using the sampled feed composition. This result indicates that using the producer formula for the feed nitrogen and ash contents in the alternative mass balance analysis is not only accurate but also simpler and more economical.

STATISTICAL EVALUATION OF THE ALTERNATIVE MASS BALANCE METHOD

Table 10 summarizes the performance evaluation of the alternative mass balance method for its application in houses 1 and 2 using standardized statistical criteria (RMSE, NMSE, and FB). Because there was no significant seasonal difference in NH₃-N emissions from the houses, these statistical parameters were calculated based on all measurements and estimations acquired over a one-year period. The RMSE values for measured and estimated NH₃-N emissions using the sampled feed composition, producer feed formula, and consultant feed formula were 0.311, 0.179, and 0.197 g NH₃-N hen⁻¹ d⁻¹, respectively, for houses 1 and 2. The estimated NH₃ emissions using the sampled feed composition showed a much higher error due to improper feed sampling. Feed formula can be used as the feed composition source with less error.

The NMSE values for measured and estimated NH₃ emissions using the feed sample data, the producer feed formula, and the consultant feed formula were 1.077, 0.426, and 0.564, respectively, and the FB values were 0.474, 0.457, and 0.367, respectively. These values indicate that the feed sample data resulted in an unacceptable NMSE value. Using the producer feed formula resulted in an acceptable NMSE value, but using the formula from the consultant resulted in a smaller FB error. For ideal model performance, NMSE and FB should be zero. However, a model can be acceptable if $NMSE \leq 0.5$, and $-0.5 \leq FB \leq 0.5$ (Kumar et al., 1993; Ahuja and Kumar, 1996). Therefore, since the estimated NH₃-N emissions showed low errors using the producer feed formula, this result was considered acceptable.

It should be realized that these statistical parameters indicate relative differences between measured and estimated NH₃-N emissions. These differences were caused by the uncertainties and errors of both methods. Even though we generally trust our measurement results more than the modeling results, we also understand that the measurement methods have errors as well. According to equation 7, measurement errors in air emissions from animal facilities come from two sources: the NH₃ concentration measure-

Table 9. Estimated NH₃-N emission calculation in house 3.

Month	Hen Age (weeks)	Feed Sample (%)		Feed Formula (%)		Eggs (%)		Manure N/Ash	Mass Flow (g hen ⁻¹ d ⁻¹)		NH ₃ -N Emissions (g hen ⁻¹ d ⁻¹)		
		N	Ash	N	Ash	N	Ash		Feed	Eggs	Estimate (feed sample)	Estimate (feed formula)	Meas. ^[a] (mean ±SD)
Apr.	24	2.94	10.25	3.47	15.77	5.87	33.10	0.19	77.18	8.22	0.819	0.431	N/A
	24	3.76	16.56	3.47	15.77	5.76	33.96	0.20	77.91	9.40	0.453	0.354	
	24	3.77	15.14	3.47	15.77	6.14	33.12	0.18	79.05	8.60	0.816	0.490	
Aug.	40	3.45	16.33	2.87	14.57	5.77	33.24	0.19	90.49	15.17	0.432	0.209	N/A
	40	3.24	16.22	2.87	14.57	5.74	33.73	0.17	90.84	15.14	0.423	0.347	
	42	3.09	14.77	2.83	14.58	5.61	32.26	0.18	91.11	15.29	0.438	0.237	
Sep.	47	3.31	16.25	2.76	14.74	5.60	33.63	0.17	90.95	13.52	0.491	0.229	N/A
Oct.	51	2.99	15.93	2.73	14.81	5.78	33.29	0.18	91.21	15.17	0.174	0.116	0.142 ±0.061
Dec.	59	3.16	15.61	2.67	15.07	5.78	33.29	0.16	91.41	15.17	0.505	0.138	0.159 ±0.044
Mean		3.30	15.23	3.02	15.07	5.79	33.29	0.18	86.68	12.85	0.505	0.284	0.237 ^[b]
SD		0.31	1.96	0.35	0.55	0.16	0.49	0.01	6.50	3.15	0.201	0.129	0.211

^[a] Measured NH₃-N emissions from house 3 are from a previous study of the same house (Sun et al., 2005). NH₃-N emission rates were calculated from NH₃ emission rates by multiplying by 14/17.

^[b] Mean value is based on all continuous NH₃ emission measurements from August 2004 to January 2005 (Sun et al., 2005).

Table 10. Statistical evaluation of alternative mass balance method.

Statistic	Feed Sample	Feed Formula		Performance Standard
		Producer	Consultant	
RMSE ^[a]	0.311	0.179	0.197	-
NMSE	1.077	0.426	0.564	NMSE ≤ 0.5
FB	0.474	0.457	0.367	-0.5 ≤ FB ≤ 0.5

^[a] RMSE is in units of g NH₃-N hen⁻¹ d⁻¹.

ment and the ventilation rate quantification. The NH₃ concentration measurement can be very accurate (down to ppb) using various NH₃ gas analyzers (Heber et al., 2006). However, quantification of the ventilation rates of poultry houses with 40 to 50 fans or more is not an easy task; it is determined by the measurement of house static pressure, the operation status of the fans, and fan performance curves (Gates et al., 2004). Significant errors can be introduced during the ventilation rate measurement due to many sources of errors. Nevertheless, we currently consider the measurement method to be the most trustworthy approach to quantify air emissions from animal facilities. Therefore, this evaluation shows the relative differences between the estimated and measured NH₃-N emissions.

REPLICATION OF SAMPLING AND MODELING EVENTS FOR ESTIMATION OF NH₃-N EMISSIONS

The manure sampling and alternative mass balance method can be used to directly estimate average NH₃-N emissions over the manure removal interval of each specific farm operation. Since the NH₃-N emission rates varied from month to month but did not demonstrate a significant seasonal difference, replication of the sampling and modeling events can result in a reliable estimate of the NH₃-N emission factors (mean NH₃-N emissions in g hen⁻¹ d⁻¹) for a poultry house. Using equation 6, the minimum number of replications of sampling and modeling events for estimation of an NH₃-N emission factor using the alternative mass balance method and producer feed formula data were estimated to be 22 and 21 for houses 1 and 2, respectively, with a 90% confidence level ($\alpha = 0.1$) and maximum error 15%. Using the sampled feed data, the number of replications was 178 for house 1 and 310 for house 2. For house 3, the number of replications was estimated to be 32 when using the producer feed formula data and 24 when using the sampled feed data.

It was found that correctly sampling the feed from the feed bin significantly reduced the feed sample errors. Therefore, an average of the minimum number of replications was determined as 22 for reliable estimation of NH₃-N emission factors from MB poultry layer houses using the alternative mass balance method. Since there was no significant seasonal difference in NH₃ emissions, the 22 sampling and modeling events can happen in any time period, depending on the purpose of the sampling and analysis. For estimating the annual average of the NH₃ emission factor for a poultry house, a spread of sampling events is recommended to cover any possible variations in NH₃ emissions over a long period.

COMPARISON WITH PUBLISHED NH₃ EMISSION DATA

Table 11 lists NH₃ emission rates reported in the literature for MB poultry layer houses. Emissions of NH₃-N

Table 11. Comparison of published NH₃-N emission rates.

Study	Emission Rate (g NH ₃ -N hen ⁻¹ d ⁻¹)	Manure Removal Interval
Hayes et al. (2006)	0.082 to 0.412	Weekly
Keener and Zhao (2008)	0.107 to 0.148	N/A
Liang et al. (2003)	0.024 to 0.376	Daily
Liang et al. (2005)	0.044 ± 0.003 0.077 ± 0.016	Daily with no drying Twice a week
Liang et al. (2005)	0.082 to 0.142	Daily
Nicholson et al. (2004)	0.037 to 0.223 0.207 to 0.592	Daily Weekly
Heber (2013)	0.05 to 0.29	N/A
This study	0.293 to 0.394 0.284 ± 0.129	Twice a week 20% of manure daily

from poultry layer houses are affected by temperature, ventilation rate, as well as manure moisture, pH, and handling activities (NRC, 2003; Liang et al., 2005). The NH₃ emission rate varied from 0.044 to 0.29 g hen⁻¹ d⁻¹ depending on manure removal frequency (Liang et al., 2005; Heber, 2013). Specifically, NH₃-N emissions ranged from 0.024 to 0.376 g hen⁻¹ d⁻¹ with daily manure removal (Liang et al., 2003; Nicholson et al., 2004; Liang et al., 2005), from 0.062 to 0.083 g hen⁻¹ d⁻¹ with manure removal twice per week (Liang et al., 2005; Fournel et al., 2012), and from 0.082 to 0.592 g hen⁻¹ d⁻¹ with weekly manure removal (Nicholson et al., 2004; Hayes et al., 2006). According to the above-mentioned literature, manure removal frequency strongly affected NH₃-N emissions from the poultry houses, and longer retention of manure on the manure belt can create higher emission rates and nitrogen loss.

The NH₃-N emissions predicted in this study were within the range of the published data but higher than the values reported by studies with similar manure removal schedules. The alternative mass balance method predicts the total manure nitrogen loss, which is an upper limit of NH₃-N emissions. In the summer, when temperature and moisture are high in poultry houses, other types of nitrogen gas emissions can occur. In addition, the average ventilation rates during the sampling days for houses 1 and 2 were 4.80 and 4.14 m³ hen⁻¹ h⁻¹, respectively, which were higher than the 0.5 to 2.0 m³ hen⁻¹ h⁻¹ reported by Liang et al. (2005) and the 3.87 m³ hen⁻¹ h⁻¹ reported by Fournel et al. (2012). The total manure nitrogen content on dry basis in houses 1 and 2 was 4.71% to 5.91%, which was lower than the 6.49% to 7.14% reported by Liang et al. (2005) and Fournel et al. (2012). This indicates possibly higher NH₃-N losses, due to the higher ventilation rates, for the poultry houses in this study.

CONCLUSIONS

The alternative mass balance method can be used to estimate NH₃ emission factors from MB poultry layer houses. Sampling schedules and procedures for feed, eggs, and manure were developed to obtain representative samples to estimate NH₃ emissions accurately. Manure samples can be preliminarily collected to decide the further sampling size for any specific poultry house. The three case studies presented here show that sample sizes of 4 for manure, 3 for

feed, and 3 for eggs were sufficient, with a 90% confidence level and a maximum error of 15%. The feed nitrogen and ash contents calculated directly from the feed formula provided by the producer according to the hen age is recommended for this alternative mass balance method. The nitrogen and ash content of eggs can be sampled as little as once or twice due to the low variance in N and ash values. For Lohmann white hens, the egg values reported in this study can be used.

The annual average NH₃-N emission factors for the MB poultry layer houses were estimated using the alternative mass balance method as 0.394 ± 0.143, 0.293 ± 0.1, and 0.284 ± 0.129 g NH₃-N hen⁻¹ d⁻¹ for houses 1, 2, and 3, respectively. The measured NH₃-N emission factors were 0.20 ± 0.067, 0.22 ± 0.036, and 0.237 ± 0.211 g NH₃-N hen⁻¹ d⁻¹ for houses 1, 2, and 3, respectively. The method estimates total nitrogen emissions, which is an upper limit of NH₃-N emissions, and therefore showed different degrees of overestimation of the NH₃ emission factor for the three case studies. The NH₃-N emission values estimated using the alternative mass balance method are within the range reported in the literature for MB poultry houses.

In comparing the measured and estimated emissions from the three houses, statistical parameters (RMSE, NMSE, and FB) were used to evaluate the performance and reliability of the method. The RMSE value for measured and estimated NH₃ emissions was 0.179 g NH₃-N hen⁻¹ d⁻¹, the NMSE value was 0.426, and the FB value was 0.457. According to the criteria for an acceptable model (NMSE ≤ 0.5 and -0.5 ≤ FB ≤ 0.5), the alternative mass balance method's estimation of NH₃-N emissions from the MB poultry houses has acceptable accuracy when using the producer feed formula.

For a 90% confidence level ($\alpha = 0.1$) and a maximum error level of 15%, a minimum of 22 replications of the mass balance sampling and modeling process are suggested for reliable estimation of the NH₃-N emission factor for MB poultry layer houses.

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