2005

Ammonia Emissions from U.S. Laying Hen Houses in Iowa and Pennsylvania

Yi Liang
Iowa State University

Hongwei Xin
Iowa State University, hxin@iastate.edu

Hong Li
Iowa State University

Eileen F. Wheeler
Pennsylvania State University

Jennifer L. Zajaczkowski
Pennsylvania State University

See next page for additional authors

Ammonia Emissions from U.S. Laying Hen Houses in Iowa and Pennsylvania

Abstract

Ammonia (NH_3) emission rates (ER) of ten commercial layer houses (six high-rise or HR houses and four manure- belt or MB houses) with different manure handling or dietary schemes were monitored for one year in Iowa (IA) and Pennsylvania (PA). Gaseous (NH_3 and CO_2) concentrations of incoming and exhaust air streams were measured using custom-designed portable monitoring units that shared similar performance to EPA-approved measurement apparatus. Building ventilation rates were determined by calibrated CO_2 mass balance using the latest metabolic rate data for modern laying hens. The field monitoring involved a total of 386 and 164 house-day measurements or 18,528 and 7,872 30-min emission data points for the HR houses and the MB houses, respectively. The ER showed considerable diurnal and seasonal variations. The annual mean ERs (g NH_3 hen^{-1} d^{-1}) and standard errors were 0.90 ±0.027 for IA-HR houses with standard diet, 0.81 ±0.02 for IA-HR houses with a nutritionally balanced 1% lower crude protein diet, 0.83 ±0.070 for PA-HR houses with standard diet, 0.054 ±0.0035 for IA-MB houses with daily manure removal, and 0.094 ±0.006 for PA-MB houses with twice a week manure removal. Mass balance of nitrogen (N) intake and output performed for IA-HR houses revealed a total N intake recovery of 94% to 101%, further verifying the certainty of the NH_3 ER measurements. Results of the study contribute to the U.S. national inventory on NH_3 emissions from animal feeding operations, particularly laying hen facilities as affected by housing type, manure handling scheme, crude protein content of the diet, and geographical location.

Keywords

Aerial emissions, Dietary manipulation, High-rise hen house, Manure belt hen house

Disciplines

Agriculture | Bioresource and Agricultural Engineering

Comments

This article is from *Transactions of the ASAE* 48, no. 5 (2005): 1927–1941.

Authors

Yi Liang, Hongwei Xin, Hong Li, Eileen F. Wheeler, Jennifer L. Zajaczkowski, Patrick A. Topper, Richard S. Gates, Kenneth D. Casey, Bruce B. Behrends, David J. Burnham, and Frank J. Zajaczkowski

AMMONIA EMISSIONS FROM U.S. LAYING HEN HOUSES IN IOWA AND PENNSYLVANIA

Y. Liang, H. Xin, E. F. Wheeler, R. S. Gates, H. Li, J. S. Zajaczkowski,
P. A. Topper, K. D. Casey, B. R. Behrends, D. J. Burnham, F. J. Zajaczkowski

ABSTRACT. *Ammonia (NH_3) emission rates (ER) of ten commercial layer houses (six high−rise or HR houses and four manure−belt or MB houses) with different manure handling or dietary schemes were monitored for one year in Iowa (IA) and Pennsylvania (PA). Gaseous (NH_3 and CO_2) concentrations of incoming and exhaust air streams were measured using custom−designed portable monitoring units that shared similar performance to EPA−approved measurement apparatus. Building ventilation rates were determined by calibrated CO_2 mass balance using the latest metabolic rate data for modern laying hens. The field monitoring involved a total of 386 and 164 house−day measurements or 18,528 and 7,872 30−min emission data points for the HR houses and the MB houses, respectively. The ER showed considerable diurnal and seasonal variations. The annual mean ERs (g NH_3 hen^{-1} d^{-1}) and standard errors were 0.90 ±0.027 for IA−HR houses with standard diet, 0.81 ±0.02 for IA−HR houses with a nutritionally balanced 1% lower crude protein diet, 0.83 ±0.070 for PA−HR houses with standard diet, 0.054 ±0.0035 for IA−MB houses with daily manure removal, and 0.094 ±0.006 for PA−MB houses with twice a week manure removal. Mass balance of nitrogen (N) intake and output performed for IA−HR houses revealed a total N intake recovery of 94% to 101%, further verifying the certainty of the NH_3 ER measurements. Results of the study contribute to the U.S. national inventory on NH_3 emissions from animal feeding operations, particularly laying hen facilities as affected by housing type, manure handling scheme, crude protein content of the diet, and geographical location.*

Keywords. *Aerial emissions, Dietary manipulation, High-rise hen house, Manure belt hen house.*

Aerial ammonia (NH_3) is the predominant pollutant gas in poultry production facilities, resulting from microbial decomposition of uric acid in bird feces. According to the U.S. Environmental Protection Agency's emission inventory (USEPA, 2002, 2004), livestock operations and fertilizer application constituted about 85% of the total national NH_3 emissions in 1998, while publicly owned treatment works, mobile sources, and combustion sources made up the remaining 15%. Ammonia emission is environmentally important because of its contribution to acidification of soil and water and increased nitrogen deposition in ecosystems. Excessive NH_3 in animal housing can also adversely affect bird performance and welfare. Moreover, NH_3 is considered a source of secondary particulate matter (Baek and Aneja, 2004) that is regulated under the U.S. National Ambient Air Quality Standard. The potential for additional federal air quality regulations for animal feeding operations necessitates better inventory and mitigation of NH_3 emissions. Limited research information is available concerning NH_3 emissions from U.S. animal feeding operations (Burns et al., 2003; Keener et al., 2002; Patni and Jackson, 1996; Maghirang and Manbeck, 1993). In comparison, more data for European livestock production facilities have been reported (Groot Koerkamp et al., 1998; Hinz and Linke, 1998; Nicholson et al., 2004; Wathes et al., 1997). However, applicability of the European emission data to U.S. conditions remains to be examined or validated due to differences in housing style, manure management practices, climate, etc. Data on NH_3 emission rates are particularly lacking for modern U.S. laying hen houses.

Manure management in laying hen facilities can greatly influence NH_3 emission. High-rise (HR) and manure-belt (MB) houses are the two most common housing styles of the egg industry in the United States. In the case of HR houses, solid manure is stored in the lower level of the building for about a year before removal. In comparison, manure in MB houses drops onto a belt beneath cages and is frequently removed from the house, say, two to seven times a week.

Article was submitted for review in November 2004; approved for publication by the Structures & Environment Division of ASABE in July 2005. Presented at the 2004 ASAE Annual Meeting as Paper No. 044104.

Mention of vendor or product names is for presentation clarity and does not imply endorsement by the authors or their affiliations, or exclusion of other suitable products.

The authors are **Yi Liang, ASABE Member Engineer,** Postdoctoral Research Associate, **Hongwei Xin, ASABE Member Engineer,** Professor, and **Hong Li, ASABE Student Member,** Graduate Research Assistant, Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, Iowa; **Eileen Fabian Wheeler, ASABE Member Engineer,** Associate Professor, **Jennifer S. Zajaczkowski,** Senior Research Technologist, and **Pat A. Topper,** Research Technologist, Department of Agricultural and Biosystems Engineering, The Pennsylvania State University, University Park, Pennsylvania; **Richard S. Gates, ASABE Member Engineer,** Professor and Department Chair, and **Kenneth D. Casey, ASABE Member Engineer,** Research Specialist, Department of Agricultural and Biosystems Engineering, University of Kentucky, Lexington, Kentucky; **Bruce B. Behrends,** General Manager, Nutritionist, Agri-Tech, a Sparboe Company, Litchfield, Minnesota; **David J. Burnham,** Nutritionist, Ajinomoto Heartland, LLC, Chicago, Illinois; and **Frank J. Zajaczkowski,** Associate Research Engineer, Computational Fluid Dynamics, Applied Research Laboratory, The Pennsylvania State University, University Park, Pennsylvania. **Corresponding author:** Hongwei Xin, 3204 NSRIC, Iowa State University, Ames, IA 50011-3310; phone: 515-294-4240; fax: 515-294-4250; e-mail: hxin@iastate.edu.

  ISSN 0001−2351

Nitrogen (N) content in feces is an important factor influencing NH_3 generation. To reduce N content in feces, rations may be formulated with reduced dietary crude protein (CP) and supplemented with limiting amino acids (AA) to match bird dietary requirements (Groot Koerkamp, 1994; Ferguson et al., 1998a, 1998b; Gates et al., 2000, 2002). Research on decreasing N excretion from poultry, swine, or cattle by optimizing nutrient availability in the diet to meet animals' maintenance and production needs have made key advances in recent years (Blair et al., 1999; CAST, 2002; Sutton et al., 2002). Studies have shown that feeding lower CP diets to poultry reduced total ammoniacal N and equilibrium NH_3 concentration of the litter or manure (Chi and Speers, 1976; Summers, 1993; Ferguson et al., 1998a, 1998b; Blair et al., 1999; Gates et al., 2000; Gates, 2001). However, data are lacking that link reduced NH_3 emission to dietary manipulation under commercial production settings.

The objective of this study was to measure NH_3 emission rate (ER) from representative U.S. layer houses as affected by housing style, manure handling practice, diet, and geographical location. The data reported here represent 386 house-day (18,528 semi-hourly) observations for six HR houses and 164 house-day (7,872 semi-hourly) observations for four MB houses over one-year period. The study was part of a multi-state project to collect baseline NH_3 emission data from representative U.S. layer and broiler houses and to evaluate the efficacy of certain management practices and mitigation strategies on house-level NH_3 emission (www.bae.uky.edu/IFAFS/).

Materials and Methods

Housing Characteristics and Management Practices

This field monitoring study involved six commercial layer houses in Iowa (IA) - Midwest region, including four high-rise (HR) houses and two manure-belt (MB) houses, and four layer houses in Pennsylvania (PA) - Northeast region, including two houses of each type. The two regions compose the majority of the U.S. egg industry. The 99% annual heating dry-bulb temperatures are −22°C and −11°C for IA and PA, respectively, with a corresponding 1% annual cooling dry-bulb and coincident wet-bulb temperatures of 31°C/23°C and 32°C/23°C (ASHRAE, 2001). Hen manure in the MB house was removed either daily (IA) or every 3 to 4 days (PA). Manure in the HR houses was handled somewhat differently in IA and PA. For IA-HR houses, manure fell onto dropping boards below the cages and was mechanically scraped twice daily into the lower-level storage through a 15 cm floor opening along the center of the cage rows. For PA-HR houses, manure dropped directly into the storage area through wide floor openings. Details of the housing characteristics and management schemes of the ten layer houses are presented in table 1. Photoperiod was 16L:8D throughout the monitoring period except during molting or new flocks.

Weekly bird performance data, including feed and water consumption, egg production, mortality, bird age, and body weight, were collected from the cooperating producers in both states. Manure samples in the four IA-HR houses were collected during manure removal in October 2003 and were analyzed in a manure analysis laboratory at Iowa State University. Manure samples from the four PA houses (HR and MB) were collected in March and July 2003 and were analyzed at the Water Quality Laboratory of the Biosystems and Agricultural Engineering Department at University of Kentucky (table 2).

Instrumentation and Measurement Protocols

Portable monitoring units (PMUs) were used in the field study, as described by Xin et al. (2002, 2003) and Gates et al. (2005). The PMU used two electrochemical (EC) NH_3 sensors (0 to 200 ±3 ppm; PAC III H, Dräeger Safety, Inc., Pittsburgh, Pa.) and an infrared CO_2 sensor (0 to 5000 or 0 to 7000 ±[20 + 2% of reading] ppm; Vaisala, Inc., Woburn, Mass.). To avoid measurement errors caused by EC sensor saturation from continuous exposure to NH_3-laden air, measurement cycles consisting of 24 min purging with fresh outside air and 6 min sampling of the exhaust air stream (as determined by trial and error) were used. This purging-sampling cycle resulted in 30 min measurement intervals of both NH_3 and CO_2 concentrations of the inlet and exhaust air streams.

Before and after each field-monitoring episode, the NH_3 sensors were checked and recalibrated, as needed, with zero and span gases. Before each trip to the MB houses, NH_3 span gas of 18 ppm (+N_2 balance, ±2% accuracy, IA) (Matheson Tri-Gas Inc., La Porte, Texas) or 18.9 ppm (+N_2 balance, ±2% accuracy, PA) (Messer, MG Industries, Morrisville, Pa.) was used to calibrate the NH_3 sensors. Before each trip to the HR houses, NH_3 calibration gas of 18 ppm (IA)/ 18.9 ppm (PA) (in summer), 49 ppm (IA)/48.3 ppm (PA) (in spring and fall), or 154 ppm (IA)/104 ppm (PA) (in winter) was used to calibrate the NH_3 sensors. Use of different concentrations of span gas for different seasons was done to better reflect the seasonal NH_3 concentrations in the exhaust air, an integral part of our quality assurance protocol.

The NH_3 loggers were programmed to collect data at 30 s (IA) or 1 min (PA) intervals. Ammonia measurements from redundant sensors in a PMU were averaged when the readings between the two were within 2 to 5 ppm of each other, with the larger difference corresponding to higher NH_3 concentrations. Whenever discrepancy between the two sensors was outside this range, readings from the sensor verified with post-monitoring check were used for emission calculation, while the other sensor was further tested and/or replaced. Use of redundant sensors enabled us to collect the NH_3 concentrations with minimal interruptions or loss of data.

The CO_2 sensors were calibrated every three months with zero, 2000 ppm, and 4000 ppm CO_2 calibration gases (+N_2 balance, ±2% accuracy, Matheson Tri-Gas Inc., La Porte, Texas). Concurrent measurements of inside and outside air temperature (±0.2°C resolution) and relative humidity (RH, ±3% resolution) were made at 30−second intervals with portable, programmable data loggers (HOBO Pro RH/Temp, Onset Computer Corporation, Bourne, Mass.).

Each data collection period consisted of 48 h or longer continuous measurements, and was performed weekly (IA-HR houses), bi-weekly (IA-MB houses), or every three weeks (PA houses). Two PMU units were installed in each

Table 1. Characteristics and management data of the commercial layer houses monitored in this study.

Building ID[a]	Diet	Width × Length (m)	Hen Breed	Manure Removal Frequency	Vent. System[b]	No. of Vent. Fans (diameter)	No. of Min. Vent. Fans	No. and Type of Inlets[c]	No. of Birds at Start	No. of Cage Rows	No. of Cage Tiers	Measure-ment Period
Iowa (IA)												
IA-MB-1,2	Standard	18 × 159	W-36	Daily	Quasi Tunnel	26 (1.2 m) 4 (0.9 m)	2	2 rows of CSCI	104,860	8	3	12/31/02 to 1/08/04
IA-HR-C-1,2	Standard	14.6 × 131.7	W-36	Annually[d]	Cross	24 (1.2 m) 2 (0.9 m)	2	5 rows of CSCI	73,938-82,219	5	4	12/18/02 to 12/15/03
IA-HR-T-1,2	Lower CP	14.6 × 131.7	W-36	Annually[e]	Cross	24 (1.2 m) 2 (0.9 m)	2	5 rows of CSCI	73,938-82,219	5	4	
Pennsylvania (PA)												
PA-MB-1	Standard	16.5 × 161.5	W-36	Semi-weekly	Cross + Tunnel[f]	36 (1.3 m) + 10 (0.9 m)	3	4 rows of CSCI (winter) Side wall curtain inlet (summer)	157,822	6	6	1/24/03 to 2/11/04
PA-MB-2	Standard	16.5 × 161.5	Bovan	Semi-weekly	Cross + Tunnel[f]	36 (1.3 m) + 10 (0.9 m)	3	Same as PA-MB-1	158,117	6	6	
PA-HR-1	Standard	16.5 × 161.5	W-98	Annually[g]	Cross	28 (1.2 m) 4 (1.0 m)	4	CPEI	93,974	6	4	2/26/03 to 2/11/04
PA-HR-2	Standard	16.5 × 161.5	W-36	Annually[h]	Cross	28 (1.2 m) 4 (1.0 m)	4	CPEI	95,984	6	4	

[a] HR = high-rise, MB = manure belt, T = treatment diet (lower crude protein), C = control diet (standard crude protein), 1 or 2 = house number.
[b] All houses used negative-pressure ventilation.
[c] CSCI = continuous slot ceiling inlet; CPEI = continuous perimeter eave inlet.
[d] Before study: 2 to 5 November 2002 (IA-HR-C-1) and 5 to 8 November 2002 (IA-HR-C-2); during study: 11 to 14 October 2003 (IA-HR-C-1) and 15 to 17 October 2003 (IA-HR-C-2).
[e] Before study: 22 to 31 October 2002 (IA-HR-T-1) and 8 to 14 November 2002 (IA-HR-T-2); during study: 8 to 10 October 2003 (IA-HR-T-1) and 18 to 20 October 2003 (IA-HR-T-2).
[f] Cross ventilation with 10 fans on sidewall during cold and mild weather; tunnel ventilation with 36 fans on both end walls during warmer weather.
[g] Before study: October 2002, not removed during study.
[h] Before study: October 2002; during study: November 2003 to January 2004.

Table 2. Characteristics of manure samples collected in Iowa and Pennsylvania layer houses.[a]

Building ID[b]	Dry Matter Content (%)	Total N (% dry basis)	pH
IA-HR-C-1	68.1	2.89	
IA-HR-C-2	74.4	3.73	
IA-HR-T-1	69.8	3.03	
IA-HR-T-2	72.3	3.48	
PA-HR-1	38.6, 59.4, 51.0	2.98, 3.28	8.6, 8.4
PA-HR-2	37.7, 57.0, 54.0	2.31, 2.76	8.7, 8.5
PA-MB-1	37.1, 49.6, 54.3	6.17, 9.88	7.6, 7.2
PA-MB-2	50.3, 44.8, 54.9	4.13, 8.38	7.1, 7.7

[a] For IA, all samples taken in October 2003.
For PA, samples were taken in the following months:
DMC: March, July, and November 2003, respectively.
Total N: July and November 2003, respectively.
pH: March and July 2003, respectively.
[b] IA = Iowa, PA = Pennsylvania, HR = high-rise, MB = manure belt, T = treatment diet (lower crude protein), C = control diet (standard crude protein), 1 or 2 = house number.

house at locations described below. The length of the sample tubing varied from 5 to 20 m, while the length of the purging tubing varied from 7 to 15 m. Sample air was drawn by the supply pump at a flow rate of 11 l/min. Only 0.6 L/min of the 11 L/min air was passing through the NH_3 and CO_2 sensors, and the remaining excessive amount was bled off just before the sensors. Use of the high flow rate was to reduce residence time of the sample air in the sample line. Data reported in this article covered the period from mid-December 2002 to mid-December 2003 (IA-HR houses), early January to late December 2003 (IA-MB houses), or late January 2003 to early February 2004 (PA houses).

Manure-Belt Houses

Iowa

One PMU was installed at each exhaust end of the quasi-tunnel ventilation houses. Composite samples from four sampling ports at each end were introduced into the respective PMU. Air temperature and RH were monitored at three locations along the length of the houses (fig. 1).

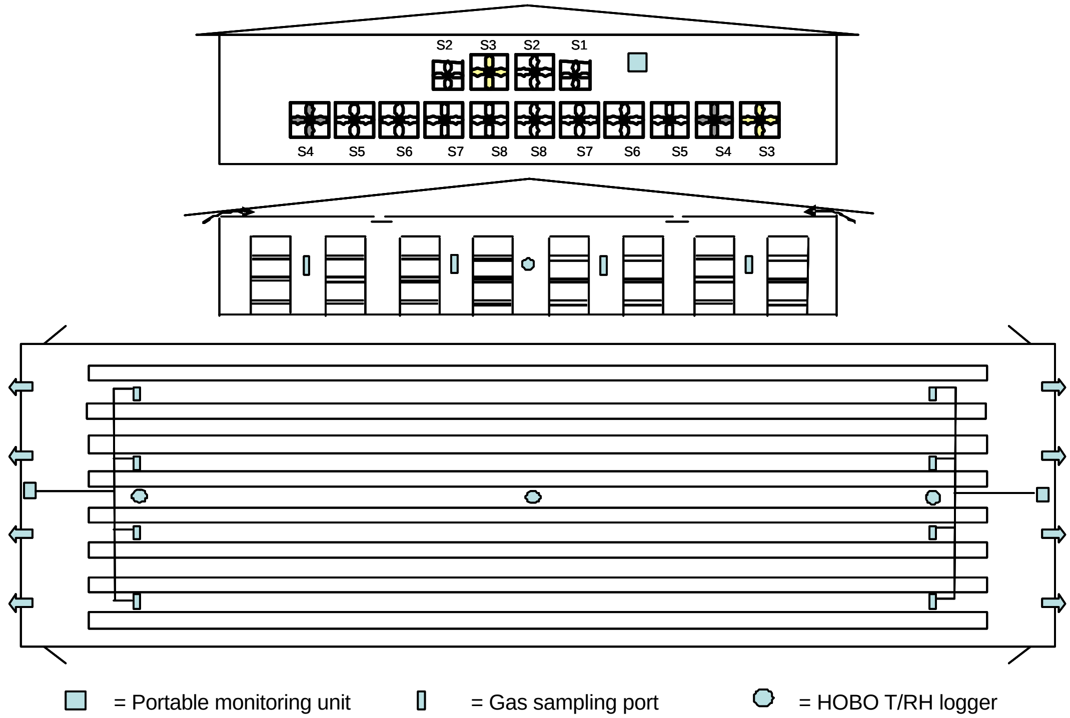

Figure 1. Schematic layout of the IA manure-belt layer house showing the end wall, cross-section, and floor plan of the house and the sampling locations. The exhaust fans are labeled by stages 1-8.

Pennsylvania

One PMU was installed close to each end near the exhaust fans of the houses that used cross-ventilation except during warm weather, when tunnel ventilation was used. Composite samples from two sampling ports (one at lower level, the other at upper level) between two cage rows near a sidewall exhaust fan were introduced into the respective PMU (fig. 2). Air temperature and RH of the lower level were monitored with duplicate sensors.

High-Rise Houses

Iowa

One PMU was installed at each end near the continuous ventilation fan(s). Composite samples from two sampling ports near the continuous fan (1/3 fan diameter down from top, 1 m setback from the sidewall, 1.5 m offset from the center of the fan) were introduced into each PMU. During warm weather, the composite sample to each PMU was expanded to include air near one of the second-stage exhaust

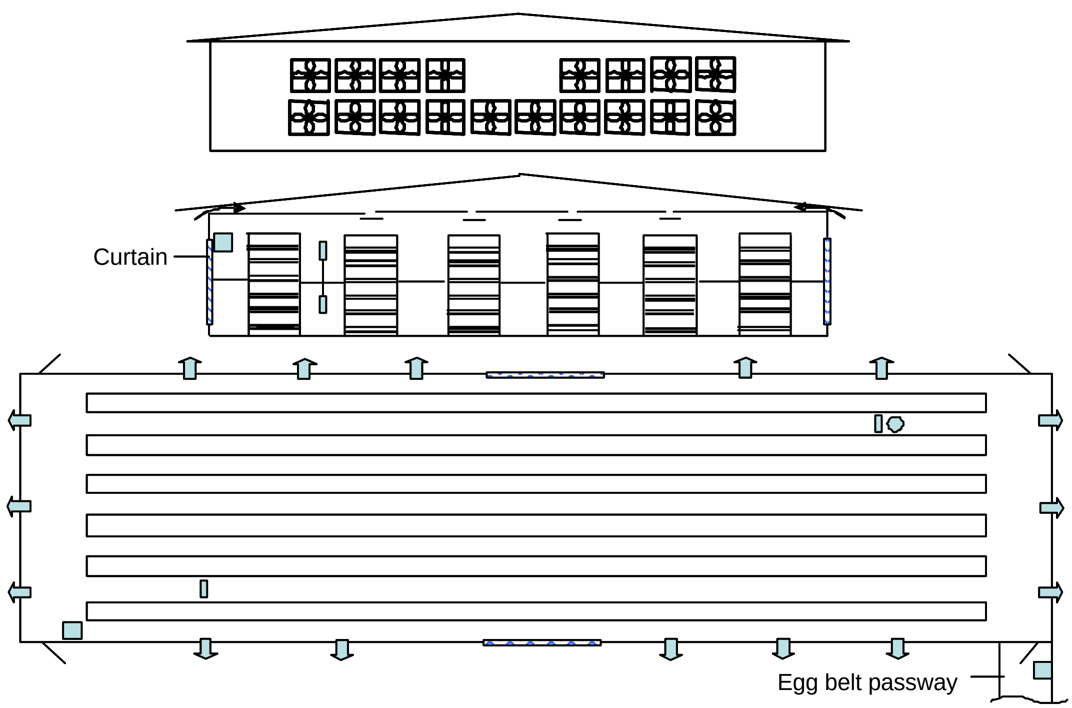

Figure 2. Schematic layout of the PA manure-belt layer house showing the end wall, cross-section, and floor plan of the house and the sampling locations (symbols are the same as in fig. 1).

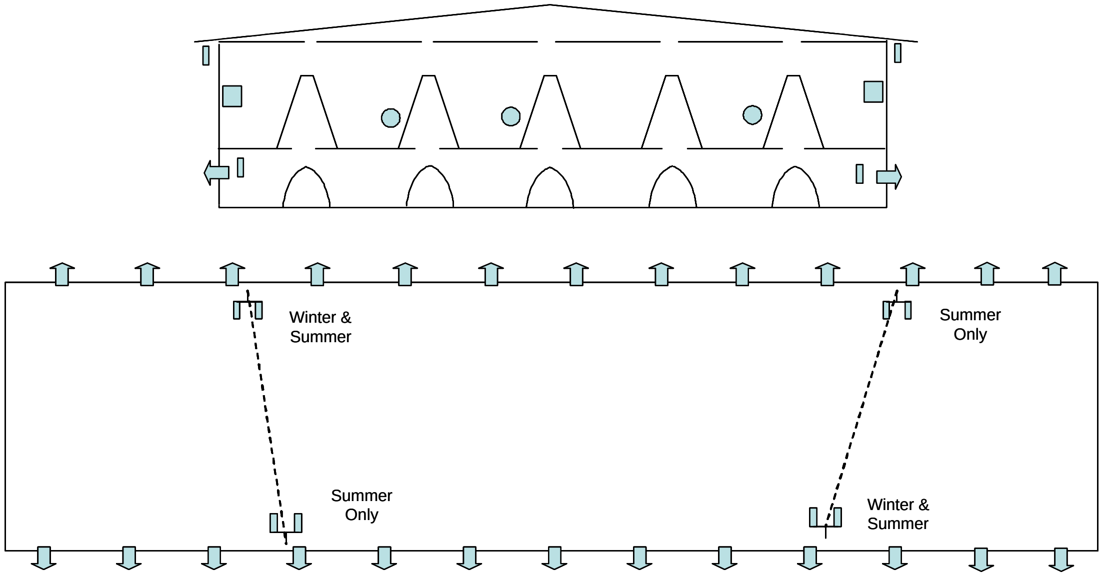

Figure 3. Schematic layout of the IA high-rise layer house showing the cross-section and floor plan of the house and the sampling locations (symbols are the same as in fig. 1).

fans that operated throughout the summer (fig. 3). In an effort to better measure CO_2 concentration from birds' respiration, two dual-beam absorption infrared CO_2 sensors (Telaire 7001, Engelhard Corp., Iselin, N.J.) in each house were hung under the manure dropping slots, and CO_2 concentrations were measured and stored every 30 s. Bird-level air temperature and RH were monitored at three locations along the length of the houses.

Pennsylvania

PMU units were installed in two fan enclosures on opposite ends and sidewalls of each house. Composite samples from three sampling ports inside the fan enclosure were introduced into each PMU to sample exhaust air (fig. 4). The purging port was positioned near the building eave inlet above the fan enclosure outside the layer houses. Air temperature and RH in the fan enclosure were monitored.

Diet Manipulation

Hens in all houses, except for two of the four IA-HR houses, received the standard ration formulation used by the cooperator. The four IA-HR houses were used to evaluate the effect of reduced CP diets on NH_3 emission rates. Two of the houses received standard CP rations (standard 1 and 2, designated as Ctrl or C-1 and C-2) and the other two received diets with lower CP content and supplemented with essential amino acids (lower CP 1 and 2, designated as Trt or T-1 and T-2). Hence, the experiment had two dietary regimens with two replicates each. However, differences existed in flock age among the four houses, which confounded the experimental design somewhat. At the start of measurements (December 2002), flock age in IA-HR-T-1 and IA-HR-C-1 (pair 1) was one week apart, while flock age in IA-HR-T-2 and IA-HR-C-2 (pair 2) was four weeks apart. Hens in IA-HR-T-1 and IA-HR-C-1 (pair 1) started 4-week molting

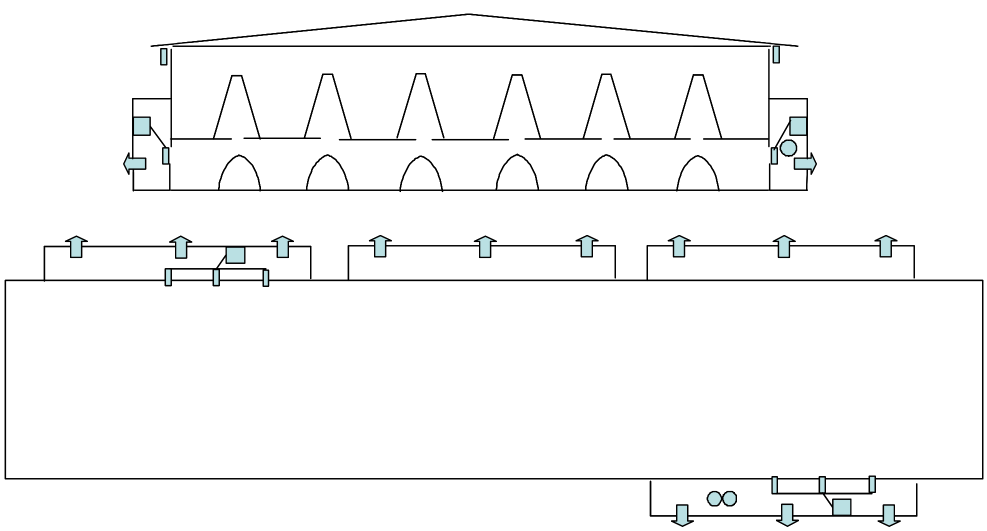

Figure 4. Schematic layout of the PA high-rise layer house showing the cross-section and floor plan of the house and the sampling locations (symbols are the same as in fig. 1).

Table 3. Bird age (week) at beginning of each month, monthly average bird weight (kg), and monthly average crude protein (CP) contents in four high-rise layer houses used in the diet manipulation study in Iowa.[a]

Month (2003)	IA-HR-T-1 Bird Age	Bird Wt.	CP (%)	IA-HR-C-1 Bird Age	Bird Wt.	CP (%)	IA-HR-T-2 Bird Age	Bird Wt.	CP (%)	IA-HR-C-2 Bird Age	Bird Wt.	CP (%)
Jan.	52	1.53	15.2	51	1.46	16.0	89	1.59	14.3	93	1.54	15.2
Feb.	57	1.59	15.0	56	1.56	15.8	94	1.59	14.2	98	1.69	14.9
March	61	1.48	14.4	60	1.45	15.3	98	1.59	13.7	102	1.58	14.3
April	65	1.54	14.4	64	1.54	15.3	102	1.71	13.7	18	1.38	16.9
May	69	1.26	15.0	68	1.25	15.0	106	1.67	13.7	22	1.45	16.9
June	74	1.45	14.4	73	1.42	15.3	111	1.51	13.7	27	1.47	16.9
July	78	1.45	14.4	77	1.42	15.3	18	1.39	15.7	31	1.47	16.9
Aug.	83	1.51	14.3	82	1.50	15.3	23	1.40	15.7	36	1.43	16.9
Sept.	87	1.53	14.3	86	1.50	15.2	27	1.43	15.7	40	1.45	16.6
Oct.	91	1.57	14.3	90	1.55	15.2	31	1.48	15.7	44	1.49	16.6
Nov.	96	1.64	14.2	95	1.60	15.2	36	1.51	15.7	49	1.50	16.6
Dec.	100	1.62	14.2	99	1.61	14.9	40	1.54	15.6	53	1.53	16.0

[a] IA = Iowa, HR = high-rise, T = treatment diet (lower crude protein), C = control diet (standard crude protein), 1 or 2 = house number.

at 68 weeks of age (April 2003), followed by resumption of regular feeding. Hens in IA-HR-C-2 were replaced with a new flock (18 weeks of age) in the first week of April 2003, while hens in IA-HR-T-2 were replaced in the first week of July 2003. This seasonal difference in flock change between IA-HR-C-2 and IA-HR-T-2 (pair 2) resulted in a bird age difference of 84 weeks during April through June, and 13 weeks during July to December 2003 (end of the monitoring period).

Details of flock information are listed in tables 1 and 3. Before the Trt flocks received the experimental diet, manure was removed from all experimental houses. Dietary compositions for each flock at the onset of the study are listed in table 4. In general, soy content was reduced for the Trt diet, and crystalline amino acids DL-methionine, L-lysine, HCL, and L-threonine were supplemented so that these essential amino acids were at the same levels in both diets for each corresponding feeding phase. Tryptophan and isoleucine in the Trt diet were slightly lower than those in the Ctrl diet (difference ranged from 0.02% to 0.06%). The Trt diet had a modest 0.4% to 1.2% lower CP than the Ctrl diet during the various feeding phases. Monthly diet CP contents for all flocks are listed in table 3.

Determination of Building Ventilation Rates and Emission Rates

Ventilation Rate Determination

Ventilation rates of the houses were determined using CO_2 balance method as governed by indirect animal calorimetry relation. The potential of using CO_2 concentration in the exhaust air from animal facilities to estimate ventilation rate has long been recognized and explored (Feddes et al., 1984; Ouwerkerk and Pedersen, 1994; Pedersen et al., 1998). Li et al. (2004) estimated building ventilation rate (Q, m^3 h^{-1} kg^{-1}) of MB layer houses based on CO_2 production of the birds only, namely:

$$Q = \frac{CO_{2,bird} \times 3600}{[CO_2]_e - [CO_2]_i} \quad (1)$$

where $[CO_2]_e$ and $[CO_2]_i$ are exhaust and incoming air CO_2 concentrations (ppm), respectively, and $CO_{2,bird}$ is the specific CO_2 production rate of the hens (mL s^{-1} kg^{-1}) derived from recently updated total heat production rates (THP) and respiratory quotient (RQ) for W-36 laying hens of different ages under light and dark conditions (Chepete and Xin, 2004; Chepete et al., 2004).

In commercial laying hen houses, CO_2 is also produced from manure breakdown; thus, it is rather difficult to measure CO_2 concentration solely from bird respiration. In this study, CO_2 production from stored manure in a HR house was quantified *in situ* during downtime (between flocks) and was used together with respiratory CO_2 production of the hen to derive the building ventilation rate. The measurements were made in the IA-HR-T-2 house on 19 June 2003, two days after removal of the flock (71,049 hens). Manure in the storage area had accumulated for about six months. Two continuously running, minimum ventilation fans and the next two staging fans, representing the four corners/quadrants of the house, were operated and monitored with four PMUs, one per corner/fan. Carbon dioxide concentrations of both intake and exhaust air streams were measured, along with building static pressure (SP) under various numbers of running fans (one to four) with an SP transducer (0 to 125 Pa, model 264, Setra Systems, Inc., Boxborough, Mass.). Average CO_2 concentrations per PMU at each stage were obtained from the last 5 min stabilized readings (usually after 40 min stabilization). Airflow rates of the four monitored fans at corresponding SP were obtained by individually measuring each fan with a Fan Assessment Numeration System (FANS) unit (Gates et al., 2004).

Carbon dioxide generation rate from each individual running fan was calculated as the product of measured CO_2 concentration difference between intake and exhaust air of

Table 4. Dietary composition (as analyzed) of the first formula for each flock at the beginning of the study in the four high-rise layer houses (Iowa) (%, unless otherwise noted).

Ingredient	Pair 1 Standard 1 (47 wk)	Pair 1 Lower CP 1 (48 wk)	Pair 2 Standard 2 (89 wk)	Pair 2 Lower CP 2 (85 wk)
Protein	16.6	15.6	15.2	14.3
ME (MJ/kg)	11.7	11.8	11.9	11.9
Lysine	0.94	0.94	0.84	0.84
Methionine	0.44	0.44	0.34	0.34
Threonine	0.66	0.66	0.61	0.61
Tryptophan	0.22	0.20	0.18	0.18
Isoleucine	0.85	0.79	0.78	0.72
Calcium	4.25	4.25	4.25	4.25
Available P	0.48	0.48	0.43	0.43

the fan and its corresponding airflow rate at measured SP. The steady-state CO_2 generation rate (ΔCO_2, m^3 CO_2 h^{-1} $house^{-1}$) from the manure at each stage was then calculated from summation of the individual fans, i.e.:

$$\Delta CO_2 = \sum_{k=1}^{n} \{([CO_2]_{e,k} - [CO_2]_{i,k}) \times 10^{-6} \times Q_k\} \quad (2)$$

where $[CO_2]_{e,k}$ and $[CO_2]_{i,k}$ are the exhaust and intake CO_2 concentrations (ppm), respectively, of running fan k, n is the number of running fans at the specific stage, and Q_k is the airflow rate of fan k, which varies from 31,450 to 35,360 m^3 h^{-1} at SP of 4 ±1.75 Pa.

Exhaust CO_2 concentrations averaged 522, 437, 422, or 389 ppm, corresponding to the operation of one, two, three, or four fans, respectively. The corresponding CO_2 generation rate from manure for the number of running fans was 7.2, 7.7, 10.1, and 9.9 m^3 h^{-1} $house^{-1}$. The higher CO_2 emission rates associated with the higher building ventilation rates (three or four running fans) presumably resulted from higher air velocity over the manure surface and greater CO_2 partial pressure deficit between the manure pile and the surrounding environment. Therefore, a CO_2 generation rate from the stored manure was taken as 7.4 m^3 h^{-1} $house^{-1}$ for winter and 10.0 m^3 h^{-1} $house^{-1}$ for the remaining seasons in our determination of the building ventilation rate.

By assuming an average of 77,500 hens in the house and 1.5 kg body mass per hen, CO_2 produced from the manure ($CO_{2,manure}$) ranged from 0.018 mL s^{-1} kg^{-1} (in winter) to 0.024 mL s^{-1} kg^{-1} (in remaining seasons). These values accounted for 5.4% to 9.0% of the total CO_2 generated from both birds and manure, depending on season and photoperiod. Ouwerkerk and Pedersen (1994) reported that CO_2 generation by manure in animal production facilities ranged from 0% to 8.5% of the total CO_2 amount, depending on the storage time and type of the manure.

Building ventilation rates (Q, m^3 h^{-1} kg^{-1}) in the HR houses were thus calculated as follows:

$$Q = \frac{(CO_{2,bird} + CO_{2,manure}) \times 3600}{[CO_2]_e - [CO_2]_i} \quad (3)$$

Emission Rate Determination

The NH_3 emission rate (ER) reported herein was the mass of NH_3 emitted from the layer houses to the atmosphere per unit time. The ER (g hen^{-1} h^{-1}) was calculated using the semi-hourly concentration readings, of the form:

$$ER = Q \times M \times ([NH_3]_e - [NH_3]_i) \times 10^{-6} \times \frac{w_m}{V_m} \times \frac{T_{std}}{T_a} \times \frac{P_a}{P_{std}} \quad (4)$$

where

Q = building ventilation rate at field temperature and barometric pressure (m^3 h^{-1} kg^{-1})

M = average body weight of the hen (kg)

$[NH_3]_i$ = NH_3 concentration of building inlet air (ppm)

$[NH_3]_e$ = NH_3 concentration of building exhaust air (ppm)

w_m = molar weight of NH_3, 17.031 g $mole^{-1}$

V_m = molar volume of NH_3 at standard temperature (0°C) and pressure (101.325 kPa) or STP, 0.022414 m^3 $mole^{-1}$

T_{std} = standard temperature, 273.15 K

T_a = absolute house temperature, (°C + 273.15) K

P_{std} = standard barometric pressure, 101.325 kPa

P_a = atmospheric barometric pressure, 98 kPa (IA) or 99 kPa (PA), based on site elevation.

During PMU development, a comparison of NH_3 concentration recordings between PMU and a chemiluminescence NH_3 analyzer was conducted *in situ*. The results showed that the maximum value of the sampling cycle with the PMU yielded similar measurement as with the analyzer (Xin et al., 2003). The readings of the PMU were further validated with the same type of NH_3 monitors held in the exhaust air stream where the PMU sample was drawn. Background NH_3 of the intake air was checked periodically during different seasons and it was proven to be negligible as compared with the exhaust concentrations. Hence, NH_3 concentration of the exhaust air ($[NH_3]_e$) without subtraction of that from the intake air ($[NH_3]_i$) was used in the calculation of emission rates for this study.

Nitrogen Balance

Mass balance of N (g N hen^{-1} d^{-1}) was performed for the four IA-HR houses. The actual annual average feed intake of 99.2 g hen^{-1} d^{-1} was used for all hens over the 12-month measurement period. The actual protein contents in the ration, differing with feeding phase and flock treatment, were used to calculate the hen protein intake. Nitrogen content was computed as 6.25% of CP content. Because production performance showed no significant difference between the Trt and Ctrl flocks (as discussed later), N retained by egg, live hens, and mortality were assumed identical for both diet regimens and were adopted from Yang et al. (2000). Retained N in year-old manure from each HR manure storage, denoted as N_{Manure}, was calculated based on N and moisture content from nutrient analysis of the manure samples (table 2), the total amount of manure removed from each house, average bird population in the house during the monitoring period, and the actual time of manure accumulation (between manure removals in 2002 and 2003). Manure samples from IA-HR houses were collected at the time of manure removal, which generally lasted two to three days. A section of the stored manure (1.5 to 1.8 m high and 1 to 1.2 m long) was cut out with a mechanical (front end) loader and mixed before the manure samples were taken. Three samples were analyzed for each house. Average NH_3-N emission measured from each house in this study, calculated by ER (g NH_3 hen^{-1} d^{-1}) × 14/17.031, was used as N loss due to gaseous NH_3 emission, denoted as NH_3-N (g N hen^{-1} d^{-1}).

Statistical Analysis

Analysis of mean comparisons was performed between MB houses in IA and PA, as well as between MB and HR houses using Student t-tests. Repeated-measures analysis was performed on daily NH_3 ER (with regard to days of manure accumulation), weekly hen-day egg production, and weekly egg case weight (with regard to bird age) using diet as fixed effect (for IA-HR houses). The SAS MIXED procedure with least square means (LSMEANS) statement was used. Throughout the one-year study, the difference of CP content between the Ctrl and Trt diets was about 1%, except for the period between April and June 2003. During this period, CP content for the IA-HR-C-2 flock was approxi−

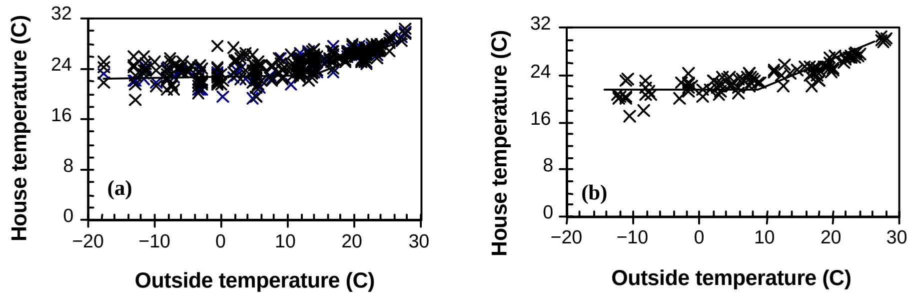

Figure 5. Daily mean air temperature versus daily mean outside temperature in (a) manure-belt and (b) high-rise IA layer houses.

mately 3.2% higher than that for the IA-HR-T-2 flock due to the relatively large difference in bird age between the two flocks (table 3). To achieve a fair comparison of the diet effect on NH_3 ER, the ER data collected between April and the beginning of July from IA-HR-C-2 and IA-HR-T-2 were excluded from the repeated-measures analysis due to the large difference in bird age. Ammonia ER during molting for IA-HR-C-1 and IA-HR-T-1 flocks was also excluded from the analysis.

Results and Discussion

Environmental Conditions

Outside daily mean temperature during the one-year measurement ranged from −17.5°C to 27.9°C with a mean of 9.4°C in IA, and −6.0°C to 27.2°C with a mean of 11.1°C in PA. Outside RH ranged from 42% to 95% with a mean of 71% in IA, and 54% to 92% with a mean of 77% in PA. Hence, the two geographic locations had similar climatic conditions during the one-year monitoring period. Daily mean house temperatures relative to outside temperatures for each building type (IA) are shown in figure 5. Inside temperature began to increase with outside temperature when outside temperature exceeded about 8°C to 10°C.

Gas Concentrations

Carbon dioxide concentrations of the inlet (purging) air ranged from 350 to 500 ppm. The difference in CO_2 concentration between inlet and exhaust air streams varied from 210 to 4300 ppm during the measurement period, with the maximum difference occurring on 21 January 2003 and the minimum difference on 20 August 2003.

Daily mean NH_3 concentrations of the exhaust air were 2.8 ppm and 5.4 ppm for the IA and PA MB houses, respectively, but 44.8 ppm and 35.9 ppm for the IA-Ctrl and PA HR houses (figs. 6 and 7). Ammonia concentrations of the HR house exhaust air decreased quite linearly with increase in outside temperature and thus building ventilation rate (fig. 8).

Ammonia Emission Rates

The mean NH_3 ERs for the MB and HR houses are summarized in table 5. The MB houses had a mean daily ER

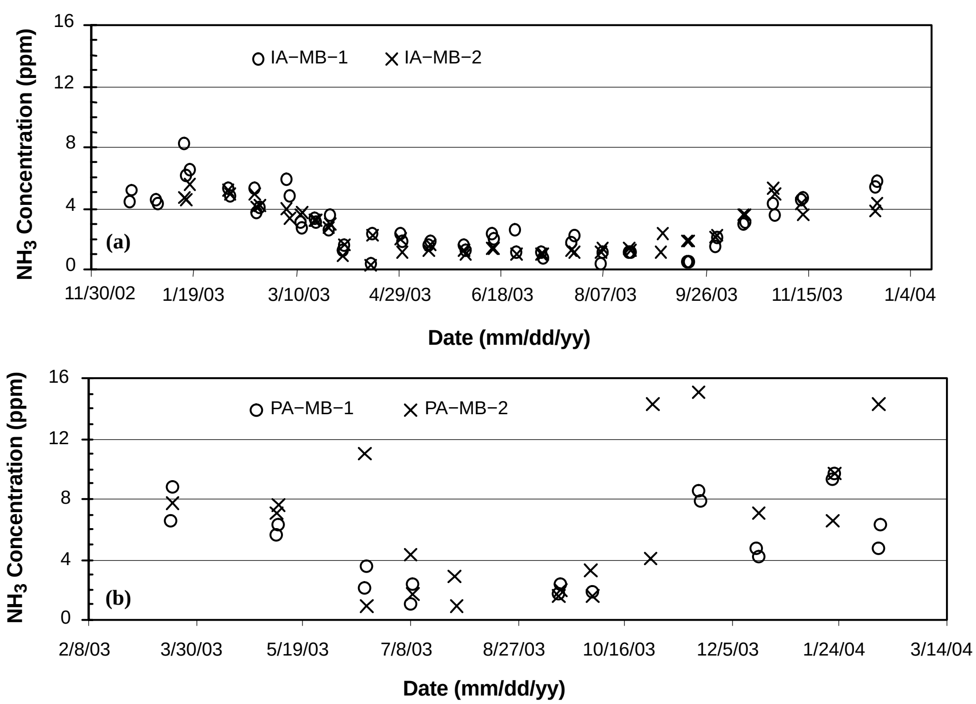

Figure 6. Daily mean ammonia concentrations in exhaust air of manure-belt layer houses in (a) IA and (b) PA.

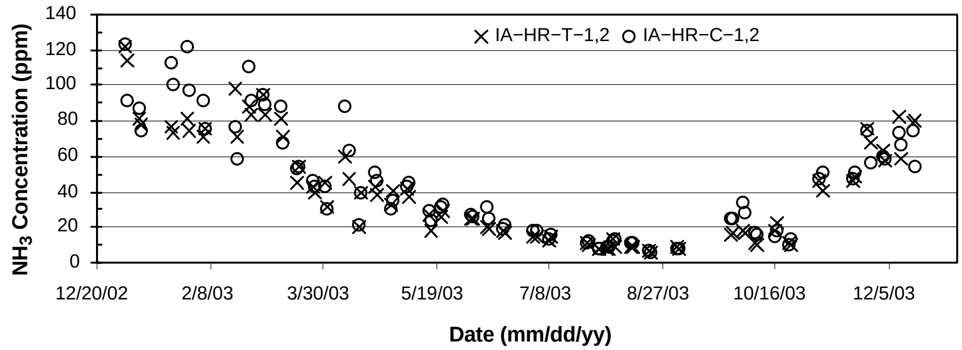

Figure 7a. Daily mean ammonia concentrations in exhaust air from high-rise (HR) layer houses in IA with either standard diet, C (¤), or lower CP diet, T (×).

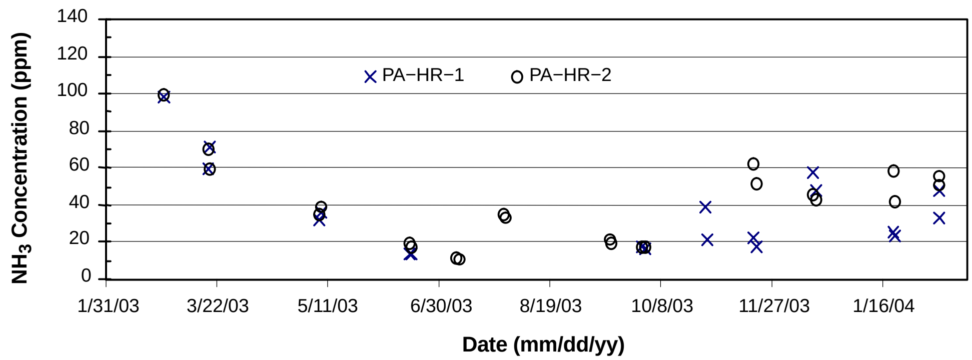

Figure 7b. Daily mean ammonia concentrations measured at exhaust fans of high-rise (HR) layer houses in PA.

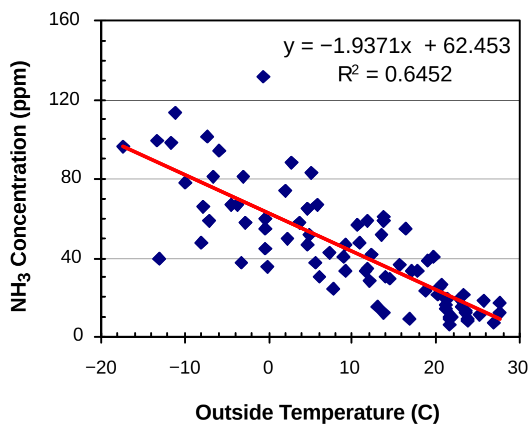

Figure 8. Daily mean ammonia concentration of the exhaust air in an IA high-rise house (with standard diet) vs. outside temperature (standard errors for slope and intercept are 0.16 and 2.4, respectively).

of 0.054 (±0.004) (IA) or 0.094 (±0.006) (PA) g hen^{-1} d^{-1} (fig. 9) during the monitoring period. In comparison, the HR houses had substantially higher ER ($P < 0.001$), averaging 0.87 (±0.06) g hen^{-1} d^{-1} for houses with the Ctrl diet in both IA and PA (fig. 10). These ER values translate to an annual NH_3 emission factor of 20 (±1) (IA) and 34 (±2) (PA) g NH_3 hen^{-1} year^{-1} for the MB houses, and 317 (±22) g NH_3 hen^{-1} year^{-1} for the HR houses with the Ctrl diet.

An emission factor of 386 g NH_3 hen^{-1} year^{-1} for deep-pit and channel layer houses in the Netherlands has been reported (Anon., 1990, as cited by Groot Koerkamp, 1994). According to Groot Koerkamp (1994), both deep-pit and channel houses used the building's lower level (referred to as "basement") as the manure storage area, with the difference being whether manure was allowed to spread over the entire

Table 5. Summary of ammonia emission rates (mean ±standard error) for four manure-belt and six high-rise layer houses monitored in Iowa and Pennsylvania, based on one-year measurements.

Building ID[a]	Days of Monitoring	NH_3 Emission Rates[b] g hen^{-1} d^{-1}	g AU^{-1} d^{-1}
Manure belt			
IA-MB-1	54	0.045 ±0.002	15.5 ±0.7
IA-MB-2	54	0.062 ±0.004	19.8 ±1.3
PA-MB-1	25	0.100 ±0.016	32.8 ±5.0
PA-MB-2	25	0.087 ±0.010	28.8 ±3.1
High-rise			
IA-HR-T-1	84	0.81 ±0.025	274 ±9
IA-HR-T-2	75	0.80 ±0.028	257 ±8
IA-HR-C-1	84	0.84 ±0.028	290 ±10
IA-HR-C-2	75	0.95 ±0.033	323 ±12
PA-HR-1	25	0.88 ±0.072	289 ±26
PA-HR-2	25	0.78 ±0.068	261 ±25
Overall			
MB, daily removal (IA)		0.054 ±0.0048	17.6 ±1.5
MB, semiweekly removal (PA)		0.094 ±0.019	30.8 ±5.9
HR, standard diet (IA)		0.90 ±0.037	306 ±16
HR, standard diet (PA)		0.83 ±0.099	275 ±36
HR, standard diet (IA and PA)		0.87 ±0.086	298 ±34
HR, lower CP diet (IA only)		0.81 ±0.044	268 ±12

[a] IA = Iowa, PA = Pennsylvania, HR = high-rise, MB = manure belt, T = treatment diet (lower crude protein), C = control diet (standard crude protein), 1 or 2 = house number. Refer to table 1 for housing characteristics and management schemes.
[b] AU = animal unit = 500 kg live weight.

basement (deep-pit, much like the HR houses in the current study) or restricted within the channels (formed by two walls) underneath each cage row. Maximum manure storage time was one year for the deep-pit houses and four months for the

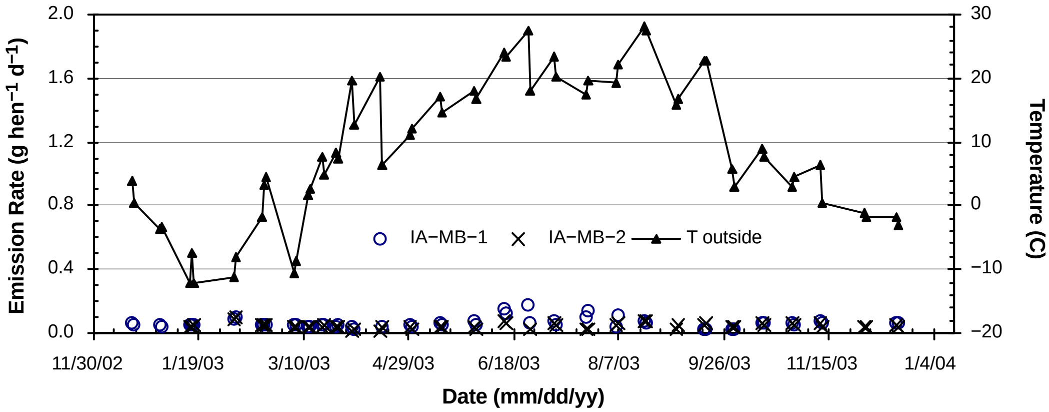

Figure 9a. Daily mean ammonia emission from manure-belt layer houses in IA, where manure was removed from the houses daily, and outside temperature.

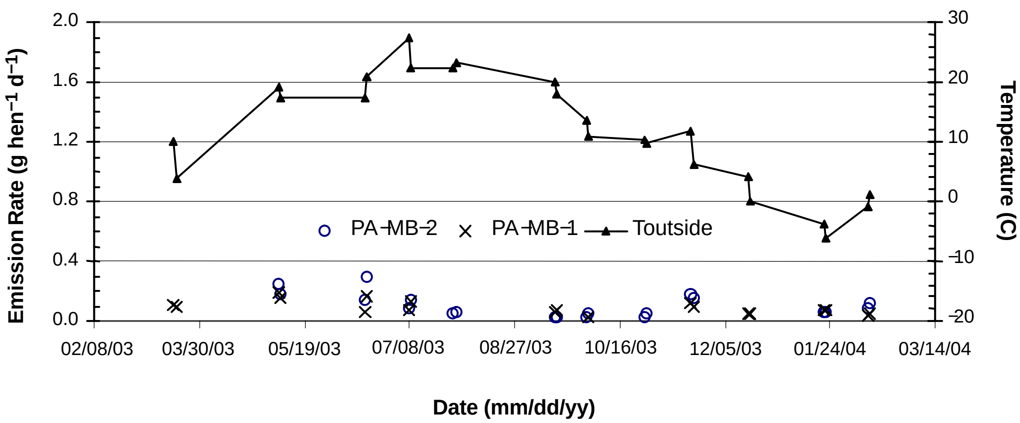

Figure 9b. Daily mean ammonia emission from manure-belt layer houses in PA, where manure was removed from the houses semi-weekly, and outside temperatures.

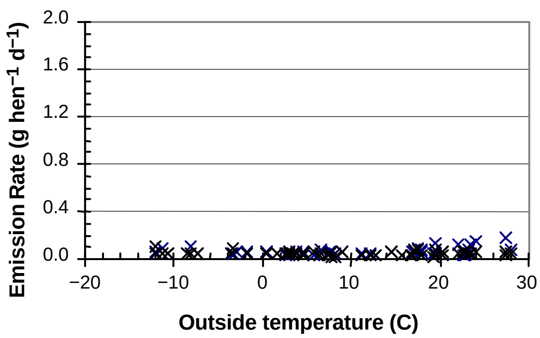

Figure 9c. Relationship between ammonia emission rates of manure-belt houses in IA and outside temperature.

channel houses. These types of houses in the Netherlands typically employ active aeration in the manure storage level in an effort to dry the manure (E. N. J. Ouwerkerk, personal communication, 2004). Moisture content of manure has a major effect on NH_3 release from the manure, as reported by Lorimor and Xin (1999). Kroodsma et al. (1988) reported an NH_3 emission factor of 34 g hen^{-1} year^{-1} for battery systems with manure removed twice a week (without drying) and 31 g hen^{-1} year^{-1} with manure drying on belts and removed once a week. Based on four days of measurement per season (winter and summer), Wathes et al. (1997) reported an NH_3 ER of 192 g NH_3 AU^{-1} d^{-1} (AU = animal unit, 500 kg live weight) in winter and 290 g NH_3 AU^{-1} d^{-1} in summer for four deep-pit layer houses in England. Groot Koerkamp et al. (1998) reported NH_3 ER values of 14 (Germany), 39 (The Netherlands), and 52 (Demark) g NH_3 AU^{-1} d^{-1} for manure-belt laying hen houses. A recent study of NH_3 emission from broiler and layer manure management systems by Nicholson et al. (2004) reported 3.3 g NH_3-N AU^{-1} h^{-1} (96 g NH_3 AU^{-1} d^{-1}) from weekly belt-scraping layer houses, 1.3 g NH_3-N AU^{-1} h^{-1} (38 g NH_3 AU^{-1} d^{-1}) from daily belt-scraping layer houses, and 8.2 g NH_3-N h^{-1} AU^{-1} (239 g NH_3 AU^{-1} d^{-1}) from a commercial deep-pit layer house in England. In comparison, the current study revealed an NH_3 ER of 17.5 and 30.8 g NH_3 AU^{-1} d^{-1} for MB houses with daily and semi-weekly manure removal, respectively, and 298 g NH_3 AU^{-1} d^{-1} for HR layer houses. Similar trends of reduced building NH_3 ER versus more frequent belt scraping were noted by both Groot Koerkamp et al. (1998) and Nicholson et al. (2004). The NH_3 ER obtained from the current study differed considerably from those reported by Keener et al. (2002) for two HR layer houses in Ohio using a mass balance approach, 573 g NH_3 hen^{-1} year^{-1} in March and 457 g NH_3 hen^{-1} year^{-1} in July. Manure moisture content was reported to be 59.8% in March and 29.2% in July, similar to that of the PA-HR houses in the current study. Keener et al. (2002) used an estimation of 16% of N retained in egg and no N retention by live or mortality hens in the system. In comparison, these two values were estimated differently for the mass balance conducted in the current study (as discussed below). For easier comparison and better readability, a summary of NH_3 ER values in the unit of g NH_3 AU^{-1} d^{-1} from the literature and the current study is presented in table 6.

Table 6. Summary of ammonia emission rates (ER, g NH_3 AU^{-1} d^{-1}) of laying hen houses with different housing and management schemes in different countries as reported in the literature and current study (1 AU or animal unit = 500 kg live weight).

Country	House Type (season)	Manure Removal Interval	NH_3 ER	Reference	Year
England	Deep pit (winter)	N/A	192	Wathes et al.	1997
England	Deep pit (summer)	N/A	290	Wathes et al.	1997
England	Deep pit (N/A)	N/A	239	Nicholsen et al.	2004
U.S.A (Ohio)	High−rise (March)	Annual	523*	Keener et al.	2002
U.S.A (Ohio)	High−rise (July)	Annual	417*	Keener et al.	2002
U.S.A (Iowa & Pennsylvania)	High−rise (all year) – *standard diet*	Annual	298	Liang et al. (this study)	2005
U.S.A (Iowa)	High−rise (all year) – 1% lower CP diet	Annual	268	Liang et al. (this study)	2005
The Netherlands	Manure Belt (N/A)	Twice a week with no manure drying	31*	Kroodsma et al.	1988
The Netherlands	Manure Belt (N/A)	Once a week with manure drying	28*	Kroodsma et al.	1988
Denmark	Manure Belt (all year)	N/A	52	Groot Koerkamp et al.	1998
Germany	Manure Belt (all year)	N/A	14	Groot Koerkamp et al.	1998
The Netherlands	Manure Belt (all year)	N/A	39	Groot Koerkamp et al.	1998
England	Manure Belt (all year)	Weekly	96	Nicholsen et al.	2004
England	Manure Belt (all year)	Daily	38	Nicholsen et al.	2004
U.S.A (Iowa & Pennsylvania)	Manure Belt (all year)	Daily with no manure drying	17.5	Liang et al. (this study)	2005
U.S.A (Iowa & Pennsylvania)	Manure Belt (all year)	Twice a week with no manure drying	30.8	Liang et al. (this study)	2005

* Based on the reported ER values in g NH_3 hen^{-1} $year^{-1}$ and an assumed hen body mass of 1.5 kg; N/A = info not available.

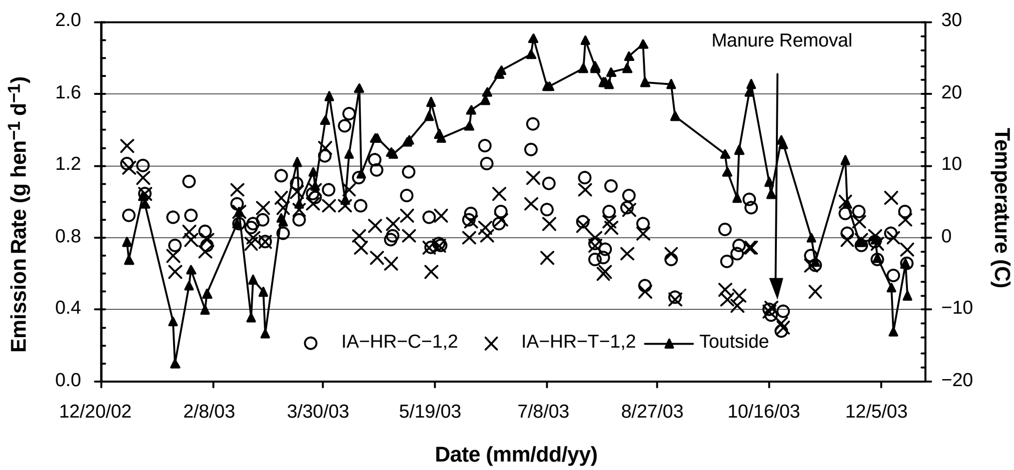

Figure 10a. Daily mean ammonia emission rates of the high-rise layer houses in IA and outside temperature.

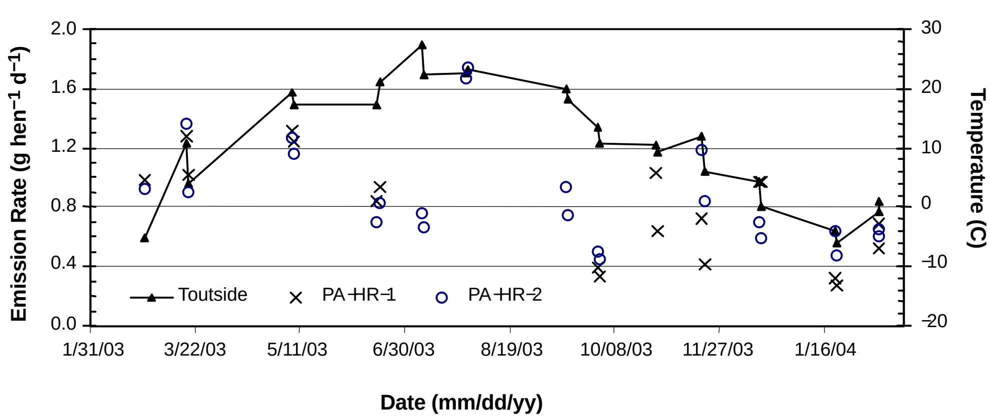

Figure 10b. Daily mean ammonia emission rate of the high-rise layer houses in PA and outside temperature.

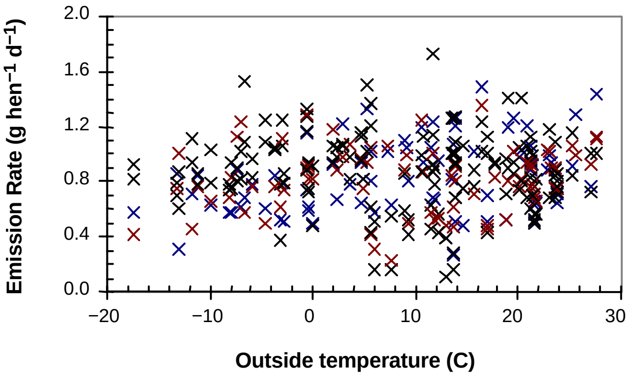

Figure 10c. Daily ammonia emission rates of four high-rise houses in IA vs. outside temperature.

During the measurement period, manure in the four IA-HR houses was removed sequentially between 8 and 20 October 2003. Ammonia ER of each house dropped drastically upon manure removal, followed by a linear increase at 0.0261 g hen^{-1} d^{-2} (r^2 = 0.85) for about 25 days, and then leveled off (fig. 11). Factors such as manure stack dimension (surface to volume ratio), manure age, oxygen availability inside the stack, moisture content, temperature, and pH all could have contributed to the formation of this dynamic emission profile. Groot Koerkamp (1994) and Pratt et al. (1998) reported that relatively fresh manure had higher NH_3 emission than did aging manure.

Manure handling practices (daily, semi-weekly, or yearly removal of manure from the buildings) greatly affected NH_3 emissions. Ammonia concentrations and ER of the MB houses were much lower than those of the HR houses. The MB houses with semi-weekly manure removal emitted about 74% more NH_3 than those with daily manure removal (0.094 g NH_3 hen^{-1} d^{-1} vs. 0.054 g NH_3 hen^{-1} d^{-1}, $P < 0.001$). Based on the daily mean NH_3 ER of MB houses, a predictive equation was derived: ER = 0.038 + 0.016·MRI, where MRI represents the manure removal interval (days). However, both slope (0.016 g NH_3 hen^{-1} d^{-2}) and intercept (0.038 g NH_3 hen^{-1} d^{-1}) of the ER equation were lower than those (0.0261 g NH_3 hen^{-1} d^{-2}; 0.108 g NH_3 hen^{-1} d^{-1}) during the first 25-day manure accumulation subsequent to cleanout in the HR houses (fig. 11).

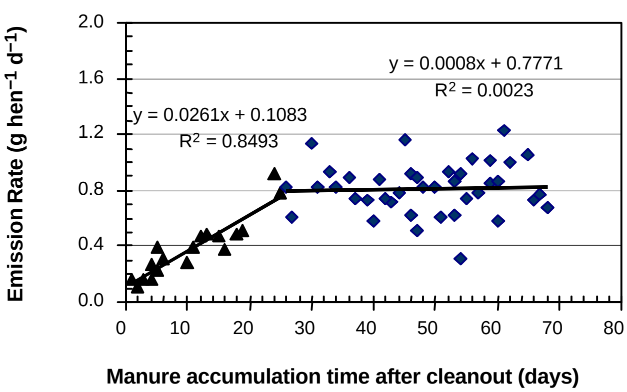

Figure 11. Ammonia emission vs. time of manure accumulation after cleanout in four high-rise houses in IA.

Effect of Diet Manipulation on Ammonia Emission and Hen Performance

Ammonia ER for the IA-HR Trt houses had an annual mean of 0.81 (±0.06) g NH_3 hen^{-1} d^{-1} or 296 ±22 g NH_3 hen^{-1} $year^{-1}$, as compared with 0.90 (±0.06) g NH_3 hen^{-1} d^{-1} for the IA-HR Ctrl houses (table 5). The difference in ER between the diets amounted to a 10% reduction by the Trt diet (i.e., with 1% lower CP), although no statistical significance could be detected (P = 0.22). The statistically non-significant nature of the ER reduction could have resulted from the low number of replications. Blair et al. (1999) reported that a reduction of dietary CP level in layer diet from 17% to 13.5% resulted in a 30% to 35% reduction in N output in manure, with higher dry matter content in the excreta.

Weekly hen-day egg production (%) and case (360 eggs) weight from the Ctrl and Trt flocks, excluding the five-week molting period, were analyzed for dietary effect on hen production performance. No significant difference was found between the two diets in hen-day egg production (80.3 ±0.2% for Ctrl diet vs. 80.2 ±0.2% for Trt diet, P = 0.62) or case weight (21.68 ±0.08 kg $case^{-1}$ or 60.2 ±0.2 g egg^{-1} for Ctrl diet, and 21.95 ±0.08 kg $case^{-1}$ or 61.0 ±0.2 g egg^{-1} for Trt diet, P = 0.21).

Variations in Ammonia Emission Rates

Ammonia ER exhibited considerable temporal variations during 48 h data collection periods in the HR houses. The daily variability in ER, as represented by the within-day coefficient of variation (CV) for the six HR houses, ranged from 12% to 58% (table 7). Figure 12 presents two 48 h dynamic profiles of ventilation rates and NH_3 ER from one HR house on mild or cold days. The trend of semi-hourly NH_3 ER closely followed ventilation rates during the warm season, but was not clear during the cold season. A similar pattern was reported for NH_3 ER for U.S. and European broiler houses (Casey et al., 2004; Demmers et al., 1999). The large daily variation in ER confirms the necessity for continuous, reasonably extended period measurements vs. spot check measurement to ensure proper representation of the overall ER. Moreover, day-to-day, month-to-month, and

Table 7. Coefficients of variation (%) of daily ammonia emission for six high-rise layer houses monitored in Iowa and Pennsylvania.

Building ID[a]	Within-day Max.	Within-day Min.	Within-day Mean	Day-to-Day[b]	Month-to-Month[c]	Season-to-Season[d]
IA-HR-T-1	59.3	8.5	27.0	28.8	18.9	17.6
IA-HR-T-1	62.6	10.7	27.9	29.7	24.9	23.0
IA-HR-C-2	65.5	15.1	27.3	31.4	20.2	15.6
IA-HR-C-2	52.6	13.5	27.6	30.3	22.5	24.2
PA-HR-1	41.2	12.8	20.1	40.8	32.2	28.6
PA-HR-2	66.9	11.8	27.0	43.3	41.7	35.0
Overall	58.0	12.1	26.2	34.0	26.7	24.0

[a] IA = Iowa, PA = Pennsylvania HR = high-rise, T = treatment diet (lower crude protein), C = control diet (standard crude protein), 1 or 2 = house number.
[b] Obtained from 75 to 84 daily observations for IA HR houses and 25 daily observations for PA HR houses.
[c] Obtained from monthly averages based on 4 to 8 observations per month for IA HR houses and monthly averages based on 2 to 4 observations per month for PA HR houses.
[d] Obtained from seasonal averages based on 14 to 22 observations per season for IA HR houses and seasonal averages based on 4 to 8 observations per season for PA HR houses.

season-to-season variations in NH_3 ER of the HR houses were respectively represented by a CV (coefficient of variation) of 34%, 27%, and 24%.

Table 8 summarizes the seasonal mean of NH_3 ER for IA-HR houses, expressed in g hen^{-1} d^{-1} and g AU^{-1} d^{-1}, along with the mean outside temperature. Actual hen body weights were used in calculating the 500 kg live weight AU. Ammonia ER was substantially lower during the fall (except for IA-HR-C-1) than during the other seasons, resulting from the initial manure accumulation following annual manure removal (8 to 20 October 2003).

Manure belt operation and manure removal, usually occurring around 5 a.m. each day (for the IA houses), resulted in a temporarily higher NH_3 emission (fig. 13). It can be noted that after an initial burst of volatilization during manure removal, ER dropped sharply and then slowly increased throughout the day, presumably as manure accumulated on the belt. This pattern was most noticeable during cold weather when the building had relatively constant and low ventilation rates.

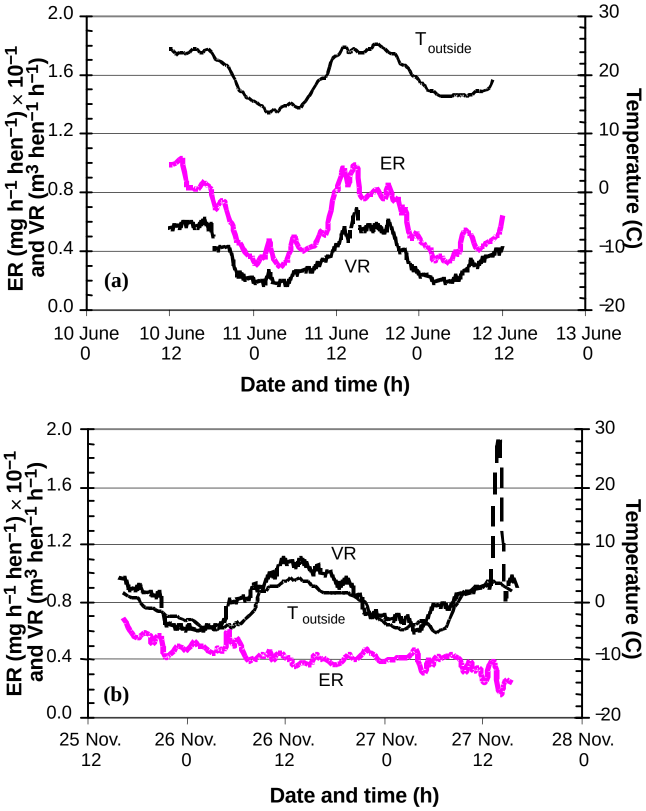

Figure 12. Ammonia emission rate (ER) and building ventilation rate (VR) of high-rise layer houses in IA during (a) mild (June) days and (b) cold (November) days.

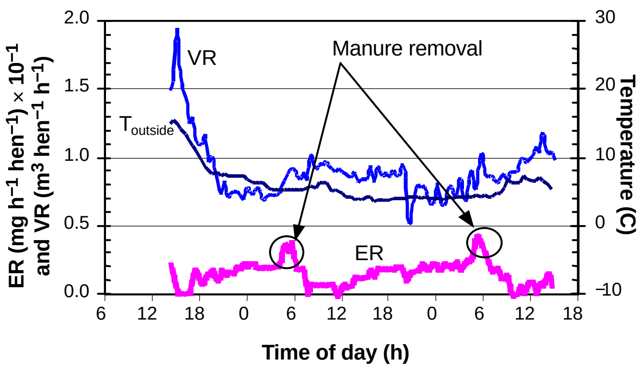

Figure 13. Example diurnal profiles of ammonia emission rate (ER) and building ventilation rate (VR) of a manure-belt layer house in IA.

Nitrogen Balance

Results of the mass balance for the four IA-HR houses are summarized in table 9. The amount of manure removed from the four buildings in the fall of 2003 averaged 687 (±51) Mg per building. Manure had an average dry matter content of 71% and N content of 3.3% (dry basis). The combined N retention in the egg and the hen amounted to about 42% of the N intake. The N loss via NH_3 emission and N retention in the stored, year-old manure accounted for 29% and 26% of total N intake, respectively. The N intake and N output had a discrepancy of −1.1% to 5.6% for the four HR houses. Patterson and Lorenz (1996) reported that 24% of N fed to laying hens remained in manure, 34% in the eggs, and 1% in the carcass; hence, 40% was presumably lost, probably as NH_3. N loss from four commercial HR laying hen houses in Iowa had previously been determined from measured performance data and chemical properties of manure using a mass balance approach by Yang et al. (2000). The results indicated that N loss was 25%, 33%, 37%, and 41% of N intake by the hens for manure moisture content of 27.5%, 33.7%, 44.1%, and 48.8%, respectively. Hence, the NH_3-N loss of 29% (at manure moisture content of 29%) revealed in the current study parallels those reported by Yang et al. (2000). The mass balance result provides a verification of our measured NH_3 emission data.

Table 8. Seasonal emission rates of ammonia (mean and standard error) from four high-rise layer houses in Iowa.

Time Period[a]	Outside Temp. (°C)	NH_3 Emission Rate (g hen^{-1} d^{-1})[b]				NH_3 Emission Rate (g AU^{-1} d^{-1})[b]			
		IA-HR-C-1	IA-HR-C-2	IA-HR-T-1	IA-HR-T-2	IA-HR-C-1	IA-HR-C-2	IA-HR-T-1	IA-HR-T-2
Winter	−4.4	0.71 ±0.05	1.00 ±0.04	0.86 ±0.06	0.88 ±0.04	231 ±16	327 ±15	274 ±18	281 ±13
Spring	13.2	0.97 ±0.06	1.09 ±0.05	0.86 ±0.05	0.90 ±0.04	351 ±20	382 ±20	314 ±13	268 ±11
Summer	22.9	0.89 ±0.05	0.94 ±0.07	0.84 ±0.04	0.74 ±0.04	311 ±19	325 ±23	290 ±14	261 ±13
Fall	9.5	0.73 ±0.05	0.59 ±0.07	0.58 ±0.04	0.52 ±0.06	238 ±17	198 ±23	182 ±13	176 ±18

[a] Winter = 31 December to 12 March 2002 and 25 November to 16 December 2003, Spring = 18 March to 4 June 2003, Summer = 10 June to 3 September 2003, and Fall = 26 September to 20 November 2003.

[b] IA = Iowa, HR = high-rise, T = treatment diet (lower crude protein), C = control diet (standard crude protein), 1 or 2 = house number, AU = animal unit = 500 kg live weight.

Table 9. Partitioning of N intake, N retained in egg, hen, N left in manure, and N lost through ammonia emission (units in g N hen^{-1} d^{-1} unless otherwise noted).

House[a]	Input	Output					Residual Error[b]
	N_{Feed}	N_{Egg}	$N_{LiveHen}$	$N_{DeadHen}$	N_{Manure}	N_{NH3}	(%)
IA-HR-T-1	2.30	0.81	0.1474	0.0113	0.590	0.67	3.11
IA-HR-C-1	2.43	0.86	0.1556	0.0119	0.575	0.69	5.58
IA-HR-T-2	2.35	0.83	0.1502	0.0115	0.609	0.66	3.54
IA-HR-C-2	2.57	0.91	0.1649	0.0127	0.729	0.79	−1.11
Overall	2.41	0.85	0.1545	0.0119	0.626	0.702	
% N input	100	35.3	6.4	0.5	26.0	29.1	2.7

[a] IA = Iowa, HR = high-rise, T = treatment diet (lower crude protein), C = control diet (standard crude protein), 1 or 2 = house number.
[b] Residual error = (input − output)/input × 100. Positive value means the amount of nitrogen from feed is not being accounted for in N output.

Conclusions

Ammonia emission rates (ER) from representative layer houses in two of the U.S. primary egg producing regions (Iowa and Pennsylvania) with different housing styles, manure handling practices, and dietary schemes were measured for a full year. The following conclusions were drawn.

- Ammonia emission of high-rise (HR) houses in both geographical locations was similar, averaging 0.87 g NH_3 hen^{-1} d^{-1} or 317 g NH_3 hen^{-1} $year^{-1}$ for HR houses fed an industry standard diet, but 0.81 g NH_3 hen^{-1} d^{-1} or 296 g NH_3 hen^{-1} $year^{-1}$ for houses fed an experimental diet with an average of 1% lower crude protein.
- Both NH_3 concentrations and ER of manure-belt (MB) houses were much lower than those of HR houses. Moreover, frequency of manure removal from the MB houses affects NH_3 ER, with semi-weekly removal emitting 74% more NH_3 than daily removal, 0.094 vs. 0.054 g NH_3 hen^{-1} d^{-1} ($P < 0.001$).
- The promise of using diet manipulation to abate NH_3 emission was demonstrated by the trend of NH_3 ER reduction (about 10%) with the 1% lower crude protein diet in HR houses, even though statistical significance was not detected, presumably due to lack of sufficient replications.
- There existed both diurnal and seasonal variations in NH_3 emissions from the HR layer houses. Using coefficient of variation (CV) to express the degree of variation, the ER values showed a CV of 12% to 58% within the day, 34% among the days, 27% among the months, and 24% among the seasons.
- Ammonia emission from HR houses following a manure cleanout showed a linear increase ($R^2 = 0.85$) with time of manure accumulation during the initial four weeks (regression slope of 0.026 g NH_3 hen^{-1} d^{-2}), and leveled off thereafter.

Acknowledgements

Financial support for this study was provided by the USDA Initiative for Future Agriculture and Food System (IFAFS) Program, the Iowa Egg Council, and the Center for Advanced Technology Development of Iowa State University. The authors wish to sincerely thank the cooperating producers in Iowa and Pennsylvania for their immense support and cooperation throughout this study; Ajinomoto Heartland, Inc., for providing the amino acid supplements and assistance with the diet formulation for the dietary manipulation evaluation; and Dr. Brian Kerr and his staff at the USDA-ARS in Ames, Iowa, for assisting with nutrient analysis of the manure samples.

References

Anon. 1990. Richtlijn ammoniak en veehouderij; Richtlijn in het kader van de Hinderwet (Directive on ammonia emissions from livestock husbandry). 's Gravenhage, The Netherlands: Ministerie van LNV and Ministerie van VROM.

ASHRAE. 2001. Chapter 27: Climatic design information. In *ASHRAE Handbook of Fundamentals*. Atlanta, Ga.: ASHRAE.

Baek, B. H., and V. P. Aneja. 2004. Measurement and analysis of the relationship between ammonia, acid gases, and fine particles in the eastern North Carolina. *J. Air and Waste Manage. Assoc*. 54(5): 623-633.

Blair, R., J. P. Jacob, S. Ibrahim, and P. Wang. 1999. A quantitative assessment of reduced protein diet and supplements to improve nitrogen utilization. *J. Applied Poultry Res*. 8(1): 25-47.

Burns, R. T., K. A. Armstrong, F. R. Walker, C. J. Richards, and D. R. Raman. 2003. Ammonia emissions from a broiler production facility in the United States. In *Proc. International Symposium on Gaseous and Odor Emissions from Animal Production Facilities*, 88-95. Horsens, Denmark. CIGR.

Casey, K. D., R. S. Gates, E. F. Wheeler, H. Xin, J. S. Zajaczkowski, P. Topper, and Y. Liang. 2004. Ammonia emission from Kentucky broiler houses during winter, spring, and summer. In *Proc. A&WMA's 97th Annual Conf. and Exhibition: Sustainable Development - Gearing up for the Challenge*, CD-ROM. Pittsburgh, Pa.: A&WMA.

CAST. 2002. Animal diet modification to decrease the potential for nitrogen and phosphorus pollution. Issue Paper No. 21. Ames, Iowa: Council for Agricultural Science and Technology.

Chepete, H. J., and H. Xin. 2004. Heat and moisture production of poultry and their housing systems: Molting layers. *Trans. ASHRAE* 110(2):274-285.

Chepete, H. J., H. Xin, M. C. Puma, and R. S. Gates. 2004. Heat and moisture production of poultry and their housing systems: Pullets and layers. *Trans. ASHRAE* 110(2): 286-299.

Chi, M. S., and G. M. Speers. 1976. Effects of dietary protein and lysine levels on plasma amino acids, nitrogen retention, and egg production in laying hens. *J. Nutrition* 106(8): 1192-1201.

Demmers, T. G. M., L. R. Burgess, J. L. Short, V. R. Philips, J. A. Clark, and C. M. Wathes. 1999. Ammonia emissions from two mechanically ventilated U.K. livestock buildings. *Atmospheric Environ.* 33(2): 217-227.

Feddes, J. J. R., J. J. Leonard, and J. B. Mcquitty. 1984. Carbon dioxide concentration as a measure of air exchange in animal housing. *Canadian Agric. Eng.* 26(1): 53-56.

Ferguson, N. S., R. S. Gates, J. L. Taraba, A. H. Cantor, A. J. Pescatore, M. J. Ford, and D. J. Burnham. 1998a. The effect of dietary crude protein on growth, ammonia concentration, and litter composition in broilers. *Poultry Sci.* 77(10): 1481-1487.

Ferguson, N. S., R. S. Gates, J. L. Taraba, A. H. Cantor, A. J. Pescatore, M. L. Straw, M. J. Ford, and D. J. Burnham. 1998b. The effect of dietary protein and phosphorus on ammonia concentration and litter composition in broilers. *Poultry Sci.* 77(8): 1085-1093.

Gates, R. S. 2001. Ammonia volatilization as affected by broiler litter rewetting and dietary manipulation. In *Proc. Int. Symp.: Addressing Animal Production and Environmental Issues*, 372-383. Research Triangle Park, N.C.: North Carolina State Animal and Poultry Waste Management Center.

Gates, R. S., A. J. Pescatore, J. L. Taraba, A. H. Cantor, K. Liberty, M. J. Ford, and D. J. Burnham. 2000. Diet manipulation of crude protein and amino acids for reduced ammonia emission from broiler litter. ASAE Paper No. 004024. St. Joseph, Mich.: ASAE.

Gates, R. S., H. Xin, and E. F. Wheeler. 2002. Ammonia losses, evaluations and solutions for poultry systems. In *Proc. 2002 National Poultry Waste Management Symposium*, 79-88. P. H. Patterson, J. P. Blake, and K. D. Robertson, eds. Auburn, Ala.: Auburn University Printing Service, National Poultry Waste Management Committee.

Gates, R. S., K. D. Casey, H. Xin, and E. F. Wheeler. 2004. Fan Assessment Numeration System (FANS) design and calibration specifications. *Trans. ASAE* 47(5): 1709-1715.

Gates, R. S., H. Xin, K. D. Casey, Y. Liang, and E. F. Wheeler. 2005. Method for measuring ammonia emissions from poultry houses. *J. Applied Poultry Res.* (in press).

Groot Koerkamp, P. W. G. 1994. Review of emissions of ammonia from housing systems for layer hens in relation to sources, processes, building design, and manure handling. *J. Agric. Eng. Res.* 59(1): 73-87.

Groot Koerkamp, P. W. G., J. H. M. Metz, G. H. Uenk, V. R. Phillips, M. R. Holder, R. W. Sneath, J. L. Short, P. P. White, J. Hartung, J. Seedorf. M. Schroder, K. H. Linkert, S. Pederson, H. Takai, J. O. Johnsen, and C. M. Wathes. 1998. Concentrations and emissions of ammonia in livestock buildings in northern Europe. *J. Agric. Eng. Res*. 70(10): 79-95.

Hinz, T., and S. Linke. 1998. A comprehensive experimental study of aerial pollutants in and emission from livestock buildings: Part 2. Results. *J. Agric. Eng. Res*. 70(10): 119-129.

Keener, H. M., D. L. Elwell, and D. Grande. 2002. NH_3 emissions and N-balances for a 1.6 million caged layer facility: Manure belt/composting vs. deep pit operation. *Trans. ASAE* 45(6): 1977-1984.

Kroodsma, W., R. Scholten, and J. W. H. Huis in ’t Veld. 1988. Ammonia emissions from poultry housing systems. In *Report 96: Proc. CIGR Seminar on Storing, Handling, and Spreading of Manure and Municipal Waste*, 2: 7.1-7.13. Uppsala, Sweden. CIGR.

Li, H., H. Xin, Y. Liang, R. S. Gates, E. F. Wheeler, and A. Heber. 2004. Comparison of direct vs. indirect ventilation rate determination for manure-belt laying hen houses. *Trans. ASAE* 48(1): 367-372.

Lorimor, J. C., and H. Xin. 1999. Manure production and nutrient concentrations from high-rise layer houses. *Applied Eng. in Agric*. 15(4): 337-340.

Maghirang, R. G., and H. B. Manbeck. 1993. Dust, ammonia, and carbon dioxide emission from a poultry house. ASAE Paper No. 934056. St. Joseph, Mich.: ASAE.

Nicholson, F. A., B. J. Chambers, and A. W. Walker. 2004. Ammonia emissions from broiler litter and laying hen manure management systems. *Biosystems Eng*. 89(2): 175-185.

Ouwerkerk, E. N. J. van, and S. Pedersen. 1994. Application of the carbon dioxide mass balance method to evaluate ventilation rates in livestock buildings. In *Proc 12th CIGR World Congress on Agricultural Engineering*, 1: 516-529. Milan, Italy. CIGR.

Patni, H. K., and H. A. Jackson. 1996. Ammonia concentrations in, and emissions from commercial, high-rise and shallow-gutter caged-layer barns. ASAE Paper No. 964092. St. Joseph, Mich.: ASAE.

Patterson, P. H., and E. S. Lorenz. 1996. Manure nutrient production from commercial White Leghorn hens. *J. Applied Poultry Res.* 5(2): 260-268.

Pedersen, S., H. Takai, J. O. Johnsen, J. H. M. Metz, P. W. G. Groot Koerkamp, G. H. Uenk, V. R. Philips, M. R. Holden, R. W. Sneath, J. L. Short, R. P. White, J. Hartung, J. Seedorf, M. Schroder, K. H. Linkert, and C. M. Wathes. 1998. A comparison of three balance methods for calculating ventilation rates in livestock buildings. *J. Agric. Eng. Res*. 70(10): 25-37.

Pratt, E. V., S. P. Rose, and A. A. Keeling. 1998. Atmospheric nitrogen losses from poultry excreta. *British Poultry Sci*. 39(supp.): S12-13.

Summers, J. D. 1993. Reducing nitrogen excretion of the laying hen by feeding lower crude protein diets. *Poultry Sci.* 72(8): 1473.

Sutton, A., T. Applegate, S. Hankins, B. Hill, G. Allee, W. Greene, R. Kohn, D. Meyer, W. Powers, and T. van Kempen. 2002. Manipulation of animal diets to affect manure production, composition, and odors: State of the science. White Paper, National Center for Manure and Animal Waste Management. Ames, Iowa: Midwest Plan Service.

USEPA. 2002. National air pollutant emission trends, 1990-1998. EPA-454/R-00-002, March. Washington, D.C.: U.S. Environmental Protection Agency.

USEPA. 2004. National emission inventory - Ammonia emissions from animal husbandry. Washington, D.C.: U.S. Environmental Protection Agency.

Wathes, C. M., M. R. Holden, R. W. Sneath, R. P. White, and V. R. Phillips. 1997. Concentrations and emission rates of aerial ammonia, nitrous oxide, methane, carbon dioxide, dust, and endotoxin in U.K. broiler and layer houses. *British Poultry Sci.* 38(1): 14-28.

Xin, H., T. Wang, R. S. Gates, E. F. Wheeler, K. D. Casey, A. J. Heber, J. Ni, and T. Lim. 2002. A portable system for continuous ammonia measurement in the field. ASAE Paper No. 024168. St. Joseph, Mich.: ASAE.

Xin, H., Y. Liang, A. Tanaka, R. S. Gates, E. F. Wheeler, K. D. Casey, A. J. Heber, J. Ni, and H. Li. 2003. Ammonia emissions from U.S. poultry houses: Part I. Measurement system and techniques. In *Proc. 3rd International Conference on Air Pollution from Agricultural Operations*, 106-115. St. Joseph, Mich.: ASAE.

Yang, P., J. C. Lorimor, and H. Xin. 2000. Nitrogen losses from laying hen manure in commercial high-rise layer facilities. *Trans. ASAE* 43(6): 1771-1780.