2013


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Abstract
There has been an increased interest in alternative housing for laying hens in certain parts of the world, including the U.S. Associated with the movement are many questions concerning sustainability of such systems. This study continually quantified concentrations and emissions of ammonia (NH₃), carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and particulate matter (PM₁₀ and PM₂.₅) for two side-by-side aviary barns each housing 50,000 Hy-Line brown laying hens, located in the Midwestern U.S. The gaseous concentrations were continually monitored using an infrared photoacoustic multi-gas analyzer, while the PM concentrations were measured with tapered element oscillating microbalances (TEOMs). Barn ventilation rate was determined by monitoring the operation time of ventilation fans that had been calibrated in situ. Nineteen consecutive months of monitored data (June 2010 to December 2011) are analyzed and presented. Daily indoor aerial concentrations (mean ±SD) were 8.7 (±8.4) ppm NH₃, 1,636 (±1,022) ppm CO₂, 10.0 (±6.8) ppm CH₄, 2.3 (±1.6) mg m⁻³ PM₁₀, and 0.25 (±0.26) mg m⁻³ PM₂.₅. The aerial emissions are expressed as quantities per hen, per animal unit (AU, 500 kg body weight), and per kg egg output. Daily emission rates (g bird⁻¹) were 0.15 (±0.08) NH₃, 75 (±15) CO₂, 0.09 (±0.08) CH₄, 0.11 (±0.04) PM₁₀, and 0.008 (±0.006) PM₂.₅. The results were compared to reported emission values for conventional (high-rise and manure-belt cage) U.S. laying-hen housing systems. Data from this study provide baseline concentration and emission values for the aviary housing system in the Midwestern U.S., which will also contribute to improvement of the U.S. national air emissions inventory for farm animal operations.

Keywords
Aerial emissions, Air quality, Aviary, Concentrations, Laying hen

Disciplines
Agriculture | Bioresource and Agricultural Engineering

Comments
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AMMONIA, GREENHOUSE GAS, AND PARTICULATE MATTER EMISSIONS OF AVIARY LAYER HOUSES IN THE MIDWESTERN U.S.

M. D. Hayes, H. Xin, H. Li, T. A. Shepherd, Y. Zhao, J. P. Stinn

ABSTRACT. There has been an increased interest in alternative housing for laying hens in certain parts of the world, including the U.S. Associated with the movement are many questions concerning sustainability of such systems. This study continually quantified concentrations and emissions of ammonia (NH\textsubscript{3}), carbon dioxide (CO\textsubscript{2}), methane (CH\textsubscript{4}), nitrous oxide (N\textsubscript{2}O), and particulate matter (PM\textsubscript{10} and PM\textsubscript{2.5}) for two side-by-side aviary barns each housing 50,000 Hy-Line brown laying hens, located in the Midwestern U.S. The gaseous concentrations were continually monitored using an infrared photacoustic multi-gas analyzer, while the PM concentrations were measured with tapered element oscillating micro-balances (TEOMs). Barn ventilation rate was determined by monitoring the operation time of ventilation fans that had been calibrated in situ. Nineteen consecutive months of monitored data (June 2010 to December 2011) are analyzed and presented. Daily indoor aerial concentrations (mean ±SD) were 8.7 (±8.4) ppm NH\textsubscript{3}, 1,636 (±1,022) ppm CO\textsubscript{2}, 10.0 (±6.8) ppm CH\textsubscript{4}, 2.3 (±1.6) mg m\textsuperscript{-3} PM\textsubscript{10}, and 0.25 (±0.26) mg m\textsuperscript{-3} PM\textsubscript{2.5}. The aerial emissions are expressed as quantities per hen, per animal unit (AU, 500 kg body weight), and per kg egg output. Daily emission rates (g bird\textsuperscript{-1}) were 0.15 (±0.08) NH\textsubscript{3}, 75 (±15) CO\textsubscript{2}, 0.09 (±0.08) CH\textsubscript{4}, 0.11 (±0.04) PM\textsubscript{10}, and 0.008 (±0.006) PM\textsubscript{2.5}. The results were compared to reported emission values for conventional (high-rise and manure-belt cage) U.S. laying-hen housing systems. Data from this study provide baseline concentration and emission values for the aviary housing system in the Midwestern U.S., which will also contribute to improvement of the U.S. national air emissions inventory for farm animal operations.

Keywords. Aerial emissions, Air quality, Aviary, Concentrations, Laying hen.

In the past decade, concerns over animal welfare issues have led to a shift among certain egg producers from conventional laying-hen cage houses to cage-free and/or enriched cage housing. There are many questions about the performance and sustainability of these alternative housing systems, including indoor air quality and air emissions. An Air Compliance Agreement (ACA) was reached in 2005 between the U.S. EPA and certain sectors of the U.S. livestock and poultry industries, namely, broiler, egg, swine, and dairy. The ACA studies have yielded or will yield more baseline data on air emissions from U.S. animal feeding operations (AFOs). However, no alternative laying-hen housing sites were monitored in the ACA studies, and there is very little information on the emissions from these alternative systems, particularly under U.S. operational conditions.

The barns used in this study are colony-style aviary houses with the Natura 60 design (Big Dutchman, Holland, Mich.; www.bigdutchmanusa.com/eggproduction/cagefree/aviary/natura60.html). The birds in this system have floor access for part of the day (light hours) and spend the rest of their time in tiered colonies (including feeding, drinking, perching, and laying eggs). The system is defined as cage-free alternative housing. Studies have been conducted to quantify aerial emissions for conventional (cage) laying-hen housing in the U.S. and conventional and alternative housing in Europe. The European cage-free systems are generally designed with no restrictions within the barns and with no ability to contain birds in colonies for certain hours of the day or night. Moreover, outdoor access is often available in these European systems. Nevertheless, results of these studies provided some insight into the elevated concentrations and emissions compared to conventional (cage) houses in the U.S.

The two constituents of most concern for elevated levels in alternative housing are ammonia (NH\textsubscript{3}) and particulate matter (PM). The European studies showed NH\textsubscript{3} emission rates for cage-free barns of 0.27 and 0.85 g bird\textsuperscript{-1} d\textsuperscript{-1} (Groot Koerkamp et al., 1998, Müller et al., 2003). The higher NH\textsubscript{3}
emission values in the reported European studies are comparable to those of high-rise housing in the U.S. Liang et al. (2003) showed NH₃ emission rates of 0.05 to 0.1 g bird⁻¹ d⁻¹ for manure-belt cage hen houses and 0.95 g bird⁻¹ d⁻¹ for high-rise cage hen houses in the U.S. Li et al. (2012) reported an almost identical NH₃ emission rate of 0.96 g bird⁻¹ d⁻¹ for high-rise cage houses in the Midwestern U.S. Based on the literature, the expectation is that the NH₃ emission rate for aviary houses will be between the values for manure-belt and high-rise cage houses. Cage-free systems in Europe were reported to have PM₁₀ emissions 2 to 3 times greater than conventional houses (Takai et al., 1998). Literature on conventional (cage) laying-hen housing reported PM₂.₅ emissions of 0.0036 to 0.014 g bird⁻¹ d⁻¹ and PM₁₀ emissions ranging from 0.019 to 0.048 g bird⁻¹ d⁻¹ (Li et al., 2011). The expectation is that PM values for the aviary houses will be higher than those of cage houses in the U.S. due to activities (e.g., dustbathing) of the hens on the litter floor. Carbon dioxide (CO₂) emissions from manure-belt cage houses have been reported to be 70 to 85 g bird⁻¹ d⁻¹ (Liang et al., 2003; Neser et al., 1997), and similar values are expected for the aviary houses. For methane (CH₄), the literature suggests that all housing systems emit between 0.08 and 0.13 g bird⁻¹ d⁻¹ (Groot Koerkamp et al., 1997; Monteny et al., 2001; Fabri et al., 2007; Wathes et al., 1997).

Therefore, the objectives of this study were to characterize concentrations and emission rates of ammonia (NH₃); the greenhouse gases (GHG) carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O); and particulate matter (PM) with aerodynamic diameter of 10 and 2.₅ μm (PM₁₀ and PM₂.₅) from colony-style aviary houses in the Midwestern U.S., one of the alternative hen housing systems being used by U.S. egg producers. The gaseous and PM emission rates were then compared to literature values. Collection of baseline emissions data for the aviary houses and comparisons of the data with those for conventional systems are important in terms of enhancing the U.S. national emissions inventory and developing realistic regulatory guidelines specific to the animal production systems.

MATERIALS AND METHODS

SITE DESCRIPTION

This field study was conducted with aviary houses that featured a commercial housing design (Natura 60, Big Dutchman, Holland, Mich.). Two aviary houses in a double-wide building located in Iowa were used. Each house measured 167.6 m × 19.8 m with a capacity of 50,000 hens (Hy-Line Brown) and had a production cycle from approximately 17 to 80 weeks of age with no molt. The new flock started the fourth week of April 2010 in one house (house 3 or H3) and the second week of September 2010 in the other (house 2 or H2). A cross-sectional schematic of the houses is shown in figure 1. Each house was divided into ten 14.5 m sections along the length. The houses had open litter floors (2.6 m wide per section for the center aisles and 1.2 m per section for the outer aisles), nest boxes, and perches. To minimize floor eggs and improve manure management, the hens were trained to be off the floor and return to the aviary colonies at night and remained in the colonies until the next morning. Each row had three tiers, and manure belts with a manure-drying air duct were placed underneath the lower two tiers. The three tiers were divided into nest, feeding, and drinking areas from top to bottom. Each house had 20 exhaust fans, all on one sidewall (fig. 2), including twelve 1.2 m fans, four 0.9 m fans, and four 0.5 m fans. Ceiling box air inlets (75 bi-directional, 0.6 × 0.6 m each) were placed. Four 73.25 kW heaters were placed equidistant along the sidewall. Compact fluorescent lighting was used with a 16 h light period. Table 1 summarizes the housing and management characteristics of the aviary houses.

Figure 1. Cross-sectional view of the monitored aviary hen house (one side of the double houses) (not to scale).
Concentrations of NH₃ and GHG (CO₂, N₂O, and CH₄) at four locations in each house were measured continually with a fast-response, high-precision infrared (IR) photoacoustic multi-gas analyzer (model 1412, Innova AirTech Instruments, Ballerup, Denmark). Two locations (near two continuous ventilation fans) were combined into one composite sample; hence, two composite sampling lines were used from the four continuously running ventilation fans per house (fig. 2). FEP Teflon tubing (0.95 cm o.d., 0.635 cm i.d.) was used for air sampling to avoid NH₃ absorption to the sampling lines. Each sampling port was equipped with a coarse filter (3011 NAPA, Atlanta, Ga.) and a fine dust filter (47 mm filter membrane, 5 to 6 μm, Savillex, Eden Prairie, Minn.) to keep particulates from plugging the sample tubing or damaging the gas analyzer. Since one gas analyzer was used to measure multiple locations in two barns, the air samples from all locations were taken sequentially using an automatically controlled (positive-pressure) gas sampling system (fig. 3). To ensure measurement of the real concentration values, considering the response time of the analyzers, each location was sampled for 6 min, with the first 5.5 min for stabilization and the last 0.5 min readings for measurement. This sequential measurement yielded 30 min data of gaseous concentrations. Each sampling location had its own designated air sampling pump; hence, a total of five pumps were utilized. Sampling pumps were run for 1 min prior to the location sampling and turned off as soon as the sampling was finished. Use of the intermittent pumping was to increase the longevity of pump’s operation. In addition, every 2 h the outside air was drawn and analyzed. Less frequent sampling and analysis of the outside air was used because its composition remained much more stable than that of the indoor air.

Concentrations of PM₁₀ and PM₂.₅ inside the houses were measured continuously with real-time tapered element oscillating microbalances (TEOM) equipped with the respective PM head (model 1400a, Thermo Fisher Scientific, Waltham, Mass.) (fig. 3). A 300 s integration time was used. Two collocated TEOM units ran continuously for two days each week in each house, with mass concentrations of both particle sizes reported every 30 s. The TEOM units were placed next to a minimum continuous ventilation fan (fan 7) in both barns. Selection of the TEOM’s location was based on prior examination of PM distributions near the

**MEASUREMENT SYSTEM**

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four minimum ventilation fans and the best representation of the exhaust air PM concentrations. Temperature (type-T thermocouple, Cole-Parmer, Vernon Hills, Ill.), RH (HMW60, Vaisala, Woburn, Mass.), and building static pressure (model 264, Setra Systems, Boxborough, Mass.) were measured at the middle of the house at 1 s intervals and reported as 30 s averages.

Instead of using a mobile air emission monitoring lab (trailer), all sampling lines, data acquisition, and instrumentation for this study were kept in an enclosure in the south end of H2. The enclosure was supplied with fresh air from the attic in a positive-pressure manner to minimize entrance of dust from the indoor air.

The building ventilation rate (VR) was determined based on *in situ* calibrated fan curves with fan assessment numeration systems (FANS) sized 0.9 m, 1.2 m, and 1.4 m (Gates et al., 2004). Individual fan curves were established for each stage (1 to 8) including operational ranges of the variable speed control of the lower stages twice each year. Fans at this site (new at commencement of the monitoring study) operated between 88% and 97% of their reported VR based on FANS calibration. Over the 19 months of monitoring, the VR decreased between 3% and 6%. The fan curves were adjusted after each semiannual calibration; however, no interpolation was made to the curves between calibrations because of these minimal drops in VR. The runtime of all stages of ventilation fans was recorded continuously with inductive current switches (Muhlbauer et al., 2011). Magnetic proximity sensors (MP1007, ZF Electronics, Pleasant, Prairie, Wisc.) were used to measure the fan speed (in rpm) of the variable-speed fans. Fan runtime and speed along with the corresponding building static pressure were recorded every second. These samples taken at 1 s intervals were averaged to 30 s values and reported to the on-site PC. Using the calibrated curves for each stage with the above data, an overall building VR was calculated. All data were collected with a data acquisition system (DAQ, Compact Fieldpoint, National Instruments, Austin, Tex.).

**Calculation of Gaseous and PM Emissions**

With the measured gaseous or PM concentrations and building VR, the emission rate (ER) of the gas or PM from the houses to the atmosphere can be calculated according to equations 1 and 2. Daily emissions were summed from the 30 s dynamic emissions calculated over each 24 h period:

\[
[\text{ER}]_G = \sum_{c=1}^{2} \left[ Q_c \right]_T \left[ G \right]_e \left( \frac{P_a}{P_i} \right) \times 10^{-6} \times \frac{w_m}{v_m} \times \frac{P_a}{P_{std}} \times \frac{T_{std}}{T_a} \times \frac{P_a}{P_{std}}
\]

\[
[\text{ER}]_{PM} = \sum_{c=1}^{2} \left[ Q_c \right]_T \left[ \text{PM} \right]_e \left( \frac{P_a}{P_i} \right) \times 10^{-6} \times \frac{T_{std}}{T_a} \times \frac{P_a}{P_{std}}
\]

where

\[
[\text{ER}]_G = \text{gaseous emission rate of the house at sample time } \tau \text{ (g house}^{-1} \text{ t}^{-1})
\]

\[
[\text{ER}]_{PM} = \text{particulate matter (PM) emission rate of the house at sample time } \tau \text{ (g house}^{-1} \text{ t}^{-1})
\]
[ERPM]_r = PM emission rate of the house at sample time τ (g house\(^{-1}\) t\(^{-1}\))

[Q]_r = building VR under field temperature and barometric pressure at sample time τ (m\(^3\) house\(^{-1}\) t\(^{-1}\))

[G] = gaseous concentration of incoming air (ppm,)

[G]_e = gaseous concentration of exhaust air at location e (ppm,)

[PM] = PM concentration of incoming air (µg m\(^{-3}\))

[PM]_e = PM concentration of exhaust air at location e (µg m\(^{-3}\))

w_m = molar weight of the gas under consideration (g mole\(^{-1}\))

V_m = molar volume of gas under consideration at standard temperature and pressure (STP; 0°C and 1 atm) (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 for the site elevation (kPa)

ρ_a = air density of incoming and exhaust air (kg dry air m\(^3\) moist air).

For quality assurance, the site was visited each week. Temperature, RH, and pressure sensors were checked for reasonable values (e.g., comparing ambient dry-bulb temperature readings with local weather and inside temperature readings with the house controller’s readings). If a sensor was suspected to be malfunctioning, it was checked against the reference or calibrated, as needed. Sampling pumps and valves were checked for flow or leakage and correct switching. All fans were checked for operational status, and sampling ports were checked for flow rate, with the in-line filters changed as needed. TEOM units were cleaned and restarted. The INNOVA analyzer was challenged to ensure readings of span gases as well as zero air were within a predetermined 5% of the expected values. More details on the standard operating procedures of site visits were described in the quality assurance project plan (QAPP) by Moody et al. (2008), and the current project followed the same QAPP. Section 7 of the QAPP (Moody et al., 2008) provides a table of the “sampling parameters and equipment quality control objectives” including sensor precision, quality control limits, and quality control testing timeline. This information is used in the error analysis to provide uncertainty values based on different scenarios. The calculations in the QAPP note that, with the standard operating procedures described, gaseous emission rate uncertainty is less than 10%. This 10% uncertainty also applies to PM when concentrations are 500 µg m\(^{-3}\). Lower PM concentrations increase the uncertainty. The same types of measurement instruments and sensors as described in the QAPP were used in the current study.

**RESULTS AND DISCUSSION**

In this study, the daily gaseous emission rates were considered valid for 358 and 349 days out of 546, yielding a 66% and 64% data completeness for NH\(_3\), CO\(_2\), and N\(_2\)O for H2 and H3, respectively. CH\(_4\) emission rates were considered valid for 341 and 338 days out of 546, yielding a 62% and 61% data completeness for H2 and H3, respectively. Days were considered valid or complete if more than 75% of the potential 30 s averages were recorded and passed the data quality assurance check. Issues with instrument calibration, instrument malfunctioning, pump failures, power outage, and flock change accounted for the days of missing or incomplete data. The PM readings were taken for two consecutive days in each sampling interval (generally one week). A total of 56 days had both PM\(_{10}\) and PM\(_{2.5}\) measurements for both houses.

**THERMAL CONDITIONS AND VR**

Both houses (H2 and H3) held fairly constant temperatures during the winter months (fig. 4). The temperature setpoint of H2 was 1.7°C to 2.8°C lower than that of H3. The setpoint of H2 was increased in February, while the setpoint of H3 stepped up in December and again in February. RH in both houses was below 80% through most of the winter but consistently above 70%. In fall 2010 H2 had a new flock, and in fall of 2011 H3 had a new flock. VR tended to be higher in the early stage of the new flocks, as setpoint temperatures were lowered to stimulate feed intake. VR was generally between 0.6 and 11 m\(^3\) h\(^{-1}\) bird\(^{-1}\) (fig. 4). As expected, there is a strong relationship between ambient temperature and VR (fig. 5), specifically:

For \(T_{amb} < 0.8°C\), VR = 0.56 (R\(^2\) = 0.95)

For \(0.8°C \leq T_{amb} \leq 29°C\), \(VR = 0.008(T_{amb})^2 + 0.095(T_{amb}) + 0.478 (R^2 = 0.91)

For \(T_{amb} > 29°C\), VR = 11 (R\(^2\) = 0.92)

**INDOOR AIR QUALITY**

Ambient temperature influences VR, which in turn affects indoor gaseous concentrations. The daily mean NH\(_3\) and CO\(_2\) concentrations were highest in the coldest weather. The NH\(_3\) concentrations continued to decrease with ambient temperature until the ambient temperature reached approximately 10°C, while CO\(_2\) concentrations continued to drop until ambient temperature reached 20°C. The CH\(_4\) concentration followed the opposite trend in that it increased with ambient temperature. Gaseous production from manure increases or remains relatively unchanged with increasing temperature (as can be seen later). However, the higher VR under warmer temperatures dilutes NH\(_3\) and CO\(_2\) concentrations, although the rate of CH\(_4\) production increased more rapidly than VR (fig. 6). It is unclear to us why CH\(_4\) emissions increased with VR. The N\(_2\)O data were excluded from the analysis and presentation due to the very low concentrations that were essentially below the detection limit of the instrument.

Diurnal trends were observed on many days. PM concentrations increased as lights were turned on, and increased again as birds were given access to the litter floor. A similar pattern was seen in CO\(_2\) concentrations, presumably due to the increased activity level of the birds. However, NH\(_3\) and other gaseous concentrations tended to drop...
during the daylight hours, resulting from higher VR (fig. 7). These trends were most obvious in winter conditions when VR was fairly consistent and close to minimum over the entire day, but to a lesser extent in spring and fall. In summer, afternoon tended to have higher concentrations of all gases and PM. On these days, with the houses at maxi-

Figure 4. Daily mean ambient and indoor and temperature, ambient and indoor relative humidity, and ventilation rate (VR) of the two aviary houses monitored in 2010 and 2011.

Figure 5. Relationship of daily mean building ventilation rate (VR) (m$^3$ h$^{-1}$ bird$^{-1}$) vs. ambient temperature.
In the afternoon, presumably resulting from the combined effects of higher temperatures influencing thermoregulation of the birds (i.e., respiration, thus CO2 production) and increased microbial activities within the manure.

Daily indoor gaseous and PM concentrations are important from the standpoint of both human and bird exposure. This site never exceeded the OSHA 8 h time-weighted average (TWA) CO2 exposure limit of 10,000 ppm. The average daily NH3 concentration exceeded 25 ppm on 24 days in H2 and on 11 days in H3, and on one day the NH3 concentration in H2 was above the OSHA 8 h TWA exposure limit of 50 ppm. It is important to note that the unusually high NH3 concentrations in H2 in December 2010 were due to a malfunction of the manure belt, which caused delays in manure removal. Overall average concentrations of gases during the 19 months were 8.7, 1636, and 10.0 ppm for NH3, CO2, and CH4, respectively. As mentioned above, the N2O concentrations were very low, with only a minimal number of values in an acceptable range (maximum concentration 0.45 ppm), and were therefore excluded from this presentation. The average PM10 and PM2.5 concentrations during the 19 months were 2.3 and 0.25 mg m−3, respectively. Although the TEOM units only ran two days per week, there were 8 days out of 153 monitored when PM10 concentrations were above 5 mg m−3, the OSHA 8 h TWA exposure limit. Overall, H2 and H3 were not significantly different in either gas or PM concentrations. Figure 8 and table 2 summarize these data.

Figure 6. Relationship of daily mean gaseous concentrations (ppm) vs. ambient temperature.
The gas and PM emissions were calculated from equations 1 and 2 and are reported as quantity per house, per bird, per animal unit (AU = 500 kg live body mass), and per kg egg produced. The emissions are summarized as daily and annual amounts. The relationships of daily NH₃, CO₂, and CH₄ emissions vs. daily mean ambient temperature are presented in figure 9, whereas PM emissions are graphed based on three average daily ambient temperature ranges: hot conditions (days with ambient temperatures >26.7°C), mild conditions (7.2°C to 26.7°C), and cold conditions (ambient temperatures <7.2°C).

Table 2. Average daily concentrations [mean (SD)] in the two aviary houses (H2 and H3) and overall.

<table>
<thead>
<tr>
<th>House</th>
<th>Ammonia</th>
<th>Carbon Dioxide</th>
<th>Methane</th>
<th>PM_{10}</th>
<th>PM_{2.5}</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2</td>
<td>9.0 (9.4)</td>
<td>1,853 (1,082)</td>
<td>10.1 (6.9)</td>
<td>2.1 (1.4)</td>
<td>0.24 (0.24)</td>
</tr>
<tr>
<td>H3</td>
<td>8.5 (7.4)</td>
<td>1,418 (956)</td>
<td>9.9 (6.7)</td>
<td>2.5 (1.9)</td>
<td>0.27 (0.28)</td>
</tr>
<tr>
<td>Overall</td>
<td>8.7 (8.4)</td>
<td>1,636 (1,022)</td>
<td>10.0 (6.8)</td>
<td>2.3 (1.6)</td>
<td>0.25 (0.26)</td>
</tr>
</tbody>
</table>

Gas and PM Emissions

The gas and PM emissions were calculated from equations 1 and 2 and are reported as quantity per house, per bird, per animal unit (AU = 500 kg live body mass), and per kg egg produced. The emissions are summarized as daily and annual amounts. The relationships of daily NH₃, CO₂, and CH₄ emissions vs. daily mean ambient temperature are presented in figure 9, whereas PM emissions are graphed based on three average daily ambient temperature ranges: hot conditions (days with ambient temperatures

![Figure 7. An example of winter diurnal patterns of PM and gaseous concentrations. The ambient temperature was -9.5°C and ventilation rate was at minimum (0.6 m³ h⁻¹ bird⁻¹). Lights came on at 5:45 a.m.; birds were given floor access at 11:45 a.m., and lights were off at 9:45 p.m.](image)

![Figure 8. Daily particulate matter (PM) concentrations (mean and SD) for different ambient conditions: “hot” means temperatures >26.7°C, “mild” means temperatures of 7.2°C to 26.7°C, and “cold” means temperatures <7.2°C.](image)
greater than 26.7°C), mild conditions (ambient temperature of 7.2°C to 26.7°C), and cold conditions (ambient temperature below 7.2°C) (fig. 10). As can be seen from the data in figure 9, NH₃ and CO₂ emissions showed no apparent trend of being influenced by ambient temperature. However, ambient temperature showed a positive influence on CH₄ emissions. Summaries of the average daily emission rates and annual emissions are listed in tables 3 and 4, respectively.

Overall, the results for gaseous concentrations and emissions observed in this study were within expectations. European studies revealed that ammonia concentrations in aviary housing were higher than that in manure-belt houses (Hörnig et al., 2001). Liang et al. (2003) reported that manure-belt cage hen houses in the Midwestern U.S. had NH₃ concentrations ranging from 1 to 7 ppm, while high-rise cage houses had concentrations ranging from 9 to 108 ppm at the exhaust (although the bird-level NH₃ concentrations were substantially lower, generally <25 ppm). With average NH₃ concentrations of 9 ppm, the aviary houses tended to have 2 to 8 ppm higher NH₃ concentrations than the manure-belt houses, which agreed with European findings. With the high concentrations on some winter days, it is important to use ammonia-protection masks or respirators. The study by Liang et al. (2003) also showed NH₃ emission rates of 0.05 to 0.1 g bird⁻¹ d⁻¹ (depending on the manure removal interval) for manure-belt cage houses and 0.95 g bird⁻¹ d⁻¹ for high-rise cage houses.

Ammonia emissions for the aviary houses averaged 0.15 g bird⁻¹ d⁻¹, which is higher than the manure-belt system but significantly lower than the high-rise system. Two European studies demonstrated the range in NH₃ emission rates for cage-free barns as 0.27 to 0.85 g bird⁻¹ d⁻¹ (Groot Koerkamp et al., 1998; Müller et al., 2003). The emissions

Figure 9. Relationship of daily emission rates of ammonia (NH₃), carbon dioxide (CO₂), and methane (CH₄) for both aviary hen houses vs. ambient temperature.
observed in this study were quite a bit lower. Many of the cage-free barns in Europe do not have a method of housing birds in tiered colonies where manure is collected and removed frequently, which would affect the litter amount and properties. For CO$_2$, the average emission rate of 75 g bird$^{-1}$ day$^{-1}$ is in line with reported values from manure-belt systems (70 to 85 g bird$^{-1}$ day$^{-1}$) (Liang et al., 2003; Neser et al., 1997). For CH$_4$, the literature suggests a manure-belt system emitting between 0.08 and 0.13 g bird$^{-1}$ day$^{-1}$ (Groot Koerkamp et al., 1997; Monteny et al., 2001; Fabbri et al., 2007; Wathes et al., 1997). The value of 0.09 g bird$^{-1}$ day$^{-1}$ from the current study fell within this range. Overall, this aviary system has emission rates that relate well to a manure-belt cage house, with the exception of NH$_3$ emission being slightly higher.

The major difference between the aviary system and manure-belt or high-rise systems lies in the PM emissions. The literature on conventional laying-hen housing reports PM$_{10}$ emissions of 0.0036 to 0.014 g bird$^{-1}$ day$^{-1}$ (Li et al., 2011), while the current study with aviary housing averages 0.008 g bird$^{-1}$ day$^{-1}$. For PM$_{10}$, the reported literature emission values range from 0.019 to 0.048 g bird$^{-1}$ day$^{-1}$ (Li et al., 2011), while this study averages 0.105 g bird$^{-1}$ day$^{-1}$. The PM$_{10}$ emissions from our study were considerably higher than those reported in the literature; however, this system had a litter floor area. A European study reported on a group of cage-free barns having a PM$_{10}$ emission rate of 0.05 g bird$^{-1}$ day$^{-1}$, with the highest value being 0.07 g bird$^{-1}$ day$^{-1}$.
While the average in the European study was above the range of conventional housing emissions, it was well below the value found in the current study. Li et al. (2011) noted that data from conventional barns in Europe, including the Takai et al. (1998) study, were lower than similar studies in the U.S. Management of the litter (e.g., moisture content) and environmental conditions (house RH and ventilation) presumably contributed to the differences in the PM10 emissions.

As was mentioned above, H2 tended to have higher gaseous emissions, but PM emissions followed the opposite trend. The setpoint temperature in H2 was a few degrees lower than in H3, which led to somewhat higher VR for H2. Litter moisture content (MC) was measured monthly and was found to be slightly higher in H2 (14.4%) than in H3 (12.2%).

Overall, this aviary site ran quite well through the winter in terms of indoor air quality. There were a few days with NH3 concentrations above the recommended 25 ppm level. However, the NH3 emissions were lower than those reported for European layer houses. In Proc. Intl. Symp. on Gaseous and Odour Emissions from Animal Production Facilities 2011: 179-187. Rosmalen, The Netherlands.


SUMMARY AND CONCLUSIONS
Concentrations and emissions of NH3, CO2, CH4, PM10, and PM2.5 for two aviary hen houses in Iowa were continuously monitored for 19 consecutive months, covering two flocks from 17 to 80 weeks of age. The following observations and conclusions were made:

- Daily indoor NH3, CO2, CH4, PM10, and PM2.5 concentrations (mean ±SD) were 8.7 (±8.4) ppm, 1,636 (±1,022) ppm, 10.0 (±6.8) ppm, 2.3 (±1.6) mg m⁻³, and 0.25 (±0.26) mg m⁻³, respectively. Concentrations of all the atmospheric constituents were highest at the coldest ambient conditions, except for CH4, which increased with ambient temperature.

- Daily NH3, CO2, CH4, PM10, and PM2.5 emissions (mean ±SD) were 0.15 (±0.08), 75 (±15), 0.09 (±0.08), 0.11 (±0.04), and 0.008 (±0.006) g bird⁻¹ d⁻¹, respectively. NH3, CO2, and PM2.5 emissions were rather independent of ambient temperature, whereas CH4 and PM10 emissions tended to increase with increasing ambient temperature.

- Annual gaseous and PM emissions (bird⁻¹ year⁻¹) were 55 g NH3, 28.4 kg CO2, 26 g CH4, 39 g PM10, and 3 g PM2.5.

Overall, this aviary system has emission rates that relate well to a manure-belt cage house, with the exception of NH3 being slightly higher. However, the NH3 emissions were lower than those reported for European layer houses.

ACKNOWLEDGEMENTS
This project was supported in part by an Agriculture and Food Research Initiative (AFRI) competitive grant (Award No. 2011-67021-20223) of the USDA National Institute of Food and Agriculture (NIFA), the Midwest Poultry Research Program, the Iowa Egg Council, and the Egg Industry Center. We thank the cooperative producers for allowing access to their flocks.

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