AMMONIA AND CARBON DIOXIDE EMISSIONS OF THREE LAYING-HEN HOUSING SYSTEMS AS AFFECTED BY MANURE ACCUMULATION TIME

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ABSTRACT. *Laying-hen housing design and management are the most significant factors affecting the generation and release of gaseous ammonia to the atmosphere. Transitioning the hen housing type from traditional high-rise (where manure is stored within the house for about one year) to modern manure-belt style (where manure is removed every 1 to 4 d and placed into long-term storage) has significantly improved in-barn air quality and reduced farm-level ammonia emissions. As a direct result of the advantages, 100% of new construction for U.S. egg production incorporates manure-belt systems that regularly remove manure from the houses. However, manure-belt system designs (e.g., active vs. passive drying of manure on the belt) and management practices (e.g., frequency of manure removal) vary considerably across the industry, leading to large variations in system performance and efficiency. Thus, questions remain about the optimal design and management of manure-belt facilities to achieve the desired reductions in ammonia emissions. As part of the Coalition for a Sustainable Egg Supply (CSES) project, 27 months of continually monitored environmental data (including ammonia and greenhouse gas emissions) were collected from three hen-housing systems: a conventional cage house (CC) with a 200,000-hen capacity, an enriched colony house (EC) with a 50,000-hen capacity, and an aviary house (AV) with a 50,000-hen capacity. All three hen houses were located on the same farm and were populated with Lohmann white hens of the same age. All houses were equipped with manure-drying air ducts above the manure belts using recirculated indoor air (flow rate ranging from 0.46 to 1.49 m^3 h^{-1} hen^{-1}). Manure on the belts was completely removed every 3 to 4 d. Average daily house-level ammonia (NH_3) and carbon dioxide (CO_2) emissions as affected by manure accumulation time (MAT, from 1 to 4 d) on the manure belts were analyzed. Results indicate that for all three types of houses, NH_3 emission rates (g hen^{-1} d^{-1}) were significantly lower for MAT of 1 and 2 d (mean ±SE of 0.061 ±0.005 and 0.064 ±0.004, respectively) than for MAT of 3 and 4 d (0.085 ±0.005 and 0.115 ±0.007, respectively) ($p < 0.001$). Emissions of CO_2 (g hen^{-1} d^{-1}) were not significantly affected by MAT, averaging 67.8 ±5.7 for CC, 74.7 ±10.2 for EC, and 75.9 ±10.5 for AV. Estimating annual NH_3 emissions from each type of house revealed that shortening the manure removal interval from every 4 d to every 2 d has the potential of reducing NH_3 emissions by 27% for the CC and EC houses and by 19% for the AV house. However, verification of the potential reductions is needed.*

Keywords. *Ammonia, Carbon dioxide, Environment, Gaseous emissions, Laying hens.*

Ammonia (NH_3) is the major noxious/pollutant gas associated with poultry production and is generated from biological breakdown of the uric acid in manure. Ammonia can have adverse impacts on animals in the housing facility and ecological systems once emitted into the atmosphere. Ammonia emissions originating from animal feeding operations have been reported to represent the largest portion (over 60%) of the national NH_3 emissions inventory in the U.S. (Battye et al. 1994). The U.S. Environment Protection Agency (EPA, 2004) estimated that NH_3 emissions from laying-hen production facilities account for 30.5% of the poultry emissions inventory and 8.3% animal agriculture emissions. Significant efforts have been made to establish baseline emissions data on livestock and poultry housing and manure storage systems (Liang et al., 2005; Wheeler, 2006; Gates et al., 2008; Li and Xin, 2010; Li et al., 2012; Hayes et al, 2013; Stinn et al., 2014; Shepherd et al., 2015). In comparison, cost-effective methods of mitigating NH_3 emission from laying-hen production systems are relatively limited (Roberts et al., 2007; Chepete et al., 2012; Li et al., 2012).

Hen-housing design and management are the most significant factors affecting the generation and release of NH_3 to the atmosphere. Changing the hen-housing system from traditional high-rise (where manure is stored within the house

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for about one year) to modern manure-belt style (where manure is removed every 1 to 4 d and placed into long-term storage) has significantly improved indoor air quality (particularly NH_3 levels) and reduced farm-level NH_3 emissions by 60% to 70% (Xin et al., 2011). As a direct result of the advantages, 100% of new construction for U.S. egg production has been using manure belts in cage-based systems since 2012 (H. Xin, 2015, personal communication).

The general operation of manure-belt hen houses is as follows: (1) manure drops onto a belt below the cages, (2) blowers continuously recirculate air across the surface of the belt to dry the manure, and (3) accumulated manure is removed from the house every 1 to 4 d and placed in an on-farm, long-term (6 to 12 months) storage facility. In the Midwestern U.S., long-term manure storage facilities are typically above-grade roofed systems constructed with a concrete foundation, floor, and perimeter walls for stacking solid or semi-solid manure. Post-and-frame storage structures typically incorporate continuous ridge and eave or sidewall inlets to provide natural ventilation. Figure 1 provides a cross-sectional view of the manure storage structure at the study site, which is representative of storage facilities used in the Midwestern U.S. When designed and managed properly, manure-belt housing systems achieve the desired benefits of improved in-barn air quality and reduced farm-level NH_3 emissions. However, the specifics of manure-belt design and management vary considerably across the industry, resulting in a large range of performances and efficiencies. Thus, the design and management of manure-belt systems remain to be optimized to achieve the needed reductions in ammonia emissions while achieving other important environmental and economic objectives, such as reducing energy use.

Research and industry experiences have shown that small changes in manure-belt management can affect in-barn manure drying efficiency and create negative or positive impacts in the hen house and during long-term manure storage. The major factors impacting manure drying efficiency are manure accumulation time (MAT), bird stocking density (SD), air velocity across the belt, and environmental conditions (e.g., in-barn temperature and humidity). Moisture content (MC) of the manure is a major factor driving biological and chemical breakdown of inorganic and organic matter and has been shown to be a significant factor in the release of NH_3 and CO_2. Li and Xin (2010) quantified gaseous emissions from low MC (50%) and high MC (77%) laying-hen manure under simulated storage conditions. Relative to the high MC manure, the low MC manure had 64% lower NH_3 emissions and 42% lower CO_2 emissions over 21 d of storage. Within the storage period, daily NH_3 and CO_2 emissions were found to peak for both MC levels within the first 2 d of storage. The data also showed that the high MC manure had consistently greater daily NH_3 emissions than the low MC manure. However, daily CO_2 emissions over the first 6 d of storage were not significantly different.

Liang et al. (2005) found that manure-belt layer facilities without in-barn manure drying with daily manure removal in Iowa had a 74% lower average daily NH_3 emission rate (ER) (0.045 to 0.062 g hen^{-1} d^{-1}) in comparison to similar facilities with twice a week removal in Pennsylvania (0.087 to 0.100 g hen^{-1} d^{-1}). In a lab-scale study with environmental chambers, Chepete et al. (2011) quantified NH_3 emissions of laying hens affected by MAT on collection trays (i.e., no active drying). The results showed that NH_3 emissions progressively increased from 0.10 ±0.01 to 0.61 ±0.01 g hen^{-1} d^{-1} when MAT increased from 1 to 5 d. Mendes et al. (2012) investigated NH_3 emissions from pullet and laying-hen manure as affected by MAT and SD, identifying the highest NH_3 ER on MAT of 4 to 6 d and lower ER at lower SD. Similar laboratory evaluations have shown that CO_2 emissions are positively correlated with MAT and should be considered when using a CO_2 balance method to indirectly determine building ventilation rates (Ning, 2008).

The objectives of this study were to evaluate house-level NH_3 and CO_2 ERs as affected by MAT from three commercially operated hen houses in the Midwestern U.S. and to quantify the potential impact of manure removal interval on annual house-level NH_3 emissions.

Materials and Methods

A 27-month environmental monitoring study of three commercial laying-hen housing systems in the Midwestern U.S. was carried out as an integral part of the Coalition for Sustainable Egg Supply (CSES) project from April 2011 to August 2013. The three housing systems included a conventional cage house (CC) with a 200,000-hen capacity, an enriched colony house (EC) with a 50,000-hen capacity, and an aviary house (AV) with a 50,000-hen capacity. All three houses were managed at the same farm under standard commercial practices and were populated with Lohmann white hens of the same age over two single-cycle (no molting) flocks. A detailed description of each housing system design and management is given by Zhao et al. (2015a).

Briefly, the CC house measured 141.1 × 26.6 × 6.1 m (L × W × H) and used quasi-tunnel ventilation with a total of 44 fans (1.32 m dia., 1.1 kW). Each cage measured 0.61 m wide × 0.51 m deep and housed six hens, yielding a manure-belt SD of 516 cm^2 hen^{-1}. Perforated manure drying tubes located beneath the cage rows supplied recirculated barn air (nomi-

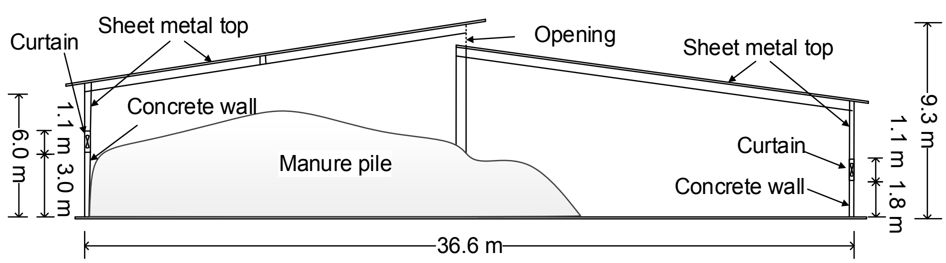

Figure 1. Cross-sectional view of the manure storage located at this study site, measuring 36.6 m wide × 146.3 m long.

nal average of 0.94 m^3 h^{-1} hen^{-1}) across the manure belts via two 40 kW blowers.

The EC house measured 154.2 × 13.7 × 4.0 m (L × W × H) and had cross-ventilation with 18 fans (fourteen of 1.32 m dia., 0.75 kW, and four of 0.92 m dia., 0.75 kW). Each colony measured 3.61 m long × 1.25 m wide and housed 60 hens, yielding a manure-belt SD of 745 cm^2 hen^{-1}. Perforated manure drying tubes located beneath the colony units supplied recirculated barn air (nominal average of 0.94 m^3 h^{-1} hen^{-1}) across the manure belts via ten 3 kW blowers.

The AV house measured 154.2 × 21.3 × 3.0 m (L × W × H) and had cross-ventilation with 18 fans (fourteen of 1.32 m dia., 0.75 kW, and four of 0.92 m dia., 0.75 kW). The AV system housed hens in colony pen units with group sizes of 850 hens (in the outside rows) or 1700 hens (in the inside rows) per pen. Each colony pen unit consisted of a three-tiered colony structure where access to feed, water, perches, nest boxes, and litter floor was provided. The AV manure belts were located below the bottom and middle tiers of the colony, providing a nominal manure-belt SD of 490 cm^2 hen^{-1} within the cage structure. The littered floor of the AV house provided hens access to an average litter area of 520 cm^2 hen^{-1} for a portion of each day, where deposited manure accumulated throughout the flock cycle. Measurement of manure production and deposition patterns during this study found that 77% to 86% of the manure in the AV was deposited on the manure belt (Lin et al., 2016), with the remainder accumulating on the litter floor. The reduced manure deposition rate within the cage structure of the AV house observed in this study yielded an estimated effective manure-belt SD of 570 to 636 cm^2 hen^{-1}. Perforated manure drying tubes located beneath the bottom and middle tiers supplied recirculated barn air (nominal average of 0.78 m^3 h^{-1} hen^{-1}) across the manure belts via three 5.5 kW blowers.

House-level environmental monitoring was conducted with a mobile air emission monitoring unit (MAEMU). A detailed description of the system and operation is given by Zhao et al. (2015b). Ammonia, greenhouse gases (GHGs), and particulate matter (PM) emissions from each housing system have been reported by Shepherd et al. (2015). The MAEMU was designed to meet the site-specific monitoring needs, integrating a gas sampling system, multiple (primary and backup) gas analyzers, and a data acquisition system (Compact Fieldpoint, National Instruments, Austin, Tex.) to automatically and sequentially collect and analyze in-house air samples from a total of ten locations (three locations per house and one ambient location). Simultaneously, the monitoring system collected data on the thermal environment, ventilation rate (VR), and concentrations of NH_3, GHG, and PM. Figure 2 provides a schematic representation of the house-level environmental monitoring layout, relative location of the MAEMU, gas sampling locations, and environmental monitoring locations. To account for in-house spatial variation, two exhaust air samples and one hen-level location were sampled along with one ambient location. Exhaust air sample locations in the CC house were placed near the stage 1 ventilation fan of the east and west endwalls, while sampling in the AV and EC houses provided a composite sample of the two stage 1 ventilation fans and a composite sample of the two stage 2 ventilation fans.

A positive-pressure gas sampling system within the MAEMU (fig. 3) was designed to sequentially collect air samples from the in-barn and ambient locations for analysis with a fast-response and high-precision photoacoustic multi-gas analyzer (Innova 1412, LumaSense Technologies A/S, Ballerup, Denmark) to provide concentrations of NH_3, CO_2, NO_2, CH_4, and dew-point temperature (DP). A 6 or 8 min sampling time per location was used to achieve stabilization of the measurements within the response time of the Innova 1412.

Building VR was derived from *in situ* calibrated fan curves with a 1.37 m (54 in.) fan assessment numeration system (FANS) (Gates et al., 2004). Individual airflow curves were developed for each ventilation stage from five calibration events conducted during the study. Runtime of each ventilation stage was continuously monitored with inductive current switches (CR9321-PNP, CR Magnetics, St. Louis, Mo.), as described by Muhlbauer et al. (2011). Static pressure (model 264, Serta, Boxborough, Mass.) was continuously measured at two locations in each house, along with barometric pressure (WE100, Global Water, Gold River, Cal.). Overall building VR was calculated at 30 s increments

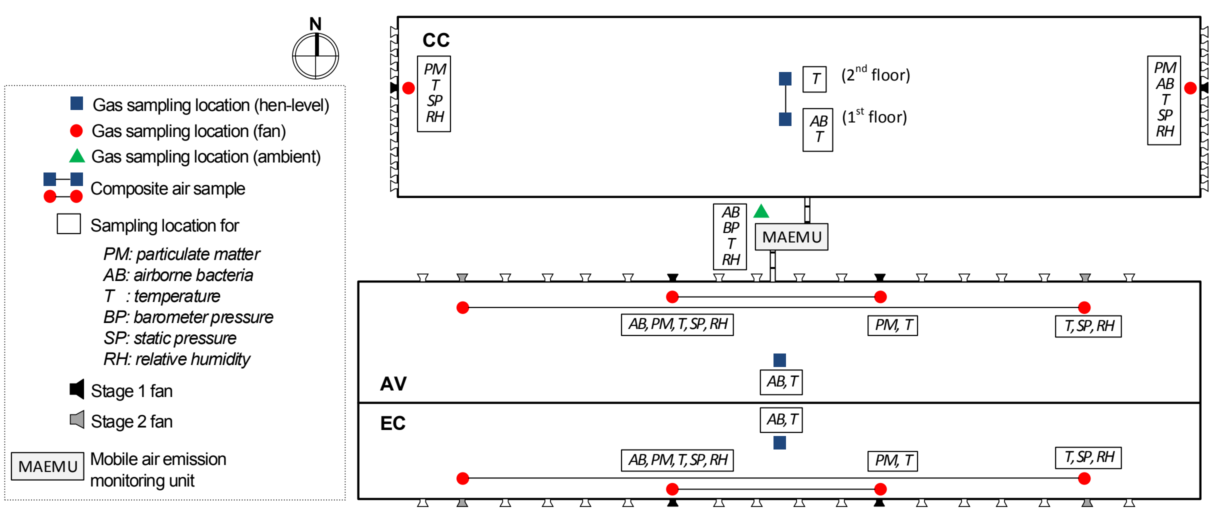

Figure 2. Schematic representation of the house layout, air sampling, and environmental monitoring locations within the conventional cage (CC), enriched colony (EC), and aviary (AV) houses (Zhao et al., 2015b).

(a) (b) (c)

Figure 3. Photographs of (a) mobile air emissions monitoring unit (MAEMU), (b) data acquisition system (DAQ) and gas analyzers, and (c) positive-pressure gas sampling system (GSS) (Zhao et al., 2015b).

using the derived fan curves for each stage, fan runtime, static pressure, and environmental conditions. Ambient and exhaust air concentrations were interpolated to correspond with the 30 s building VR values and were coupled with the environmental conditions to calculate the house-level emissions.

Manure belts were operated twice per week (Monday and Friday), completely removing the accumulated manure on the belts. Each manure removal event took 1 to 2 h and was typically completed by 12:00 noon each day. A temporary increase in house-level NH_3 concentrations was noted during manure removal on cool days when VR remained relatively constant. Daily ERs observed in this study were related to MAT covering the period from 12:00 p.m. to 12:00 p.m. (noon to noon). The duration of MAT ranged from 1 to 4 d, with MAT of 1 d representing the daily emissions immediately following the manure removal event, and MAT of 4 d representing the daily emissions after up to 4 d of manure accumulation.

Data days included in this analysis were first processed with quality assurance and quality control (QA/QC) checks as described by Zhao et al. (2015b) to ensure proper operation of instrumentation, sample collection, sample analysis, and continuous environmental monitoring for at least 75% of each day. Data completeness over the 27-month monitoring period of daily house-level emissions of NH_3 and CO_2 was 64% (Shepherd et al., 2015). For the current analysis, the emissions dataset was further screened to exclude days without 100% continuous data (corresponding to routine weekly site visits) and days with reported manure belt operational issues (e.g., broken belts, partial barn removal, or substantial water leak). This led to a total of 454, 457, and 460 d of valid data for AV, EC, and CC, respectively, providing 55% data completeness over the 27-month monitoring period.

Statistical analysis was performed to compare the daily NH_3 and CO_2 ERs of the three housing types based on MAT using PROC MIXED in SAS (ver. 9.4, SAS Institute, Inc., Cary, N.C.). The model treated each manure removal event as a random factor, and MAT was treated as a fixed factor and a repeated measure. An LSMEANS statement was used to compare differences between the daily ERs of each MAT. The effects were considered significant at a threshold probability level of 0.05. Average daily ER was computed and compared for each of the four MAT levels (1 to 4 d).

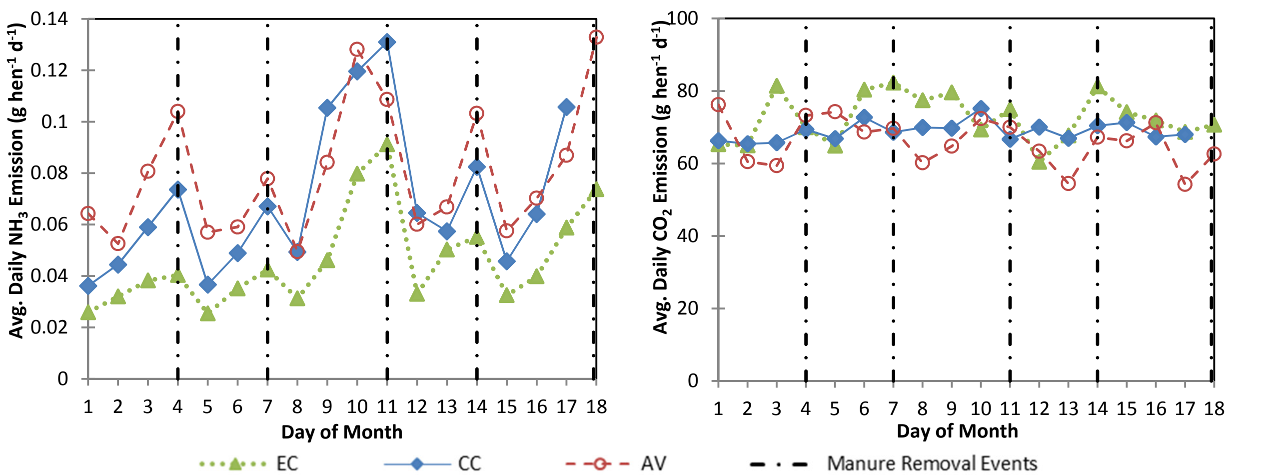

Figure 4. Typical ammonia (NH_3) and carbon dioxide (CO_2) emission patterns for the enriched colony (EC), conventional cage (CC), and aviary (AV) hen houses and the corresponding 3 and 4 d manure removal events represented by the vertical dashed lines (April 2013).

RESULTS AND DISCUSSION

Figure 4 shows typical house-level NH_3 and CO_2 emission patterns for the three housing types in this study with corresponding manure removal events (vertical dashed lines). These graphs illustrate the dynamic nature of daily NH_3 and CO_2 ERs and the apparent pattern of reduced NH_3 ERs on days immediately following a manure removal event.

Average daily NH_3 ERs for each MAT are listed in table 1. Across all housing types, MAT of 1 and 2 d had significantly lower ERs in comparison to MAT of 3 and 4 d, with 4 d MAT having the highest ER ($p < 0.001$). Both flocks monitored provided similar trends of increasing NH_3 emissions with increasing MAT. The effects of MAT on NH_3 ERs in this field study were consistent with the laboratory studies conducted by Chepete et al. (2011) and Mendes et al. (2012). Figure 5 provides a comparison of the three housing types in this study with the laboratory findings at two bird SD levels: low density (LD, 250 cm^2 hen^{-1}) and high density (HD, 187 cm^2 hen^{-1}). Although the magnitude of ERs between these two studies could not be directly compared due to differences in SD and management practices, the general relationship between MAT and ER was consistent. The results also mirrored those of Chepete et al. (2011), who reported NH_3 ERs of 0.101, 0.259, 0.395, and 0.485 g hen^{-1} d^{-1} for MAT of 1, 2, 3 and 4 d, respectively, with manure collected in pans under the cages (no active drying). Shepherd et al. (2015) reported that the differences in house-level NH_3 ER between the CC and EC in this study were likely driven by differences in hen SD, and hence the manure load on the belt and the effectiveness of each in-barn manure-drying system. The higher ERs observed in the AV in this study were primarily attributed to the accumulation of manure on the litter floor, which was an additional NH_3 emission source.

For all housing types, no significant difference was found in CO_2 ER at different MAT. Figure 6 compares this study with the laboratory experiments conducted by Ning (2008), who reported that the decomposition of manure contributed 1% to 8% of the house-level CO_2 emissions as MAT increased from 1 to 4 d. While the CO_2 ERs observed in the current study were not significantly affected by MAT, a slight trend of increasing CO_2 emissions with increasing MAT could be noticed for the EC house. It is probable that changes in biological activity and CO_2 generated from manure decomposition were masked in the field by environmental factors influencing hen activity and metabolism rates, which account for 92% to 98% of house-level CO_2 production. The lower CO_2 ER of the CC house presumably

Table 1. Summary of house-level average daily ammonia (NH_3) emission rates (ER) of the enriched colony (EC), conventional cage (CC), and aviary (AV) houses for different manure accumulation times (MAT).[a]

House		Average Daily NH_3 Emission Rate (g NH_3 hen^{-1} d^{-1}) 1 d MAT	2 d MAT	3 d MAT	4 d MAT
EC	Mean ER	0.038 c,C ±0.002	0.041 c,C ±0.002	0.056 b,C ±0.003	0.080 a,C ±0.007
	(flock 1 / flock 2)	(0.036 / 0.040)	(0.042 / 0.040)	(0.059 / 0.054)	(0.097 / 0.067)
	No. of data	132	130	119	76
CC	Mean ER	0.058 c,B ±0.006	0.061 c,B ±0.005	0.086 b,B ±0.005	0.121 a,B ±0.009
	(flock 1 / flock 2)	(0.071 / 0.046)	(0.074 / 0.050)	(0.100 / 0.075)	(0.139 / 0.109)
	No. of data	132	121	136	71
AV	Mean ER	0.086 c,A ±0.006	0.090 c,A ±0.006	0.114 b,A ±0.006	0.144 a,A ±0.006
	(flock 1 / flock 2)	(0.103 / 0.073)	(0.107 / 0.076)	(0.128 / 0.104)	(0.170 / 0.124)
	No. of data	131	129	118	76

[a] "Mean ER" values are means ±SE for both flocks; values in parentheses are means for each flock (flock 1 / flock 2). Within a housing type (row), means followed by different lowercase letters are significantly different ($p < 0.05$). Within a given MAT (column), means followed by different uppercase letters are significantly different ($p < 0.05$).

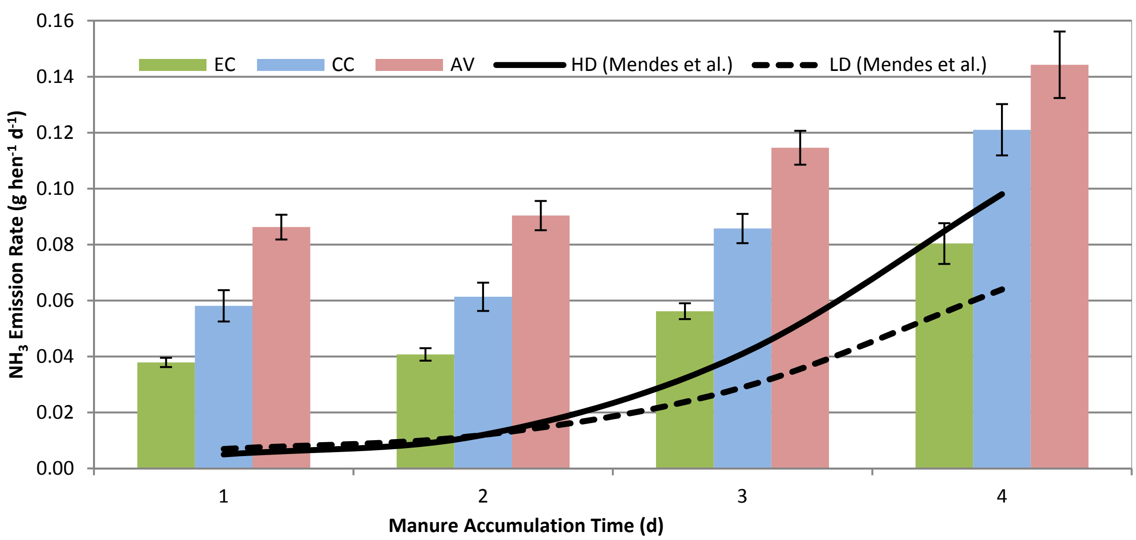

Figure 5. Average daily ammonia (NH_3) emission rate (ER) (g hen^{-1} d^{-1}, mean and SE) vs. manure accumulation time (MAT) for the enriched colony (EC), conventional cage (CC), and aviary (AV) houses, and ERs of a lab study by Mendes et al. (2012) for hens housed at high stocking density (HD, 187 cm^2 hen^{-1}) and low stocking density (LD, 250 cm^2 hen^{-1}).

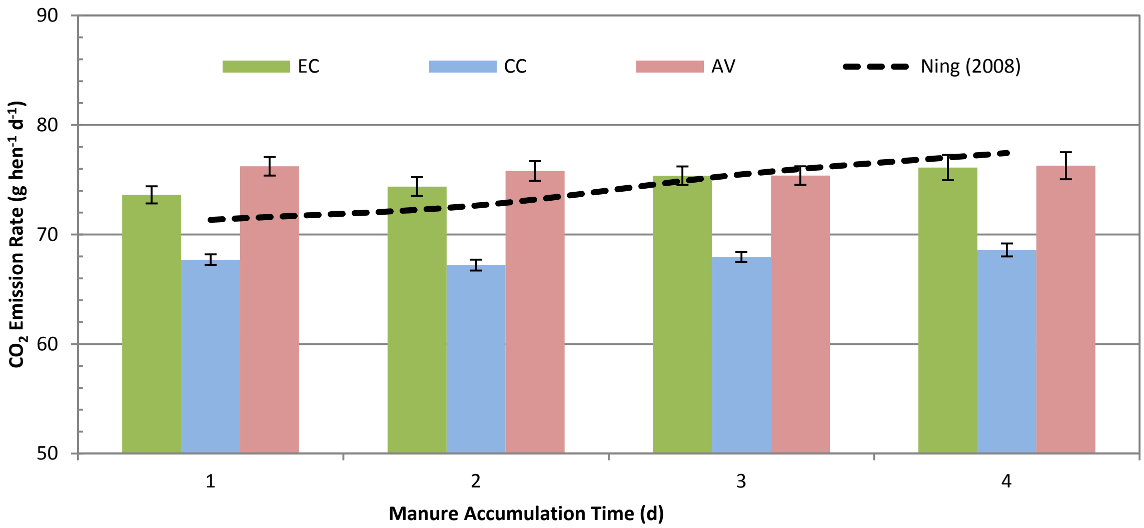

Figure 6. Average daily carbon dioxide (CO_2) emission rates (ERs) (g hen^{-1} d^{-1}, mean and SE) vs. manure accumulation time (MAT) for the enriched colony (EC), conventional cage (CC), and aviary (AV) houses and average ERs reported by Ning (2008) from laboratory experiments.

stemmed from less activity of the hens, as compared to the hens in the EC and AV houses.

To assess the impact of manure-belt management (i.e., manure removal interval) on house-level NH_3 emissions, average annual emissions were estimated for manure removal intervals ranging from daily to every 4 d using the mean daily ERs reported in table 1. The emission reduction potential for each case was then determined based on comparison to a 4 d manure removal interval. Table 2 provides a summary of the annual NH_3 emissions from each housing type based on manure removal interval and the respective emission reduction potential. The EC and CC houses showed the highest NH_3 emission reduction potential by reducing the manure removal interval. Use of daily removal led to an estimated NH_3 emission reduction of 30% for EC, 29% for CC, and 21% for AV. A 2 d removal interval provided similar emission reduction potentials of 27% for EC and CC and 19% for AV. Thus, daily manure removal for all the houses would not provide a significant further emission reduction in comparison to a 2 d manure removal interval. A 3 d manure removal interval would yield a moderate emission reduction of 16% for EC and CC and 11% for AV. Variability between the two flocks in NH_3 ER reduction potential as a result of reducing the manure removal interval from 4 d to 2 d was highest for EC (21% to 34%), followed by CC (24% to 31%), and least for AV (18% to 21%). Extrapolating the emission reduction potential for CC to the U.S. egg industry, assuming that 50% of the total laying hens (305 million) in the U.S. are housed in manure-belt CC houses, changing manure removal from every 4 d (29.8 g NH_3 hen^{-1} $year^{-1}$) to every 2 d (21.8 g NH_3 hen^{-1} $year^{-1}$) could achieve a potential annual NH_3 emission reduction (27%) of approximately 1800 tonnes.

It should be noted that the ERs for the 1 d and 2 d MAT scenarios were estimated while the manure was actually removed after 3 or 4 d of accumulation on the belt. The resulting estimated ERs for 1 or 2 d MAT might differ had the manure been removed at 1 d or 2 d MAT. The difference (underestimation or overestimation) could stem from disturbance of the manure, which may facilitate ammonia emission, and the potential residual effect of 3 or 4 d manure removal on the 1 d MAT ER that immediately followed. However, with the much smaller amount of manure and shorter time (1 to 2 d) on the belt as compared to 3 or 4 d accumulation, the elevation of ammonia emission from such disturbance is expected to be quite small. Nevertheless, it is advisable to verify the reduction potentials through further field monitoring that involves the respective distinct manure removal intervals.

Liang et al. (2005) reported 74% lower NH_3 emissions from manure-belt layer houses with daily manure removal (17.5 g NH_3 hen^{-1} $year^{-1}$) in comparison to semi-weekly manure removal (30.8 g NH_3 hen^{-1} $year^{-1}$). In comparison, the current study estimates a lower emission reduction potential of 22% for the CC house when comparing daily (21.2 g NH_3 hen^{-1} $year^{-1}$) to semi-weekly (27.4 g NH_3 hen^{-1} $year^{-1}$) ma-

Table 2. Observed and estimated annual house-level ammonia (NH_3) emissions for different manure accumulation times (MAT) for the enriched colony (EC), conventional cage (CC), and aviary (AV) houses and reduction of NH_3 emissions for lower MAT (1, 2, or 3 d) relative to 4 d MAT.[a]

	EC		CC		AV	
MAT (d)	NH_3 ER (g hen^{-1} $year^{-1}$)	ER Reduction (%)	NH_3 ER (g hen^{-1} $year^{-1}$)	ER Reduction (%)	NH_3 ER (g hen^{-1} $year^{-1}$)	ER Reduction (%)
1	13.8	30%	21.2	29%	31.5	21%
2	14.4	27%	21.8	27%	32.2	19%
3	16.4	16%	25.0	16%	35.4	11%
4	19.6	0%	29.8	0%	39.7	0%

[a] ER values for 1 d and 2 d MAT conditions were estimated from the analysis of daily ERs when the houses used 3 or 4 d manure removal interval. As such, the values might have deviated, to some extent, from those if the manure had been removed at 1 d or 2 d MAT.

nure removal. Differences in the magnitude of emission reductions are most likely attributable to the housing system design, hen SD, and weather conditions. The manure-belt houses used by Liang et al. (2005) did not provide in-barn drying of the manure, as used in all the barns of the current study, and reported manure moisture content (MC) for the Pennsylvania layer houses with semi-weekly manure removal ranging from 45% to 63%. Thus, it is possible that, without in-barn drying, manure removal frequency may have a more significant impact on house-level NH_3 emissions, as wetter manure maintained in the house for extended periods has a higher emission potential.

Lin et al. (2016) performed a nutrient mass balance analysis on the three laying-hen houses monitored in this study, providing periodic measurements of MC and nutrient content (nitrogen, carbon, sulfur, phosphorus, and potassium) of manure at both 3 and 4 d removal intervals. Their study reported that across the two flocks, the average manure MC for EC (46%) was significantly lower than for AV (52%) and CC (54%). Comparison of manure removal intervals identified that manure removed on day 4 was 3% to 6% drier than manure removed on day 3, while the dry-basis nitrogen content was slightly lower on day 4. During long-term storage, NH_3 emissions are primarily impacted by physical properties (e.g., bulk density and MC), nitrogen content, ambient temperature, and the surface area to volume ratio of the manure stack (Li and Xin, 2010). Removing manure at a 2 d interval may lead to slightly wetter manure entering storage in comparison to a 3 or 4 d interval, which could potentially increase the farm-level NH_3 emissions originating from the storage, thereby offsetting some of the house-level emission reductions achieved. However, as manure is stacked in storage, the surface area to volume ratio decreases significantly in comparison to the manure on the belts, leading to significant changes in the NH_3 emission potential. Management practices such as placing an impermeable cover over the manure stack, albeit not commonly practiced, would provide significant reductions in farm-level NH_3 emissions. Additional efforts to dry or acidify the manure before or during storage may also provide reductions in farm-level NH_3 emissions. Simultaneous monitoring of laying-hen houses and their associated manure storages in this research project found that 60% to 72% of farm-level NH_3 emissions originated from the storage structure (Shepherd et al., 2015). Thus, incorporating house-level mitigation strategies and optimizing the design and management of manure storages will prove conducive to reducing farm-level NH_3 emissions.

Summary and Conclusions

Gaseous emissions over two single-cycle (to 80 weeks of age) production flocks from three commercial hen housing types, conventional cage (CC), enriched colony (EC), and aviary cage-free (AV), in the Midwestern U.S. were monitored and analyzed to quantify the effect of manure accumulation time (MAT) of 1 to 4 d on ammonia (NH_3) and carbon dioxide (CO_2) emissions. The effect of shortening the manure removal interval (i.e., 1 d or 2 d MAT) on annual house-level NH_3 emission reduction potentials was assessed by using the respective 1 d and 2 d MAT emission rates (ERs) while the manure was removed every 3 or 4 d. As such, the resulting estimated reduction potentials contained some inherent uncertainty. The following observations were made.

- Across all three housing types, MAT of 1 d or 2 d yielded significantly lower ERs compared to MAT of 3 d or 4 d, with 4 d MAT having the highest ER ($p < 0.001$).
- Use of a 3 d manure removal interval versus a 4 d interval would lead to a 16% reduction in house-level NH_3 emissions for the EC and CC houses but 11% for the AV house.
- Shortening the manure removal interval from 4 d to 2 d could potentially reduce NH_3 emissions by 27% for the EC and CC houses but 19% for the AV house.
- Further shortening of the manure removal interval from 2 d to daily did not seem to have a significant impact on NH_3 emission reduction for all three housing systems.
- MAT did not significantly impact overall CO_2 emissions for all three housing systems.

Results from this field study were consistent with laboratory studies concerning MAT and stocking density effects on manure NH_3 emissions. Further research is needed to identify the optimal manure-belt design and management strategies to ensure adequate in-barn drying relative to the management of manure, and the impact on NH_3 emissions during long-term and short-term storage. The ammonia reduction potentials achieved by shortening the removal interval from 3 or 4 d to 2 d or 1 d need further field verification.

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References

Battye, R., Battye, W., Overcash, C., & Fudge, S. (1994). Development and selection of ammonia emission factors. Final report. Prepared for the U.S. EPA Office of Research and Development. Retrieved from http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100ERTR.txt

Chepete, J. H., Xin, H., & Li, H. (2011). Ammonia emissions of laying-hen manure as affected by accumulation time. *J. Poult. Sci., 48*(2), 138-143. https://doi.org/10.2141/jpsa.010087

Chepete, J. H., Xin, H., Li, H., Mendes, L., & Bailey, T. (2012). Ammonia emissions and performance of laying hens as affected by different dosages of *Yucca schidigera*. *J. App. Poult. Res., 21*(3), 530-538. https://doi.org/10.3382/japr.2011-00420

EPA. (2004). National emission inventory: Ammonia emissions from animal husbandry operations. Draft report. Washington, DC: U.S.Environmental Protection Agency. Retrieved from http://www.epa.gov/ttn/chief/ap42/ch09/related/nh3inventorydraft_jan2004.pdf

Gates, R. S., Casey, K. D., Wheeler, E. F., Xin, H., & Pescatore, A. J. (2008). U.S. broiler ammonia emissions inventory model. *Atmos. Environ., 42*(14), 3342-3350. https://doi.org/10.1016/j.atmosenv.2007.06.057

Gates, R. S., Casey, K. D., Xin, H., Wheeler, E. F., & Simmons, J. D. (2004). Fan assessment numeration system (FANS) design and calibration specifications. *Trans. ASAE, 47*(5), 1709-1715. https://doi.org/10.13031/2013.17613

Hayes, M. D., Xin, H., Li, H., Shepherd, T. A., Zhao, Y., & Stinn, J. P. (2013). Ammonia, greenhouse gas, and particulate matter concentrations and emissions of aviary layer houses in the Midwestern USA. *Trans. ASABE, 56*(5), 1921-1932. https://doi.org/10.13031/trans.56.10053

Li, H., & Xin, H. (2010). Lab-scale assessment of gaseous emissions from laying-hen manure storage as affected by physical and environmental factors. *Trans. ASABE, 53*(2), 593-604. https://doi.org/10.13031/2013.29574

Li, H., Xin, H., Burns, R. T., Roberts, S. A., Kliebenstein, J., & Bregendahl, K. (2012). Reducing ammonia emissions from high-rise laying-hen houses through dietary manipulation. *J. Air Waste Mgmt. Assoc., 62*(2), 160-169. https://doi.org/10.1080/10473289.2011.638414

Liang, Y., Xin, H., Wheeler, E. F., Gates, R. S., Li, H., Zajaczkowski, P. S., & Burnham, D. J. (2005). Ammonia emissions from U.S. laying-hen houses in Iowa and Pennsylvania. *Trans. ASAE, 48*(5), 1927-1941. https://doi.org/10.13031/2013.20002

Lin, X. J., Zhang, R., Jiang, S., Elmashad, H. M., & Mitloehner, F. (2016). Nutrient flow and distribution in conventional cage, enriched colony, and aviary layer houses. *Poult. Sci., 95*(1), 213-224. https://doi.org/10.3382/ps/pev307

Mendes, L. B., Xin, H., & Li, H. (2012). Ammonia emissions of pullets and laying hens as affected by stocking density and manure accumulation time. *Trans. ASABE, 55*(3), 1067-1075. https://doi.org/10.13031/2013.41511

Muhlbauer, R. V., Shepherd, T. A., Li, H., Burns, R. T., & Xin, H. (2011). Technical note: Development and testing of an induction-operated current switch for monitoring fan operation. *Appl. Eng. Agric., 27*(2), 287-292. https://doi.org/10.13031/2013.36482

Ning, X. (2008). Feeding, defecation, and gaseous emission dynamics of W-36 laying hens. MS thesis. Ames, IA: Iowa State University, Department of Agricultural and Biosystems Engineering.

Roberts, S. A., Xin, H., Kerr, B. J., Russell, J. R., & Bregendahl, K. (2007). Effects of dietary fiber and low crude protein on 29 ammonia emission from laying-hen manure. *Poult. Sci., 86*(8), 1625-1632. https://doi.org/10.1093/ps/86.8.1625

Shepherd, T. A., Zhao, Y., Li, H., Stinn, J. P., Hayes, M. D., & Xin, H. (2015). Environmental assessment of three egg production systems: Part II. Ammonia, greenhouse gas, and particulate matter emissions. *Poult. Sci., 94*(3), 534-543. https://doi.org/10.3382/ps/peu075

Stinn, J. P., Xin, H., Shepherd, T. A., Li, H., & Burns, R. T. (2014). Ammonia and greenhouse gas emissions of a modern U.S. swine breeding-gestation-farrowing system. *Atmos. Environ., 98*, 620-628. https://doi.org/10.1016/j.atmosenv.2014.09.037

Wheeler, E. F., Casey, K. D., Gates, R. S., Xin, H., Zajaczkowski, J. L., Topper, P. A., & Pescatore, A. J. (2006). Ammonia emissions from twelve U.S. broiler chicken houses. *Trans. ASABE, 49*(5), 1495-1512. https://doi.org/10.13031/2013.22042

Xin, H., Gates, R. S., Green, A. R., Mitloehner, F. M., Moore, P. A., & Wathes, C. M. (2011). Environmental impacts and sustainability of egg production systems. *Poult. Sci., 90*(1), 263-277. https://doi.org/10.3382/ps.2010-00877

Zhao, Y., Shepherd, T. A., Li, H., Stinn, J. P., Hayes, M. D., & Xin, H. (2015b). Environmental assessment of three laying-hen housing systems: Part I. Monitoring system and indoor air quality. *Poult. Sci., 94*(3), 518-533. https://doi.org/10.3382/ps/peu076

Zhao, Y., Shepherd, T. A., Swanson, J. C., Mench, J. A., Karcher, D. M., & Xin, H. (2015a). Comparative evaluation of three egg production systems: Housing characteristics and management practices. *Poult. Sci., 94*(3), 475-484. https://doi.org/10.3382/ps/peu077