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Environmental and energy assessment of an aviary laying-hen housing system in the Midwestern United States

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by

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CHAPTER 1
General Introduction

The laying-hen industry in the United States has been under pressure to change or modify the conventional housing systems. Traditionally, hens have been kept in conventional cages inside environmentally-controlled buildings. These cages are stacked wire mesh enclosures with mechanized egg collection, feed and water delivery systems. Over the past decade there has been much pressure to improve the welfare of the hens by replacing conventional cages with alternative housing systems. There are a number of alternative housing options under consideration or being used. The enriched cage option is a system that allows for hens to nest, perch, and scratch while still confining the hens to a larger cage (usually with a group size of 60 hens). The next option is a cage-free barn system. In this system the birds have access to the floor, but are limited to the inside of a barn. The aviary system is a subset of this system where a tiered structure is used to increase space allocation to the hen while accommodating more hens (than a single level barn). The aviary system also use mechanized egg collection, feed and water delivery systems similar to traditional barns. The final system is a free-range system, where birds are given access to the outdoor environment. When the studies described in this dissertation were started, information on the aviary system seemed quite valuable, but the timeliness of the data has become even more apparent over the last few years. Where some states had previously been dealing with transitions to lower stocking densities (fewer hens per unit of area) or alternative systems, there is now an agreement on the table that may bring this transition to a national level. With this potential transition come many questions about the operational performance or characteristics of these alternative barns.

Driving factors in the shift to alternative laying-hen housing

The laying-hen industry welfare standards change constantly; these changes occur due to pressure from many different groups. Often changes from within industry take place as a means to improve production or avoid negative publicity. These changes are implemented after research and an economic analysis has been completed. When issues are not addressed by industry or solutions are not found fast enough, the animal welfare/rights groups and media bring the issues to the public. The public opinion is the largest contributor to changes in industry (Downs, 1972). The public and/or consumers make demand directly and indirectly. Consumer purchases directly influence what is produced. Also these consumer purchases and requests influence the products that larger corporations (retailers, wholesale buyers, restaurants, ect.) demand. Another method by which the public indirectly causes change is through legislation. If consumers are concerned enough and the laying-hen industry does not respond in a timely manner legislation may be introduced to address the issue.

The poultry industry has worked to avoid having issues come under public scrutiny by addressing the issues internally and proactively. The laying-hen industry has many groups, which work proactively to ensure welfare concerns are addressed. The United Egg Producers (UEP), an industry cooperative organization, has set for guidelines for laying hen welfare based on the recommendations of a scientific advisory committee on animal welfare. These guidelines include laying-hen housing, space allowance, beak trimming, molting, handling and transportation (UEP, 2002). In terms of spacing the UEP has a recommendation of 432 to 555 cm^2/bird (67 to 86 in^2/bird). They also have guidelines for cage-free laying hens of 929 to 1394 cm^2/bird (144 to 216 in^2/bird) (UEP, 2002).

There are a number of groups that push for humane treatment and/or animal rights. These groups devote a lot of resources to lobby for new regulations as well they spend a huge amount of money on marketing campaigns to develop more public support. The largest American organization, the Humane Society of the United States (HSUS) has just completed a campaign with regards to laying hens. This campaign is "No Battery Eggs," which is aimed at eliminating the battery cage system from the laying hen industry (HSUS, 2008). The campaign has been fairly successful at pushing through legislation in states with ballot initiatives. For instance, it was integral in pushing Proposition 2 through during the 2008 election in California. The details of this proposition will be discussed below, but in general the wording in the law makes battery cages an impossible option. In addition to lobbying for these regulations, the HSUS works hard to get commitments from corporations to improve animal care.

McDonald's is an example of this corporate demand for high animal welfare standards. McDonald's has set up its own Animal Welfare Guiding Principles, having its own audits done at slaughter plants and its own laying-hen production guidelines. These guidelines include 465 cm^2/bird (72 in^2/bird) of floor space, 10 cm/bird (4 inch/bird) of feeder space, no feed or water withdrawal during a molt, and no excessive beak trimming is allowed (McDonald's, 2007). Burger King, Denny's, Carl's Jr. and Hardee's have also made commitments to use between 2 and 10% cage-free eggs (HSUS, 2008).

If the public still feels the animal welfare issue is not being addressed fully, it often moves to the legislature. Animal welfare has been a regulatory issue in the United States for more than a hundred years. The first regulations that addressed animal welfare were related to transport and food safety. In 1906 Upton Sinclair wrote *The Jungle*, which caused a public demand for safer meat (McGlone, 2001). The Meat Inspection Act of 1906 not only made requirements on meat processing facility sanitation and carcass inspection, but also on the condition of live animals. The act required that all livestock including poultry be evaluated prior to slaughter. Since that time there have been a number of other laws in the food safety realm, which regulate the live animals. Because the US Constitution does not mention animals, it has been suggested that the primary authority for animal well-being regulations is state government (Farve et al, 1993). Most national regulations that deal with farm animal welfare also deal with food safety and/or transportation that include interstate commerce. In 2007, the federal government covered animal fighting under the Animal Welfare Act (AWIC, 2012). All states have anti-cruelty laws, but thirty states have some provision for livestock and/or poultry. However many states do have laws that relate to poultry welfare. Most states have their own laws to address animal fighting; some states also have laws that go beyond cockfighting to address meat birds and laying hens (Farve et al, 1993).

In 1999 the European Union passed a directive, which would ban traditional or battery cages on January 1, 2012. With the ban "a domino effect is feared by the U[nited] S[tates], Canada, and Australia" (Farrant, 1999). On November 4, 2008 this concern was justified as the state of California passed Proposition 2. Under current wording proposition 2 requires that birds must be able to "fully spread both wings without touching the side of an enclosure or other egg-laying hens." This poses a major issue for the laying-hen industry because it not only would eliminate conventional cages, but also limit stocking density in enriched cages (League of Women Voters, 2008). Following California ballot initiatives were run in Michigan (2009, 929 cm^2/bird or 144 in^2/bird) and Ohio (created an advisory board and then agreed to no new conventional cages built) (Ricker, 2011). Many states followed Ohio's plan and created advisory groups, in an effort to prevent ballot initiatives. In early 2011 initiatives were promoted in both Washington and Oregon.

In July 2011, a major shift in thoughts about alternative housing occurred. While there had previously been many state balloting measures, in July 2011 the issue became national. The UEP and HSUS announced that they had reached an agreement for a piece of proposed legislation. The agreement essentially required the phase out of conventional cage housing over "an ample phase-in period". The agreement also allowed for enriched cages to be the new standard in the industry with stocking densities of 800 cm^2/bird (124 in^2/bird) for white hens and 929 cm^2/bird (144 in^2/bird) for brown hens. The proposed legislation would mandate labeling based on housing (conventional, enriched cage, cage-free and free-range) and would prohibit sale of eggs not meeting these requirements (UEP, 2011). While this agreement has not yet become legislation, the implications of the agreement are clear. The pressure to move to alternative systems has increased. With the shift in housing, the need for information on all alternative systems is vital to producers who need to make decisions on the types of alternative housing and prepare to install new systems. The information is also vital to engineers who design and modify these alternative systems.

Questions about the aviary housing system

Because the aviary system is so different from conventional housing, there are questions about the impact and performance of such a system. The most obvious difference in all alternative housing, including aviaries, is the lower stocking density. With the lower stocking density, there are many questions about the correct management of houses, especially in winter. The potential issue with ventilation for indoor air quality at the lower stocking density is the possible need for supplemental heat and its proper distribution in the house. This dissertation looks at this issue from many different angles including ventilation rate, indoor air quality, heat and moisture production of the birds, fuel usage, and the birds' preference for winter temperature-ammonia combinations. With the lower stocking density there is also a concern that the labor and utilities provided on a per bird basis will be higher. Another concern with the systems is that a portion of manure from the birds is held in the house on the floor as litter. The litter on the floor impacts indoor air quality. The ammonia and dust concentrations and emissions were two of the major concerns with regard to the litter. With the aviary system, the birds have the ability to be more active. There are questions about how this activity level impacts the heat and moisture production rates of these birds. Overall, there is very little information on the aviary system in the United States. Because Iowa is number one in egg production with over 14 billion eggs produced annually, nearly double any other state, it is an ideal location to gather information on this system (USDA 2012). Information from the European Union is available, but does not always translate well to US practices due to environmental and management differences. The objectives of the studies described in this dissertation were:

1. Quantify average daily gaseous and particulate matter concentrations and emission rates from aviary houses in the Midwestern US. As well, daily house temperatures, relative humidity, and ventilation rates needed to be defined. Using these values annual emissions were to be summarized.
2. Quantify whole-house total and latent heat production rates. These numbers were broken down into light and dark period to evaluate the impact of bird activity on heat production rates.
3. Quantify the electricity and fuel use in two aviary laying-hen houses.
4. Confirm that concentrations of ammonia that are aversive to hens using a preference test chamber; and determine if a low (<10 ppm) NH_3 condition with a cool air temperature (18.3 ℃) is preferred to an aversive NH_3 concentration (30 ppm) combined with a TN air temperature (23.9 ℃).

Organization of dissertation

Corresponding to the objectives stated above, the following four chapters of this dissertation include three papers from a 19-month monitoring project at a commercial aviary site and a fourth paper from environmental preference testing done in the lab. The first paper characterizes gaseous and dust concentrations and emissions in two commercial aviary houses. With the lower stocking density and differences in manure management there is a need to consider ventilation design, indoor air quality, and potential emission concerns. The second paper delineates the heat and moisture production rates of the hens and their housing system. This heat and moisture production data give valuable insight, which would be helpful in future supplemental heating and ventilation designs. The third paper characterizes electricity and propane usage in the same two commercial aviary houses. The final paper in the dissertation is a lab study, which evaluates environmental preference for ammonia and ammonia/temperature winter combinations. The dissertation ends with a final summary of findings from these four papers.

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CHAPTER 2

Ammonia, Greenhouse Gas, and Particulate Matter Concentrations and Emissions of Aviary Layer Houses in the Midwestern USA

A manuscript prepared for submission to Transactions of the ASABE

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

Abstract

There has been an increased interest in alternative housing for laying hens in certain parts of the world, including the United States. Associated with the movement are many questions to be addressed concerning sustainability of such systems. This study continually quantifies concentrations and emissions of ammonia (NH_3), carbon dioxide (CO_2), methane (CH_4,), nitrous oxide (N_2O), and particulate matters (PM_{10} and $PM_{2.5}$) for two side-by-side aviary barns each housing 50,000 Hy-Line brown laying hens, located in the Midwestern US. The gaseous concentrations were continually monitored using a photoacoustic multi-gas analyzer, while the PM concentrations were measured with tapered element oscillating microbalances (TEOMs). Barn ventilation rate was determined through monitoring the operation time of ventilation fans that had been calibrated in-situ. Nineteen consecutive months of monitored data (June 2010 – Dec 2011) are analyzed and presented. Daily indoor NH_3, CO_2, CH_4, PM_{10}, and $PM_{2.5}$ 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. The aerial emissions are expressed as quantities per hen, per animal unit (AU, 500 kg body weight), and per kg of egg output. Daily emission rates were 0.15 (±0.08) NH_3, 75 (±15) CO_2, 0.09 (±0.08) CH_4, 0.11 (±0.04) PM_{10}, and 0.008 (±0.006) $PM_{2.5}$ g/bird. The results are compared to reported emission values for conventional (high-rise and manure-belt) US laying-hen housing systems. Data from this study provide baseline concentration and emission values from the aviary housing system in the Midwestern US.

Keywords: Aviary, Air Quality, Aerial Emissions, Concentrations, Laying Hen

Introduction

In the past decade there has been increased pressure to move from traditional laying hen cage houses with both high rise and belt manure systems to cage-free and enriched cage housing. With this pressure there are many questions about the performance of these alternative systems. There is very little information on the emissions from these alternative systems, particularly as they are operated in the U.S. This study was conducted in aviary barns with the Natura 60 (Big Dutchman, Holland, MI) design, from which we collected baseline data on concentrations and emissions for particulate matter with aerodynamic diameter of 10 or 2.5 µm (PM_{10} and $PM_{2.5}$); greenhouse gasses (GHG)- carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O); and ammonia (NH_3). An Air Compliance Agreement (ACA) was reached between the EPA and certain sectors of the U.S. livestock and poultry industries, namely, the broiler, egg, swine, and dairy industries in 2005. The ACA studies will yield more baseline data on air emissions from U.S. AFOs. However, no alternative laying-hen housing sites were monitored in the ACA studies.

Studies have been conducted to quantify aerial emissions for conventional laying-hen housing in the US and conventional and alternative housing in Europe. The study by Liang et al. (2003) showed NH_3 emission rates of 0.05 to 0.1 g/bird-day for conventional manure belt hen houses and 0.95 g/bird-day for high-rise hen houses. European studies showed NH_3 emission rates from cage-free barns of 0.27 and 0.85 g/bird-day (Groot Koerkamp et al, 1998, Muller et al., 2003). The European reported values for ammonia emissions at the higher end are comparable to high-rise housing. Reported values for CO_2 from belt houses are 70 to 85 g/bird-day (Liang et al., 2003, Neser et al., 1997). For CH_4 literature suggests all housing systems emitting between 0.08 and 0.13 g/bird-day (Groot Koerkamp et al.; 1997; Monteny et al., 2001; Fabbri et al., 2007; Wathes et al., 1997). Literature on conventional laying-hen housing reports $PM_{2.5}$ emissions of 0.0036 to 0.014 g/bird-day; and for PM_{10} the reported literature emission values range from 0.019 to 0.048 g/bird-day (Li et al., 2011). Cage-free systems in Europe were reported to have PM_{10} emissions 2 to 3 times greater than conventional houses (Takai et al., 1998).

The objectives of this study were to quantify average daily gaseous and particulate matter concentrations and emission rates from aviary houses in the Midwestern US. As well, daily house temperatures, relative humidity (RH), and ventilation rates (VR) needed to be determined. Using these values annual emissions were to be summarized and compared to earlier studies.

Materials and Methods

Site Description

Two aviary hen houses in a double-wide building located in Iowa were used in this field study. Each house measured 167.6 m x 19.8 m (550 ft x 65 ft) 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 (new flock started the fourth week of April 2010 in barn 3 and the second week of September 2010 in barn 2). A cross-sectional schematic of the houses is shown in figure 2.1, and a timeline of the monitoring and flocks is shown in figure 2.2. Each house was divided into ten 14.5-m (48-ft) sections along the length. The houses had open litter floor (2.5 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 belt with a manure-drying air duct was placed underneath the lower two cage tiers. The three tiers were divided into nest, feeding, and drinking area from top to bottom. Each house had 20 exhaust fans, all on one sidewall (fig. 2.3), including twelve 1.2-m (4-ft), four 0.9-m (3-ft), and four 0.5-m (20 inch) fans. Ceiling box air inlets (75 bi-directional 0.6 x 0.6 m) were used. Four 73.25 kW (250,000 BTU/hr) heaters were placed equidistant along the sidewall. Compact fluorescent lighting was used with a 16 hour light period. Table 2.1 summarizes housing and management characteristics of the aviary houses.

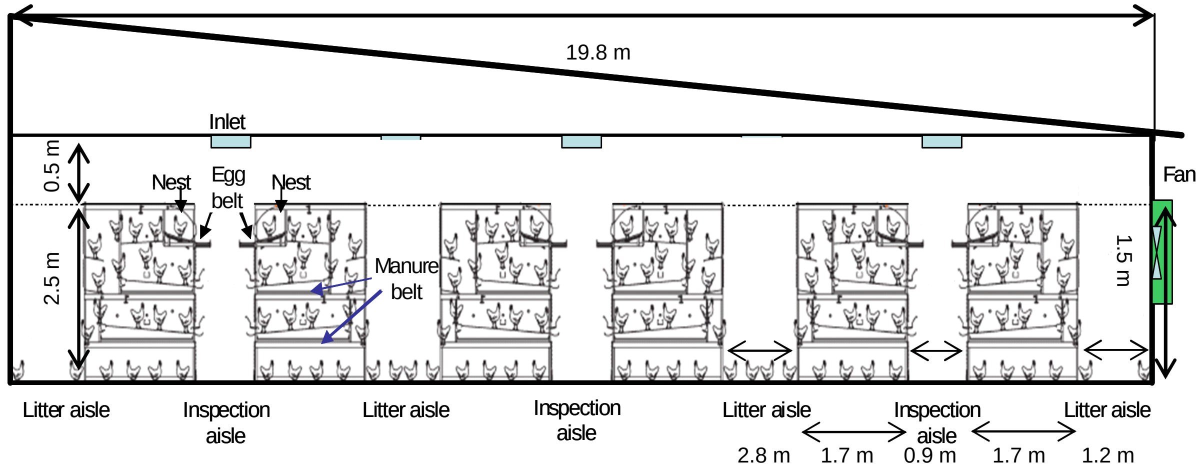

Figure 2.1. Cross-sectional view of the aviary hen house (one side of the double houses) to be monitored in this study. (not drawn to scale)

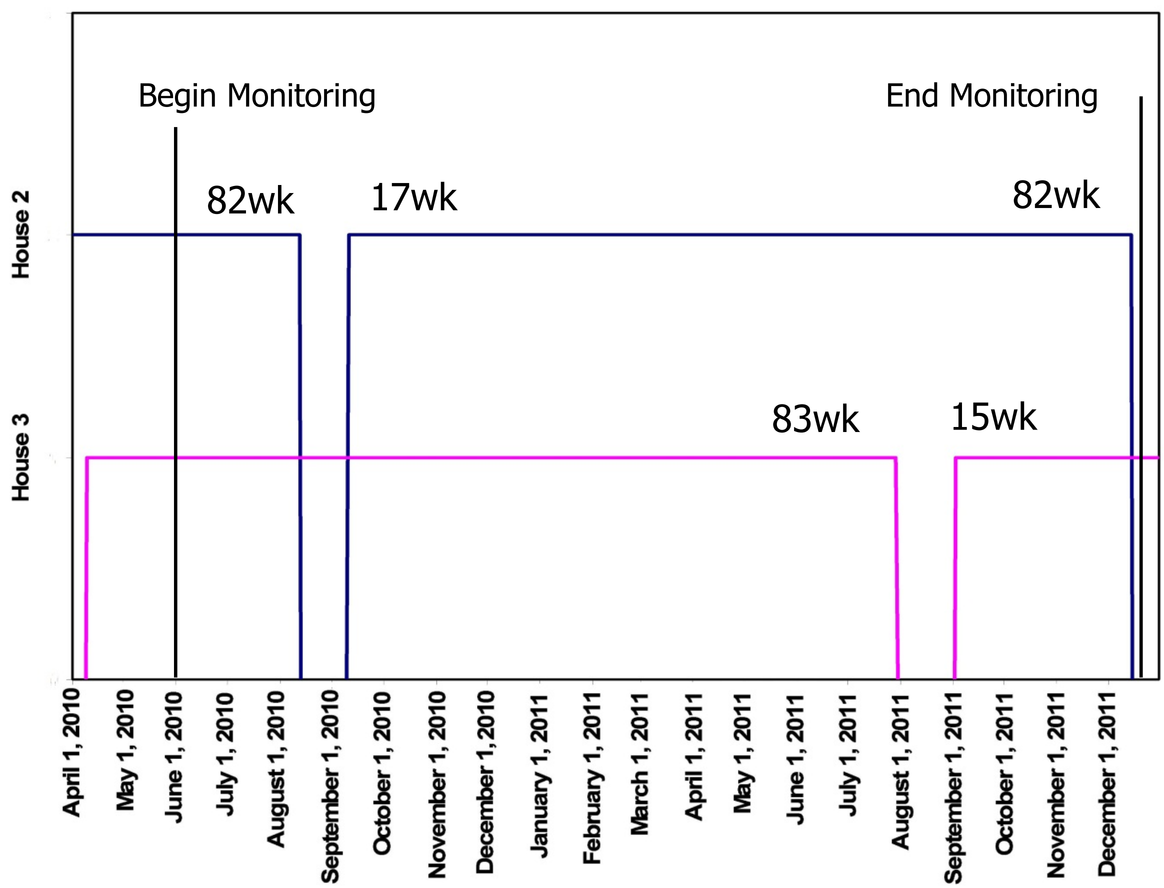

Figure 2.2. Timeline of monitoring and the two aviary flocks monitored.

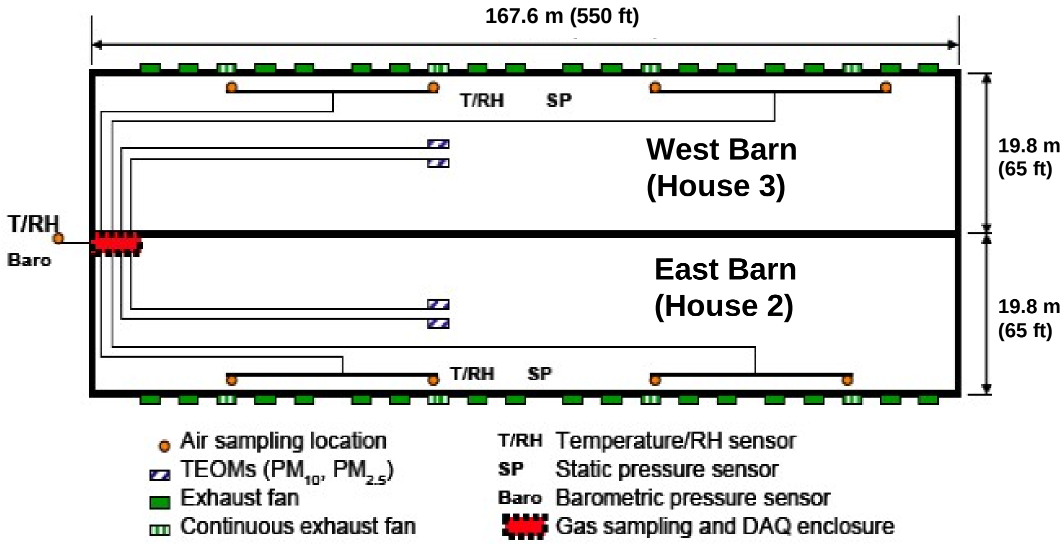

Figure 2.3. Schematic representation of the aviary hen houses and sampling locations. (not drawn to scale)

Table 2.1. Housing characteristics of the aviary hen houses monitored in this study

Ventilation				
	# Fans	Fan Size	Motor Size	On if > setpoint by, °C
Stage 1	4	0.5 m	250 W	continuous
Stage 2	4	0.9m	375 W	1.1
Stage 3	2	1.2m	750W	1.1
Stage 4	2	1.2m	750 W	1.1
Stage 5	2	1.2m	750W	1.1
Stage 6	2	1.2m	750 W	1.1
Stage 7	2	1.2m	750W	1.1
Stage 8	2	1.2m	750 W	1.1
Heater				
	# Heaters		Capacity	On if < setpoint by, °C
	4		73.25 kW	2.2
Manure Drying Blower				
	# Blowers		Motor Size	
	3		5.6 kW	
Lighting				
	# Lights	Bulb Type	Nominal Size	
Inspection Aisle	315	CFL	9W	dimmable
Litter Aisle	180	CFL	15W	dimmable
Worker Area	16	Incandescent	75W	
Timing				
Feeding	5:45 AM	11:15 AM	3:30 PM	7:15 PM
Lights On/Off	Lights On	5:30 AM	Light Off	9:45 PM
Floor On/Off	On Floor	11:30 AM	Off Floor	9:30 PM
Daily Manure Belt Movement	1/3 belt (winter)	15 min	1/7 belt (summer)	7 min
Spacing Allowance (50,000 hens)				
Wire Floor	1096	cm^2/bird		
Litter Floor	613	cm^2/bird		
Nest Space	9.3	cm^2/bird		
Perch	15.9	cm/bird		
Feed Trough	10.6	cm/bird		
Nipple Drinker	8.55	bird/nipple		

Measurement System

Concentrations of NH_3 and GHG (CO_2, N_2O, CH_4) at four locations in each house were measured continually with a fast-response and high-precision photoacoustic multi-gas analyzer (model 1412, Innova AirTech Instruments, 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 barn (fig. 2.3). FEP Teflon tubing (3/8-inch o.d. and ¼-inch i.d.) was used for air sampling to avoid NH_3 absorption to the sampling lines. Each sampling port was equipped with a course and a fine dust filter to keep large 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. 2.4). To ensure measurement of the real concentration values, considering the response time of the analyzer, each location was sampled for 6 minutes, with the first 5.5 min for stabilization and the last 0.5 minute readings for measurement. This sequential measurement yielded 30-min data of gaseous concentrations. Sampling pumps were run for one minute prior to the location sampling, and turned off as soon as the sampling was finished. In addition, every 2 hours the outside air was drawn and analyzed. The less frequent sampling and analysis of the outside air is because its compositions remain much more stable than those of the indoor air.

Concentrations of PM_{10} (inhalable dust) and $PM_{2.5}$ (respirable dust) inside the barns were measured continuously with real-time Tapered Element Oscillating Microbalances equipped with the respective PM head (TEOM, Model 1400a, Thermo Fisher Scientific Inc., Waltham, MA, USA) (fig. 2.4). A 300-s integration time was used. A pair of TEOMs were run continuously for two days each week in each barn, with mass concentrations of both particle sizes reported every 30 s. The pair of TEOMs were placed near sidewall at minimum ventilation fan (fan 7) in both barns. Temperature (type-T thermocouple, Cole-Parmer, Illinois, USA), RH (HMW60, Vaisala, MA, USA), and building static pressure (264, Serta, MA, USA) were measured at the middle of the barns at 1-second intervals and reported as 30-second 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 the eastern barn (barn 2). The enclosure was supplied with fresh air from the attic to provide a positive pressure system in an effort to minimize entrance of dust from the indoor air.

Figure 2.4. Gaseous and particulate matter (PM) concentration monitoring system (*L- R: positive-pressure gas sampling system or P-P GSS, gas analyzers, and Tapered Element Oscillation Microbalance or TEOM PM monitors***).**

The building VR was determined based on *in situ* calibrated fan curves with fan assessment numeration systems (FANS) sized 0.9 m (36 inch), 1.2 m (48 inch), and 1.35 m (54 inch) (Gates et al., 2004). Individual fan curves were established for each stage (1-8) including operational ranges of the variable speed control of the lower stages. The runtime of fans was recorded continuously with inductive current switches (Muhlbauer et al, 2011). Magnetic proximity sensors (MP1007, ZF Electronics, WI, USA) were used to measure the fan speed (rpm) of the variable speed fans. Fan runtime and speed along with the corresponding building static pressure were recorded every second. Using the calibrated curves for each stage with the above data an overall building VR was calculated. All data were collected in a data acquisition system (DAQ, Compact Fieldpoint, National Instruments, TX, USA). All samples taken at 1-second intervals were averaged to 30-second values and reported to the on-site PC.

Calculation of Gaseous and Particulate Matter Emissions

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

$$[ER_G]_t = \sum_{e=1}^{2}[Q_e]_t\left([G]_e - \frac{\rho_e}{\rho_i}[G]_i\right)\times 10^{-6}\times\frac{w_m}{V_m}\times\frac{T_{std}}{T_a}\times\frac{P_a}{P_{std}} \quad [1]$$

$$[ER_{PM}]_t = \sum_{e=1}^{2}[Q_e]_t\left([PM]_e - \frac{\rho_e}{\rho_i}[PM]_i\right)\times 10^{-6}\times\frac{T_{std}}{T_a}\times\frac{P_a}{P_{std}} \quad [2]$$

where $[ER_G]_t$ = Gaseous emission rate of the house at sample time t (g house^{-1} t^{-1})

$[ER_{PM}]_t$ = PM emission rate of the house (g house^{-1} t^{-1})

$[Q_e]_t$ = Average building VR under field temperature and barometric pressure at sample time t (m^3 house^{-1} t^{-1})

$[G]_I$ = Gaseous concentration of incoming air (ppm$_v$)

$[G]_e$ = Gaseous concentration of the exhaust air (ppm$_v$)

$[PM]_I$, = PM concentration of incoming ventilation air (ug m^{-3})

$[PM]_e$ = PM concentration of exhaust ventilation air (ug m^{-3})

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

V_m = molar volume of NH_3 gas at standard temperature (0°C) and pressure (1 atmosphere) (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 for the site elevation, kPa

ρ_i, ρ_e = 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. Sampling pumps and valves were checked for flow and correct switching. All fans were checked for operation status, and sampling ports were checked for flow rate, with filters changed as needed. TEOMs were cleaned and restarted. The INNOVA analyzer was checked to ensure all span gasses as well as a zero reading were within 5% of the expected values. More details on standard operating procedures of site visits were described in the quality assurance project plan (QAPP) (Moody et al., 2008), and the current project followed the same QAPP.

Results and Discussion

Indoor Air Quality

In this study, the daily gaseous emission rates were taken on 358 days out of 546, giving a 66% data completeness. Issues with instrument calibration, instrument functioning, pump failures, data recording, and power failures account for the days of missing data. The PM readings were taken for 2 consecutive days. A total of 56 days had both PM_{10} and $PM_{2.5}$ for both houses. Both houses 2 and 3 held fairly constant temperatures over the winter months. House 2 had a setpoint that was 1.7 to 2.8℃ (3 to 5℉) lower than house 3. The setpoint of house 2 was increased in February, while the setpoint of house 3 stepped up in December and again in February. The higher temperatures in house 3 corresponded to lower VR. RH in both houses was below 80% through most of the winter, but RH consistently above 70%. VR was generally between 0.6 and 11m^3/hr-bird. Figure 2.5 plots these trends. As expected, there is a strong relationship between ambient temperature and VR.

$$VR = 0.56, \quad T_{amb} < 0.8℃ \quad [3]$$
$$VR = 0.008(T_{amb})^2 + 0.095(T_{amb}) + 0.478, \quad 0.8℃ \leq T_{amb} \leq 29℃ \quad [4]$$
$$VR = 11, \quad T_{amb} > 29℃ \quad [5]$$

.

VR was a constant value below 0.8℃ (minimum ventilat ion, eq 3, R^2 = 0.95).Using a second order polynomial, the relationship for both houses is (eq 4, R^2 = 0.91) when ambient temperature is greater than 0.8℃ and less than 29℃ . The VR again becomes constant above 29℃ (maximum ventilation, eq. 5, R^2 = 0.92). These equations were plotted in figure 2.6.

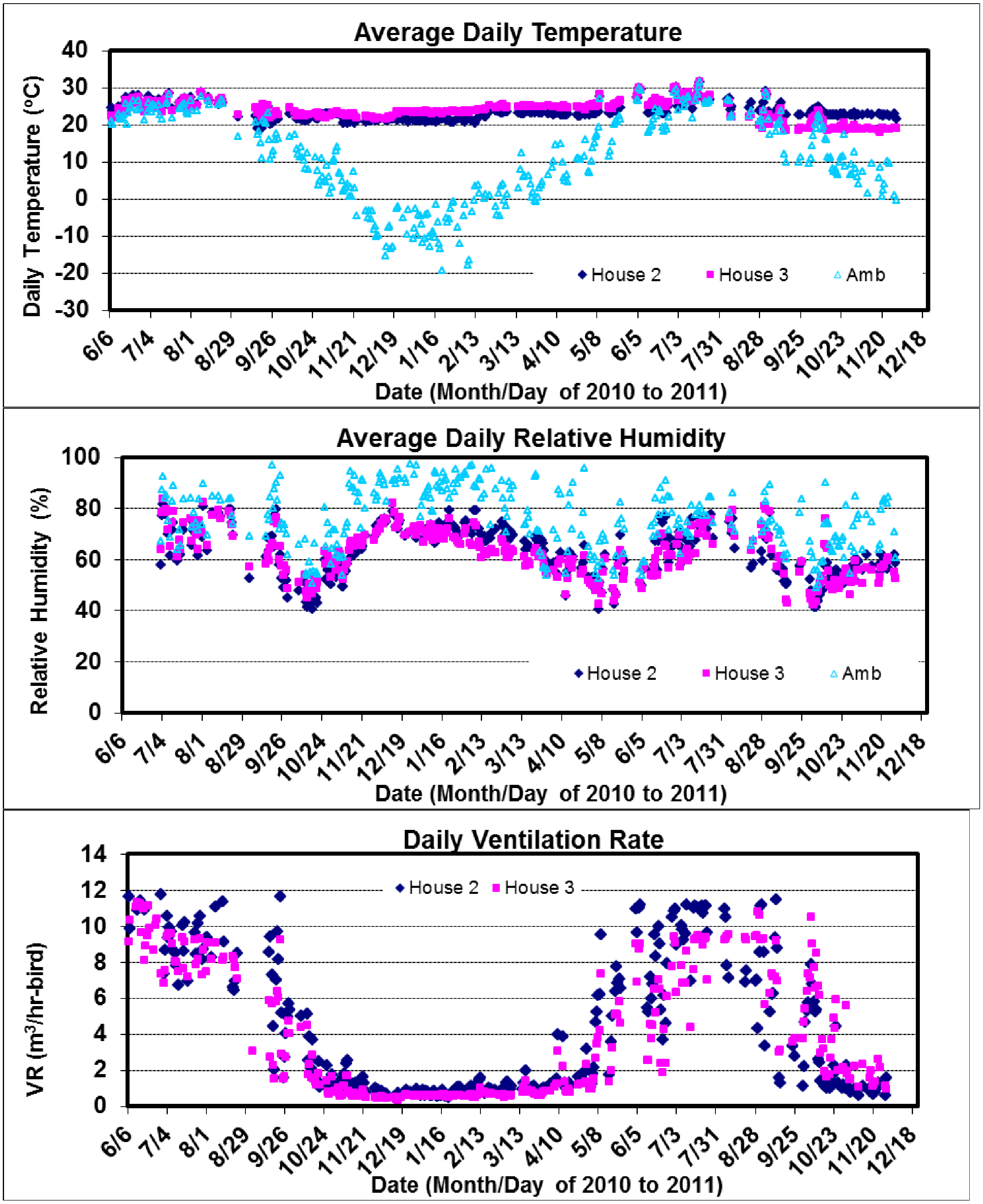

Figure 2.5. Daily temperature, relative humidity, and ventilation rate (VR) of the two aviary houses monitored and the ambient.

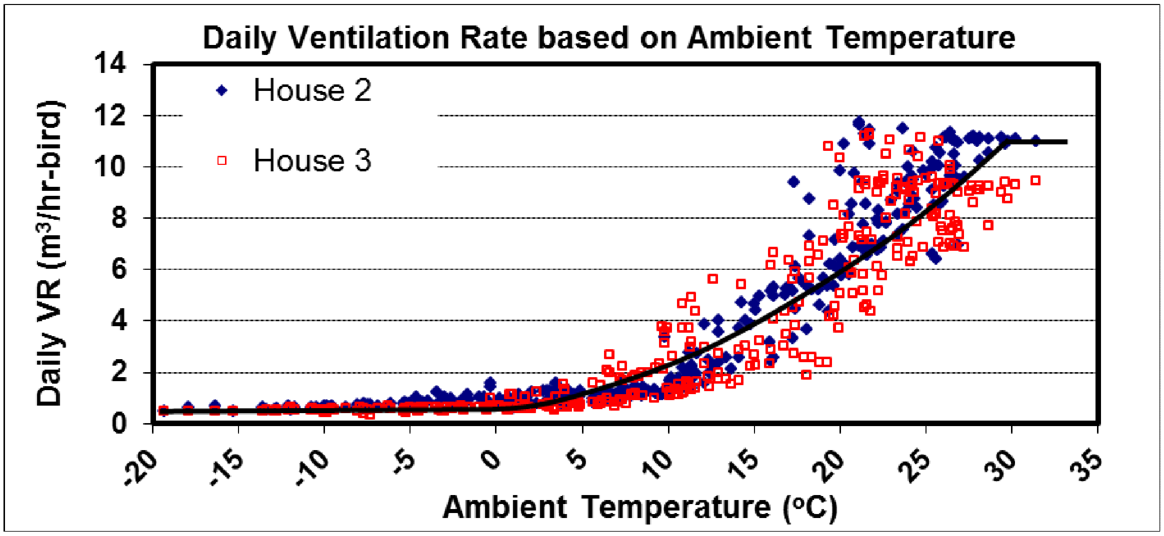

Figure 2.6. Plot of ventilation rate (VR) (m^3/hr-bird) vs. ambient temperature.

As ambient temperature influences VR it also influences indoor gaseous concentrations. The daily NH_3 and CO_2 concentrations are highest in the coldest weather. The NH_3 concentrations drop in value until the ambient temperature reaches approximately 10 ℃ while CO_2 concentrations continue to drop until 20 ℃. The CH_4 concentration follows the opposite trend with concentrations increasing with increasing ambient temperature. Figure 2.7 shows these trends. N_2O may show a similar trend, but due to the low concentrations (there are 23 daily values in house 3 and only 6 values in house 2) The data was not analyzed.

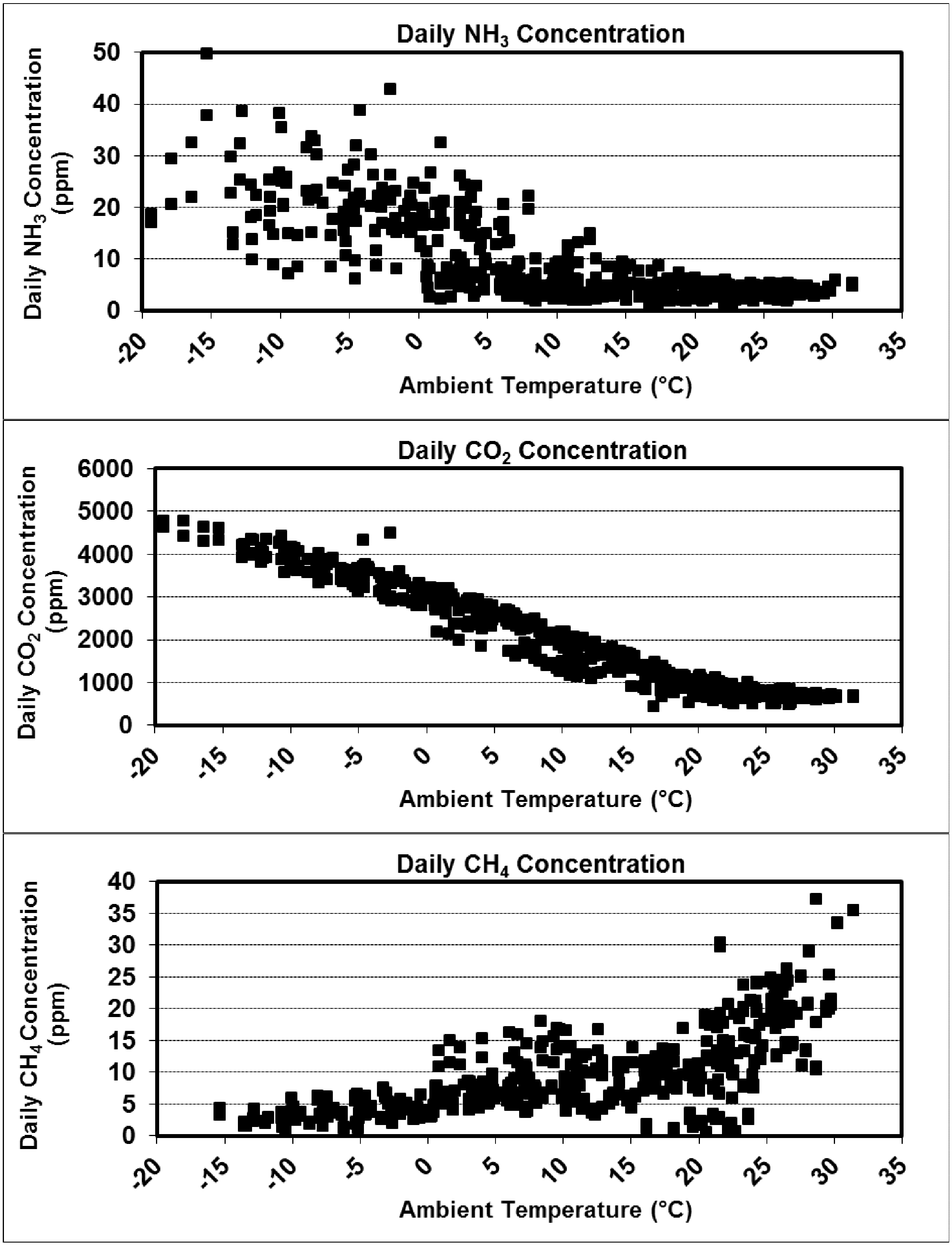

Figure 2.7. Plot of gaseous concentrations (ppm) vs. ambient temperature

Some particular 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 floors. A similar pattern was seen in CO_2 concentrations. However NH_3 and other gaseous concentrations tended to drop during the daylight hours due to higher VR (figure 2.8). These trends are most obvious in winter conditions when ventilation is fairly consistent and close to minimum over the whole day.

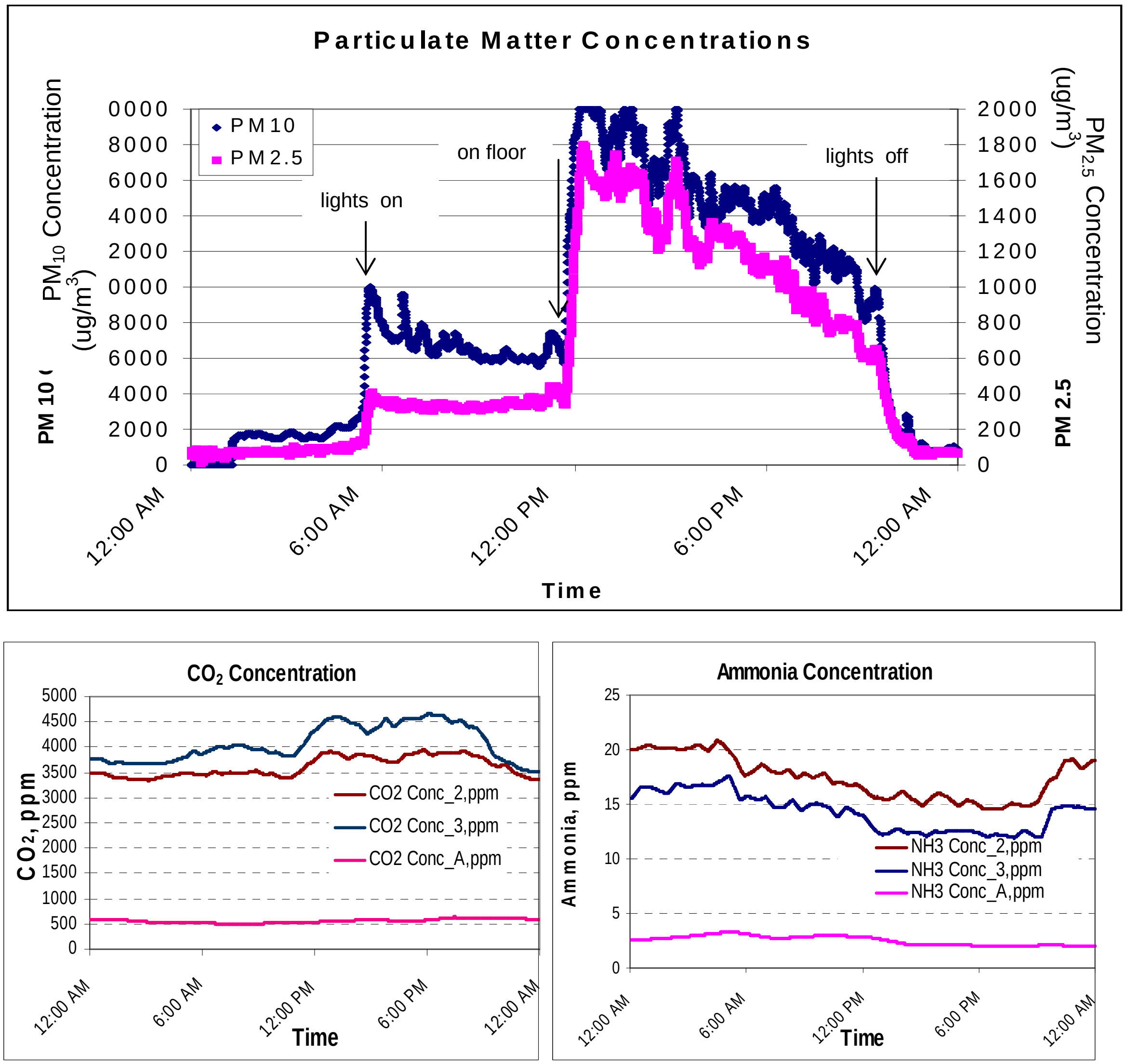

Figure 2.8. Typical winter diurnal patterns of gaseous and PM concentrations. The ambient temperature was -9.5 ℃ and ventilation rate was at minimum, 0.6 m^3/hr-bird. Lights came on at 5:45AM; birds given floor access at 11:45AM, lights off at 9:45PM.

Daily indoor gaseous and particulate matter concentrations are of concern from the standpoint of both human and bird exposure. This site never exceeded the OSHA 8-hour time weighted average (TWA) exposure limit of 10,000 ppm for CO_2. The average daily NH_3 concentrations exceeded 25 ppm on 24 days in house 2 and 11 days in house 3, and on one day NH_3 concentration in house 2 was above the OSHA 8-hour TWA exposure limit of 50 ppm (figure 2.9). Overall average concentrations over the 19 months were 8.7, 1636, and 10.0 ppm for NH_3, CO_2, and CH_4, respectively. As was mentioned above the N_2O concentrations were very low with only a minimal number of values in an acceptable range (maximum concentration 0.45 ppm), and are therefore not displayed below. The average PM_{10} and $PM_{2.5}$ concentrations over the 19 months were 2.3 and 0.25 mg/m^3. Although the TEOMs only ran two days per week, there were 8 days out of 153 monitored where PM_{10} concentrations were above 5 mg/m^3, the OSHA 8-hour TWA exposure limit during lighted hours. Figure 2.10 and Table 2.2 summarize these concentration data.

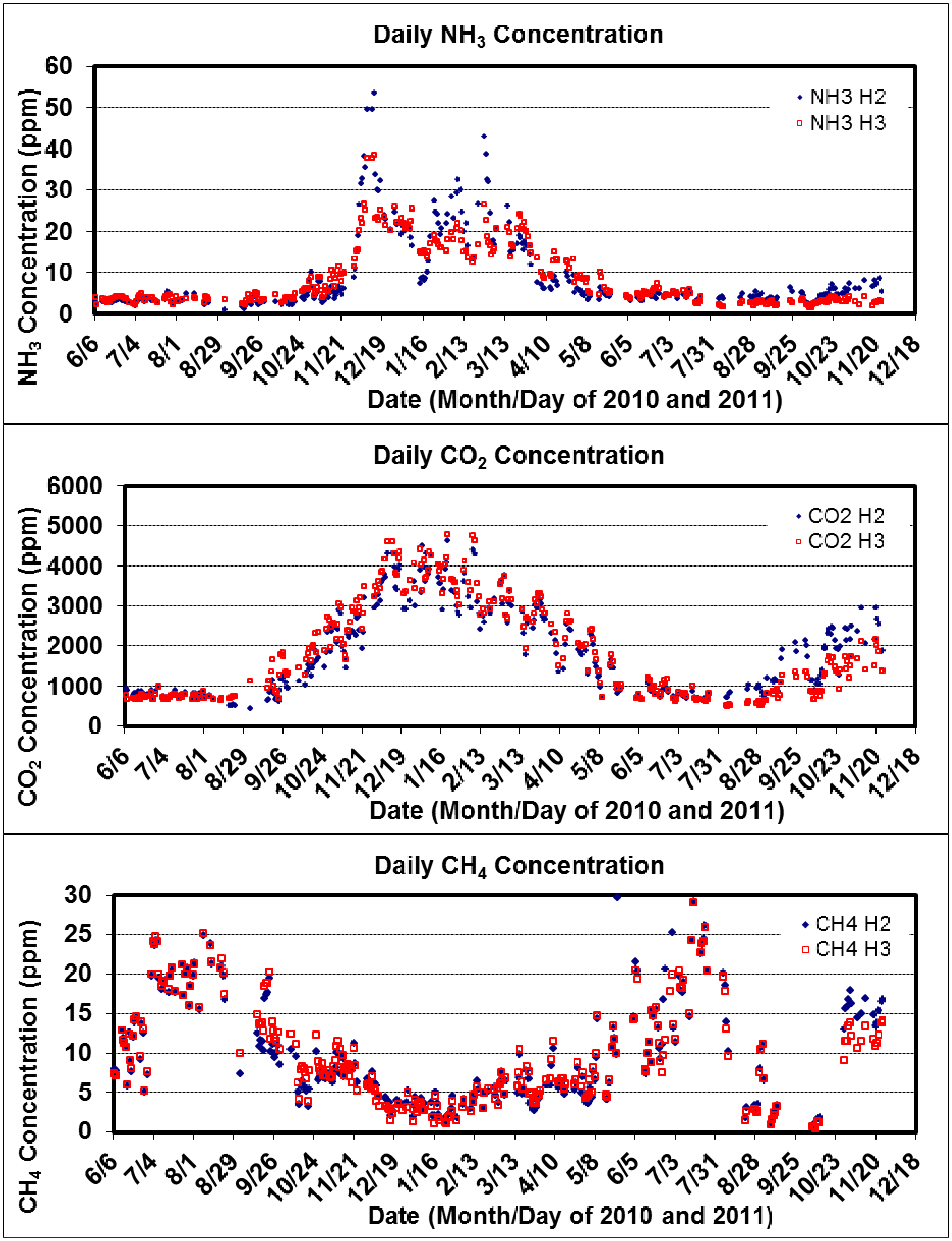

Figure 2.9. Average daily concentrations of ammonia (NH_3), carbon dioxide (CO_2), and methane (CH_4) in the two aviary hen houses monitored.

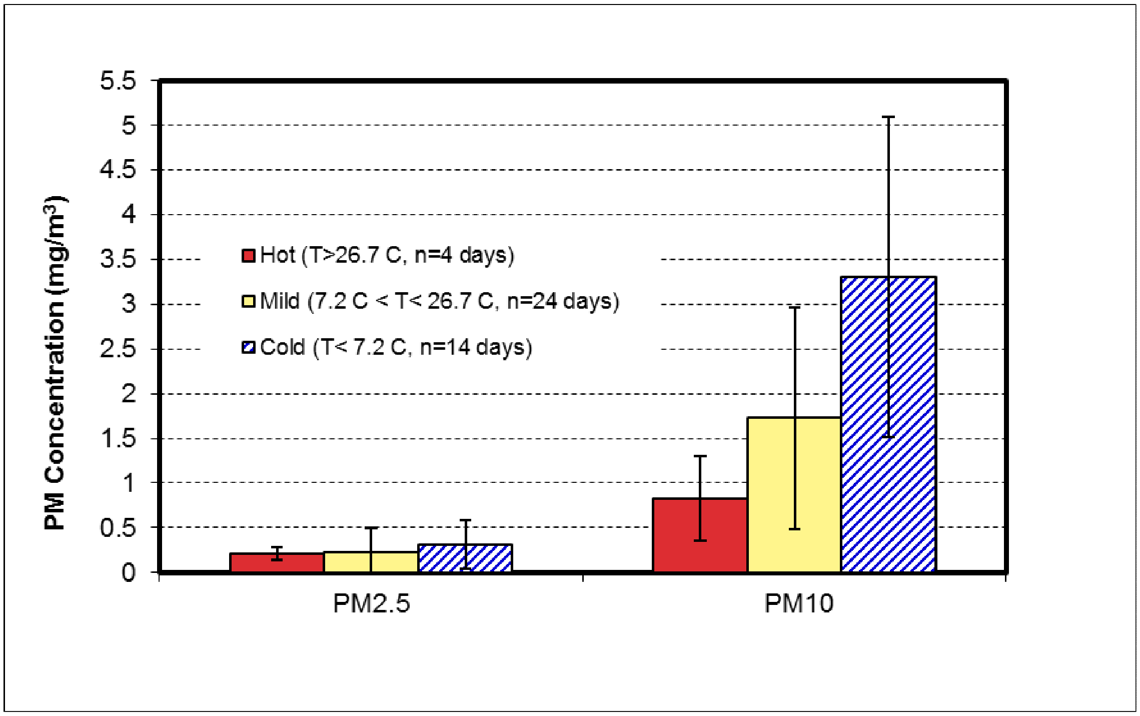

Figure 2.10. Daily particulate matter (PM) concentrations (mean and standard deviation) classified by ambient temperature with hot condition for temperatures higher than 26.7℃ (80℉), mild condition for temperatures of 7.2-26.7 ℃ (45-80℉), and cold condition for temperatures below 7.2℃ (45℉).

Table 2.2. Average daily concentrations [mean (SD)] for the two aviary houses (2 and 3) and overall. The average weight of hens was 1.76 and 1.78 kg in houses 2 and 3, respectively. The average population was 48,250 and 47,600 hens for houses 2 and 3, respectively.

House	Gas, ppm			PM, mg/m^3	
	Ammonia	Carbon Dioxide	Methane	PM_{10}	$PM_{2.5}$
2	9.0 (9.4)	1,853 (1,082)	10.1 (6.9)	2.1 (1.4)	0.24 (0.24)
3	8.5 (7.4)	1,418 (956)	9.9 (6.7)	2.5 (1.9)	0.27 (0.28)
Overall	8.7 (8.4)	1,636 (1,022)	10.0 (6.8)	2.3 (1.6)	0.25 (0.26)

Gas and Particulate Matter (PM) Emissions

The gas and PM emissions were calculated from equations 1 and 2 and reported as emissions per house, per bird, per animal unit (AU, AU=500 kg live body mass), and per kg egg produced. Reported values are summarized as average daily emission rates and annual emissions. Ammonia, carbon dioxide, nitrous oxide, and methane emissions are presented on a gram per bird basis (fig. 2.11). The particulate matter emissions are graphed based on three average daily ambient temperature ranges: hot condition includes days with ambient temperatures greater than 26.7℃ (8 0℉), mild conditions (ambient temperature of 7.2-26.7℃ or 45-80℉), and cold condi tions (ambient temperature below 7.2℃ or 45℉) (fig.2.12).

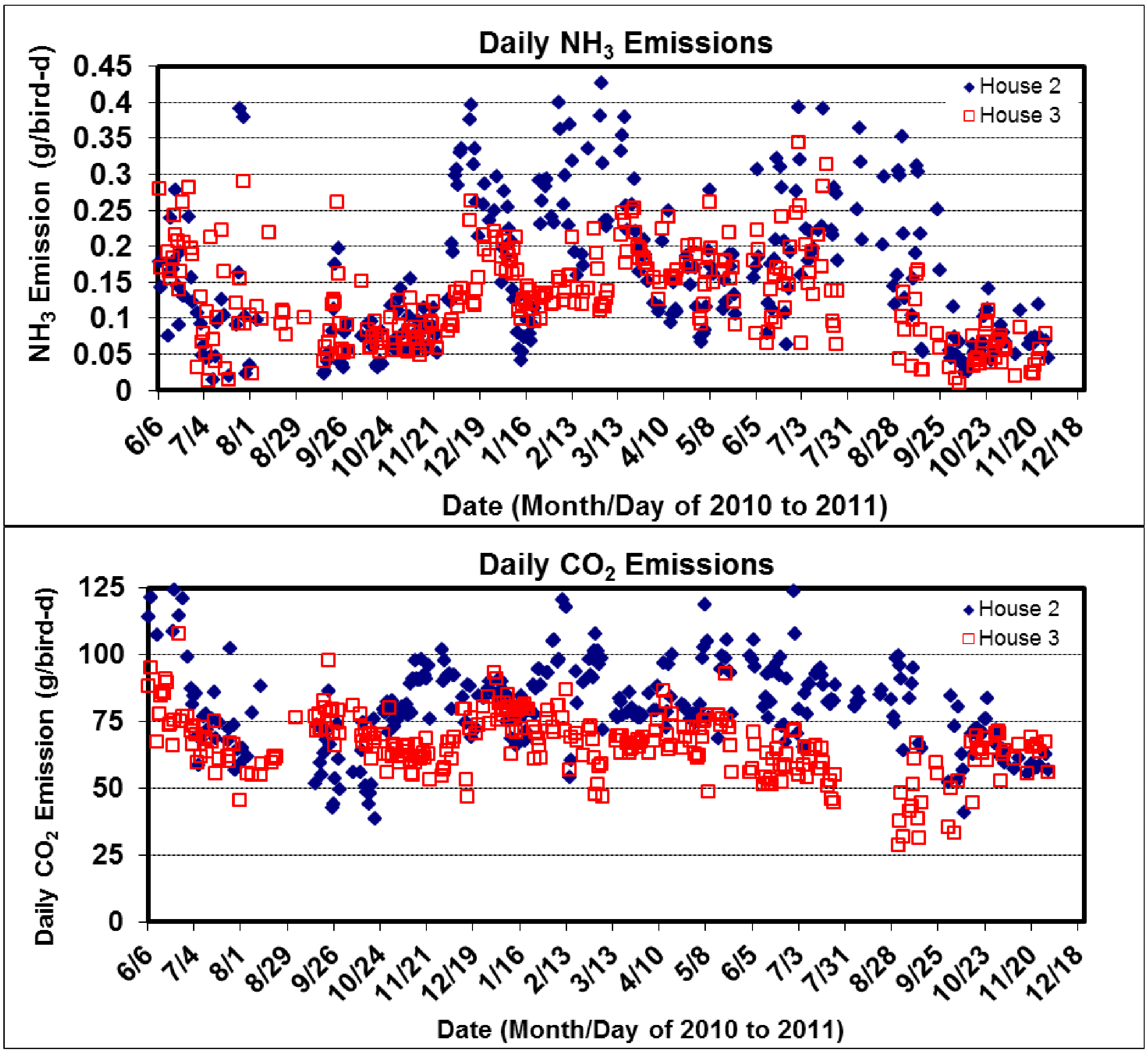

Figure 2.11. Daily emission rates of ammonia (NH_3), carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) for the two aviary hen houses monitored.

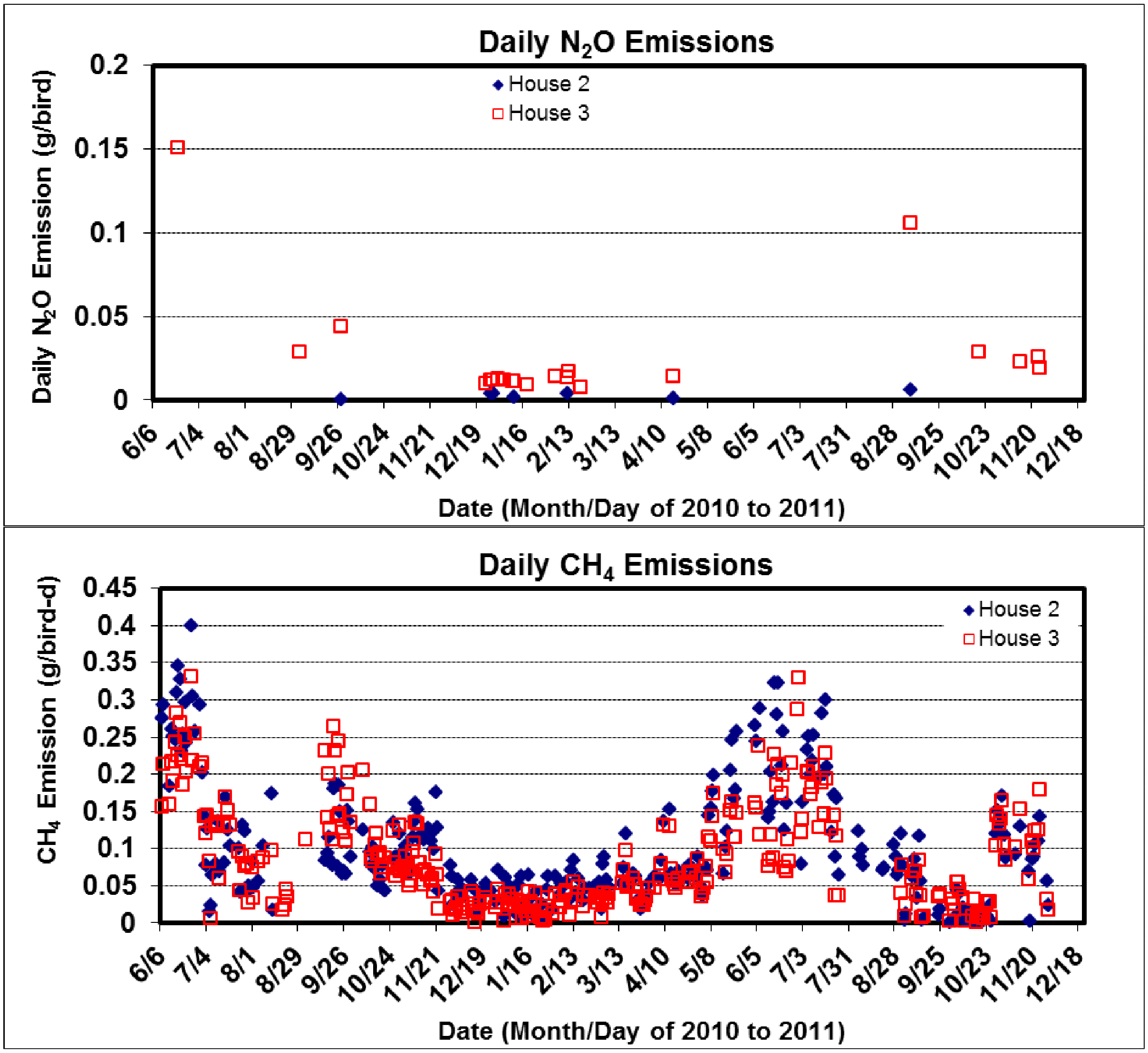

Figure 2.11 (cont). Daily emission rates of ammonia (NH_3), carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) for the two aviary hen houses monitored.

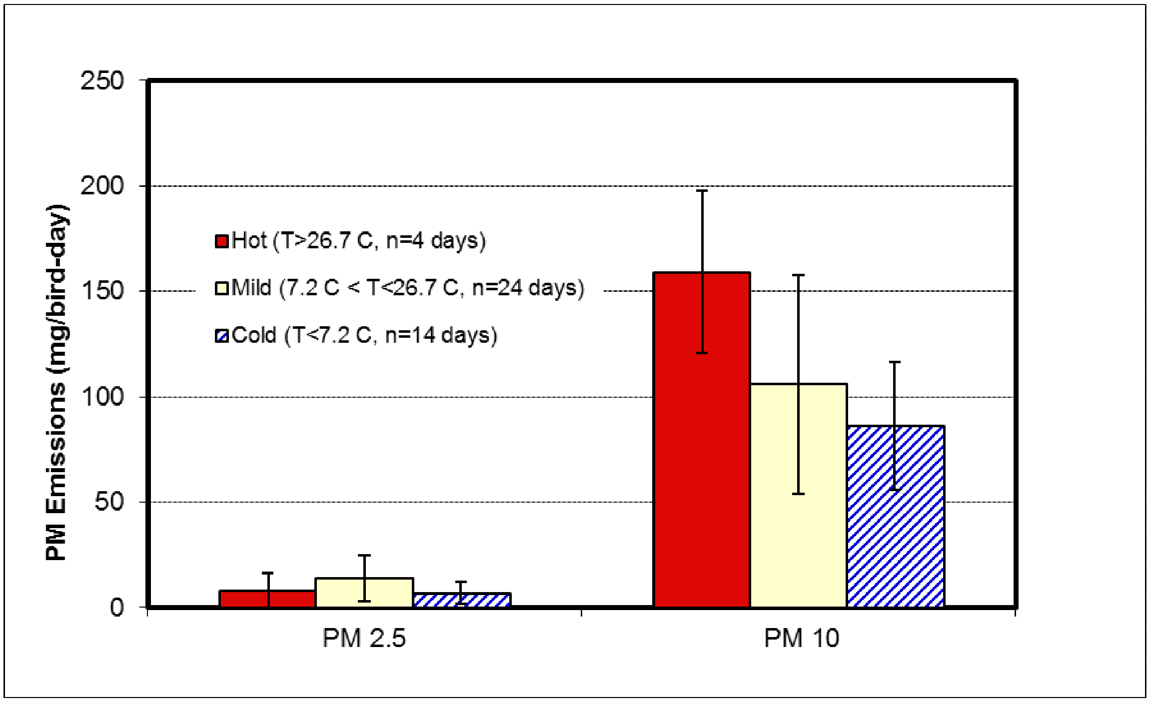

Figure 2.12. Daily particulate matter emissions (mean and standard deviation) classified by ambient temperature, with hot condition including temperatures greater than 26.7℃ (80℉), mild including the range from 7.2-26.7℉ (45-80℉) , and cold including temperature below 7.2℃ (45℉).

Similar to concentrations, there is an influence of ambient temperature on gaseous emissions of CH_4. Both NH_3 and CO_2 showed no trends of change with ambient temperatures. Methane, however, did show an increasing daily emission rate with increasing ambient temperature.

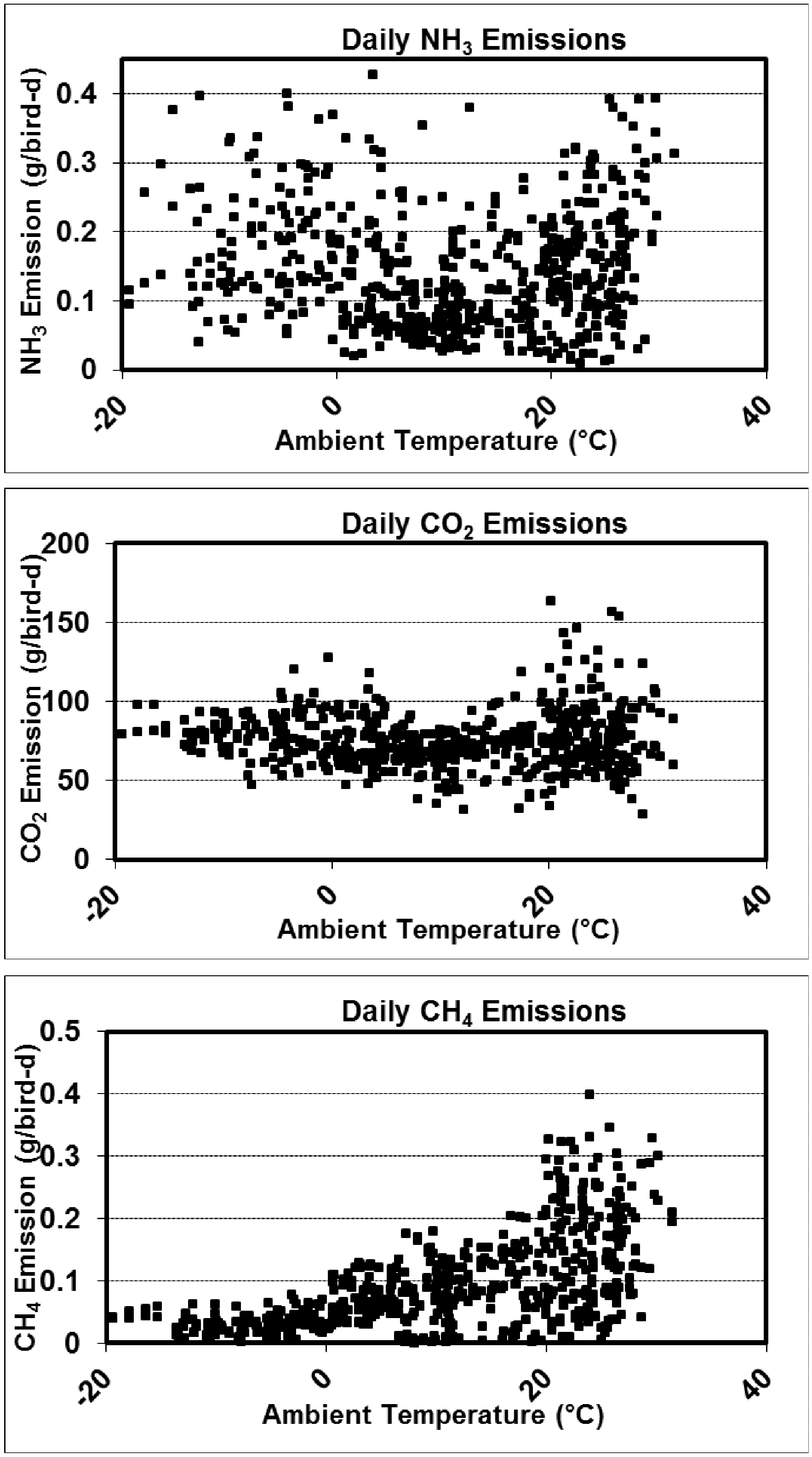

Figure 2.13. Daily emission rates of ammonia (NH_3), carbon dioxide (CO_2), and methane (CH_4) for both aviary hen houses monitored plotted against ambient temperature.

Summaries of the average daily emission rates and annual emissions are reported in Tables 2.3 and 2.4, respectively. The gaseous emissions for this study were slightly higher in house 2 than in house 3, while PM emissions followed the opposite trend, i.e., higher in house 3 than in house 2. The higher gaseous emission rates and lower PM emission rates might be due to the higher moisture content of the litter in house 2 compared to house 3.

Table 2.3. Daily emission rates [mean (std dev)] for the aviary hen houses (2 and 3) and overall values. The average body weight of the hens was 1.76 and 1.78 kg in houses 2 and 3, respectively, and the average population was 48,250 and 47,600 hens, respectively.

		Gases and Particulate Matter				
House	Unit	Ammonia	Carbon Dioxide	Methane	PM_{10}	$PM_{2.5}$
2	kg/house-d	7.9 (5.3)	3,776 (1,127)	5.4 (10.6)	3.9 (1.9)	0.24 (0.19)
	g/bird-d	0.16 (0.1)	83 (19)	0.10 (0.08)	0.08 (0.04)	0.005 (0.004)
	g/AU-d	45 (28)	23,580 (5,398)	28 (23)	23 (11)	1.4 (1.1)
	g/kg egg	3.4 (2.2)	1,738 (637)	2.5 (5.1)	1.8 (0.9)	0.10 (0.09)
3	kg/house-d	6.2 (4.2)	3,065 (943)	4.1 (3.4)	6.2 (1.9)	0.48 (0.38)
	g/bird-d	0.13 (0.06)	67 (11)	0.08 (0.07)	0.13 (0.04)	0.011 (0.008)
	g/AU-d	37 (17)	19,034 (3,125)	23 (20)	37 (11)	2.8 (2.2)
	g/kg egg	3.1 (2.0)	1,513 (599)	2.0 (1.7)	3.1 (0.9)	0.21 (0.16)
Overall	kg/house-d	7.1 (4.8)	3,421 (1035)	4.8 (7.0)	5.1 (1.9)	0.36 (0.29)
	g/bird-d	0.15 (0.08)	75 (15)	0.09 (0.08)	0.11 (0.04)	0.008 (0.006)
	g/AU-d	41 (23)	21,307 (4,262)	25 (21)	29.5 (11)	2.1 (1.7)
	g/kg egg	3.3 (2.1)	1,626 (618)	2.3 (3.4)	2.5 (0.9)	0.16 (0.13)

Table 2.4 Annual emissions of Hy-Line brown laying hens in aviary houses. The average body weight of the hens was 1.76 and 1.78 kg in houses 2 and 3, respectively; and the average population was 48,250 and 47,600 hens for houses 2 and 3, respectively.

		Gases and Particulate Matter				
House	Unit	Ammonia	Carbon Dioxide	Methane	PM_{10}	$PM_{2.5}$
2	kg/house-yr	2,831	1,450,750	1,307	1,425	88
	g/bird-yr	58	30,295	27	31	2
	kg/AU-yr	16	8,606	8	9	0.6
3	kg/house-yr	2,464	1,250,163	1,130	2,262	175
	g/bird-yr	52	26,436	24	46	4
	kg/AU-yr	15	7,426	7	13	1.1
Overall	kg/house-yr	2,647	1,350,456	1,219	1,844	132
	g/bird-yr	55	28,366	26	39	3
	kg/AU-yr	15	8,016	7.5	11	0.85

Overall, the results on gaseous emissions observed from this study were within expectations. European studies suggest aviary ammonia concentrations are higher than belt houses (Hörnig et al., 2001). Liang et al. (2003) reported manure-belt hen house in the Midwestern US had NH_3 concentrations ranging from 1 to 7 ppm, while high-rise houses had concentrations ranging from 9 to108 ppm at the exhaust (note: the bird-level NH_3 concentrations were substantially lower). With average NH_3 concentrations of 9 ppm, the aviary houses tended to have somewhat higher NH_3 concentrations than manure-belt houses, which agreed with European findings. With some of the high winter concentrations, it is important to remember to use face masks with ammonia filters. The study by Liang et al. (2003) also showed NH_3 emission rates of 0.05 to 0.1 g/bird-day (depending on the manure removal interval) for belt houses and 0.95 g/bird-day for high-rise houses. Ammonia emissions for the aviary houses averaged 0.15 g/bird-day, which is higher than the belt system but significantly lower than the high-rise system. Two European studies demonstrated the range in NH_3 emission rates for cage-free barns as 0.27 to 0.85 g/bird-day (Groot Koerkamp et al, 1998; Muller et al., 2003). The emissions observed from this study were quite a bit lower. Many of the cage-free barns in Europe do not have a method of locking birds in the tiered structure, which may affect litter amount and quality. For CO_2 the average emission rate of 75 g/bird-day is in line with reported values from belt systems (70 to 85 g/bird-day) (Liang et al., 2003; Neser et al., 1997). For CH_4 literature suggests a belt system emitting between 0.08 and 0.13 g/bird-day (Groot Koerkamp et al., 1997; Monteny et al., 2001; Fabbri et al, 2007; Wathes et al., 1997). The value of 0.09 g/bird-day from the current study did fall inside this range. Overall this aviary system has emission rates that relate well to a traditional belt 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. Literature on conventional laying-hen housing reports $PM_{2.5}$ emissions of 0.0036 to 0.014 g/bird-day (Li et al., 2011), while the current study with aviary housing averages 0.008 g/bird-day. For PM_{10} the reported literature emission values range from 0.019 to 0.048 g/bird-day (Li et al., 2011), while this study averages 0.105 g/bird-day. The emissions from our study were higher than those reported in literature; however this system did have a litter floor area. A European study reports on a group of cage-free barns having a PM_{10} emission rate of 0.05 g/bird-day, however the most extreme site in the study has an emission rate of 0.07 g/bird-day (Takai et al., 1998). While the average in the European study was above the range of conventional housing emissions, it is 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 US. Management of the litter (e.g., moisture content) and environmental conditions (house RH and ventilation) presumably contributed to the difference in the PM_{10} emissions.

As was mentioned above, house 2 tended to have higher gaseous emissions, while PM emissions followed the opposite trend, i.e., higher in house 3 than house 2. The setpoint temperature in house 2 was a few degrees lower than in house 3, which led to somewhat higher VR for house 2. Litter moisture content (MC) was tested and found to be slightly higher in house 2 as compared to house 3.

Overall, this aviary site ran quite well through the winter in terms of indoor air quality. There were a few days with NH_3 concentrations above the recommended 25 ppm level for hen's health. The RH was somewhat high on these days. A slightly higher minimum VR would have improved the situations. Emissions from the site were as expected. However, the dust concentration and emissions were quite high, emphasizing the importance of personal protection (wearing dust masks), and practical means to reduce dust generations in such housing systems should be explored.

Conclusions

Air emissions (NH_3, CO_2, CH_4, PM_{10}, and $PM_{2.5}$) from two aviary hen houses in Iowa were continuously monitored for 19 consecutive months, covering 2 flocks from 17 to 80 weeks of age. The following observations and conclusions were made:

- Daily indoor NH_3, CO_2, CH_4, PM_{10}, and $PM_{2.5}$ 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. NH_3, CO_2, PM_{10}, and $PM_{2.5}$ concentrations were highest at coldest ambient conditions, although CH_4 increased with ambient temperatures.
- Daily NH_3, CO_2, CH_4, PM_{10}, and $PM_{2.5}$ 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, respectively. NH_3 and CO_2 emissions were rather independent of ambient temperatures. CH_4 emissions increased with increasing ambient temperature. PM_{10} and $PM_{2.5}$ generally decreased with increasing ambient temperatures.
- Annual NH_3, CO_2, CH_4, PM_{10}, and $PM_{2.5}$ emissions were 55 g/bird, 28.4 kg/bird, 26 g/bird, 39 g/bird, and 3 g/bird, respectively.

Overall this aviary system has emission rates that relate well to a conventional belt house, with the exception of ammonia being slightly higher. The ammonia emissions were lower than those reported for European layer houses, however.

Acknowledgements

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CHAPTER 3

Bioenergetics of Hy-Line Brown Hens in Aviary Houses

A manuscript prepared for submission to Transactions of the ASABE

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Abstract

In considering hen-housing systems, applicable heat and moisture production values are essential to producing properly designed and managed ventilation and supplemental heating systems. The aviary system is one housing type under consideration by egg producers. The aviary system has a much lower bird stocking density and more freedom of movement compared to conventional cage housing. This study was conducted to obtain baseline heat and moisture production values for Hy-Line Brown hens in such barns in the Midwestern US. The study continually monitored the house-level thermal environment, air quality, and bird production performance of two commercially operated 50,000-hen aviary houses over a 19-month period. The two houses used similar management strategies and Hy-Line Brown hens with a 20-week difference in age. Data were collected for a complete flock (17-83 weeks, no molt) in each house. Total heat production (THP) of the hens, house-level moisture production (MP), house-level sensible heat production (SHP), and respiratory quotient (RQ) were determined from monitored variables using indirect calorimetry and mass/energy balance, respectively. Variations in THP, MP, SHP and RQ within the day were delineated. Results of the study showed the THP, house-level MP, house-level SHP and RQ values of 5.94 W/kg, 1.83 W/kg, 4.11 W/kg, and 0.94 for the aviary housing system. The new data are expected to improve the design and operation of building ventilation and supplemental heating system, and ultimately production efficiency of the aviary housing systems. The THP and RQ data will also prove useful to indirect determination of building ventilation rate using CO_2 balance method.

Keywords: Aviary, Bioenergetics, Indirect Calorimertry, Environmental Control, Laying Hen

Introduction

In the past decade there has been increased pressure to move from conventional cage laying-hen houses to non-cage and/or enriched cage housing systems. However, limited information is available on the management, performance, and production from these alternative systems, particularly as they are operated in the U.S. This study was conducted in aviary barns (a form of non-cage housing system) with the Natura 60 design (Big Dutchman, Holland, MI, USA).

Traditionally measurement of heat and moisture production rates is done in environmental or calorimeter chambers with single animals or small groups of animals. Indirect animal calorimetry is the method used to quantify energy production by measuring respiratory gas consumption and production. For monogastric animals, quantification of total heat production rate (THP) or metabolic rate generally requires the knowledge of carbon dioxide (CO_2) production and oxygen (O_2) consumption of the animals. Knowing the concentrations of air entering and leaving the enclosure and the ventilation rate through the enclosure, one can calculate the gas consumption/production rates. The ratio of CO_2 production and O_2 consumption is referred to as respiratory quotient (RQ) which is indicative of the metabolic activities within the animal. The use of environmental or calorimeter chambers generally allows for better environmental control and more precise measurement. An inherent limitation with the chamber measurement is the representation of the production conditions which affect the partitioning of THP into sensible and latent modes. To represent non-cage housing systems, adequate space is needed in the chambers, which poses challenges. Heat and moisture production of animals and their housing systems are affected by genetics, dietary nutrition, animal age or production stage, activity level, thermal environment, and manure management practices (Chepete and Xin, 2001). As we look to assign heat and moisture production values to alternative systems like the aviary system, both the activity level of the bird and the genetics could be different from conventional housing (Green and Xin, 2009a,b).

Very few studies have been done to measure heat and moisture production under commercial poultry production conditions. There have been a few done on broiler houses

(Deaton et al., 1969; Gates et al., 1996; Pedersen and Thomsen, 2000; Xin et al. 2001). As well, a few studies were done on layers, pullets and broiler breeders (Feddes et al., 1985; O'Connor et al., 1987; Zulovich et al., 1987). All of these studies were direct calorimetry studies (where wet-bulb and dry-bulb temperatures were taken and sensible and latent heat production rates were calculated). In such direct calorimeter studies other heat sources (e.g., space heaters, motors, lights) are difficult to quantify and be excluded from the calculation. In order to capture heat and moisture production data under commercial production conditions of aviary housing systems, it is necessary to perform whole-house measurements. The review of literature showed one study that looked at heat and moisture production in aviary laying-hen systems, which found heat production being 22% higher than CIGR guidelines (Wachenfelt et al., 2001). The study used direct calorimetry methods in rooms with 685 Lohmann hens.

The objectives of this study were to quantify whole-house total and latent heat production rates. These numbers were to be compared to current literature and broken down into light and dark period to evaluate the impact of bird activity on heat production rates. Indirect calorimetry was used for quantifying THP of the hens, while mass balance was used to quantify house-level moisture production (MP), and finally the difference between THP and house-level latent heat production (LHP, derived from MP) was used to determine the house-level sensible heat production (SHP). These data will be useful in more efficient design and operation of the ventilation system.

Materials and Methods

Site Description

The study was conducted in 2 barns at one site in Iowa over 19 months in an effort to capture flocks from placement to the end of production. Each house measured 167.6 m x 19.8 m with a capacity of 50,000 hens (Hy-Line Brown) and a production cycle of 17 to about 80 weeks of age (new flock started the fourth week of April 2010 in barn 3 and the second week of September 2010 in barn 2). A cross-sectional schematic of the houses is shown in figure 3.1. Each house was divided into ten 14.5 m (48 ft) sections along the length direction. The houses had open litter floor (2.5 m x 14.5 m per section for the center aisles and 1.2 m x 14.5 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 belt with a manure-drying air duct was placed underneath the lower two cage tiers. The three tiers were divided into nest, feeding, and drinking area from top to bottom. Each house had 20 exhaust fans, all on one sidewall (fig. 3.2), including twelve 1.2 m, four 0.9 m, and four 0.5 m fans. Ceiling box air inlets were used. Compact fluorescent lighting was used, further details about the site and management practices are described by Hayes et al. (2012).

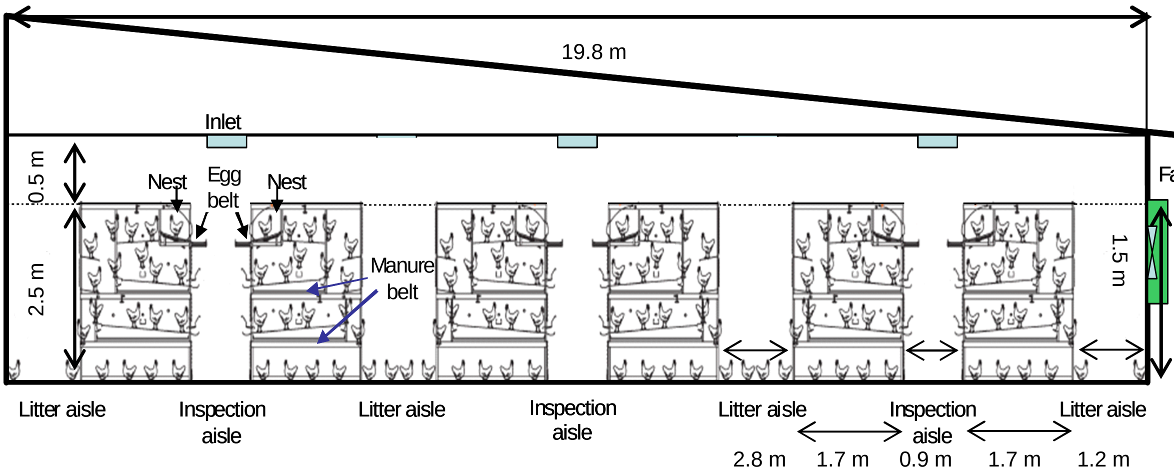

Figure 3.1. Cross-sectional view of the aviary hen house (one side of the double houses) to be monitored in this study. (not drawn to scale)

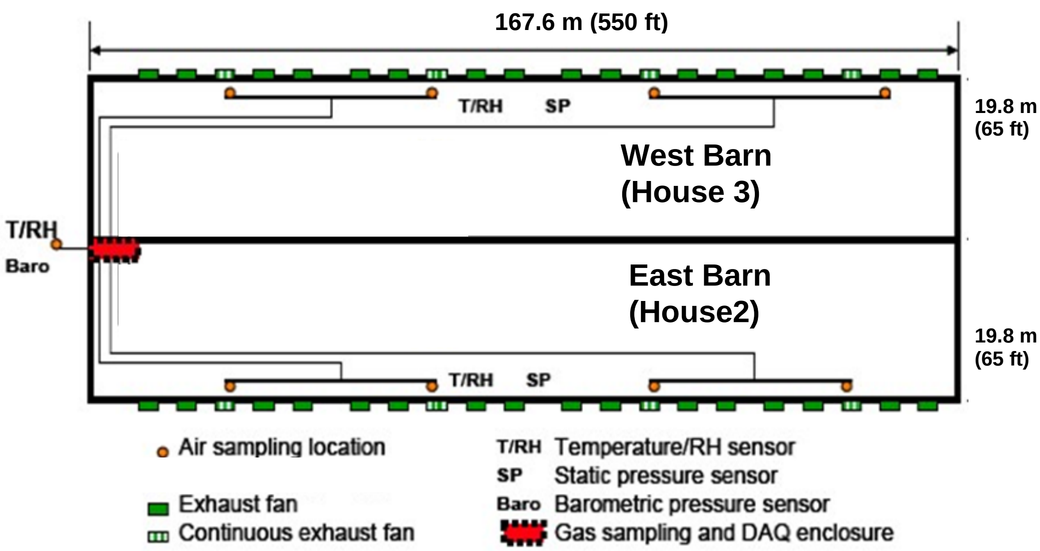

Figure 3.2. Schematic representation of the aviary laying hen houses and air sampling locations. (not drawn to scale)

Measurement System

Concentrations of CO_2 and dew-point temperature at four locations in each house were measured continually with a fast-response and high-precision photoacoustic multi-gas analyzer (model 1412, Innova AirTech Instruments, Denmark). Oxygen concentration was measured with a paramagnetic gas analyzer (755A, Rosemount Analytical, California, USA). Two locations (near two continuous ventilation fans) were combined into one composite sample, hence there were two composite sampling lines per barn (fig. 3.2). FEP Teflon tubing (0.95-cm or 3/8-inch o.d. and 0.635-cm or ¼-inch i.d.) was used for the air sampling lines to avoid ammonia absorption to the sampling lines. Each sampling port was equipped with a dust filter to keep large 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. 3.3). To ensure measurement of the real concentration values, considering the response time of the analyzer, each location were sampled for 6 minutes, with the first 5.5 min for stabilization and the last 0.5 minute readings for measurement. This sequential measurement yielded 30-min data of gaseous concentrations. In addition, every 2 hours the outside air was drawn and analyzed. The less frequent sampling and analysis of the outside air was because its compositions remain much more stable than those of the indoor air. The values for heat and moisture production were calculated every 30 seconds and averaged to determine daily heat and moisture production rates.

Instead of using a mobile air emission monitoring lab (trailer), all sampling lines, data acquisition and instrumentation for this study were kept in enclosures in the south end of the eastern barn (barn 2). The enclosure was supplied with fresh air from the attic to provide a positive pressure system in an effort to minimize entrance of dust from the indoor air.

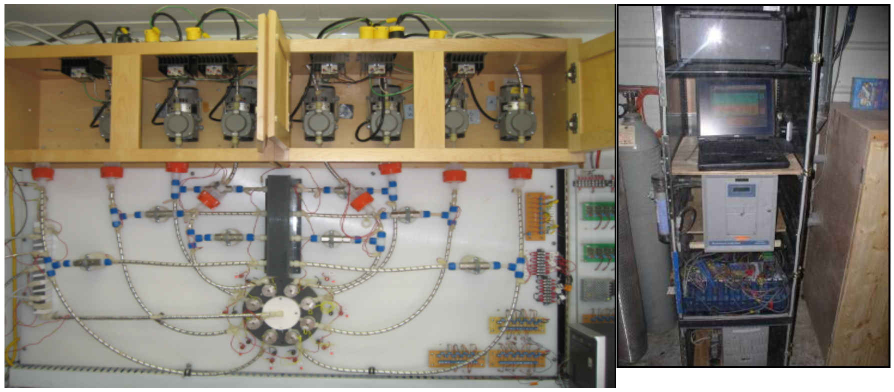

Figure 3.3. Gaseous concentration and dew point temperature monitoring system (*L-R: positive-pressure gas sampling system or P-P GSS, gas analyzers***).**

The building ventilations rate (VR) was determined based on *in situ* calibrated fan curves with fan assessment numeration systems (FANS) sized 0.9 m (36 inch), 1.2 m (48 inch), and 1.4 m (54 inch). Individual fan curves were established for each stage (1-8) including operational ranges of the variable speed control of the lower stages (Gates et al., 2004). The runtime of fans was recorded continuously with inductive current switches (Muhlbauer et al., 2011). Magnetic proximity sensors (MP1007, ZF Electronics, Wisconsin) were used to measure the fan speed (rpm) of the variable speed fans. Fan runtime and speed along with the corresponding building static pressure were recorded every second. Using the calibrated curves for each stage with the above data an overall building VR was calculated. All data were collected in a data acquisition system (DAQ, Compact Fieldpoint, National Instruments, Texas). All samples taken at 1 second intervals were averaged to 30-second values and reported to the on-site PC.

Determination of Total Heat Production (THP), Moisture Production (MP) and Sensible Heat Production (SHP)

THP of the hens was determined using the indirect calorimetry technique. Namely, THP of the birds can be related to their O_2 consumption and CO_2 production, of the following form (Brouwer, 1965):

$$THP = 16.18\ O_2 + 5.02\ (CO_2 - CO_{2manure}) \quad [1]$$

where THP = total heat production rate of the animal, W

O_2 = oxygen consumption rate, mL s^{-1}

CO_2 = total carbon dioxide production rate of the house, mL s^{-1}

$CO_{2manure}$ =carbon dioxide produced from litter & manure belt microbial activity, mL s^{-1}

The O_2 consumption rate and CO_2 production rate were determined from the data of O_2 and CO_2 concentrations for both incoming and exhaust air and the building VR adjusting for changes in temperature, pressure, and moisture content (McLean, 1972):

$$O_2 = (V_o/\alpha)\ ([O_{2a}] - \alpha[O_{2o}])*10^{-6} \qquad [2]$$

$$CO_2 = (V_o/\alpha)\ (\alpha[CO_{2o}] - [CO_{2a}])*10^{-6} \qquad [3]$$

$$RQ = CO_2 / O_2 \qquad [4]$$

where O_2 = oxygen consumption rate, mL s^{-1}

CO_2 = carbon dioxide production rate, mL s^{-1}

$[O_{2o}]$, $[O_{2a}]$ = oxygen concentration at outlet and ambient, respectively, ppm

$[CO_{2o}]$, $[CO_{2a}]$ = carbon dioxide conc. at outlet and ambient, respectively, ppm

V_o = ventilation rate at STPD (20℃, 101.325kPa, dry b asis) measured at outlet

α = $V_o / V_a = (1-([O_{2a}] + [CO_{2a}])*10^{-6}) / (1-([O_{2o}] + [CO_{2o}])*10^{-6})$

The values of manure CO_2 production rate for the belts came from Ning (2008) in a lab study on the effect of manure accumulation time. The belts ran 1/3rd per day in the winter and 1/7th per day in the summer.

$$CO_{2manure} = CO_{2belt} + CO_{2litter} \qquad [5]$$

where CO_{2belt} = Summer (7-day belt cycle) = $0.05* CO_2$;

Winter (3-day belt cycle) = $0.01* CO_2$

$CO_{2litter}$ = $0.03 * CO_2$

For the litter, because the moisture content is lower than that of manure on belts, an empirical value was found. A static flux chamber similar to Gates et al. (1997) and Ferguson et al. (1998) was used to determine CO_2 emission rate from the litter (fig. 3.4). The CO_2 concentration was measured with the CO2 probe (Vaisala, GMK 220, MN). Readings were taken every 5 seconds over a 30 minute period. The initial linear portion of concentration was used to calculate the time rate change in concentration. The flux calculation is listed as equation 6 (Rolston, 1986).

$$F= (V/A)* dC/dt \qquad [6]$$

where F = flux ($\mu g/m^2$-hr)

V = volume of flux chamber (0.055 m^3)

A = surface area of litter under chamber (0.18 m^2)

dC/dt = time rate change of gas concentration ($\mu g/m^3$-hr)

MP at the house level, including latent heat of the birds and moisture evaporation from the manure or spilled water, was calculated by the following mass-balance equation:

$$MP= \rho Q (W_o - W_a) \qquad [7]$$

where MP = moisture production rate, kg s^{-1}

W_o, W_a = humidity ratio of outlet and ambient air, respectively, g g^{-1}

Q = building ventilation rate, $m^3 s^{-1}$

ρ = air density, g m^{-3}.

SHP at the house level was calculated as the difference between THP of the hens and latent heat production of the barn, of the form:

$$SHP = THP - MP \cdot h_{fg} \cdot 1000 \qquad [8]$$

where h_{fg} = 2427 latent heat of vaporization for water, J/g

1000 = conversion of MP from kg s^{-1} to g s^{-1}

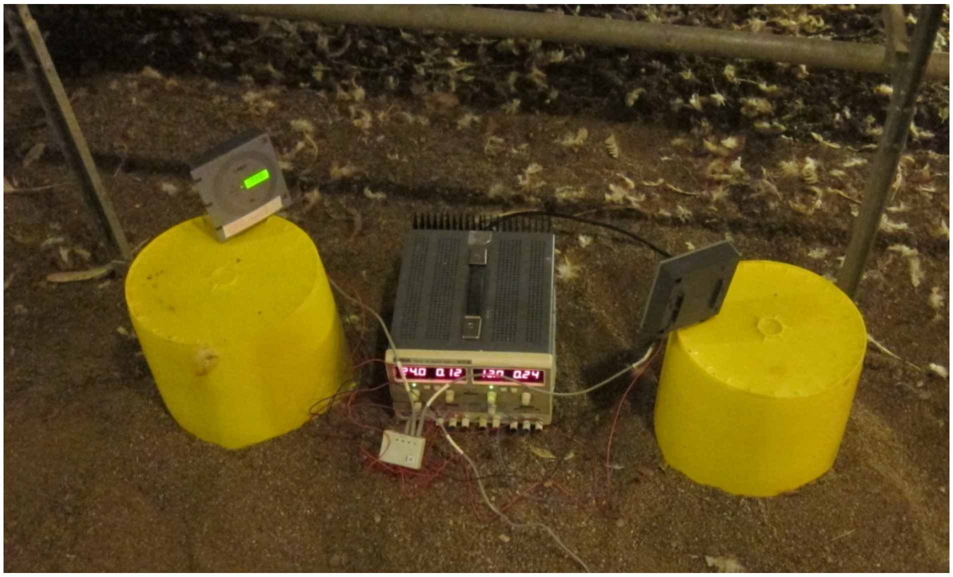

Figure 3.4. Image of the static flux buckets with small internal mixing fan used to measure CO_2 flux from the litter surface. CO_2 probe was on the top of the bucket and measuring approximately 6 cm from the top of the bucket.

Results

Over the 19 months THP and SHP had 58% data completeness due to issues with either the INNOVA or the O_2 analyzer. Because MP determination was not dependent on the oxygen analyzer, it had 68% data completeness. THP showed a diurnal pattern of increasing as lights came on and again when birds were given access to the littered floor area (fig. 3.5). Figures 3.6-3.9 show the average daily RQ, THP, MP, and SHP on a whole house basis. The data are summarized in Table 3.1.

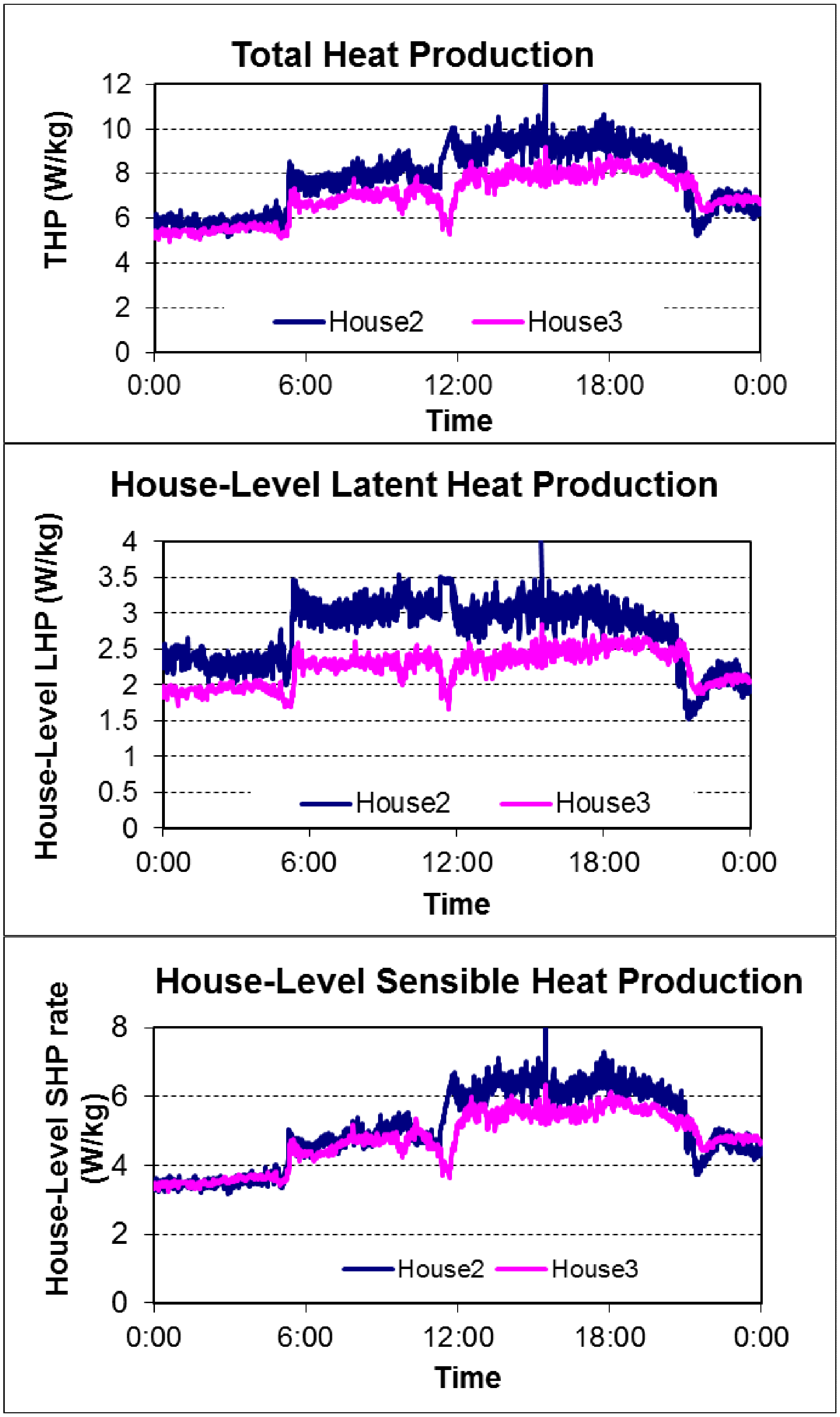

Figure 3.5. Typical winter diurnal total latent and sensible heat production (THP, LHP, SHP) pattern under minimum VR of 0.6m^3/hr-bird. Lights came on at 5:45AM. The birds were given floor access at 11:45AM, light were off at 9:45PM.

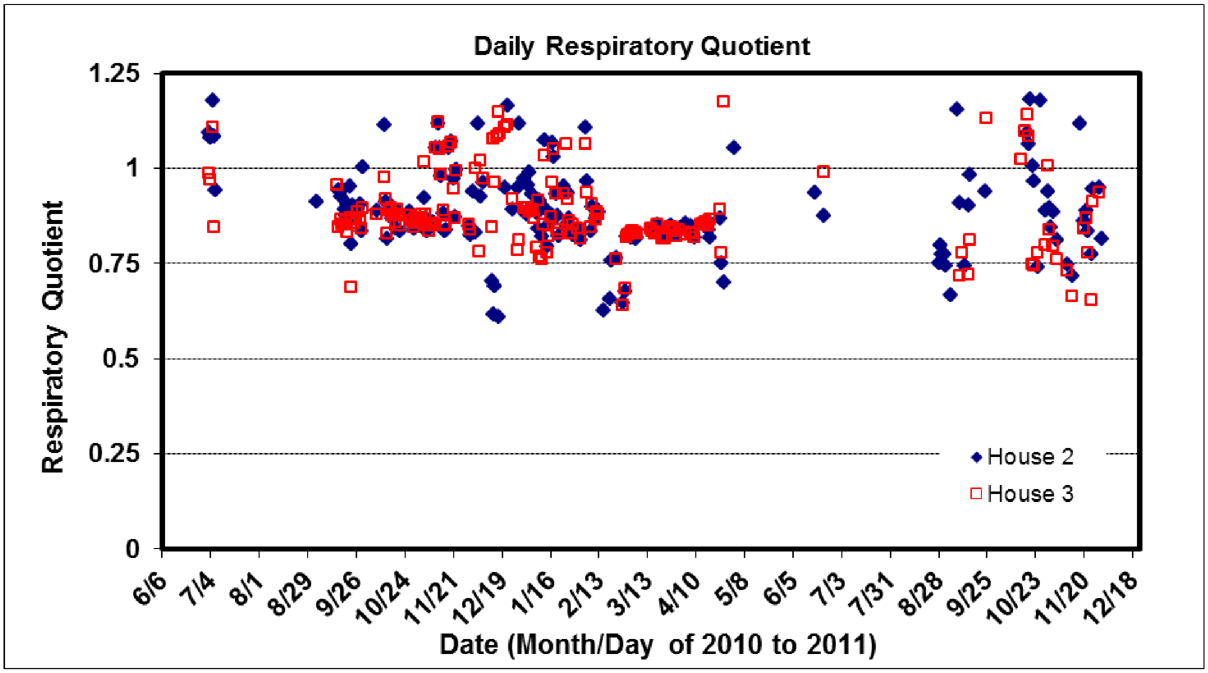

Figure 3.6. Daily mean respiratory quotient (RQ) of Hy-Line brown hens in aviary housing system, averaging 0.94 for House 2 and 0.95 for House 3, overall mean of 0.94. House 3 flock was 24 weeks at the beginning of monitoring, new flocks at 17 weeks of age were placed in houses 2 and 3 the first week of September 2010 and 2011, respectively.

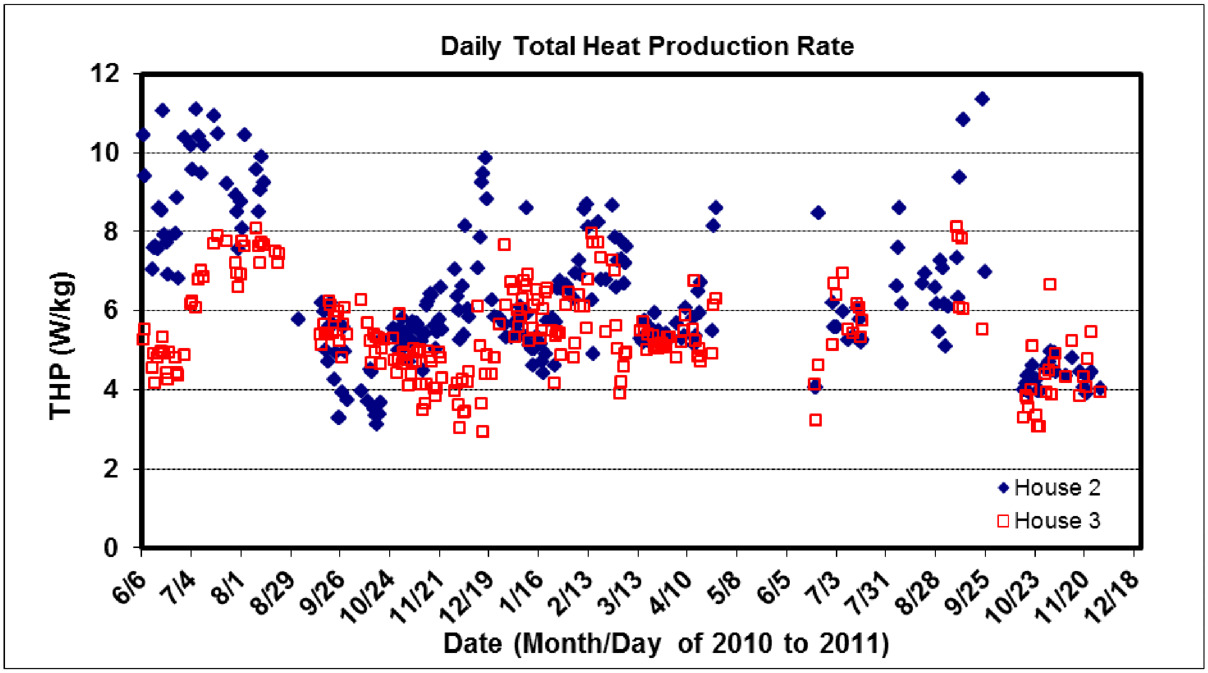

Figure 3.7. Daily mean total heat production rate (THP, W/kg) of Hy-Line brown hens in aviary houses averaging 6.4 W/kg for House 2 and 5.5 W/kg for House 3, overall mean of 5.9 W/kg. House 3 flock was 24 weeks at the beginning of monitoring, new flocks at 17 weeks of age were placed in houses 2 and 3 the first week of September 2010 and 2011, respectively.

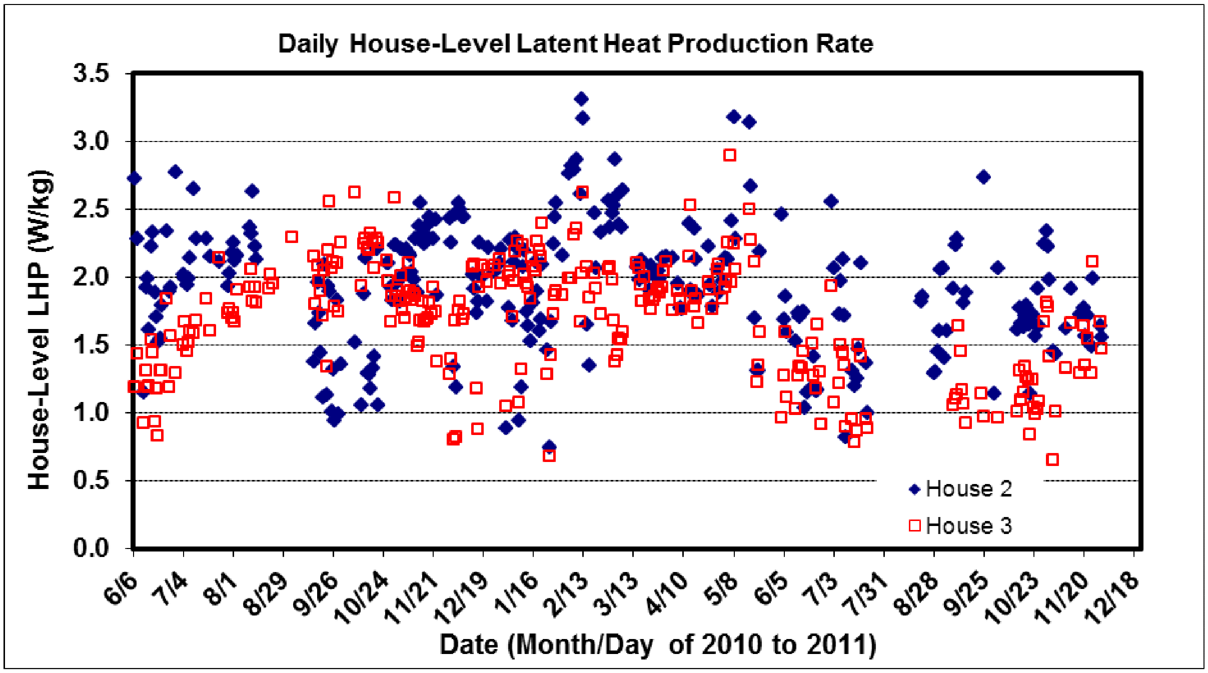

Figure 3.8. Daily mean house-level latent heat production rate (LHP, W/kg) of Hy-Line brown hens in aviary houses, averaging 2.0 W/kg for House 2 and 1.7 W/kg for House 3, overall mean of 1.8 W/kg. House 3 flock was 24 weeks at the beginning of monitoring, new flocks at 17 weeks of age were placed in houses 2 and 3 the first week of September 2010 and 2011, respectively.

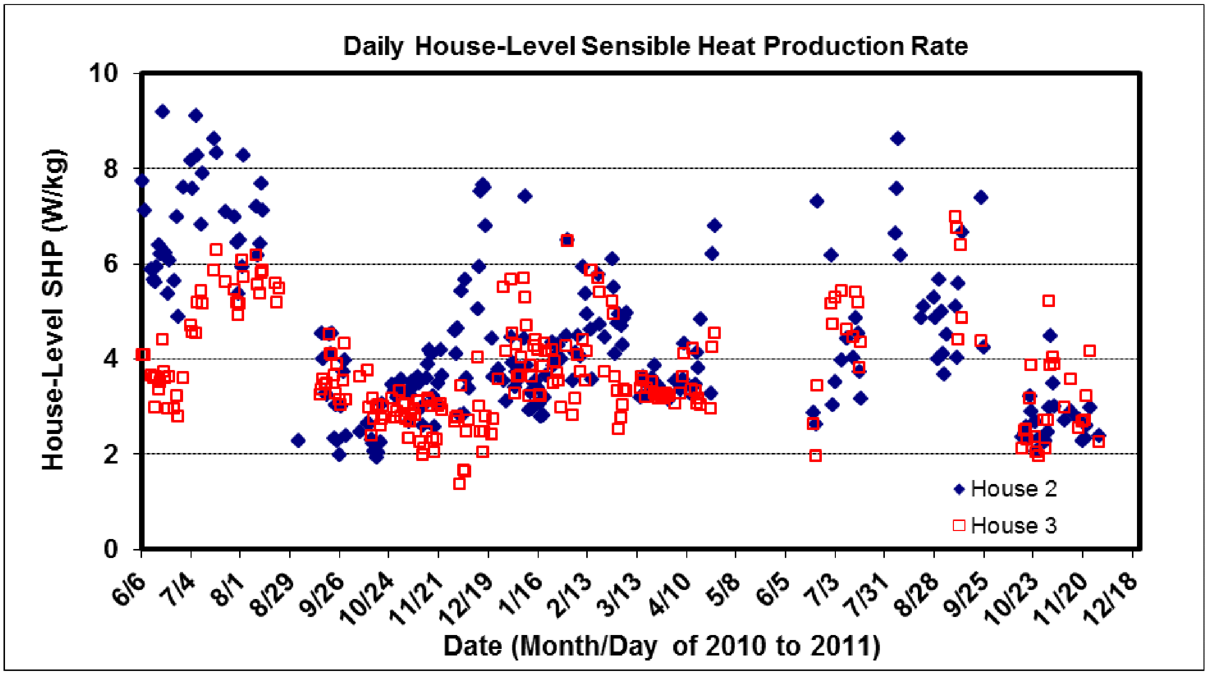

Figure 3.9. Daily house-level sensible heat production rate (SHP, W/kg) of Hy-Line brown hens in aviary houses, averaging 4.5 W/kg for House 2 and 3.8 W/kg for House 3, overall mean of 4.1 W/kg. House 3 flock was 24 weeks at the beginning of monitoring, new flocks at 17 weeks of age were placed in houses 2 and 3 the first week of September 2010 and 2011, respectively.

With this data being run over a complete flock, there are some considerations for the effect of temperature and bird age. None of the heat production rates (THP, LHP, SHP) nor RQ show any trend with in house temperature. There was an expectation for increased latent heat production in the summer period when indoor temperatures surpassed 26 ℃. There were no significant differences based on in-house temperature, which may be due to winter condensation issues (fig 3.10). With regard to bird age, there was one age grouping that was significantly different from other ages with regard to total, latent, and sensible heat production (p=0.01, 0.02, 0.02). Latent heat production had some differences within age groups where 57-64 weeks of age and 73 to end of cycle age categories had lower LHP rates. Neither of these age groups is independent to all other age groups, like the youngest birds however. These trends are displayed in figures 3.11 3.12 and 3.13.

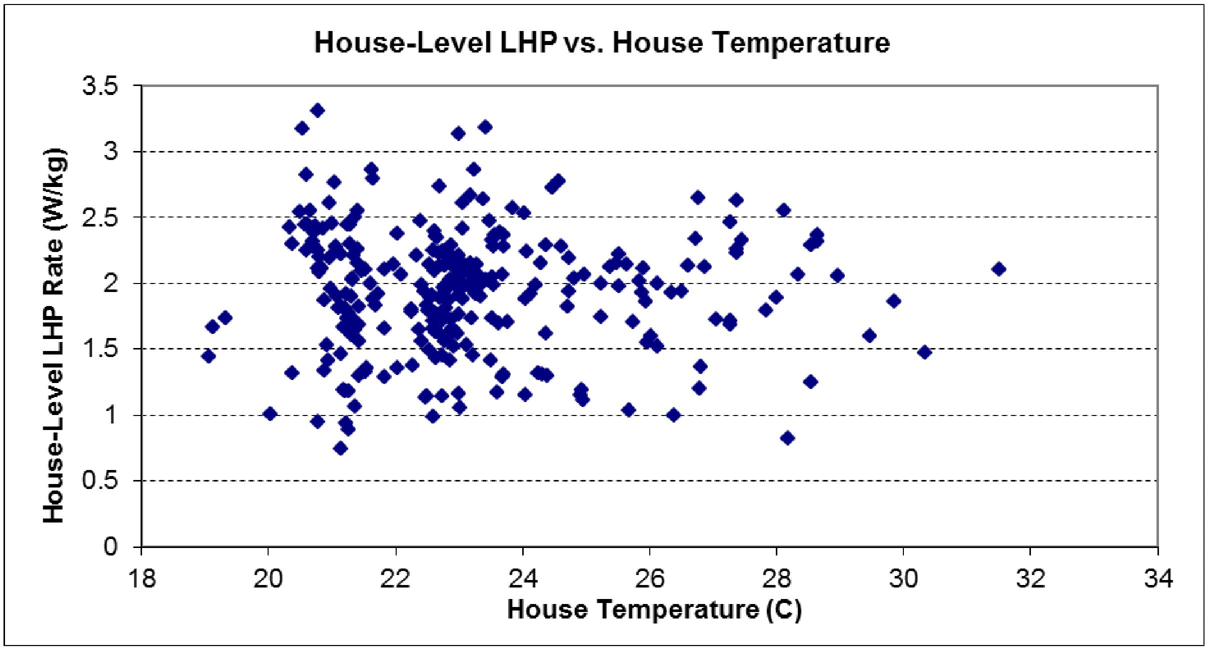

Figure 3.10. Average daily latent heat production (LHP) plotted by in-house temperature. No noticeable increase in LHP as house temperature increases.

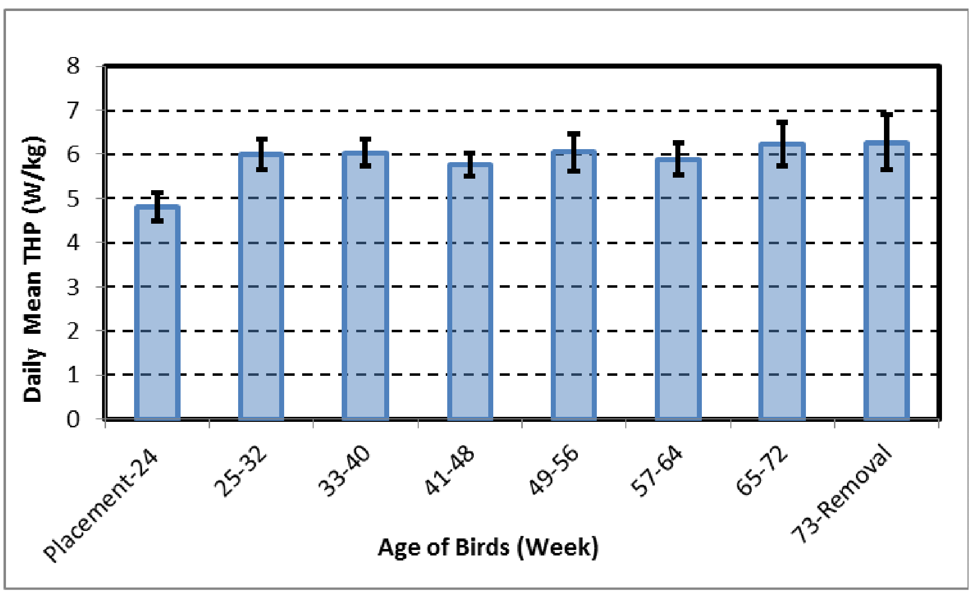

Figure 3.11. Average daily total heat production (THP) broken down by bird age with 95% CI, placement age is between 15 and 17 weeks and removal is between 80 and 83 weeks.

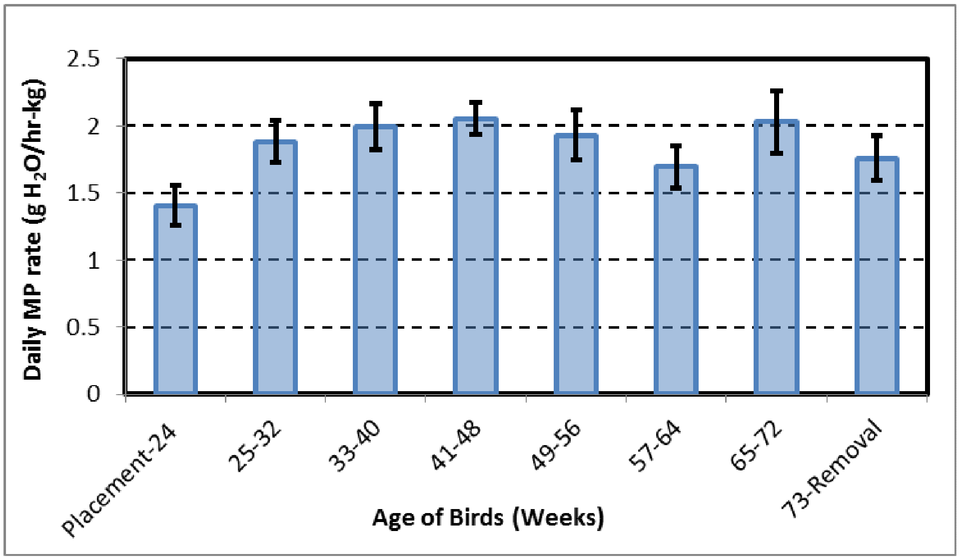

Figure 3.12. Average daily moisture production (MP) broken down by bird age with 95% CI, placement age is between 15 and 17 weeks and removal is between 80 and 83 weeks.

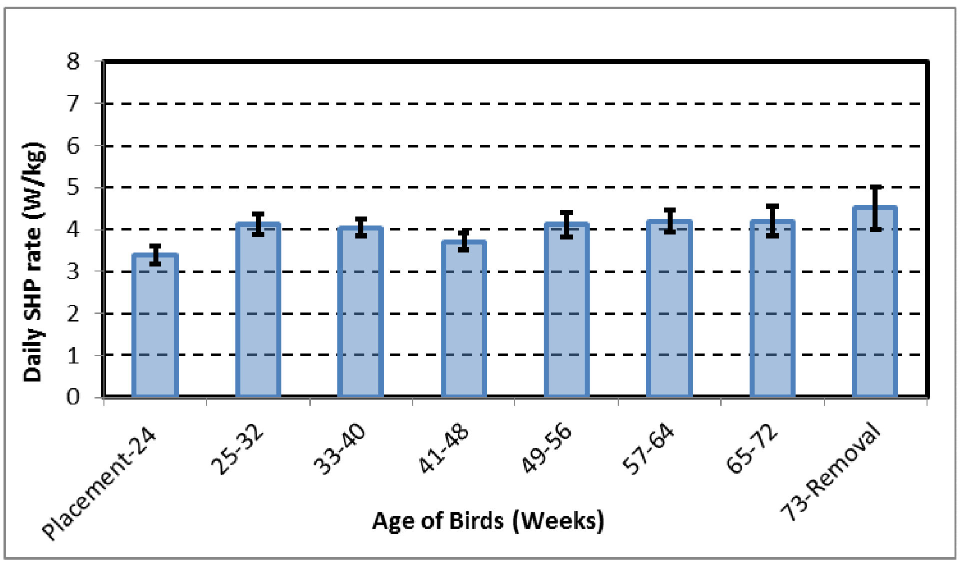

Figure 3.13. Average daily sensible heat production (SHP) broken down by bird age with 95% CI, placement age is between 15 and 17 weeks and removal is between 80 and 83 weeks.

Table 3.1. Average daily total, latent and sensible heat production rates (THP, LHP, SHP) of Hy-Line brown laying hens in aviary houses (mean and std error) for light and dark periods as well as a time weighted average (TWA). The average weight of hens was 1.76 and 1.78 kg in houses 2 and 3 and average population was 48,250 and 47,600 hens for houses 2 and 3, respectively. Note that the LHP and SHP values were for house-level that account for the effect of moisture evaporation from the housing system (e.g., manure and possible spilled water).

		RQ	THP (W/kg)			LHP (W/kg)			SHP (W/kg)		
House		**TWA**	**Light**	**Dark**	**TWA**	**Light**	**Dark**	**TWA**	**Light**	**Dark**	**TWA**
2	Mean	0.89	6.53	4.51	6.27	2.14	1.57	1.97	4.39	2.94	4.35
	SE	*0.007*	*0.11*	*0.14*	*0.11*	*0.05*	*0.04*	*0.03*	*0.09*	*0.11*	*0.11*
3	Mean	0.89	5.80	4.21	5.40	1.86	1.47	1.69	3.94	2.74	3.69
	SE	*0.008*	*0.08*	*0.07*	*0.07*	*0.04*	*0.03*	*0.03*	*0.07*	*0.06*	*0.07*
Overall	Mean	0.89	6.17	4.36	5.94	2.00	1.52	1.83	4.17	2.84	4.11
	SE	*0.008*	*0.10*	*0.11*	*0.09*	*0.04*	*0.03*	*0.03*	*0.08*	*0.08*	*0.08*

Discussion

Overall, the daily average heat and moisture production values (mean ± SE, W/kg) for houses 2 and 3 were, respectively, THP of 6.3 (±0.11) and 5.4(±0.07), LHP of 2.0 (±0.03) and 1.7(±0.03), and SHP of 4.4 (±0.11) and 3.7 (±0.07). These values were pooled averages over a complete flock of the Hy-Line brown hens between 17 and 83 weeks of age. Overall these values matched or were slightly lower than the literature reported values for white birds. In conventional housing THP of white hens (Hy-Line W36) ranges from 6.5 to 6.9 W/kg, LHP ranges from 2.8 to 3.5 W/kg, and SHP ranges from 3.1 to 3.3 W/kg (Chepete et al., 2004; Green and Xin, 2009a). These brown birds were 15 to 20% heavier than those white hens, and specific heat production rate (W/kg) is expected to decrease with increasing body mass (per surface area law). However, on a W/bird basis, the values are in the reported range. The average daily RQ for both houses was 0.89. This RQ is in line with literature values of 0.88 and 0.92 (Xin et al., 1996; Chepete et al., 2004).

The relationship of THP to LHP should be noted. On average LHP accounted for 31% of THP. This value was on the lower end of the reported data where manure moisture losses are accounted for in the room-level MP. Literature values are closer to 40% (Chepete et al., 2004).

The reduction in THP from light to dark has been reported to be 25-26% (Xin et al., 1996), 25% (Xin and Green, 2009a), and 35% (MacLeod and Jewitt, 1984). This study showed approximately 30% THP reduction from light to dark. Since THP is related to physical activities (Boshouwers and Nicaise, 1985), the higher-level activities of the hens in the aviary houses, as compared to hens in conventional cage housing, during the lighted hours would have caused the lighted THP to be greater relative to the dark THP. The fact that this value is on the higher end of reported differences is interesting but within expectation.

Wachenfelt et al. (2001) reported that the heat and moisture production in aviary system was 22% higher than current guidelines provided by CIGR at 20 ℃. The CIGR equations used for this study were from 1985 and may not reflect current genetics. In the Wachenfelt study a large room was used to calculate heat production using direct calorimetry, housing Lohmann hens at greater than 60 weeks of production. A direct comparison was not possible with the current study because there were no values for brown hens housed in conventional cage system.

Conclusions

Total heat production rate (THP) of Hy-Line brown laying hens and house-level latent heat or moisture production (LPH, MP) and sensible heat production rate (SHP) in an aviary housing system (two houses of approximately 50,000 hens per house) were quantified over the entire production cycle (17 – 83 wk) using indirect calorimetry technique. Specific THP values were 6.17, 4.36, and 5.94 W/kg for light periods, dark periods, and daily time-weighted average (TWA), respectively. Specific LHP values were 2.00, 1.52, and 1.83 W/kg for light periods, dark periods, and TWA, respectively. Specific SHP values were 4.17, 2.84, and 4.11W/kg for light periods, dark periods, and TWA, respectively. Finally the TWA RQ was 0.89. These original heat and moisture production data lay a foundation for the design and efficient operation of ventilation, cooling and heating systems for the alternative aviary hen housing.

Acknowledgements

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CHAPTER 4

Electricity and Fuel Usage of Aviary Layer Houses in the Midwestern USA

A manuscript prepared for submission to Applied Engineering in Agriculture

M. Hayes, H. Xin, H. Li, T. Shepherd, and J. P. Stinn

Abstract

Recently, there has been much interest in and movement toward alternative housing systems for laying hens. Associated with the movement are many questions to be addressed concerning sustainability of such systems. This study quantifies electricity and propane usage in two side-by-side aviary houses each holding 50,000 laying hens, located in Iowa. The study also partitions electricity usage into different housing components, including ventilation, lighting, and manure-drying. Electricity for ventilation is most variable in that it was the largest of all the components with almost 60% of the total electric energy in summer but only approximately 5% in winter. The ventilation efficiency was approximately 25.5 m^3/(hr–Watt) (15 CFM per Watt) at static pressure of 12.5 Pa (0.05 inch water column). The continuously operating manure-drying blowers accounted for largest proportion of electricity use in winter with approximately 350kWh daily consumption. Over the 15-month monitoring period, both houses had an average electricity cost of 3.6 cents per kg of egg produced (based on the rate of $0.09/kWh). The fuel usage was minimal (less than 425 liters of propane in one year).

Keywords: Aviary, Energy, Electricity Usage, Propane, Ventilation Efficiency

Introduction

In the past decade there has been increased pressure to move from conventional laying-hen cage houses (both high-rise and manure-belt systems) to cage-free and/or enriched cage housing. With this pressure there are many questions about the performance of these alternative housing systems. One concern in this transition to these houses with much lower stocking densities is what will happen with utility costs including electricity and fuel usage. There is an indication from European Union data that utilities are slightly higher.

It has been reported that the largest electricity usage in egg production comes from mechanical ventilation (Stout, 1984, Flout and Baird, 1980). Most data on electricity usage in the US are from earlier studies which reflect conventional housing with high-rise manure management and incandescent lighting. With differences in housing and management, there are issues relating these values to current energy consumption characteristics. Understanding the efficiency of mechanical components in the houses may affect purchasing consideration, particularly with the major electricity consumers. A summary of data from the European Union make a few notes on energy consumption (Sonesson et al., 2009). The study states that similar to earlier studies ventilation and lighting are a large portion of electricity consumption. To improve energy efficiency the study recommends using energy-efficient lighting, but cautions not to use normal fluorescent lighting due to flickering. The study recommends not drying manure unless it is necessary for transporting/stacking due to energy demands. Moreover, the study notes up to 10% of the energy could be saved by cleaning and following good maintenance of the houses and fans in particular (Sonesson et al., 2009). Based on these comments and recommendations from Europe, the applicability of energy consumption data to US production and management conditions is questionable. Therefore, the objectives of this study were to quantify the electricity and fuel use in two aviary laying-hen barns in the Midwestern US.

Materials and Methods

Site Description

Two aviary hen houses in a double-wide building located in Iowa were used in this field study. Each house measured 168 m x 19.8 m (550 ft x 65 ft) with a capacity of 50,000 hens (Hy-Line Brown) and had a production cycle from approximately 17 to 80 weeks of age (new flock started the fourth week of April 2010 in barn 3 and the second week of September 2010 in barn 2). A cross-sectional schematic of the houses is shown in figure 4.1. The houses had open litter floor, 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 belt with a manure-drying air duct was placed underneath the lower two cage tiers. Further descriptions are included in table 4.1. The three tiers were divided into nest, feeding, and drinking area from top to bottom. Each house had 20 exhaust fans, all on one sidewall, including twelve 1.2 m, four 0.9 m, and four 0.5 m fans. Ceiling box air inlets were used (75 bi-directional 0.6 x 0.6 m). Compact fluorescent lighting was used in the inspection and litter floor aisles. Four 73.25 kW (250,000 BTU/hr) heaters were placed equidistant on the sidewall to provide supplemental heat. The ventilation design for the barns was controlled by management software (Command III, Poultry Management Systems, Inc., Saranec, MI). Based on a selected setpoint temperature, if the house temperature deviated more than 1.1℃ (2℉) from the setpoint, every 2 minutes the controller would turn on or off the next stage of fans. If at minimum ventilation the house temperature was still 2.2℃ (4℉) from setpoint, the h eaters would run.

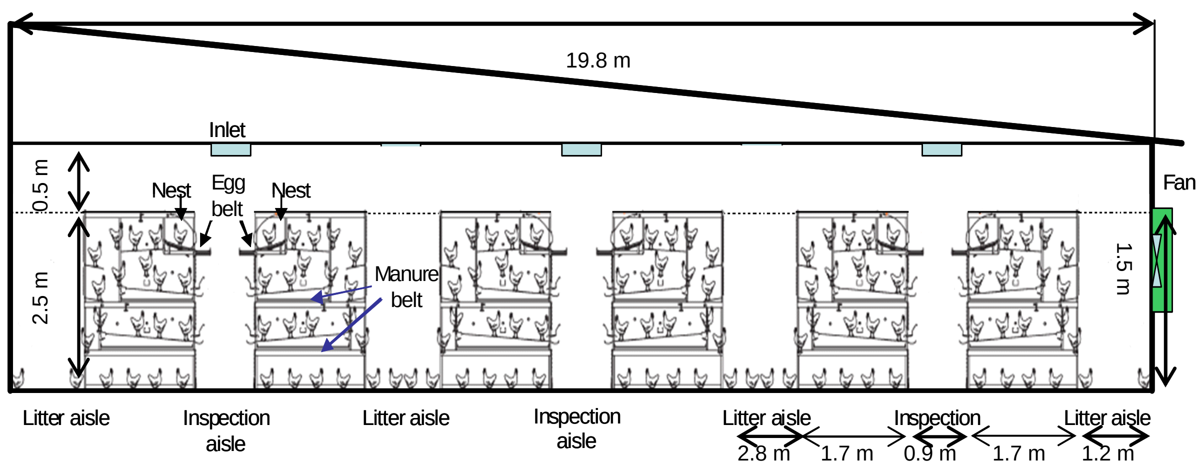

Figure 4.1. Cross-sectional view of the aviary hen house (one side of the double houses) to be monitored in this study.

Table 4.1. Descriptions and motor sizes for some of the major mechanical systems in the aviary laying hen houses.

Ventilation				
	# Fans	Fan Size	Motor Size	On if > setpoint by, °C
Stage 1	4	0.5 m	250 W	continuous
Stage 2	4	0.9m	375 W	1.1
Stage 3	2	1.2m	750W	1.1
Stage 4	2	1.2m	750 W	1.1
Stage 5	2	1.2m	750W	1.1
Stage 6	2	1.2m	750 W	1.1
Stage 7	2	1.2m	750W	1.1
Stage 8	2	1.2m	750 W	1.1
Heater				
	# Heaters		Capacity	On if < setpoint by, °C
	4		73.25 kW	2.2
Manure Drying Blower				
	# Blowers		Motor Size	
	3		5.6 kW	
Lighting				
	# Lights	Bulb Type	Nominal Size	
Inspection Aisle	315	CFL	9W	dimmable
Litter Aisle	180	CFL	15W	dimmable
Worker Area	16	Incandescent	75W	
Timing				
Feeding	5:45 AM	11:15 AM	3:30 PM	7:15 PM
Lights On/Off	Lights On	5:30 AM	Light Off	9:45 PM
Floor On/Off	On Floor	11:30 AM	Off Floor	9:30 PM
Daily Manure Belt Movement	1/3 belt (winter)	15 min	1/7 belt (summer)	7 min
Spacing Allowance (50,000 hens)				
Wire Floor	1096	cm^2/bird		
Litter Floor	613	cm^2/bird		
Nest Space	9.3	cm^2/bird		
Perch	15.9	cm/bird		
Feed Trough	10.6	cm/bird		
Nipple Drinker	8.55	bird/nipple		

Electricity Use Monitoring

This site had two 240V 3-phase delta supplies into each house. As well there was one 240V supply between the houses and manure storage used to run all manure belts. In this study, continuous monitoring was run on the supplies for the house, but not the manure belt supply. Of the two supplies to the house the first source went into one panel, while the second source was split into two remaining panels. The first panel included lower ventilation stages, two of the manure belt blowers, and some lighting. The second and third panels included feed and egg systems, remaining lighting, remaining blower, 20 mixing fans, electrical outlets, and the automatic curtains (Hired Hand Inc, Bremen, AL).

Fan, lighting, manure blower, and total house current were measured every second using inductive current sensors (AcuAmp ACTR 200) that were interfaced with a data acquisition system (DAQ, Compact Fieldpoint, National Instruments, TX). The 1-second data were averaged to 30-second values and output to the on-site PC. The data for whole house current came from 6 current sensors, each meter measuring one phase of a supply. The eight ventilation stages were measured with each leg of all eight stages through one of three current sensors. The lighting was run through a seventh current sensor, and the three legs of one blower were run through the eighth current sensor. It was assumed that all three blowers operated in the same manner (continuously).

While these meters gave us continuous current, in order to calculate electricity use, a relationship had to be developed. A Fluke 1735 power logger (Fluke, Everett, WA) was used to develop this relationship. The power logger collected data from each independent electricity source for 4 days. Output from the monitoring included current and voltage from each leg as well as power factor, total, reactive, and apparent power for the circuit as a whole. These data were used first to verify current measurements from the current sensors. Then these data were used to develop appropriate power factors to use in calculating total from the current sensors. After logging the supply power consumption for the whole house, individual circuits were checked for short periods of time (~10 minutes per circuit to identify power consumption by individual systems).

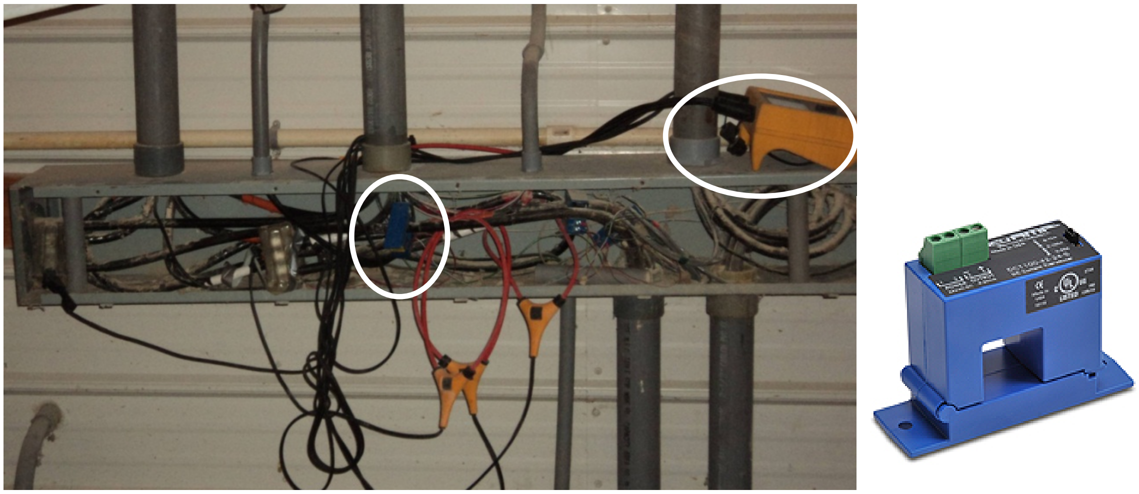

Figure 4.2. (left) The power logger (right oval) used to verify and develop power relationships for the inductive current sensors (left oval). The electric conduit cover was temporarily removed for making the measurement. (right) Close up of the current sensor.

Fuel Monitoring

For fuel monitoring, temperature compensated diaphragm gas meters (AM-205, Elster American, Nebraska City, NE) were placed in-line between the propane tanks (1890 liter or 500 gallons each) and the two 73.25 kW (250,000 BTU/hr) supplemental heaters along the sidewall that they serviced. There were two tanks for each house, and therefore two meters. The gas meters had digital counters, which were checked weekly. In addition, each meter had pulse output collected at 1-second intervals to the data acquisition system (DAQ, Compact Fieldpoint, National Instruments, TX). The data, similar to current metering, were output as 30-second averages.

Heater status was determined by the management program on site. The management software (Command III, Poultry Management Systems, Inc., Saranec, MI) had an input for the setpoint of the house. If the temperature dropped below the set point by more than 1.1℃ (2℉), every 2 minutes the controller would turn off another stage. When the house temperature dropped by 2.2℃ (4℉) from the setpoint at minimum ventilation, the heaters cane on. This means heater run time was controlled exclusively by house temperature. With regard to fuel usage, this study determined if the heaters were running at necessary moments as determined by the balance temperature (T_{bal}), which is the outside temperature below which supplemental heat is needed to maintain target indoor temperature and RH. The equation used to calculate T_{bal} is as follows,

$$t_{bal} = t_i - \frac{3.6\times10^6 \cdot SHP \cdot BW \cdot n \cdot (W_i - W_o)}{MP \cdot BW \cdot n \cdot Cp + 3.6\times10^6 \cdot (W_i - W_o) \cdot (BHLF)} \quad [1]$$

Where: t_{bal} = ambient temperature below which supplemental heat is used to maintain setpoints of indoor temperature and RH

t_i = indoor setpoint temperature (21.7; 23.6 ℃)

SHP = sensible heat production (4.1 W/kg)

BW = average body weight (1.79; 1.78 kg)

n = house population (48,875; 47,125 hens)

W_i, W_o = humidity ratio inside and outside (ambient) (kg water/kg dry air)

MP = moisture production (1.25 g/kg-hr)

C_p = specific heat (1006 J/kg-℃)

BHLF = building heat loss factor (1140 W/℃)

The values for t_i, BW, and n were based on average production values for Dec 2010-April 2011 (house 2; house3). The BHLF was calculated based on information from the barn design (Appendix). SHP and MP values were adopted from Hayes et al. (2012). The humidity ratios varied based on the RH setpoint.

Results and Discussion

Climactic Conditions and Ventilation

Both houses 2 and 3 held fairly constant temperatures over the winter months. House 2 had a setpoint that was 1.6 to 2.8℃ (3 to 5℉) lower tha n house 3. The setpoint of house 2 was increased in mid-February, while the setpoint of house 3 stepped up in December and again in mid-February. The higher temperatures in house 3 corresponded to lower VR. RH in both houses were below 80% through most of the winter, but RH was consistently above 70%. The VR was generally between 0.6 and 11m^3/hr-bird. Figure 4.3 plots these trends.

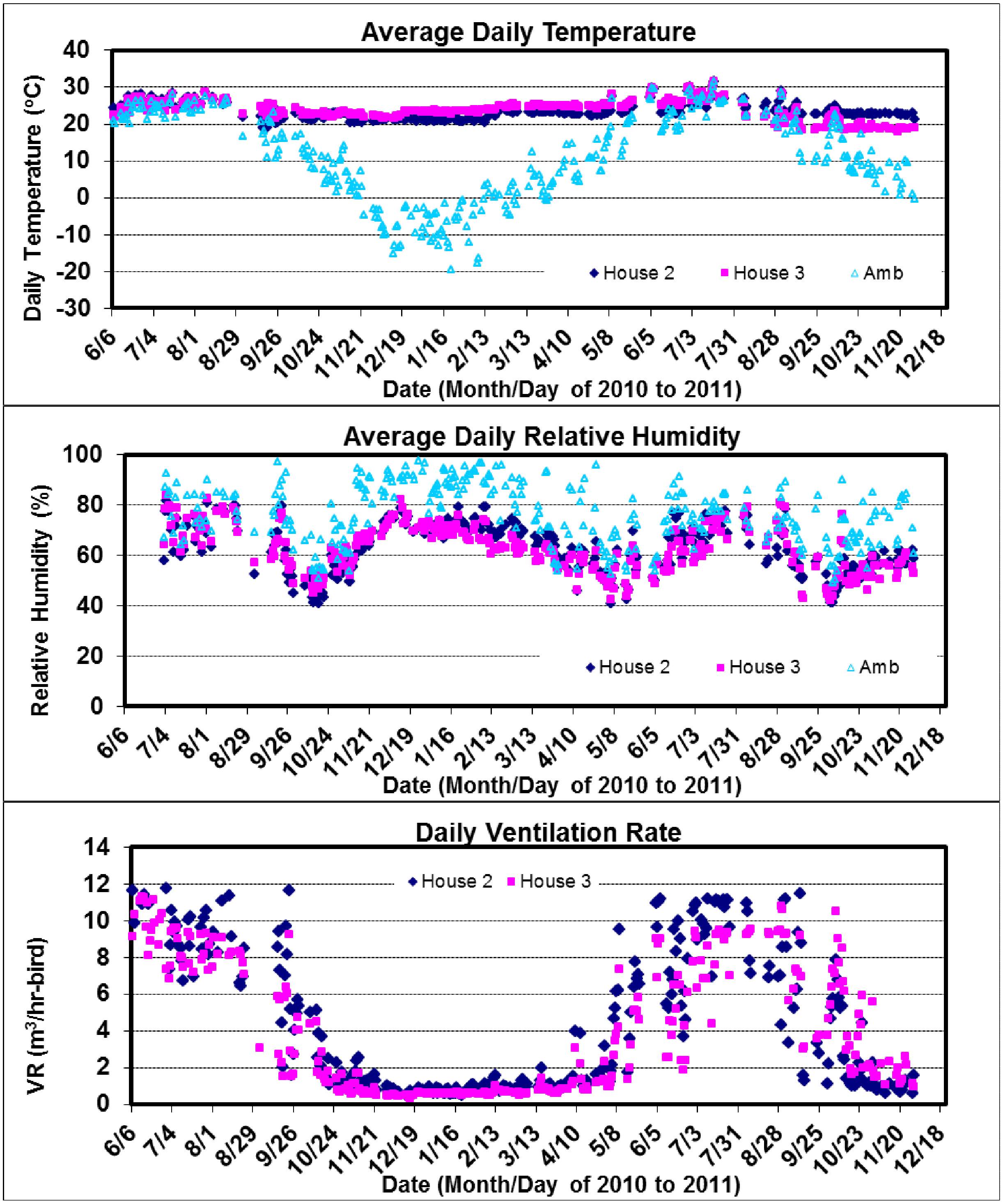

Figure 4.3. Daily temperature, relative humidity (RH), and ventilation rate (VR) of the two aviary houses monitored and the ambient.

Electricity Use

From the power logger, the amperage and power factor for some specific circuits were identified, as shown in Table 4.2. These specified currents give some valuable insight in the power requirements by the systems. In these houses some portion of ventilation fans and manure-drying blowers ran continuously. As well, the lights were on ~16 hours each day. The mixing fans ran intermittently. The egg belts ran for just under two hours per day and the feed system ran for 15 to 20 minutes per feeding, 4 times a day. The manure-belt runtime depended on how often the belt was cleared (every 3 days in winter and every 7 days in summer). The manure belts were on a separate power supply and therefore not included in the continuous current monitoring values calculated below. From the individual circuit demands and the whole house power logging, the continuous current monitoring can be converted to power use. Figure 4.4 shows the breakdown of monthly electricity use for the monitoring period. The value is broken down into major components. The ventilation was the most variable user of electricity, ranging from 32 kWh per day to almost 750 kWh per day. Electricity use for the blowers was consistent at about 345 kWh per day. Lighting and feed system were also consistent at approximately 30 kWh and 20 kWh per day, respectively. The final component included mixing fans, electrical outlets, the egg belts, and the curtains on ventilation fans that were used in place of shutters. Figure 4.5 displays the % of total consumption each component used on a monthly basis. Stout (1984) broke down energy use for egg production as 64% in mechanical ventilation, 17% in lighting, 5% in operation of feeders, 5% in miscellaneous, and 9% in operation of egg coolers. These values were from housing without manure belts and with incandescent lighting. Although the two sets of data between the current study and the report by Stout (1984) are not directly comparable, the general relationship agreed. Both Figures 4.4 and 4.5 show the average of both houses. For each month, the difference in total electricity consumption between the two houses is less than 10%. The exception is for September and October 2011, where house 3 was repopulated with a new flock and had ventilation demands that nearly doubled those in house 2. When ventilation power consumption was removed, the houses' monthly total consumption difference was less than 3%.

Table 4.2. Power logging outputs for some major circuits and systems in the aviary house (numbers on a per house basis).

Circuit(s)	Description	Voltage nominal (V)	Current (A)	Power Factor
Exhaust Fans				
variable speed	Stage 1-4x20inch*	240	8-19	0.53-0.69
variable speed	Stage 2-4x36inch	240	10-27	0.68-0.72
	Stage 3-2x48inch	240	24	0.82
	Stage 4-2x48inch	240	24	0.82
	Stage 5-2x48inch	240	24	0.82
	Stage 6-2x48inch	240	24	0.82
	Stage 7-2x48inch	240	24	0.82
	Stage 8-2x48inch	240	24	0.82
Feed System		240	180	0.43
Manure Belt				
Blowers	3 total	240	117	0.5
Egg Belts		240	10	0.41
Egg Rod Conveyor		240	4.5	0.4
Lighting	~500 CFL	120	35	0.45
Mixing Fans	10 center litter aisles	120	13.4	0.71
Manure Belts	12 belts total	240	55	0.59

* Stage number - Number of fans in the stage x the diameter of the fan

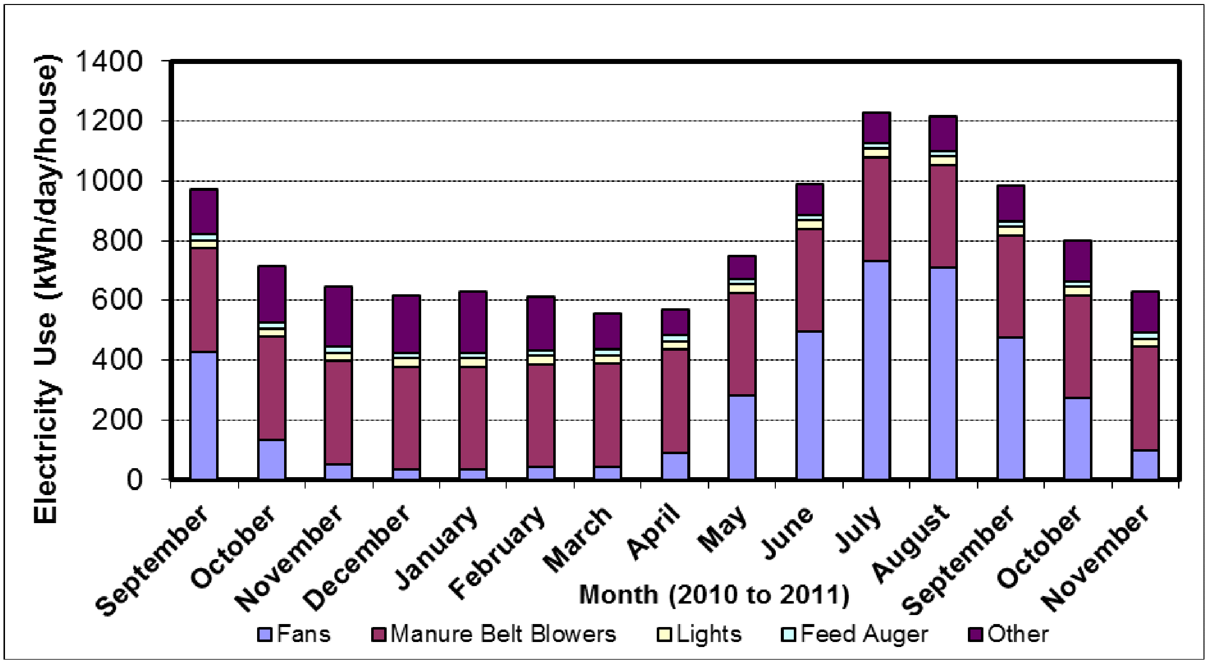

Figure 4.4. Monthly mean daily electricity use (kWh/day) partitioned into major components for the monitored aviary hen houses (~50,000 hens per house). Other components include egg belts, mixing fans, curtains on fans, and electrical outlets.

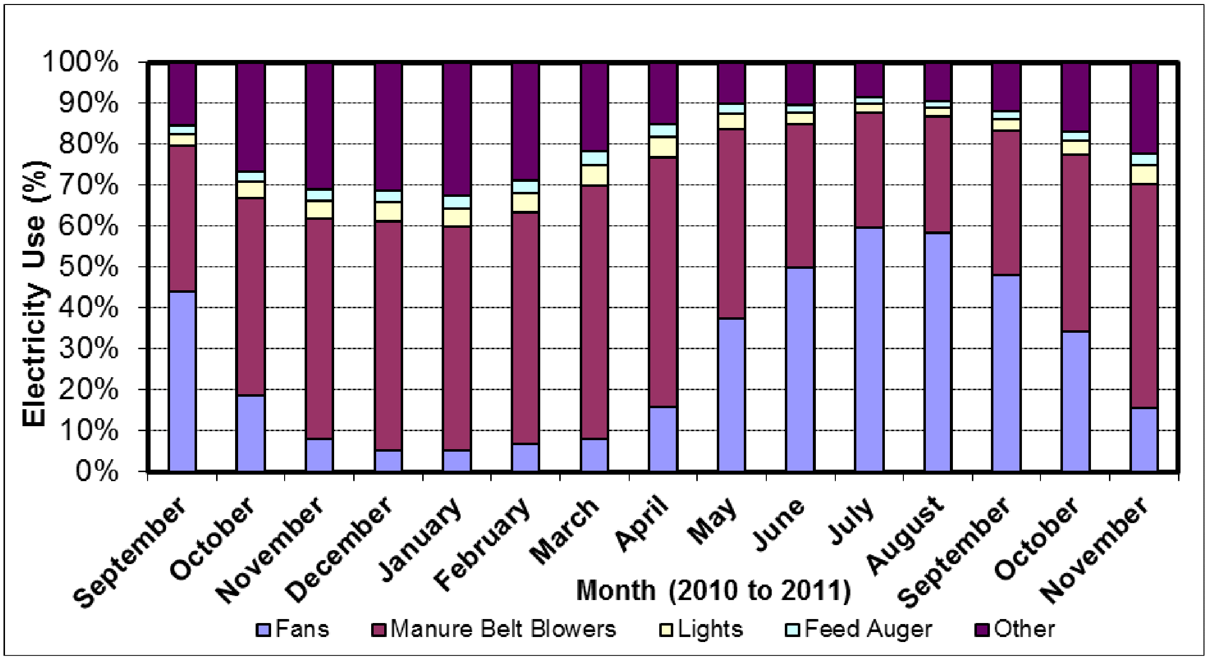

Figure 4.5. Electricity use distribution among major components (as % of monthly total) for the monitored aviary hen houses (~50,000 hens per house). Other components include egg belts, mixing fans, curtains on fans, and the electrical outlets.

From these monthly values, total electricity use from both houses for the 15 months can be calculated. This results in total power usage of approximately 365 mWh/house over the 15 months. In order to calculate electric energy use on a per kg egg basis, farm production data were used to obtain the monthly egg production of 60,575 kg egg/house. A summary of European studies by Sonesson et al. (2009) suggested electricity demands between 175 and 450 kWh per metric ton of egg. The current study showed 402 kWh per metric ton of eggs. Assuming an electricity rate of 9 cents per kWh, the electricity cost amounted to 3.6 cents per kg egg (64 g/egg). With the Hy-Line Brown hens used in this current study (i.e., slightly larger eggs than white eggs), this equates to 2.8 cents per dozen eggs. The European Union has been in transition towards alternative housing systems for a number of years. In one study of this transition, utility costs were summarized (table 4.3). The ten European countries below show an average increase of 20% in utility cost when moving from traditional cage housing to cage free barn housing. Although our value can not be directly compared, a recent value for conventional cage barns in the Midwestern US has been estimated to be 1.6 cent/kg egg, during a producer survey for life cycle analysis of egg production and processing (Ibarburu, 2012, Personal Communication).

Table 4.3. Typical utility costs for 10 European Union countries during the transition from cage housing to alternative housing.

Country	Unit	Conventional Cage	Barn-Cage Free
Belgium[1]	€ cent/ kg egg	2.15	2.47
Denmark[1]	€ cent/ kg egg	0.96	2.00
Finland[1]	€ cent/ kg egg	3.37	5.20
France[1]	€ cent/ kg egg	1.14	1.11
Germany[1]	€ cent/ kg egg	1.80	2.84
Greece[1]	€ cent/ kg egg	0.80	0.80
Ireland[1]	€ cent/ kg egg	2.55	2.67
Italy[1]	€ cent/ kg egg	8.66	9.30
Netherlands[1]	€ cent/ kg egg	0.96	2.00
United Kingdom[1]	€ cent/ kg egg	2.54	1.74
United States[2,3]	$ cent/ kg egg	1.60	**3.60**

Data from [1] Agra CEAS Consulting, 2004; [2] Ibarburu, 2012; [3] this study.

Because the ventilation was monitored using current sensors, a relationship between building ventilation rate (VR) and power usage can be identified. The VR was determined based on *in situ* calibrated fan curves with fan assessment numeration systems (FANS) sized 0.9 m (36 inch), 1.2 m (48 inch), and 1.35 m (54 inch) (Gates et al., 2004). Individual fan curves were established for each stage (1-8) including operational ranges of the variable speed control of the lower stages. As well the current and power factors were determined for the variable speed fans at various speeds and operating static pressures (Table 4.4). For the larger fans the m^3/hr and m^3/(hr-W) (CFM per fan and CFM/W) were determined at the static pressures of 12.5 and 25 Pa (0.05 and 0.1 inches w.c.). These values were compared to Bioenvironmental and Structural Systems Laboratory (BESS) performance data. For the stage 2 fans the on-farm VR was calculated as 18,250 m^3/hr at 12.5 Pa (10,740 CFM at 0.05 inch w.c), while BESS lab reports 18,700 m^3/hr (11,000 CFM). For stages 3-8, the on-farm VR was 38105 m^3/hr (22,428CFM) while BESS reports 39,900 m^3/hr (23,500 CFM). Both sets of fans performed well in the field. The CFM per Watt relationship, namely, fan efficiency, was not as strong. Stage 2 had an efficiency of 15.3 and 13.9 CFM/Watt whereas BESS lab reports 20 and 17.5 CFM/Watt for 0.05 and 0.1 inch w.c. static pressure, respectively. For stages 3-8 the 15.7 and 14.5 CFM/Watt were also less than the BESS lab reporting values of 20 and 18 CFM/Watt for 0.05 and 0.1 inch w.c. static pressure, respectively. In both stages at both static pressures, the CFM per Watt was 75-80% of the reported value.

Table 4.4. The ventilation rate (m^3/hr & CFM) to power (W) relationship.

Stage	Hz	SP (Pa)	m^3/ hr-stage*	CFM/ stage	Amp/ stage	PF	kW/ stage	m^3/ hr-Watt	CFM/ Watt
1	30	7.5	13551	7976	8	0.53	0.6	22.9	13.5
1	30	15	11676	6872	8	0.53	0.6	19.7	11.6
1	30	30	7924	4664	8	0.53	0.6	13.4	7.9
1	45	7.5	29658	17456	13	0.61	1.1	27.0	15.9
1	45	15	27782	16352	13	0.61	1.1	25.3	14.9
1	45	30	24031	14144	13	0.61	1.1	21.9	12.9
1	60	7.5	45764	26936	19	0.69	1.9	24.8	14.6
1	60	15	43889	25832	19	0.69	1.9	23.8	14
1	60	30	40137	23624	19	0.69	1.9	21.7	12.8
2	30	7.5	32087	18886	10	0.68	0.7	45.9	27
2	30	15	28071	16522	10	0.68	0.7	40.1	23.6
2	30	30	20038	11794	10	0.68	0.7	28.5	16.8
2	45	7.5	53877	31711	19	0.695	1.5	37.2	21.9
2	45	15	49861	29347	19	0.695	1.5	34.3	20.2
2	45	30	41828	24619	19	0.695	1.5	28.9	17
2	60	7.5	75667	44536	27	0.72	2.8	27.0	15.9
2	60	15	71650	42172	27	0.72	2.8	25.7	15.1
2	60	30	63617	37444	27	0.72	2.8	22.8	13.4
2	60	12.5	72989	42960	27	0.72	2.8	26.0	15.3
2	60	25	66295	39020	27	0.72	2.8	23.6	13.9
3-8	60	12.5	76209	44855	24	0.82	2.9	26.7	15.7
3-8	60	25	70186	41310	24	0.82	2.9	24.6	14.5

* Air flow rate per fan calculated using *in-situ* performance curves; highlighted values relate to BESS Lab performance data. See table 4.2 for fan stage numbers.

Propane Use

The final consideration in this paper is fuel usage. Both barns used heaters throughout the winter 2010-2011 and spring 2011. There was no heater use in fall 2011 because the heaters were intentionally turned off at the electrical panel. Over the entire monitoring period house 2 had lower fuel use than house 3. The set-point temperature for house 2 averaged 1.7℃ lower than house 3 over the 6 months r eported below (Figure 4.6). It is important to note the propane usage was not greatest during the coldest periods, but instead in the later spring when there were major swings in daily temperature. Overall house 2 used less than 75 liters (20 gal) of propane while house 3 used approximately 400 liters (110 gal).

Based on the T_{bal} equation [1] described above, the daily T_{bal} averaged -2.4℃ (27.7℉). The average daily ambient temperature generally fell below T_{bal} (64 out of 96 monitored days $T_{amb} < T_{bal}$) for the months Dec. 1, 2010 through March 31, 2011. However, the heaters only ran 8 days over this period. As was stated above, the ventilation control in this barn was managed to maintain indoor temperature, not RH. Because the heaters did not regularly run over the winter months, the minimum ventilation designed was lower than the ventilation needed for RH management. When the humidity ratios were adjusted from maintaining 60% to 80% RH, the T_{bal} dropped by 5.4 ℃ (T_{bal}= -7.8℃). With this drop, the number of days when supplemental heat was needed was reduced to 13 days. The 8 days heaters did run corresponded to these 13 days. Based on an energy content of 7.1 kWh/liter of propane (DOE, 2011), the propane needs in each barn to maintain T_{bal} was 1003 liters at 80% RH. Again this number is much higher than the monitored fuel use. Because the heater run time was not actually determined by setpoint temperature, but instead it was run 2.2℃ lower, this difference was not unexpected. Overall, the VR in this barn was managed for barn temperature. The minimum VR was lower than that needed to maintain RH, as evidenced by the lower propane usage.

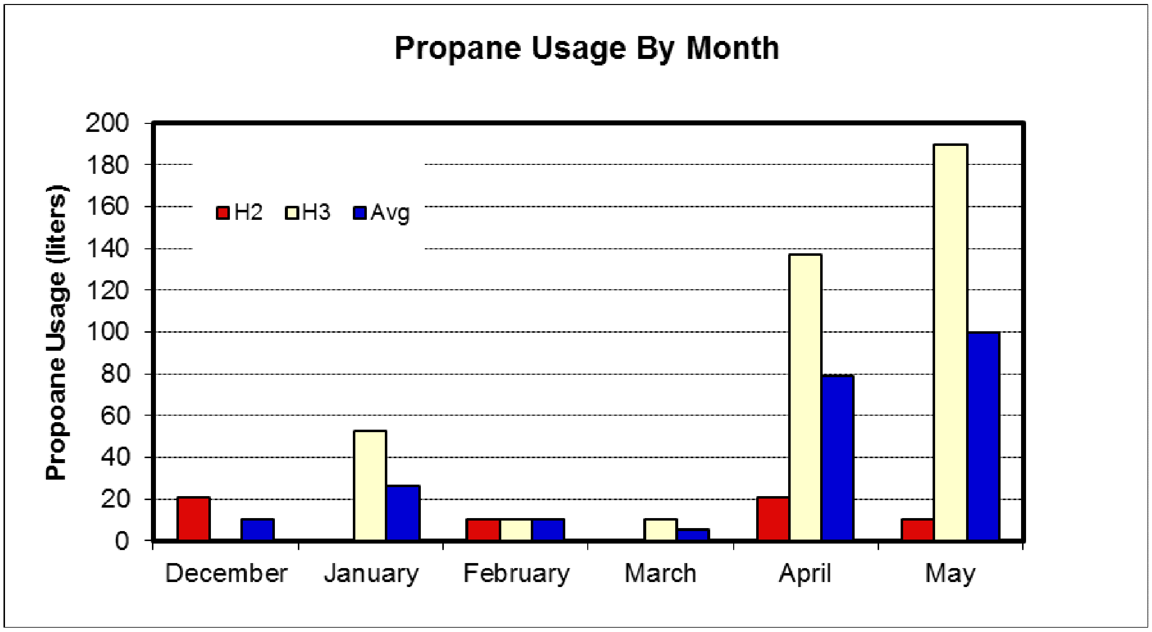

Figure 4.6. Propane usage per barn (2010 to 2011)

Conclusions

During this study, electricity current was continuously monitored for ventilation fans, manure drying blowers, lighting, and the whole house. This information combined with short duration power logging provided whole house and component power usage. The ventilation system is the most variable user in that in summer it accounted for almost 60% of the total electric energy, while in the winter it accounts for approximately 5%. The efficiency of the ventilation system (26 m^3/hr-Watt) was less than 80% of the reported performance efficiency. The manure belt blowers ere the second major user of electricity (largest in winter) with 25% to 60% of the monthly electricity consumption. Electricity cost over the 15-month production period averaged 3.6 cent per kg of egg produced (i.e. 0.39 kWh/kg egg at a cost of \$0.09/kWh). Overall the propane fuel usage was minimal (0.26 mL/kg egg); this means the ventilation scheme in this barn was successful at maintaining setpoint temperature using the birds sensible heat. However, because the ambient temperatures were below T_{bal} and the heaters were not running regularly, the ventilation scheme was not necessarily achieving ideal RH control. RH in the barns was consistently between 70 and 80%, with 23 days having a portion of the day above 80%. The propane usage in the spring does indicate over-ventilation may be occurring on days where there are large swings in ambient temperature.

Acknowledgements

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Appendix

Diagram of Heat Transfer (Top View)

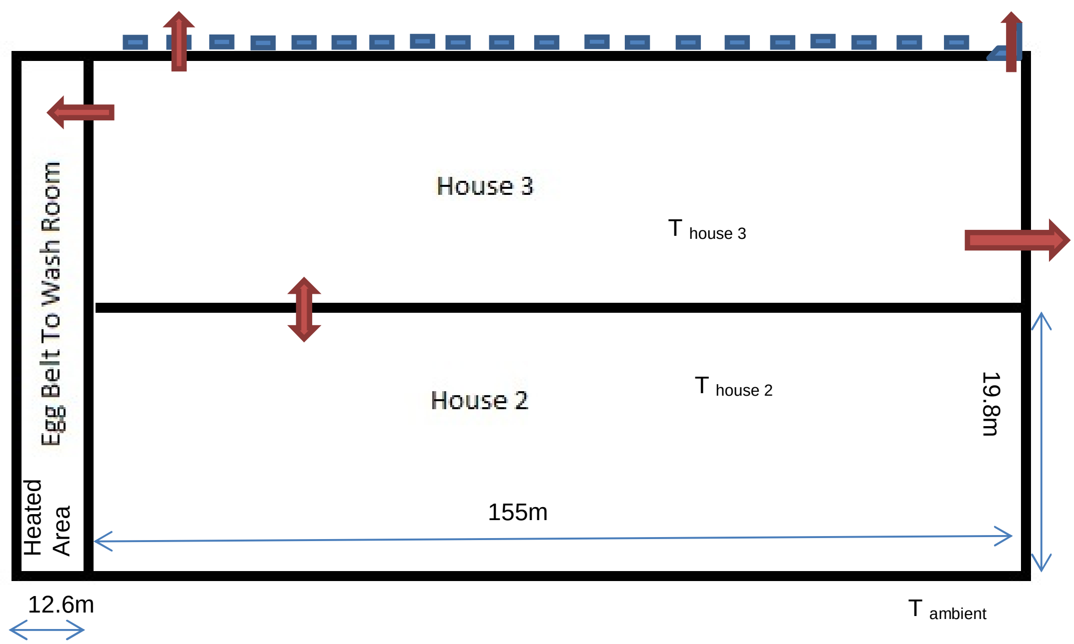
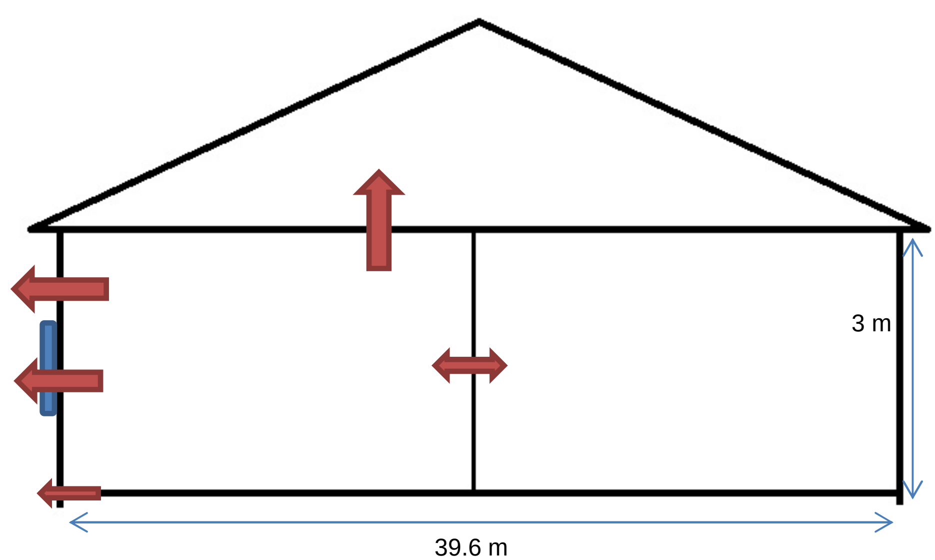


Diagram of Heat Transfer (Side View)



Building Heat Loss Factor (BHLF) Calculation

	Area	R-value	
	m^2	***m^2°C/W***	***W/°C***
Sidewall fans	21.5	0.15	143.5
Exterior doors	1.6	0.29	5.5
walls	346.3	2.65	130.7
ceiling	3069.0	5.30	579.1
perimeter	175 *m*	1.6 *W/m-°C*	280
BHLF			**1139**

Other Interior Heat Transfer:

Wall between egg belts and houses:
213 W (assuming raceway at 12.5°C, house 22°C)

Wall between houses:
351 W (assuming 1.15 °C difference in house tempera ture)

CHAPTER 5

Evaluating ammonia and temperature-ammonia combination preferences of pullets and young laying hens

A manuscript prepared for submission to Transactions of the ASABE

Morgan Hayes, Hongwei Xin, Hong Li, Dianne Cook

Abstract

This study first evaluated if pullets and young laying hens avoided an environment with a higher ammonia (NH_3) condition of about 25 or 50 ppm compared to a lower NH_3 level of <10ppm. The study then evaluated if an environment with a cool temperature and low NH_3 concentration or a comfortable temperature with an aversive level of NH_3 was preferred by the hen. The evaluation of hen aversion was done using an Environmental Preference Test Chamber (EPTC). The test birds were continually monitored for occupation time and feed usage under different environmental conditions. Occupation time during light period indicated that the birds spent more time in the lower NH_3 condition compared to both high NH_3 conditions of 25 (p= 0.02). In the Midwestern US in winter there is a potential to over-ventilate barns beyond thermal comfort levels when the ventilation management is based on indoor air quality. This is especially true for hen houses at lower stocking densities, such as those utilizing alternative production systems. Hence, in the second part of the study that evaluated the preference of NH_3-temperature combination, the birds were monitored for the occupation time and feed and water use under two conditions: a) a cool air temperature of 18.3℃ and an NH_3 level of <10 ppm, designated as the 'low' condition, and b) a comfortable air temperature of 23.9℃ and an NH_3 levels of 30 ppm, designated as the 'high' condition. No clear preference of the environmental conditions was observed for occupation time, feed use, or water use as the response criteria (p= 0.51, 0.26, 0.28, respectively). This lack of clear preference suggests that the birds do not avoid one condition over the other. From the hen's welfare perspective, this study does not oppose the use of ventilation to improve indoor air quality while conserving energy efficiency by lowering temperature setpoint down to 18.3℃.

Keywords: Ammonia, Laying hen, Preference chamber, Temperature, Welfare

Introduction

Maintaining comfortable environmental temperatures in laying-hen houses is accomplished by lowering ventilation rate and possibly supplying supplemental heat in the winter. In the Midwestern US winter minimum ventilation is designed to provide moisture control and maintain adequate indoor air quality. As barns are adjusted to provide a lower stocking density (more space per bird) or designed as alternative hen housing systems, they will hold a fewer number of birds. Fewer birds produce less heat; as such, in the winter there is often a struggle between thermal comfort and indoor air quality. Because the minimum ventilation rate for maintaining adequate air quality is greater than the ventilation desired for thermal comfort, the house will either encounter a cooler environment or require supplemental heating to maintain the desired temperature.

The thermoneutral zone (TNZ) described by Sainsbury (2000) for hens covers a significant range of 12 to 24 ℃, while Hy-Line Management Guid e (2007) suggests a narrower range of 20 to 25 ℃. The Hy-Line's lower TNZ limit of 20 ℃ was previously suggested by Aulie and Toien (1988). A study by Ariele et al. (1979) suggests the TNZ is more closely related to the temperature in which domestic hens are acclimatized. Using the calculations from the Ariele et al. study for birds in a mechanically ventilated house with a minimum temperature of 19.4 ℃, the birds would have a lower critical temp erature (LCT) of around 19.5 ℃. This study implies that when hens are acclimated, their TNZ can be below 20 ℃, but not below the acclimation temperature. However when the ambient temperature is greater than 20 ℃, the LCT remains near 20 ℃ (Ariele et al., 1979). W hile the LCT is slightly ambiguous, the recommended temperature range for optimal production is clearer at 21 to 24 ℃ (Appleby et al., 2004) or 21 to 27 ℃ (Hy-Line, 2007).

In order to reduce energy and/or feed costs, ventilation rate may be lowered below the suggested minimum value. In laying-hen housing, ammonia (NH_3) is a major contributor to air quality concerns (Carlile, 1984). This low ventilation rate will result in increased ammonia levels, which may affect the health and performance of laying hens (Anderson et al., 1964; Charles and Payne, 1966) and the human occupants. The United Egg Producers (UEP) has set forth guidelines for laying hen welfare including atmospheric ammonia concentrations being <25 ppm (UEP, 2002). For humans, ammonia exposure limits have been set at 25 ppm and 50 ppm by US National Institute of Occupational Safety and Health

(NIOSH) and US Occupational Safety and Health Administration (OSHA), respectively, for 8-hr daily time weighted average (NIOSH, 2005; OSHA, 2006).

Literature indicates that concentrations of 25 ppm or greater are aversive to hens (Kristensen et al., 2000; Jones et al., 2005). Therefore, our hypothesis was that both high conditions (25 and 50 ppm) would result in aversive response by the birds when they also have the option of <10ppm NH_3. A similar previous temperature-ammonia combination study with pigs found that pigs would choose ammonia comfort to a point. When the temperature dropped below the pigs' LCT, they switched their preference to thermal comfort (Jones et al., 1999). Although the 'cool' temperature in the current study falls slightly below the hen's optimal performance it may not be below the LCT.

This study had two objectives: a) to confirm that ammonia at concentration of 25 or 50 is aversive to hens as compared to a low condition (<10 ppm), using preference test chamber; b) to determine if a low (<10 ppm) NH_3 condition with a cool air temperature (18.3 ℃) is preferred to an aversive NH_3 concentration (30 ppm) combined with a TN air temperature (23.9 ℃). For the ammonia testing, the low NH_3 level will be known as "low" while the high NH_3 level will be known as "high." In this paper, the treatment of low NH_3 level with the cool temperature is referred to as the "low+cool" condition, whereas the treatment of high NH_3 level with TN temperature is referred to as the "high+TN" condition. The hypothesis was that the hens would choose ammonia comfort over thermal comfort.

Materials and Methods

The experiment was run with the environmental preference test chamber (EPTC) originally developed by Green and Xin (2008) and refined by the authors. Two mixing boxes suspended above the compartments provided air to the four compartments. For the ammonia test (objective a) the compartments had separate air supplies with airflow rate ranging from 9.2 to 11.1 m^3/hr. For the temperature-ammonia combination test (objective b), the compartments had separate air supplies with airflow rates ranging from 9.5 to 15.7 m^3/hr. The wider range of airflow rate was due to the two cool temperature compartments being provided maximum airflow, while the TN compartments were provided a lower flow rate. In order to provide a cool temperature condition of 18.3 ℃, the air supply for the mixing box was given primary access to the room inlet and a 4100 Watt (14000 BTU/hr) portable air conditioning unit (Haier CPN14XC9, New York, NY) was used to supply cool air

(16.1℃) to the mixing box. In the warm air mixing box two heating fins were used together with small mixing fans to ensure more uniform air temperatures. Ammonia could be injected into individual compartments to achieve the desired levels. Each compartment was divided into two areas: 1.) an area for 3 stimulus birds that remained in an individual compartment, and 2.) an area for the test bird that had access to the other compartment. The EPTC had a doorway in the passages between two adjacent compartments to limit inter-compartmental air exchange. The doors had been made of clear acrylic, which swung from the top of the passageway. As shown in figure 5.1, the doorways between compartments 2 and 3 and between 1 and 4 were closed and sealed to prevent airflow. The clear solid acrylic doors were also covered with opaque plastic to provide a visual barrier. In this way, one test bird could be tested in compartments 1 and 2 while a second test bird was simultaneously and independently tested in compartments 3 and 4. The weight of the swinging doors in the used passageways was too heavy for the pullets to operate in the ammonia test, hence a 2-cm, double-layer vinyl strip door was used to replace the heavier door. This door type was effective at limiting airflow, but occasionally the birds lay down in the passageway under the door, causing inter-compartmental airflow. For the temperature-NH_3 combination test, the doors were switched back to the clear acrylic swinging doors.

Each test bird was recorded continuously using video recording software (Argus Surveillance, Toronto, CAN); and an infrared (IR) detection system was used to determine in which compartments the birds resided. The IR detectors took readings every 2 seconds to identify short duration movements. The IR detection system was verified using the video recording over 24 hours, and the average difference was 3.4%. Table 5.1 shows the percentage of time spent in each compartment, or percent occupation time (POT), calculated with both the IR detectors and video recording. Note compartments with smaller percent occupation time had higher percent difference between methods.

Individual feeders in each compartment were weighed at the beginning and end of a test period to determine the feed use. During the ammonia testing, although a wire screen was placed on top of the feeder to prevent raking of feed, there were still feed losses visible. Feed use for stimulus birds was approximately half of that for the test bird due to wastage. The stimulus birds' average feed usage followed the expected intake as indicated in the Hy-Line Management Guide (2007). For the temperature-ammonia combination trials, test birds had different individual feeders and a new watering system in each compartment. Feeders were commercial solid bottom rabbit feeder (Model LGAF3ML, Little Giant, Eagan, MN) with a screen to prevent raking. Water was weighed at the beginning and end of the treatment periods to determine the use during all trials. Water supplies were held in half liter bottles placed in a bucket on the ceiling so that gravity provided the pressure for nipple drinkers in each compartment. Stimulus birds were supplied water by nipple drinkers attached to a constant water supply through a pressure regulator.

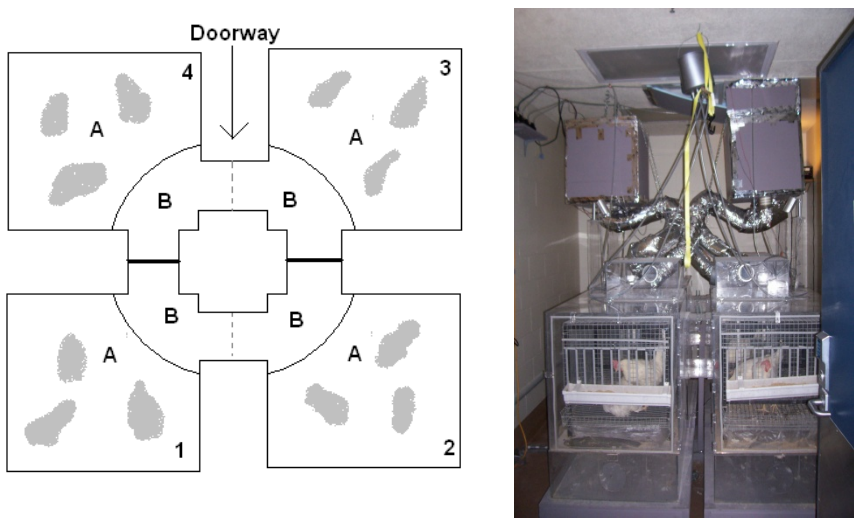


Figure 5.1. Top view of the EPTC with the four compartments labeled and a picture view of compartments 1 and 2 of the EPTC during the temperature ammonia combination trials. The mixing box on the top left of the picture provides air for the high condition and the mixing box on the right provides air for the low condition. (A= stimulus birds area, B= test bird area)

Table 5.1. Percentage of occupation time over 24 hours in each compartment calculated using infrared (IR) detection system and by reviewing video images.

	Compartments			
	1	**2**	**3**	**4**
IR	14.60	13.08	66.49	5.83
Video	14.99	11.52	67.96	5.54
% Diff	2.6	-13.5	2.1	-5.2

The ammonia experiments at both 25 and 50 ppm were each run with 12 Hy-Line W-36 pullets and laying hens at 14 to 32 weeks of age (each test took approximately 1 week and two test birds per week could be tested; note the age of test birds at time of testing in table 5.2). The temperature-ammonia combination experiment was run with 15 Hy-Line W-36 laying hens ranging from 26 to 35 weeks of age at the time of testing. All pullets for these trials were obtained from pullet houses with manure belts at a commercial farm. Because the pullets were from a belt house, it was assumed that they had been under relatively low ammonia levels [<10 ppm, as observed by Liang et al., 2005]. The pullets were acclimated in 21℃ and <5 ppm ammonia environmental conditions f or a least 2 weeks prior to testing. The housing during acclimation consisted of two adjoining compartments with an identical door to the one joining the EPTC compartments.

Two test birds were randomly selected for trials in the EPTC each week. The birds were first provided baseline condition of fresh air (<5 ppm NH_3, 22.8℃). They were then provided different target conditions based on the specific trial which consisted of:

25 ppm NH_3 vs. fresh air (<10 ppm NH_3),

50 ppm NH_3 vs. fresh air (<10 ppm NH_3),

23.9℃ (75℉) and 30 ppm NH_3 vs. 18.3℃ (65℉) and <10 ppm NH_3.

The treatments were assigned in a randomized block. The birds were given at least 3 hours to acclimate to the EPTC and observed to confirm progressions into both compartments. Data were taken for 3 days under baseline conditions, 2 days under treatment conditions, and 2 days with the treatment conditions switched to the opposite compartments (fig. 5.2). Switching of treatment between the compartments in two treatment periods was to avoid potential bias in baseline preferences toward specific compartments. Although the doorways between compartments 1 and 4 and compartments 2 and 3 were sealed to prevent air changes and made opaque to prevent visual contact, by providing adjacent compartments different conditions potential interactions between test birds were managed. If the birds did interact, one bird would show an increase in POT in the high compartment while the other bird would show an increase in POT of the low compartment. When the treatments were switched, manure was removed, feed and water were weighed and replenished, and eggs were collected, if present.

The POT value of each compartment was calculated using data from the IR sensors. The sensor output was processed to create a summary data set with total time and POT in each compartment and feed utilized by the test bird in each compartment. Because the birds tend to be inactive at night (dark hours) and much more active during the day (lighted hours), data were analyzed on a whole day and lighted period basis. The pullets followed the lighting regime suggested by Hy-Line (2007). Table 5.2 shows the lighting program used for the study. Analyzing the lighted periods separately would remove the bias due to the birds not being willing to move in the dark as well as ambiguous data where the bird remained in the passageway not entirely in either compartment, which occurred in the ammonia tests primarily at night.

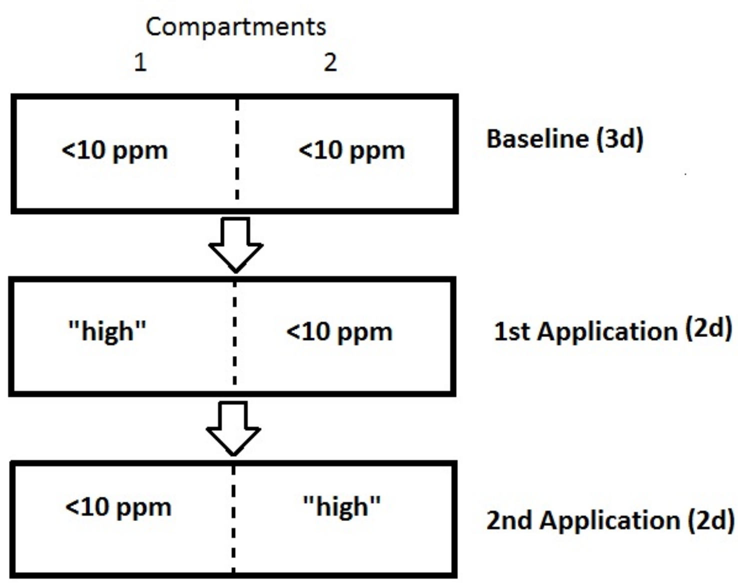


Figure 5.2. Diagram of the trial including baseline, 1st treatment application, and 2nd treatment application. "High" condition is either 25 or 50 ppm ammonia based on the trial.

The summary data sets were analyzed using SAS PROC MIXED to determine if the first and second treatment applications were significantly different. As well, the same command evaluated if the compartmental baseline preferences were related to the test condition compartmental choices. The treatment application and baseline preference were confounding factors. Based on the PROC MIXED results above, the more significant factor was addressed. In all trials the baseline compartmental preference was more significant and eliminated in the t-test. SAS PROC T-TEST was used to determine if the high and low conditions were significantly different. Because the occupation data were normalized to POT, the POT values of "low – baseline" and "high – baseline" are equal with opposite signs, as shown below,

$$POT_{low} + POT_{high} = 100 = POT_{baseline\_low} + POT_{baseline\_high} \quad (1)$$

$$POT_{low} - POT_{baseline\_low} = -(POT_{high} - POT_{baseline\_high}) \quad (2)$$

In order to remove compartmental effect the t-test was used to determine if the difference in POT between the low condition or the high condition and the respective baseline was significantly different from zero. If this difference is significantly different from zero, a negative value (of $POT_{low} - POT_{baseline\_low}$) means the high condition was preferred and a positive value means the low condition was preferred and viceversa for $POT_{high} - POT_{baseline\_high}$. Effects were considered significant at α=0.05.

Table 5.2. The lighting regime used for the pullets and young laying hens in ammonia tests

Bird age (wk)	Test Bird #	Minimum Light Level (Lux)	Light Duration (hr)
14-17	1-6	7	12
18	7-8	7	13
19	9-10	7	13.5
20		7	14
21	11-12	7	14.5
22	13-14	7	15
23	15-16	7	15.5
24-32	17-24	7	16

Results

Ammonia testing

The first analysis was to determine if the first and second applications of the treatment conditions were significantly different. The mean values for high condition and low condition for the high condition of 50 ppm NH_3 was (24.5H: 35.5L) (±10.5 S.E.) minutes per hour for the first application implicating a preference for the low condition, and (36.6H: 23.4L) (±7.4

S.E.) minutes per hour for the second application implying a preference for the low condition. These applications are not significantly different (p=0.15). The mean high condition and low condition with the high condition of 25 ppm NH_3 was (26.6H: 33.4L) (±9.5 S.E.) minutes per hour for the first application, and (27H: 33L) (±7.8 S.E.) minutes per hour for the second application. The overall order of applications were not significantly different (p=0.93). These values show there is no significant difference between the first and second applications of treatments, hence the data was pooled from the 1st and 2nd treatments for further analysis.

The second analysis evaluated if the baseline compartmental choice influenced the preference when environmental conditions were applied. When analyzed using SAS PROC T-TEST these values again did not indicate a significant difference in compartmental choices between baseline and application of the test conditions (p=0.11). However, this borderline p value indicates that there might be a significant interaction that was not recognized. One third of the test birds (8 out of 24) showed the same compartmental preference in both treatment applications and the baseline period; almost another third of the test birds (7 out of 24) showed the compartmental choices that were opposite of the baseline compartmental preferences.

The final analysis was done with a t-test. In order to remove compartmental effect the t-test was used to determine if the difference in POT between the low condition and the baseline was significantly different from zero. If this difference is significantly different from zero, a negative value of POT_{low}- $POT_{baseline\ low}$ means the high condition was preferred and a positive value means the low condition was preferred. For the 25 ppm NH_3 the average POT difference between the low compartment and the same compartment at baseline was close to significant at 5.3±2.7% (mean±SE, p=0.06). For lighted hours, the average POT difference was significant at 6.5±2.7% (mean±SE, p=0.025). This indicates that these birds did make a clear choice between the two NH_3 conditions provided. When the same analysis was done for 50 ppm NH_3 the average POT difference between the low compartment and the same compartment at baseline was -1.0±4.8% (mean±SE, p=0.84). For lighted hours, the average occupation difference is 5.0±5.5% (mean±SE, p=0.27). Though not significantly different, the lighted data did indicate a possible preference towards the low NH_3 condition. Figure 5.3 shows the overall mean and SE of POT for the 12 birds that spent in the high and low conditions for both 25 and 50 ppm NH_3.

Feed use was evaluated using a similar t-test. In this case the data were not normalized, so the feed use at both conditions minus the same compartments at baseline was tested for significant differences. For the trials with a high NH_3 concentration of 25 ppm, the average feed use difference was 22.8±7.2 g/day between the low condition and baseline and was 8.09±8.7 g/day between high and baseline (p=0.21). For 50 ppm NH_3 average low minus baseline was 38.5±8.2 g/day and high minus baseline was 18.3±11.8 g/day (p=0.17). In this case feed use was not significantly different, although it was consistently higher for the low-condition compartments. As was mentioned above, the feed use for test birds in these trials was high. Because the stimulus birds were the same age and were from the same flock, it is assumed the difference in feed usage is due mainly to feed loss by the test bird. Feed wastage was observed on the manure trays and was occasionally weighed to try and identify wastage. Manure and feed separation was impossible for accurate wastage amounts however. It is possible that running baseline for three days rather than the two days used for treatment periods resulted in less wastage. During the three day period, the feed level in the feeders was lower, which made raking feed harder.

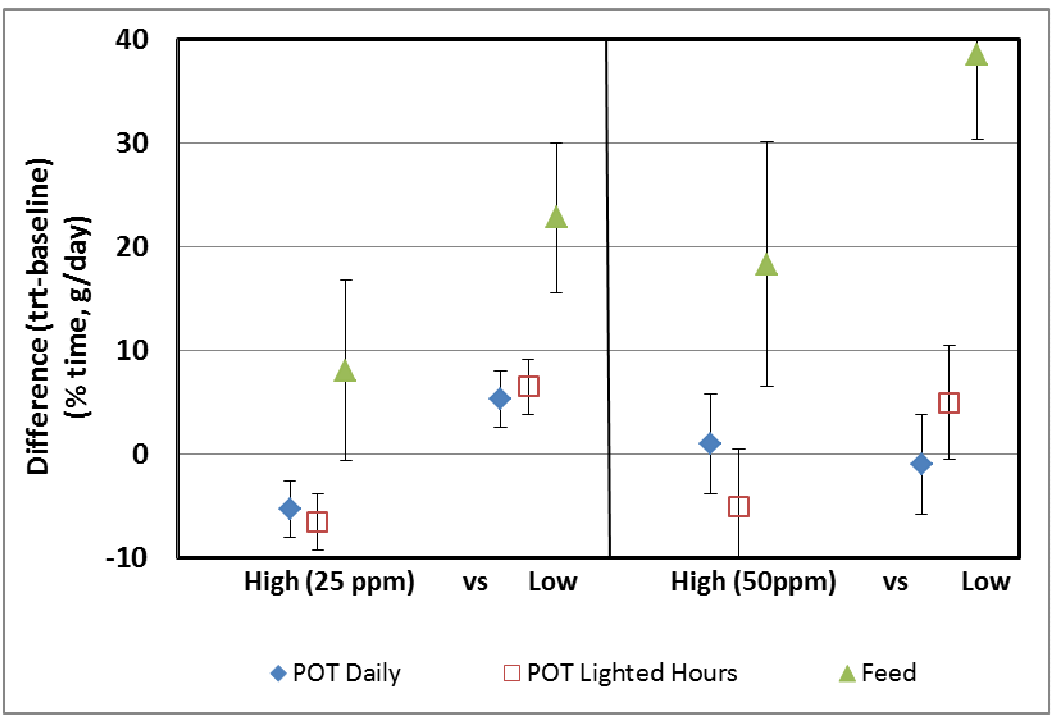


Figure 5.3. Daily and lighted-hour only difference in percent occupation time (POT) and feed use in each environmental condition vs. the same compartments at baseline (n=12) (mean ± SE). The high condition was 25 or 50 ppm NH_3, while the low condition was <10 ppm NH_3.

Table 5.3. Percent of occupation time (POT) by the hen under baseline and low testing conditions as determined using the EPTC system (low= <10 ppm NH_3, high= 25ppm NH_3). Shaded cells indicate where hens switched their preferred compartment from baseline to application tested. Light periods noted in Table 5.2 above.

Bird	Trt*	Order of Application	POT in Low Compartment		Baseline POT in Compartment Corresponding to Low Condition		POT Difference** (low-baseline)	
			Daily	*Light only*	Daily	*Light only*	Daily	*Light only*
1	1L2H	1	74.7	*58.3*	23.2	*29.4*	51.5	*28.9*
1	1H2L	2	28.0	*40.8*	76.8	*70.6*	-48.8	*-29.8*
2	3L4H	1	14.5	*23.9*	47.8	*73.7*	-33.3	*-49.8*
2	3H4L	2	80.1	*81.4*	52.2	*26.3*	27.9	*55.1*
3	1H2L	1	38.2	*63.3*	36.0	*56.9*	2.2	*6.5*
3	1L2H	2	64.8	*43.4*	64.0	*43.1*	0.8	*0.3*
4	3H4L	1	84.0	*79.7*	51.3	*29.9*	32.7	*49.8*
4	3L4H	2	49.9	*84.5*	48.7	*70.1*	1.2	*14.4*
13	1L2H	1	99.7	*99.4*	100.0	*99.9*	-0.2	*-0.5*
13	1H2L	2	3.3	*4.6*	0.0	*0.1*	3.3	*4.5*
14	3L4H	1	86.4	*83.5*	27.3	*51.7*	59.1	*31.8*
14	3H4L	2	64.8	*39.7*	72.7	*48.3*	-7.9	*-8.6*
15	1H2L	1	25.7	*42.7*	15.7	*27.2*	10.0	*15.4*
15	1L2H	2	54.9	*51.4*	84.3	*72.8*	-29.4	*-21.3*
16	3H4L	1	42.0	*24.7*	100.0	*99.0*	-58.0	*-74.3*
16	3L4H	2	75.2	*85.7*	0.0	*1.0*	75.2	*84.7*
17	1L2H	1	49.0	*51.0*	24.8	*39.1*	24.2	*11.9*
17	1H2L	2	72.1	*58.6*	75.2	*60.9*	-3.1	*-2.3*
18	3L4H	1	76.1	*70.3*	75.8	*63.8*	0.4	*6.5*
18	3H4L	2	34.7	*51.0*	24.2	*36.2*	10.5	*14.7*
19	1H2L	1	35.1	*52.8*	28.1	*40.9*	6.9	*12.0*
19	1L2H	2	65.9	*47.0*	71.9	*59.1*	-6.0	*-12.2*
20	3H4L	1	42.1	*32.2*	14.8	*21.4*	27.3	*10.8*
20	3L4H	2	65.9	*87.1*	85.2	*78.6*	-19.3	*8.5*
	Average (SE)		**55.3**	**56.5**	**50.0**	**50.0**	**5.3**	**6.5[1]**
	SE		**2.7**	**2.7**	**6.2**	**5.4**	**2.7**	**2.7**

[1] Indicates a significant effect α=0.05
***TRT notation 1H2L indicated compartment 1 is the "high" and compartment 2 is "low" condition**
Table focuses on “low” condition, “high” time in compartment and corresponding baseline are (100-displayed %) respectively, high minus baseline difference will be -1*(low-baseline)
**** a negative value of POT_{low}- $POT_{baseline}$ means the high condition was preferred and a positive value means the low condition was preferred**

Table 5.4. Percent of occupation time (POT) by the hen under baseline and low testing conditions as determined using the EPTC system (low= <10 ppm NH_3, high= 50ppm NH_3). Shaded cells indicate where hens switched their preferred compartment from baseline to application tested. Light periods noted in Table 5.2 above.

Bird	Trt*	Order Applied	POT in Low Compartment		Baseline POT in Compartment Corresponding to Low Condition		POT Difference (low-baseline)	
			Daily	*Light only*	Daily	*Light only*	Daily	*Light only*
5	1L2H	1	57.8	*39.9*	50.5	*42.6*	7.3	*-2.7*
5	1H2L	2	38.6	*38.6*	49.5	*57.4*	-10.9	*-18.8*
6	3L4H	1	94.1	*93.6*	48.8	*48.0*	45.3	*45.6*
6	3H4L	2	21.6	*21.6*	51.2	*52.0*	-29.6	*-30.4*
7	1H2L	1	53.2	*63.7*	35.3	*33.9*	17.8	*29.9*
7	1L2H	2	26.6	*38.2*	64.7	*66.1*	-38.1	*-27.9*
8	3H4L	1	75.7	*65.7*	76.2	*64.0*	-0.5	*1.7*
8	3L4H	2	26.2	*37.2*	23.8	*36.0*	2.3	*1.2*
9	1L2H	1	31.2	*52.6*	34.5	*51.6*	-3.3	*1.0*
9	1H2L	2	28.2	*44.9*	65.5	*48.4*	-37.3	*-3.5*
10	3L4H	1	80.5	*72.8*	29.2	*25.8*	51.3	*47.0*
10	3H4L	2	85.2	*99.1*	70.8	*74.2*	14.5	*24.9*
11	1H2L	1	96.2	*96.6*	36.2	*45.4*	60.0	*51.2*
11	1L2H	2	12.1	*10.5*	63.8	*54.6*	-51.7	*-44.1*
12	3H4L	1	76.5	*94.7*	32.0	*39.5*	44.6	*55.2*
12	3L4H	2	53.6	*95.8*	68.0	*60.5*	-14.4	*35.3*
21	1L2H	1	0.0	*0.0*	24.8	*39.1*	-24.8	*-39.1*
21	1H2L	2	48.2	*80.6*	75.2	*60.9*	-27.0	*19.7*
22	3L4H	1	24.3	*39.5*	75.8	*63.8*	-51.5	*-24.3*
22	3H4L	2	33.4	*11.0*	24.2	*36.2*	9.2	*-25.3*
23	1H2L	1	37.9	*29.3*	43.9	*49.1*	-5.9	*-19.7*
23	1L2H	2	68.6	*82.1*	56.1	*50.9*	12.4	*31.2*
24	3H4L	1	81.5	*73.1*	59.6	*52.3*	21.9	*20.7*
24	3L4H	2	25.5	*38.0*	40.4	*47.7*	-14.9	*-9.7*
	Average		**49.0**	***55.0***	**50.0**	**50.0**	**-1.0**	***5.0***
	SE		**5.6**	***6.1***	**3.6**	**2.4**	**4.8**	***5.5***

*** TRT notation 1H2L indicated compartment 1 under "high" and compartment 2 under "low" condition**

Table focuses on "low" condition, "high" time in compartment and corresponding baseline are (100-displayed value, %), respectively, (high – baseline) equals –(low – baseline).

**** a negative value of POT $_{low}$- POT $_{baseline}$ means the high condition was preferred and a positive value means the low condition was preferred**

Table 5.5. Feed use (g $bird^{-1}day^{-1}$) of the test and stimulus birds under the three applied conditions for each of the three trials.

		Stimulus Birds		Test Birds	
Trial	**Trt**	**mean**	***SE***	**mean**	***SE***
High=25 ppm NH_3, Low <10 ppm NH_3	High	98	*1.5*	171	*19*
	Low	97	*1.2*	186	*12*
	Baseline	96	*2.4*	163	*13*
High=50 ppm NH_3, Low <10 ppm NH_3	High	98	*3.5*	167	*17*
	Low	99	*3.7*	187	*13*
	Baseline	102	*3.3*	149	*10*
High=30ppmNH_3 T=23.9℃, Low <10ppmNH_3 T=18.3℃	High	99	*3.1*	123	*6.4*
	Low	101	*3.4*	136	*13*
	Baseline	97	*2.1*	128	*8.4*

*Due to difficulties with the test bird feeding system, the feed wastage by test birds was high. Modifications for the temperature ammonia combination trial did reduce wastage, but usage was still higher than stimulus birds.

Temperature-ammonia combination testing

The first and second treatment applications of the conditions were tested for significant differences. The mean difference between “high+TN” condition and “low+cool” condition was 16.4 (±8.6 S.E.) minutes per hour for the first application indicating the “high+TN” was preferred, and - 8.5 (±10.8 S.E.) minutes per hour for the second application indicating the “low+cool” condition was preferred. The applications show a potential difference ($p=0.09$). Ultimately the responses to learned and relearned conditions were not significantly different, but this value still deserves further evaluation. All the results below were first broken down into treatment application 1 and 2, but as none were significantly difference ($\alpha=0.05$), the average of the two applications are reported.

The second analysis evaluated if the baseline compartmental choice influenced the preference when environmental conditions were applied. Result of the analysis showed a strong relationship between compartmental choices at baseline and their compartmental choice when the conditions were applied ($p=0.021$). The majority of the test birds (9 out of 15) showed the same compartmental preference in both treatment applications that they showed in the baseline period. In this study one test bird preferred the low+cool condition while two test birds preferred the high+TN condition in both treatment applications. Shaded values in Table 5.6 shows the compartment used the majority of the time in baseline was not retained during treatment application.

The final analysis done was a t-test to determine if the difference in compartment occupation time between the low+cool condition and the baseline was significantly different from zero. When this difference is significantly different from zero, a negative value means the high condition was preferred and a positive value means the low condition was preferred. The average difference between the low+cool compartment and the same compartment at baseline was -1.7±4.9% of occupation time (mean±SE, p=0.51). This indicates that these birds did not make a clear choice between the two conditions provided. Figure 5.4 shows the overall mean and standard error in minutes per hour the 15 birds spend in the high+TN or low+cool conditions. Feed and water usage was evaluated using a similar t-test. The average feed usage difference between the low+cool condition and baseline was 4.08±5.25 g/day, and the difference was -5.51±6.48 g/day (mean±SE, p=0.26) between high+TN and baseline. The average water usage difference between the low+cool condition and baseline was 6.4 ±9.3 g/day (mean±SE, p = 0.30).

In this study the number of movements each test bird made during the periods during treatment application were noted. Table 5.6 shows these values for each treatment application period. The overall number of movements for the treatment application period (~48 hours) was 57±8 (mean±SE). In the table the periods with the very high numbers of movements (>100) are shaded. There were four such periods. Three of these four periods correspond to the hen's switching of her compartmental preference from baseline to testing conditions. Each time a hen switched a compartmental preference from baseline to the treatment is noted in this table as a bold number. There are seven such periods during this study. There seems to be an indication (by the large number of movements) that some birds were having a difficult time choosing a compartment/condition.

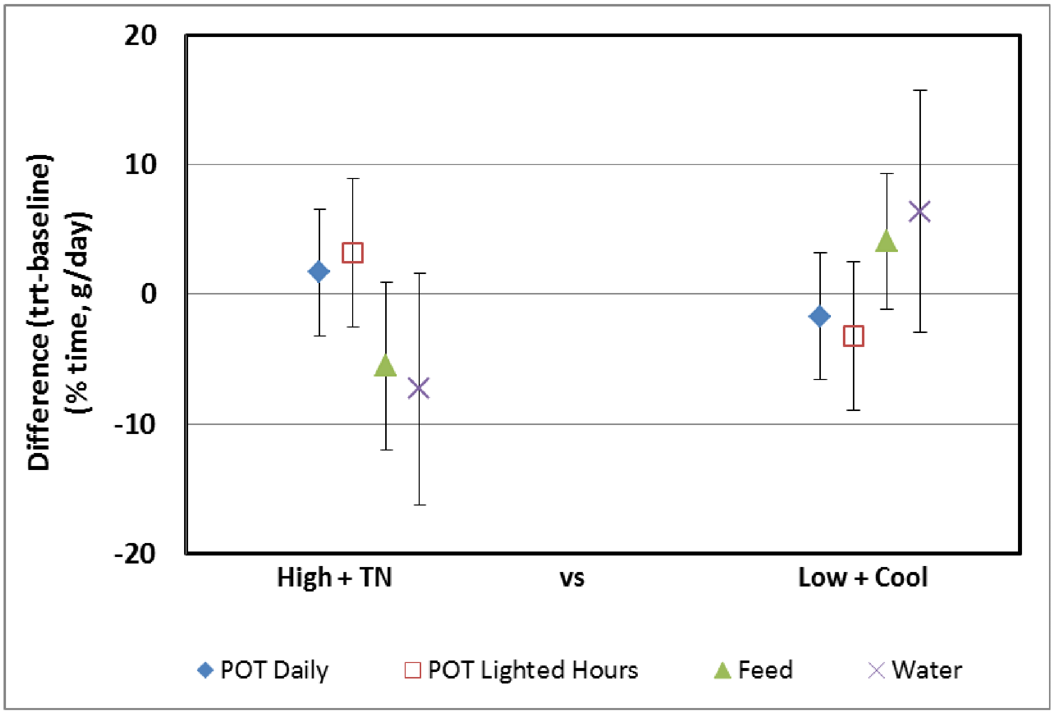


Figure 5.4. Daily and lighted-hour only difference in time spent and feed use in each environmental condition vs. the same compartments at baseline (n=15) (mean ± SE). The "low+cool" environment consists of <10 ppm ammonia and 18.3℃, while the "high+TN" condition was 30 ppm ammonia and 23.9℃.

Table 5.6. Percent of occupation time (POT) and compartment changes by the hen under baseline and low+cool testing conditions as determined using the EPTC system (low = <10 ppm ammonia and 18.3℃); Bold values are >100 movem ents, shaded cells indicate where hens switched their preferred compartment from baseline to application tested. Lighting was (16h light: 8h dark).

Test Bird	Trt *	Period Applied	POT in Low Compartment		Number of Compartment Changes		Baseline POT Corresponding to Low Condition		Difference (low-baseline)	
			Daily	*Light*	Daily	*Light*	Daily	*Light*	Dailyy	*Light*
1	1H2L	1	97.3	*95.9*	44	*44*	83.2	*89.8*	14.1	*6.1*
1	2H1L	2	1.4	*1.4*	22	*18*	16.8	*10.2*	-15.4	*-8.8*
2	3H4L	1	0.9	*1.4*	26	*26*	0.8	*1.2*	0.1	*0.2*
2	4H3L	2	87.8	*90.0*	24	*18*	99.2	*98.8*	-11.5	*-8.8*
3	2H1L	1	59.6	*37.5*	52	*52*	57.1	*38.9*	2.5	*-1.4*
3	1H2L	2	68.5	*53.0*	**147**	***143***	42.9	*61.1*	25.6	*-8.1*
4	4H3L	1	31.8	*24.2*	43	*42*	26.3	*35.6*	5.6	*-11.4*
4	3H4L	2	58.8	*62.7*	96	*95*	73.7	*64.4*	-15.0	*-1.8*
5	2H1L	1	6.2	*4.7*	21	*18*	4.5	*7.9*	1.7	*-3.2*
5	1H2L	2	78.8	*68.8*	42	*42*	95.5	*92.1*	-16.7	*-23.3*
6	4H3L	1	70.9	*73.7*	59	*59*	61.3	*73.5*	9.6	*0.2*
6	3H4L	2	25.2	*0.0*	41	*41*	38.7	*26.5*	-13.6	*-26.5*
7	3H4L	1	26.7	*40.7*	91	*91*	26.5	*38.6*	0.2	*2.1*
7	4H3L	2	95.9	*93.9*	59	*55*	73.5	*61.4*	22.4	*32.5*
8	2H1L	1	40.5	*57.2*	94	*88*	74.1	*77.7*	-33.7	*-20.4*
8	1H2L	2	86.8	*79.9*	40	*38*	25.9	*22.3*	61.0	*57.6*
9	4H3L	1	22.3	*3.9*	72	*56*	52.3	*61.0*	-30.0	*-57.1*
9	3H4L	2	81.6	*96.2*	67	*52*	47.7	*39.0*	33.8	*57.2*
10	1H2L	1	26.3	*39.5*	**105**	***105***	29.6	*27.1*	-3.3	*12.4*
10	2H1L	2	33.7	*0.0*	**180**	***180***	70.4	*72.9*	-36.8	*-72.9*
11	3H4L	1	74.2	*85.7*	61	*43*	30.3	*46.7*	43.9	*39.0*
11	4H3L	2	5.3	*7.8*	39	*30*	69.7	*53.3*	-64.4	*-45.5*
12	1H2L	1	88.8	*91.3*	19	*12*	55.5	*61.0*	33.3	*30.3*
12	2H1L	2	29.2	*19.3*	33	*26*	44.5	*39.0*	-15.2	*-19.6*
13	3H4L	1	40.3	*60.5*	55	*49*	41.7	*32.3*	-1.4	*28.1*
13	4H3L	2	16.7	*24.2*	**120**	***116***	58.3	*67.7*	-41.6	*-43.5*
14	2H1L	1	4.7	*7.2*	5	*5*	26.7	*40.5*	-22.0	*-33.3*
14	1H2L	2	94.7	*92.4*	7	*7*	73.3	*59.5*	21.4	*32.9*
15	4H3L	1	1.7	*2.5*	5	*3*	0.8	*1.2*	1.0	*1.3*
15	3H4L	2	91.5	*88.2*	27	*23*	99.2	*98.8*	-7.7	*-10.6*
	Average		**48.3**	***46.8***	**57**	***53***	**50.0**	**50.0**	**-1.7**	***-3.2***
	SE		**6.2**	**6.6**	**8**	**8**	**5.1**	**5.0**	**4.9**	**5.7**

*** TRT notation 1H2L stands for compartment 1 under the "high" and compartment 2 under the "low" condition**

Table focuses on low condition, high time in compartment and corresponding baseline are (100-displayed %) respectively, high minus baseline difference will be –(low –baseline)

**** a negative value of POT $_{low}$- POT $_{baseline}$ means the high condition was preferred and a positive value means the low condition was preferred**

Conclusions

The ammonia preference trials evaluated if the pullets and laying hens would avoid ammonia concentrations of 25 or 50 ppm when an environment with <10 ppm NH_3 was present. In the 25 ppm trial the birds avoided the higher condition (In the 50 ppm trial, indication that the birds might be avoiding the high condition is not significant). Percentage of occupation time (POT) was the significant indicator, with the preference being more apparent during lighted hours of the day. Feed use by the test birds was higher than normally expected values, most likely due to wastage, but did show a trend of being higher in the low NH_3 condition. Interestingly, of the two NH_3 concentrations of 25 and 50 ppm, preference for the <10 ppm environment (as evidenced by significance in POT) was more apparent over the 25 ppm than over the 50 ppm condition.

The temperature-ammonia combination trial evaluated if the birds would choose thermal comfort or better air quality. The data suggested no clear preference, as evidenced by POT, feed and water use under the test conditions. Instead the hens showed strong compartmental preferences that they had developed during baseline conditions, which carried through the application of environmental conditions. Birds that did change compartmental preference with environmental conditions often had more frequent movements, possibly indicating difficulty with the choice. This study shows that the hens will not avoid a cool condition of 18.3℃ (65℉) when combi ned with better air quality. This means that from the hens' comfort perspective, extra ventilation may be used to improve indoor air quality so long as the indoor temperature is kept at or above 18.3℃ (65℉).

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CHAPTER 6

Final Summary

This dissertation attempts to cover a number of questions and concerns regarding the aviary laying-hen housing system. The four papers included look at a variety of factors and implications of the aviary system. The first three papers were developed from monitoring at two commercial aviary laying hen houses. Each house was populated with approximately 50,000 Hy-Line brown hens, which were kept in the barn from approximately 17 to 80 weeks of age with no molt. The site was monitored for 19 months in order to gather complete flock information from both houses. The final paper is from a lab study looking at environmental preference. The following is a summary of the findings and conclusions from the studies.

1. The first paper reports daily gaseous and particulate matter concentrations and emission rates, along with daily house temperatures, relative humidity, and ventilation rates. The average daily indoor NH_3, CO_2, CH_4, PM_{10}, and $PM_{2.5}$ concentrations were 8.7 ppm, 1,636 ppm, 10.0 ppm, 2.3 mg/m3, and 0.25 mg/m3, respectively. Overall this system has emission rates that relate well to a conventional cage houses with manure belts, with the exception of ammonia being somewhat higher. The ammonia emissions are lower than those reported on aviary systems in Europe however. Daily NH_3, CO_2, CH_4, PM_{10}, and $PM_{2.5}$ emissions were 0.15, 75, 0.09, 0.11, and 0.008 g/bird, respectively. The high dust concentrations and emission are of concern, especially from the birds' health perspective and possible particulate matter emission regulation.
2. The objectives of work reported in the second paper were to evaluate whole-house total and latent heat production rates. These numbers were to be compared to current literature and broken down into light and dark period as a way to see if bird activity affects heat production rates. Total heat production rate (THP) of Hy-Line brown laying hens and house-level latent heat (LPH) and sensible heat production rate (SHP) for both houses were quantified over the entire production cycle (17 – 83 wk) using indirect calorimetry and mass balance techniques. The values were 5.94, 1.83, 4.11W/kg for TWA THP, LHP, and SHP, respectively. The THP values matched well with recent literature values, while the LHP values were lower than

those reported for W36 hens measured in lab settings. The ratio of light to dark THP was somewhat higher than in previous studies, which is most likely due to the increased activity level of the birds when they were given access to the floor. These original heat and moisture production data lay a foundation for the design and efficient operation of ventilation, cooling and heating systems for the alternative aviary hen housing.

3. The third paper describes monitoring of electricity and fuel use in the aviary housing. Electricity monitoring was applied to ventilation circuits, manure belt blowers, lighting, to whole house to determine power usage. The ventilation system is the most variable electricity consumer. The ventilation rate to power input ratio (or fan efficiency) was less than 80% of the reported efficiency values. The manure belt blowers were the second major user of electricity and the potential for intermittent operation of the blowers deserves further evaluation. Propane usage was also monitored continuously over 15 months and was quite low. Because the ambient temperatures were below T_{bal} (temperature below which supplemental heat is needed to maintain temperature) and the heaters were not running regularly, although ventilation scheme may have been achieving good indoor temperature it was not necessarily achieving ideal RH control.
4. The final study was designed to look at behavioral response of pullets and hens to the potential winter conditions. The initial trials were designed to identify ammonia levels at which the birds avoid the compartments. In the trial the birds avoided the higher condition (25 vs <10 ppm). Percentage of occupation time (POT) was the significant indicator, with the preference being more apparent during lighted hours of the day. The temperature-ammonia combination trial evaluated if the birds would choose thermal comfort or better air quality. The data suggested no clear preference, as evidenced by POT, feed and water use under the test conditions. This study did not show that the hens avoided a cool condition of 18.3℃ (65℉) when combined with better air quality. From the hens' comfort perspective, extra ventilation may be used to improve indoor air quality as long as the indoor temperature is kept at or above 18.3℃ (65℉) witho ut compromising the hen’s welfare.

Overall, the alternative laying hen housing systems are of interest in the US laying hen industry. The aviary system is perhaps the most mechanized cage-free alternative housing system option on the market. There are certainly issues and concerns with this system for example the particulate matter concentration and emissions as well as potential ammonia emissions. The lower stocking density and its impacts on ventilation, fuel and energy use are also concerns. Overall at this commercial site, perhaps the most difficult issue necessary to be addressed is the particulate matter. It would be nice to have more data on the dust level from other sites to determine if these levels are similar on other sites or unique to the site/management or are a prevalent issue for the industry as a whole. There are also concerns about cost, many of which are not discussed above. This dissertation does note some of the issues and provides unique field-based data that may be used in designing or modifying these houses in the future.