FINAL PROJECT REPORT

on

Southeastern Broiler Gaseous and Particulate Matter Emissions Monitoring

Submitted to

Tyson Foods Inc.

by

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and

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Date of Submission: December 2009

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Executive Summary

This report describes the measurement methodologies and results of gaseous and particulate matter (PM) emissions (ammonia, carbon dioxide, hydrogen sulfide, non-methane hydrocarbon or NMHC, total suspended particulate or TSP, PM_{10}, and $PM_{2.5}$) from two typical Tyson broiler production houses located on two separate farm sites in western Kentucky. Each broiler house was 43 ft x 510 ft (13 m x 155 m), with an initial, nominal placement of 25,800 (winter) to 24,400 (summer) Cobb-Cobb straight-run broilers per flock. The broilers were grown on new or built-up litter to an average age of 52 d (50 - 54 d), with flock downtime (i.e., empty house) ranging from 9 to 41 d.

Two state-of-the-art environmentally-controlled mobile air emissions monitoring units, one for each site, were used for the year-round, continuous measurements. The instruments used to measure the concentrations of the aerial constituents in the background and exhaust air of the broiler houses included a photoacoustic multi-gas analyzer for ammonia (NH_3) and carbon dioxide (CO_2), a UV pulsed-fluorescence analyzer for H_2S, a dual-channel methane/NMHC/total hydrocarbon analyzer with a dual flame ionization detector (FID) for NMHC, and tapered element oscillating microbalances (TEOMs) for TSP, PM_{10} and $PM_{2.5}$. Building ventilation rate (VR) was measured by precisely monitoring building static pressure and operation time (1 s sampling interval) of all exhaust fans. The performance of each fan was carefully calibrated *in-situ* with a state-of-the-art ventilation fan calibration device, known as the Fan Assessment Numeration System or FANS. The emission rate (ER) was then determined based on the measured concentration difference between exhaust air and incoming air and the corresponding VR, with corrections for air temperature, air density, and barometric pressure effects. Operation and maintenance of the monitoring instruments and collection and management of the data followed the protocols as set forth in an EPA-approved Category I Quality Assurance Project Plan (QAPP). A particularly noteworthy aspect of the QAPP was the component error analysis that revealed the uncertainty of the measured air emission values to be less than 10% under the monitoring conditions.

The gaseous and PM emissions were monitored quasi-continuously at 2 to 6 min intervals over a 13-month time period, covering nearly six consecutive flocks per house. Consequently, the amount of emission data collected for each constituent, expressed in house-day, was 718 for NH_3, 616 for H_2S, 471 for NMHC, 602 for TSP, 596 for PM_{10}, 578 for $PM_{2.5}$, and 714 for CO_2.

The gaseous and PM emissions from the broiler houses were expressed in various units to meet different purposes of the data application, as follows: 1) annual total emission per house, 2) annual average emission per 1,000 birds or per bird marketed, 3) annual average emission per animal unit (AU = 500 kg or 1100 lb live body weight) marketed and 4) daily mean emission per house. All values included emissions during the period between flocks or downtime. In addition, regression equations were developed to relate gaseous and PM ER to broiler age. The respective emission values (mean ± standard deviation) were:

1) Annual total emission per house (mean ± S.E.): 5.1 ± 0.19 US tons (4,620 ± 171 kg) NH_3, 42.3 ± 2.1 lb (19.2 ± 0.92 kg) H_2S, 510 lb ± 59.6 (231 ± 27 kg) NMHC, 1,731 ± 58.6 lb (785 ± 26.6 kg) TSP, 727 ± 93.4 lb (330 ± 42.3 kg) PM_{10}, 71.7 ± 4.4 lb (32.5 ± 2.0 kg) $PM_{2.5}$, and 718 ± 21.6 US ton (651 ± 9.8 metric ton) CO_2.

2) Annual average emission per 1,000 birds marketed (mean ± S.E.): 78.1 ± 3.1 lb NH_3, 0.32 ± 0.01 lb H_2S, 3.9 ± 0.45 lb NMHC, 13.2 ± 0.46 lb TSP, 5.56 ± 0.71 lb PM_{10}, 0.55 ± 0.04 lb $PM_{2.5}$, and 5.49 ± 0.16 US ton CO_2. Expressed on a per-bird-marketed basis, the annual average emissions were: 35.4 ± 1.32 g NH_3, 0.147 ± 0.01 g H_2S, 1.77 ± 0.21 g NMHC, 6.01 ± 0.21 g TSP, 2.52 ± 0.33 g PM_{10}, 0.25 ± 0.01 g $PM_{2.5}$, and 4.98 ± 0.15 kg CO_2.

3) Annual average emission per 500 kg AU marketed (mean ± S.E.): 6.25 ± 0.23 kg of NH_3, 26.0 ± 1.26 g of H_2S, 0.29 ± 0.03 g NMHC, 1.06 ± 0.04 kg TSP, 0.45 ± 0.06 kg PM_{10}, 0.044 ± 0.003 kg $PM_{2.5}$, and 881 ± 26.5 kg CO_2.

4) Daily mean emission per house (mean ± S.D.): 31.4 ± 14.9 lb (14.2 ± 6.8 kg) NH_3, 0.14 ± 0.09 lb (65.7 ± 42 g) H_2S, 1.68 ± 0.94 lb (0.8 ± 0.4 kg) NMHC, 6.13 ± 4.13 lb (2.78 ± 1.87 kg) TSP, 2.57 ± 1.88 lb (1.16 ± 0.85 kg) PM_{10}, 0.25 ± 0.22 lb (0.11 and 0.10 kg) $PM_{2.5}$, 2.55 ± 1.32 us-ton (2.31 ± 1.2 mton) CO_2. For the downtime between flocks, the daily mean emission per house were: 18.5 ± 17.8 lb (8.39 ± 8.1 kg) NH_3, 0.020 ± 0.028 lb (9.0 ± 12.5 g) H_2S, 0.45 ± 0.64 lb (0.2 ± 0.3 kg) NMHC, 0.12 ± 0.19 lb (0.05 ± 0.086 kg) TSP, 0.052 ± 0.085 lb (0.024 ± 0.039 kg) PM_{10}, 0.03 ± 0.06 lb (0.014 ± 0.027 kg) $PM_{2.5}$, 0.21 ± 0.20 US-ton (0.19 ± 0.18 metric ton) CO_2.

To improve convenience of reading and application, we have presented the emissions data in a summary table (Table I). The data from this comprehensive and extensive monitoring of broiler production houses are expected to enhance the national emissions inventory on animal feeding operations.

Table I. Summary of air emissions from two commercial broiler houses in western Kentucky continually monitored over a 13-month period involving nearly 6 consecutive flocks (mean ± S.E. or S.D.)

Emission Values	Gaseous and Particulate Matter Constituents						
	NH_3	H_2S	NMHC	TSP	PM_{10}	$PM_{2.5}$	CO_2
Annual Total per House (± S.E.)	5.1 ± 0.19 US ton (4620 ± 171 kg)	42.3 ± 2.1 lb (19.2 ± 0.92 kg)	510 lb ± 59.6 lb (231 ± 27.0 kg)	1731 ± 58.6 lb (785 ± 26.6 kg)	727 ± 93.4 lb (330 ± 42.3 kg)	71.7 ± 4.4 lb (32.5 ± 2.0 kg)	718 ± 21.6 US ton (651 ± 9.8 metric ton)
Annual Average per 1,000 Birds Marketed (± S.E.)	78.1 ± 3.1 lb	0.32 ± 0.01 lb	3.9 ± 0.45 lb	13.2 ± 0.46 lb	5.56 ± 0.71 lb	0.55 ± 0.04 lb	5.49 ± 0.16 US ton
Annual Average per Bird Marketed (± S.E.)	35.4 ± 1.32 g	0.147 ± 0.01 g	1.77 ± 0.21	6.01 ± 0.21 g	2.52 ± 0.33 g	0.25 ± 0.01 g	4.98 ± 0.15 kg
Annual Average per AU Marketed (± S.E.)	6.25 ± 0.23 kg	26.0 ± 1.26 kg	0.29 ± 0.03 kg	1.06 ± 0.04 kg	0.45 ± 0.06 kg	0.044 ± 0.003 kg	881 ± 37.5 kg
Daily Mean per House (± S.D.)	31.4 ± 14.9 lb (14.2 ± 6.8 kg)	0.14 ± 0.09 lb (65.7 ± 42 g)	1.68 ± 0.94 lb (0.8 ± 0.4 kg)	6.13 ± 4.13 lb (2.78 ± 1.87 kg)	2.57 ± 1.88 lb (1.16 ± 0.85 kg)	0.25 ± 0.22 lb (0.11 ± 0.1 kg)	2.55 ± 1.32 US ton (2.31 ± 1.2 metric ton)
Downtime Daily Mean per House (± S.D.)	18.5 ± 17.8 lb (8.39 ± 8.1 kg)	0.02 ± 0.028 lb (9.0 ± 12.5 g)	0.45 ± 0.64 lb (0.2 ± 0.3 kg)	0.12 ± 0.19 lb (0.05 ± 0.086 kg)	0.052 ± 0.085 lb (0.024 ± 0.039 kg)	0.03 ± 0.06 lb (0.014 ± 0.027 kg)	0.21 ± 0.20 US ton (0.19 ± 0.18 metric ton)

NMHC = non-methane hydrocarbon; TSP = total suspended particulate, AU = animal unit = 500 kg live body weight

Introduction

According to recent estimates by EPA (2005), broiler operations constitute 54% of poultry contributions to the U.S. ammonia inventory, and 14.8% of animal agriculture emissions. A comprehensive review by the National Academy of Science (NAS) (National Research Council, 2003) regarding air emissions data pertaining to U.S. animal feeding operations (AFOs) concluded that such data are lacking for U.S. animal production conditions. The review called for collection of baseline emission data and development of process-based models to predict such air emissions. In response to the NAS recommendations, the United States Department of Agriculture (USDA) has made quantification of air emissions from AFOs one of the top priorities in its Initiative for Future Agriculture and Food System (IFAFS) Program and subsequently the National Research Initiative (NRI) Program. As a result, since 2002 great strides have been made toward collection of baseline air emissions from U.S. AFO facilities. Noticeable among the funded studies was the six-state (IA, IN, IL, MN, NC, TX) project on air emissions from cattle and swine facilities, and the three-state (IA, KY and PA) project on ammonia emissions from layers (in Iowa and Pennsylvania; Liang et al., 2005) and broilers (in Kentucky and Pennsylvania; Wheeler et al., 2006). There is a lack of air emissions (except for ammonia) data for broiler housing systems. During this time period, more research findings on ammonia emissions from European broiler houses have been reported (Nicholson et al., 2004). However, with the exception of the study by Lacey et al. (2003), information regarding emission rates of particulate matter (PM), hydrogen sulfide (H_2S) and nonmethane hydrocarbons (NMHC) from broiler houses remains meager.

The objective of this study was to determine and report air emissions based on continuous measurement of aerial pollutant concentrations and fan airflow data over a one-year period from two broiler houses representative of commercial broiler production in the southeastern United States. The aerial pollutants quantified in this monitoring study include ammonia (NH_3), carbon dioxide (CO_2), H_2S, NMHC, total suspended particulate (TSP), PM with aerodynamic diameter ≤ 10 μm (PM_{10}), and PM with aerodynamic diameter ≤ 2.5 μm ($PM_{2.5}$). The emissions data presented in this report were collected using continuous air emissions monitoring over a 13-month period at two Tyson broiler production houses in western Kentucky.

Monitoring System Description

Study Sites and Monitoring System Overview

Two broiler houses, located on two different sites (40 miles or 64 km apart), associated with Tyson Foods broiler operations in western Kentucky were selected. Their locations are shown in Figure 1, and the location of the specific house at each site is shown in aerial photos in Figure 2. The monitored broiler production houses used tunnel ventilation and static pressure controlled box air inlets along the sidewalls (Figure 3), which are representative of the typical production practices in terms of housing style (tunnel ventilation) and environmental control strategy (pancake brooders along with space heaters), bird management (half-house brooding), and litter management and handling schemes (de-caking of litter between flocks and annual litter removal).

To continuously quantify dynamic air emissions from the broiler production systems, an accurate and responsive measurement system was required. The mass of air pollutants emitted from a facility is the product of the pollutant concentration difference between outgoing and incoming air streams and volume of air exchanged through the facility. The use of intermittent ventilation by cycling ventilation fans off and on, especially when the birds were young, made it necessary to coincide in-house pollutant concentrations to periods of fan operation in order to properly capture the representative emissions.

Concentrations of the gaseous and PM constituents were measured with the following instruments: photoacoustic NH_3 and CO_2 analyzer (0-2000 ppm ± 1% NH_3; 0-34000 ppm ± 1% CO_2; INNOVA model 1412, INNOVA AirTech Instruments A/S, Denmark[1]), UV pulsed-fluorescence H_2S analyzer (0-20000 ppb ± 0.5%; Model 101E, Teledyne API, San Diego, CA), dual-channel methane/NMHC/total hydrocarbon analyzer with a dual flame ionization detector (FID) (0-100 ppm ± 1%; Model 200, VIG Industries Inc., Anaheim, CA), and Tapered Element Oscillating Microbalance (TEOM) PM monitors (0-10,000 ± 5 ug/m^3; Model 1400a, Thermo Fisher Scientific, Waltham, MA). The gaseous and PM analyzers were used in conjunction with a custom-fabricated multi-point sampling and data acquisition system. Building ventilation rate of the exhaust air was based on individual fan performance curves obtained on-site using the Fan Assessment Numeration System (FANS) developed in the US (Gates et al., 2004).

Each broiler house had its own Mobile Air Emissions Monitoring Unit (MAEMU) that housed the gaseous and PM concentration measurement and fan flow monitoring systems, and provided an environment-controlled space (Figure 4). Air sampling lines from the broiler house sampling points (representing the building exhaust air streams) to the MAEMU/analyzers were protected against in-line moisture condensation with insulation and temperature-controlled resistive heating cable. Fan operational status and building static pressure were both continuously monitored (1-second intervals). These data were used in conjunction with individual fan operation curves to calculate the exhaust ventilation rate by each fan during operation. A real-time data acquisition system (DAQ) program was developed using LabView 7 software (National Instruments Corporation, Austin, TX) and used to acquire data, automate control of sampling locations, display real-time data, and deliver data and system operation status (Figures 5 and 6). The system was connected to the internet via a high-speed satellite. Each MAEMU housed a gas sampling system (GSS), gas analyzers, environmental instrumentation, a computer, data acquisition system, and other peripheral devices and equipment needed for the study. Gaseous emissions were sampled continuously at 120-second intervals. NH_3 and CO_2 samples were continuously collected and analyzed every 30 seconds, with every fourth concentration value used as the stabilized reading in the emission calculation. PM concentrations were recorded at 300-s intervals. Emissions were calculated using the concentrations measured when the house ventilation system was in operation. Complete details of the monitoring system and data collection are described below.

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[1] Mention of product or company names is for presentation clarity and does not imply endorsement by the authors or their affiliation not exclusion of other suitable products.
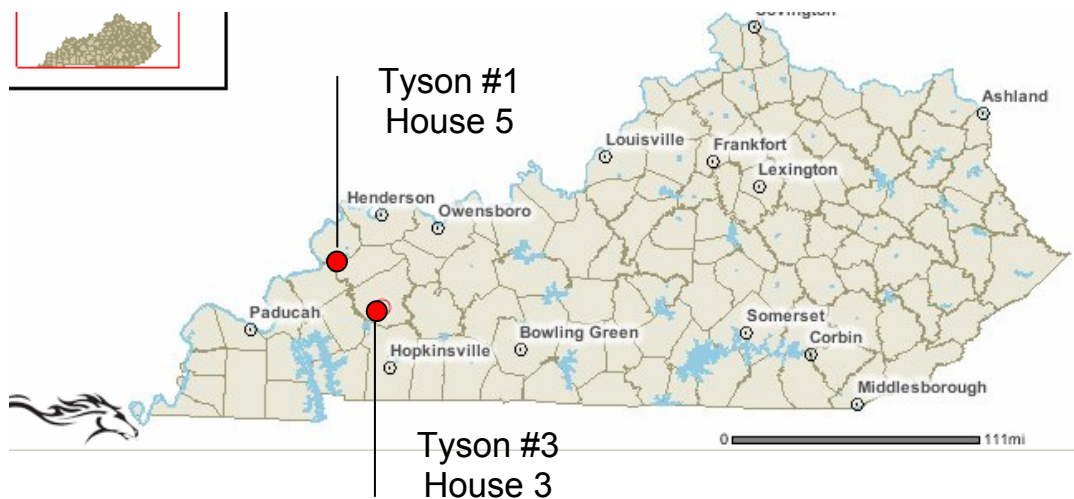
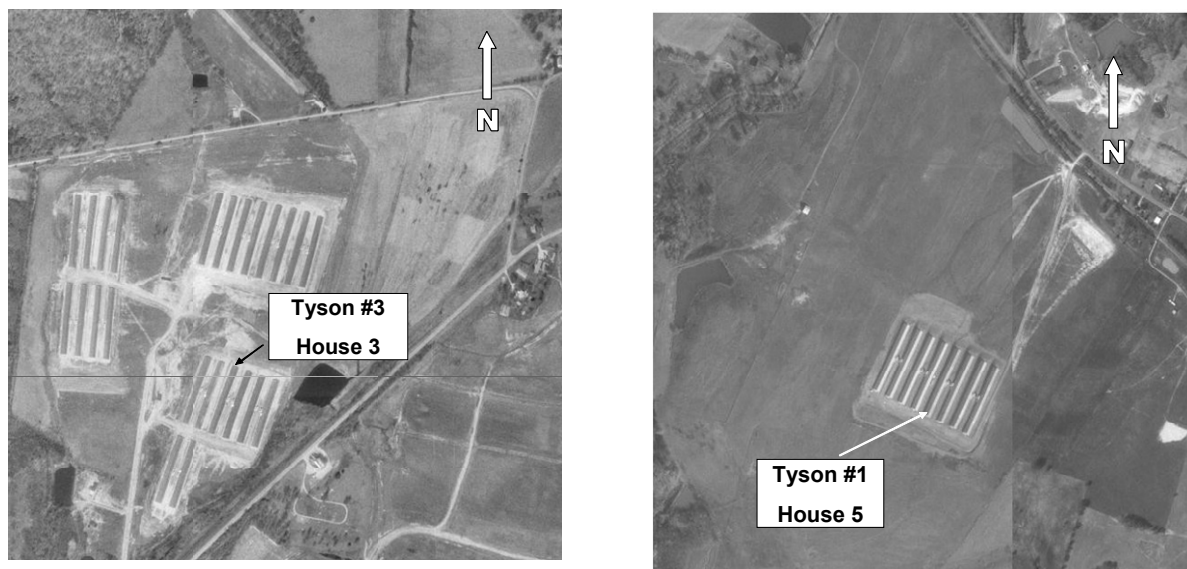**Figure 1. Broiler house air emission measurement sites in Kentucky.**

Figure 2. Aerial photos indicating the locations of each monitored broiler house.

Figure 3. Tunnel ventilation fans and static pressure-controlled box air inlets representative of typical southeastern U.S. broiler facilities.

Figure 4. Environmentally-controlled Mobile Air Emissions Monitoring Units (MAEMU).
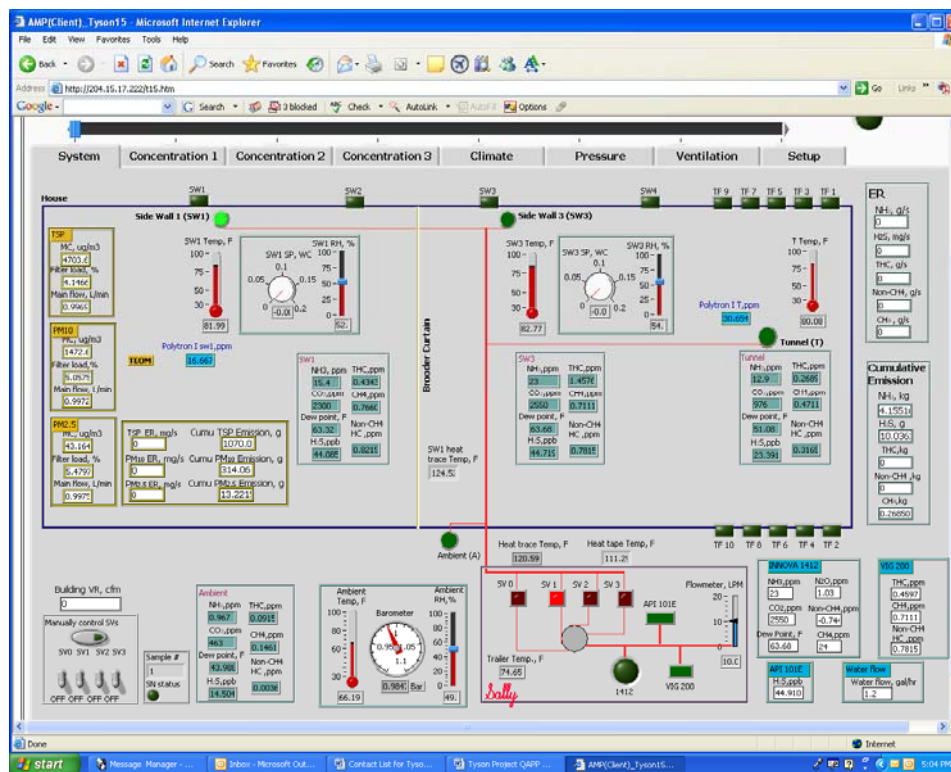
Figure 5. Screen display of the broiler emissions monitoring program developed in LabView 7.
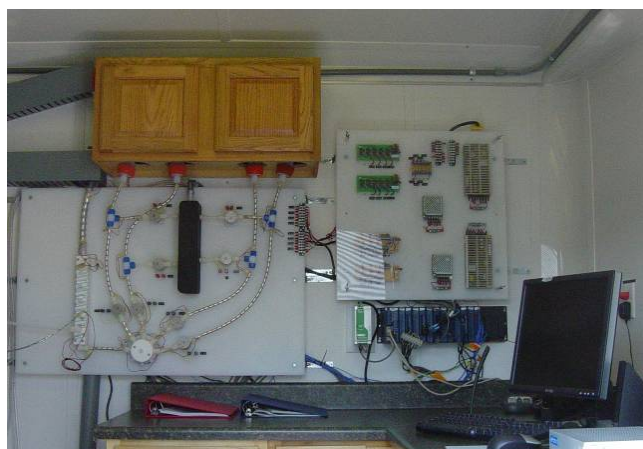

Figure 6. Photograph of the positive-pressure gas sampling system used in the study.

Broiler House Characteristics

The two broiler houses each measured 43 ft x 510 ft (13.1 m x 155.5 m) and were built in the early 1990s. Each houses had insulated drop ceilings (about R19), box air inlets (6 x 26 inch or 15 x 66 cm) along the sidewalls (26 per sidewall), 26 pancake brooders (30,000 Btu/hr or 8.8 kW each), three space furnaces (225,000 Btu/hr or 65.9 kW each), four 36-inch (91-cm) diameter sidewall exhaust fans spaced about 120 ft (36.6 m) apart, and ten 48-inch (123-cm) diameter tunnel fans. One 36-inch (91-cm) fan (SW1) used for minimum ventilation was located in the brooding end of the house. Two 80-ft (24-m) sections of evaporative cooling pads were

located in the opposite end from the tunnel fans. The houses were also equipped with foggers for additional cooling, if needed. Rice hulls were used as litter bedding in both houses.

Flock Characteristics

The sampling periods were 13 months (Feb 14, 2005 to March 14, 2007) and 12.5 months (Feb 20, 2005 to March 5, 2007) for Tyson 1-5 and Tyson 3-3, respectively. The 13 month duration assured that the project characterized long-term emissions, hence the impacts of climatic conditions of different seasons and grow-out cycles (litter age and condition). At the ending dates, six full flocks had been monitored from Tyson 1-5 and the sixth flock was ongoing for Tyson 3-3 (Table 1). Each house had an initial, nominal placement of 25,800 Cobb-Cobb straight-run (mixed sex) broilers in winter and 24,400 in summer. The average grow-out period was 52 days. An automatic bird weigh-scale system (Model RSC-2, Rotem, Petach Tikva, Israel) was placed in each house to continuously monitor bird body weight. Bird mortality was also recorded, allowing for expression of emission on the basis of per bird or per 500 kg animal unit (AU). Both houses had new bedding at the beginning of monitoring. During the one-year period, one cleanout of the litter was performed for Tyson 1-5 on Aug 26, 2006 (after 3 flocks) and new bedding was placed on Aug 29, 2006; Tyson 3-3 had a litter cleanout after 5 flocks (on Feb 3, 2007) and new bedding was placed (on Feb 5, 2007).

Table 1. Description of flock and downtime (empty house between flocks) information during the aerial emissions monitoring study

	Start Date	End Date	Flock No.	House Condition	Litter condition*	# of birds placed	Total # of days	Complete-data days (CDD)						
								NH_3	CO_2	H_2S	NMHC	TSP	PM_{10}	$PM_{2.5}$
Tyson 1-5	2/14/2006	4/4/2006	1	Occupied	BUL	25,830	50	50	50	50	29	48	48	48
	4/5/2006	4/20/2006		Empty	BUL		16	14	14	14	4	6	6	6
	4/21/2006	6/9/2006	2	Occupied	BUL	22,995	50	50	50	50	41	48	46	48
	6/10/2006	6/21/2006		Empty	BUL		12	11	11	10	11	6	0	5
	6/22/2006	8/10/2006	3	Occupied	BUL	24,465	50	50	50	27	17	45	47	33
	8/11/2006	9/4/2006		Empty	Mixed		25	24	24	9	17	4	4	0
	9/5/2006	10/25/2006	4	Occupied	NB	25,695	51	51	51	51	49	48	48	44
	10/26/2006	11/16/2006		Empty	BUL		22	21	21	21	20	2	2	2
	11/17/2006	1/9/2007	5	Occupied	BUL	25,080	54	50	50	50	46	46	46	42
	1/10/2007	1/21/2007		Empty	BUL		12	12	12	12	11	5	2	5
	1/22/2007	3/14/2007	6	Occupied	BUL	26,600	52	48	48	48	23	46	46	46
Tyson 3-3	2/20/2006	4/10/2006	1	Occupied	BUL	25,515	50	44	44	19	24	46	46	46
	4/11/2006	5/21/2006		Empty	BUL		41	39	39	15	16	21	21	21
	5/22/2006	7/11/2006	2	Occupied	BUL	24,450	51	48	48	32	33	46	46	46
	7/12/2006	7/27/2006		Empty	BUL		16	15	15	8	1	8	8	8
	7/28/2006	9/19/2006	3	Occupied	BUL	24,380	54	53	53	46	30	51	51	51
	9/20/2006	10/4/2006		Empty	BUL		15	14	14	14	10	8	8	8
	10/5/2006	11/27/2006	4	Occupied	BUL	25,778	54	53	49	49	34	52	52	50
	11/28/2006	12/13/2006		Empty	BUL		16	14	14	14	8	5	8	8
	12/14/2006	2/2/2007	5	Occupied	BUL	24,970	51	27	27	47	32	47	47	47
	2/3/2007	2/11/2007		Empty	BUL		9	8	8	8	5	3	3	3
	2/12/2007	3/5/2007	6	Occupied	NB	26,013	22	22	22	22	10	11	11	11

* NB= New bedding; BUL= Built-up litter

Monitoring System Specifics

Concentrations of NH_3 and CO_2 for the background (or incoming air) and exhaust air were measured with an advanced photoacoustic multi-gas analyzer (INNOVA model 1412, INNOVA AirTech Instruments A/S, Denmark), an EPA-accepted measurement instrument for AFO NH_3 emission monitoring. This type of analyzer has been widely used by European scientists and recently used by U.S. scientists in AFO air emission studies (Fergusun et al. 1998ab, Fenyvesi, et al., 2001, Nicks et al., 2003, Guarino et al., 2003, Li, 2006,). These units proved to be accurate, responsive and stable. The INNOVA 1412 multi-gas analyzer was setup with a 1-second (s) sampling integration time and fixed flushing time: 2 s for the chamber and 3 s for the tubing; the required time to complete one sampling cycle for NH_3, CO_2 and dew-point temperature measurements was approximately 22 s. The response time of the analyzer to step changes in gas concentrations was tested extensively. The response time for the measured concentration to reach 98% of the calibration gas value (T-98) for the given NH_3 calibration gas was 88 seconds using NH_3 calibration gas of both 22.8 and 60.8 ppm (±2% accuracy) (Matheson Gas Products, Inc., Montgomeryville, PA). Thus, four measurement cycles (88 seconds) were required to reach the 98% response level for NH_3. Using this approach, the first three readings were discarded and only the fourth reading was used for emission calculations. In April 2006, hydrocarbon and nitrous oxide (N_2O) filters were added to the INNOVA 1412. The time to complete a single measurement cycle was increased from 22 s to 30 s. In turn, this increased the time to complete four cycles from 88 s to 120 s. As practiced before, only the fourth cycle measurements were used for the emissions calculations.

The UV pulsed fluorescence H_2S analyzer (Model 101E, Teledyne API, San Diego, CA) is a microprocessor controlled analyzer that determines the concentration of H_2S in a sample of gas drawn through the instrument. It requires that sample gases be supplied at ambient atmospheric pressure in order to establish a constant gas flow through the sample chamber. The 98% response time of the API 101E is 96 s. According to the response time of INNOVA 1412, the last H_2S readings correlated to the four INNOVA cycles were used for the H_2S emission calculation.

A VIG model 200 methane/nonmethane/total hydrocarbon analyzer (Model 200, VIG Industries Inc., Anaheim, CA) uses column technology to separate methane and non-methane from total hydrocarbons and uses a dual FID (flame ionization detectors) to measure each component in the air sample. The response time of NMHC is 70 s, and the NMHC reading was updated every 3 minutes. Every NMHC reading from the VIG 200 analyzer was identified with the corresponding sampling location and used for the emission calculation.

Air samples were drawn from three locations in each house as well as from an outside location to provide the ambient background data (Figure 7). One sampling location was near the primary minimum ventilation (36-in) sidewall fan (SW1) used for cold weather ventilation (in the brooding half of the house). The second sampling location was near the third sidewall (36-in) fan (SW3, non-brooding end). The third location was at the tunnel end (TE). The ambient sample location (A) was between the inlet boxes opposite of the sidewall with the exhaust fans. The mass of

pollutant in the background (inlet) air was subtracted from that in the exhaust air when calculating aerial emissions from the house.

Placement of the air sampling ports was as follows: for the two sidewall sampling locations, the sampling ports and temperature sensors were located 4 ft (1.2 m) from the fan in the axial direction, 7.5 ft (2.3 m) in the radial direction, and 3 ft (1 m) above the floor. For the tunnel-end sampling location, the sampling port and temperature sensor were located at the center line of the house (i.e. 21.5 ft or 6.6 m from each sidewall) and 24 ft (7.3 m) from the end wall. Sampling locations and placement of the sampling ports were chosen to maximize representativeness of the air leaving the houses. Each sample inlet point was equipped with dust filters to keep large PM from plugging the sample tubing, servo valves, and the measurement instruments. Each sample port consisted of two separate filter inlets joined in a "tee" to provide redundancy in the event of filter clogging.

A positive pressure gas sampling system (PP-GSS) was used in the MAEMU for measurement of broiler house air emissions (Figure 8). The PP-GSS continuously pumps sample air from all locations using the location-designated individual pumps. The sample air was by-passed when not analyzed. The schedules of sampling events and sequences were as follows. If the ventilation fans at the three in-house sampling locations (SW1-location 1, SW3-location 2 and TE-location 3) were all running, air samples from each location were collected sequentially via the controlled operation of the servo valves of the PP-GSS. In this case, sampling/analysis sequence was SW1, SW3, TE, and then the cycle was repeated. If fans at SW3 or TE were not running (for example, during half-house brooding), sample analysis was repeated for the SW1 location only, and the same was true for TE sampling when fans at SW1 and SW3 were not running (for example, during tunnel ventilation mode). Every two hours, air samples from the ambient (background) location were collected and analyzed for 8 minutes. The longer sample analysis time for the ambient point was to account for the longer response time of the instrument when measuring a potentially large step change in gas concentration. Selection of the 2-hour interval for the analysis of the ambient concentrations was due to the fact that the ambient conditions remained relatively constant in comparison to the in-house conditions. This arrangement helped maximize the number of data points collected from the exhaust air and thus provided more data for determination of house emissions.
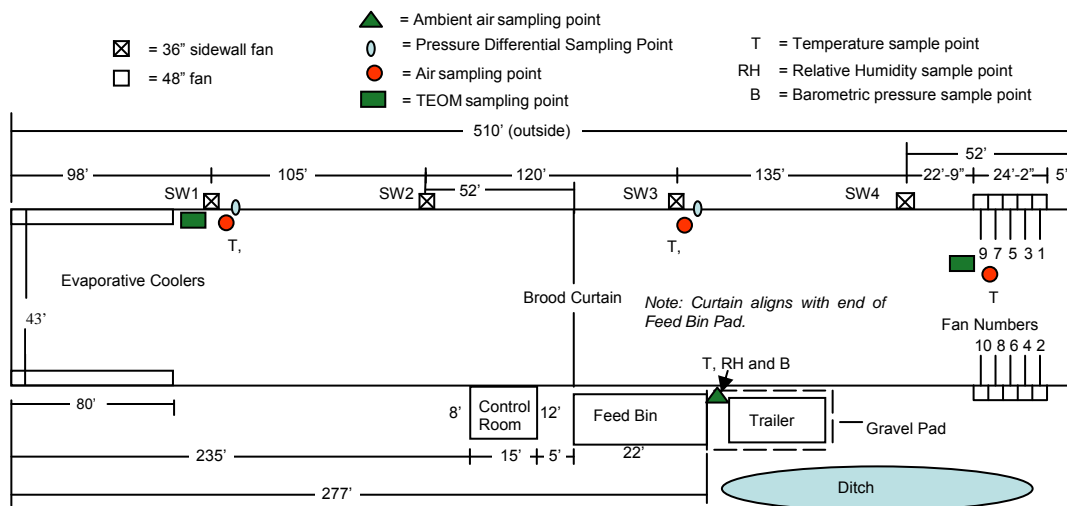
The PM mass concentration of the exhaust air was measured with the Rupprecht & Patashnick TEOM series 1400a monitor (Thermo Fisher Scientific, Waltham, MA) designated as Reference Method number EQPM-1090-79 as per 40 CFR Part 58. For measuring TSP, PM_{10}, and $PM_{2.5}$, three different inlet heads were used. The TEOM 1400a is a gravimetric instrument that draws ambient air through a filter at a constant flow rate, continuously weighing the filter and calculating near real-time (2 s) mass concentration. The mass concentration was calculated by an internal exponential smoothing algorithm based on the total mass loaded on the filter. The TEOMs, located inside the house, operated with the following parameters: a flow rate of 0.59 ft^3/min (0.035 ft^3/min main flow and 0.555 ft^3/min auxiliary flow) (a total of 16.7 L/min flow with 1 L/min main flow and 15.7 L/min auxiliary flow); 300 s averaging time for the total mass and mass rate/mass concentration; and 50°C sample stream temperature. The output of the mass

concentration was based on a standard temperature and pressure of 25°C and 1 atmosphere (atm), respectively. The mass concentration was recorded at 1-s intervals and the average readings, which were correlated to the INNOVA 1412 sampling interval, were used for the PM emissions calculation.

Considerable discussion and investigation went into the placement of the TEOM PM samplers (TSP, PM$_{10}$, and PM$_{2.5}$) in the house. Since no data were available in terms of TEOM responses to different air velocity fields as would be encountered in the broiler houses, we conducted an in-house evaluation of the TEOM performance for air velocity ranging from 250 to 1200 ft/min (1.3 – 6 m/s). The results revealed that the TEOM readings were unaffected by the tested air velocity range. Prior to the TEOM tests, we had assumed continuity in PM concentrations from the center of the house to the exhaust. Since we were concerned that the TEOMs might not function properly under high velocity conditions near the exhaust fan, the TEOMs were located near the center, across the width of the house. Comparison of two TEOM readings near the building center versus near the exhaust fan revealed that concentrations near the exhaust were generally lower than concentrations near the building center. Since velocity showed no impact on the concentration measurement and we were to quantify the emissions leaving the house, we placed the TEOMs near the exhaust fan(s).

The specifics of final TEOM placement were as follows. During the half-house brooding period, the TEOMs were placed near SW1. The TSP TEOM was located 2 ft (0.6 m) from the fan in the axial direction, 3.5 ft (1.1 m) in the radial direction to the left of the fan, and 5 ft (1.5 m) above the floor. The PM$_{10}$ TEOM was located 2 ft (0.6 m) from the fan in the axial direction, 3.5 (1.1 m) in the radial direction to the right of the fan, and 5 ft (1.5 m) above the floor. The PM$_{2.5}$ TEOM was located 2 ft (0.6 m) from the fan in the axial direction, 7 ft (2.2 m) in the radial direction to the right of the fan, and 5 ft (1.5 m) above the floor. Once the birds were released into the full house (between 10-14 days of age), the TEOMs were moved to the TE location. For the TE sampling location, the TSP TEOM was located 16 ft (4.9 m) from the tunnel fan in the axial direction, 36 ft (11 m) from the tunnel end of the house, and 5 ft (1.5 m) above the floor. The PM$_{10}$ TEOM was located 16 ft (4.9 m) from tunnel the fan in the axial direction, 32 ft (9.8 m) from the tunnel end of the house, and 5 ft (1.5 m) above the floor. The PM$_{2.5}$ TEOM was located 16 ft (4.9 m) from the tunnel fan in the axial direction, 28 ft (8.5 m) from the tunnel end of the house, and 5 ft (1.5 m) above the floor. The TEOMs were placed outside the broiler houses to measure the ambient background PM concentrations at Tyson 1-5 from March 22 to April 21, 2007.
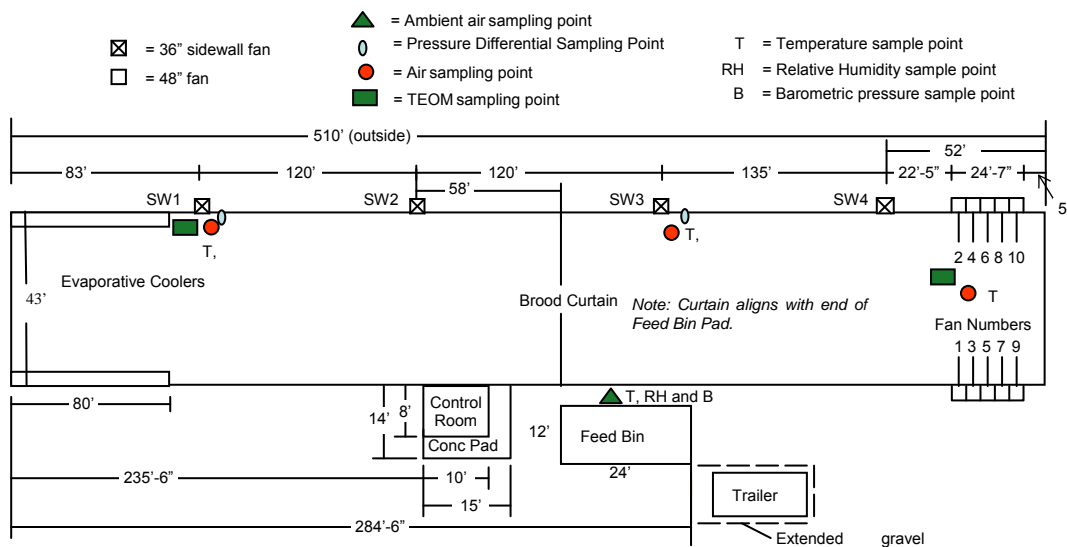
Tyson 1-5
Drawing not to scale

▲ = Ambient air sampling point
0 = Pressure Differential Sampling Point
● = Air sampling point
■ = TEOM sampling point

⊠ = 36" sidewall fan
☐ = 48" fan

T = Temperature sample point
RH = Relative Humidity sample point
B = Barometric pressure sample point

510' (outside)

98'   105'   120'   135'   52'
                                    22'-9" | 24'-2" | 5'

SW1   SW2 52'   SW3   SW4

Evaporative Coolers

Brood Curtain   Note: Curtain aligns with end of Feed Bin Pad.

9 7 5 3 1
T
Fan Numbers
10 8 6 4 2

43'

80'

T, RH and B

8' | Control Room | 12' | Feed Bin | Trailer | Gravel Pad

235'   15' + 5' | 22'

277'

Ditch

Tyson 3-3
Drawing not to scale

▲ = Ambient air sampling point
0 = Pressure Differential Sampling Point
● = Air sampling point
■ = TEOM sampling point

⊠ = 36" sidewall fan
☐ = 48" fan

T = Temperature sample point
RH = Relative Humidity sample point
B = Barometric pressure sample point

510' (outside)

83'   120'   120'   135'   52'
                                    22'-5" | 24'-7"

SW1   SW2 58'   SW3   SW4   5'

Evaporative Coolers

Brood Curtain   Note: Curtain aligns with end of Feed Bin Pad.

2 4 6 8 10
T
Fan Numbers
1 3 5 7 9

43'

80'

▲ T, RH and B

14' 8' | Control Room | 12' | Feed Bin
Conc Pad | 24'

235'-6'   10' | Trailer

15'

284'-6'   Extended   gravel

Figure 7. Schematic layout of Tyson 1-5 and Tyson 3-3 broiler houses.
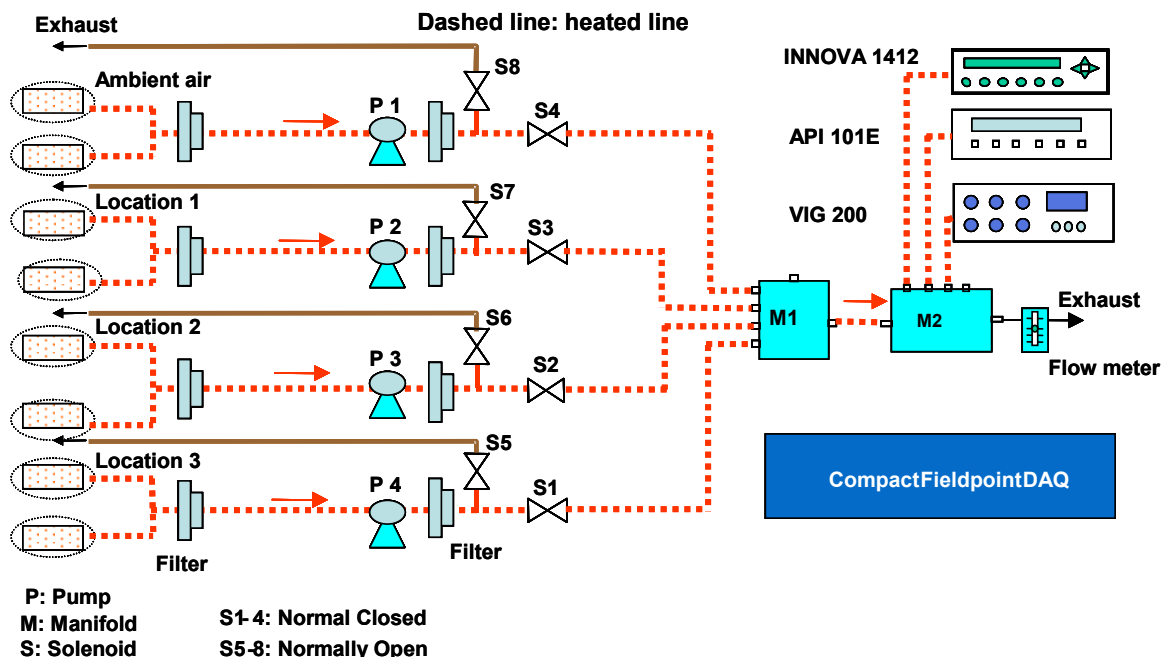
Figure 8. Schematic representation of the positive pressure gas sampling system (PP-GSS) used in the MAEMU for measurement of broiler house air emissions.

The PP-GSS continuously collected air from all locations with the location-specific pumps. Teflon tubing (Fluorotherm FEP tubing) of 3/8-inch (0.95-cm) o.d. and 1/4-inch (0.64-cm) i.d. was used to deliver the sample air. The sample air was by-passed when not analyzed. Use of individual pumps to continuously draw air from the respective sampling locations reduced line-purging time and eliminated possible cross-location residual effect, especially between ambient/background air and exhaust air samples. The choice of sequential sampling was based on the assumption that any concentration changes at the given location during the two adjacent measurements (maximum of 360 seconds) followed a linear pattern. Hence, linear interpolation from the two adjacent measured values was used to determine intermediate values for the location, as needed. The use of one sampling location at the tunnel fan end of the house assumed good mixing of air and thus uniform distribution of the aerial concentrations during tunnel ventilation conditions. Examination of ammonia concentrations across the house in this section, through concurrent measurements using four INNOVA 1412 analyzers, confirmed the validity of this assumption. Moreover, the vertical stratifications in aerial concentrations were measured and found to be negligible when the exhaust fans were in operation. Incidentally, appreciable vertical stratifications existed when the fans were off. Only samples collected when fans were operating were used for the calculation of ammonia emissions from the broiler houses.

Ventilation rates of the houses were measured using the following procedure. First, each exhaust fan was individually calibrated *in-situ* with a state-of-the-art fan assessment numeration system (FANS) to obtain the actual ventilation curves (airflow rate vs. static pressure) (Gates et al., 2004). This calibration was essential to the accurate measurement of the house ventilation

rate because actual fan airflow rates can vary in excess of 25% from one another and from the nominal values supplied by the fan manufacturer (Figure 9). The deviation arises from the field operational conditions that differ drastically from those under which the default values were established, for example, loose motor belts, and dirty shutter or fan blades. After the actual airflow curves were established for all of the exhaust fans and their combinations, runtime of each fan was monitored using an inductive current switch (with analog output) attached to the power supply cord of each fan motor (Figure 10). Analog output from the current switches was connected to the compact Fieldpoint modules. Concurrent measurement of each house static pressure was made with two static pressure sensors (Model 264, Setra, Boxborough, MA), each for half of the house. While the static pressure was not expected to differ at the two locations, two sensors were used to provide redundancy in this critical measurement. Summation of airflows from the individual fans during each monitoring cycle or sampling interval produced the overall house ventilation rate. This method of determining dynamic ventilation rates of mechanically ventilated animal confinement has been successfully used in recent AFO air emission studies in the United States (Liang et al, 2005; Wheeler et al. 2006). Fan runtime and static pressure was recorded continuously (1-second intervals).
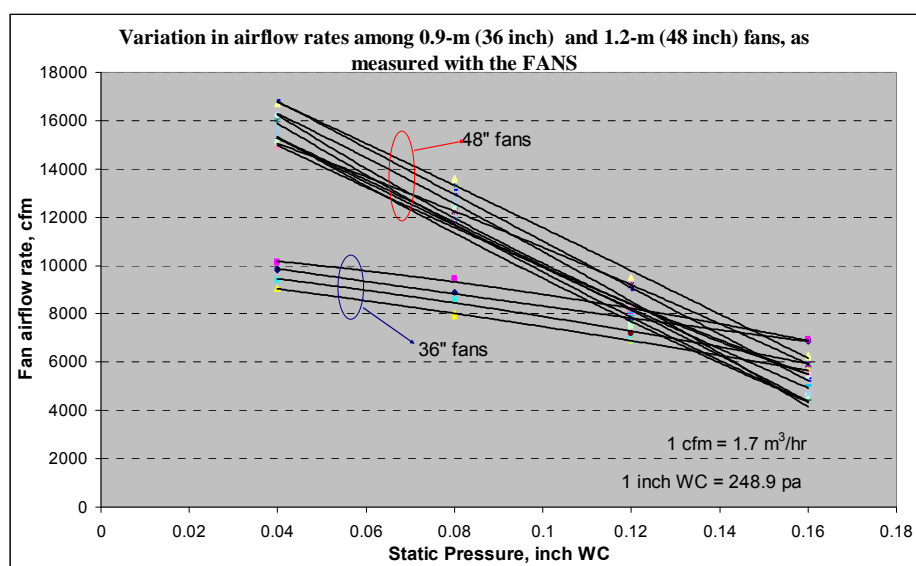
Figure 9. Variation in fan airflow rates among the seemingly identical 36-inch (0.9 m) or 48-inch (1.2 m) fans in Tyson 1-5 broiler house.

Fan runtime sensor

Fan calibration by FANS unit

Figure 10. Photographical views of the fan operational sensor and the FANS unit.

Indoor and outdoor temperature and relative humidity (RH) were measured with robust and stable temperature (Type T thermocouple, Cole-Parmer, Vernon Hills, IL) and RH probes (HMW60, Vaisala, Woburn, MA) that were connected to the PC-based data acquisition system (DAQ). In addition, portable temperature/RH loggers were used as back-ups. Analog output of the static pressure sensors was also connected to the DAQ.

All the variables of air pollutants concentration, fan runtime, static pressure, air temperature and RH were continuously measured and recorded at 1-second intervals throughout the one-year study period. The collected raw data were archived and backed up daily.

Emission Rate Determination

Gaseous or PM emission rate (ER) from an animal house to the atmosphere is the difference between the quantity of gases or PM leaving the house and the quantity of gases or PM entering the house. The relationship of ER to gaseous or PM concentration of inlet and exhaust air and building ventilation rate may be expressed as follows:

$$\mathrm{ER}_G = \sum_{e=1}^{3} Q_e \left([G]_e - \frac{\rho_e}{\rho_i}[G]_i \right) \times 10^{-6} \times \frac{w_m}{V_m} \times \frac{T_{std}}{T_a} \times \frac{P_a}{P_{std}} \qquad [1]$$

$$\mathrm{ER}_{PM} = \sum_{e=1}^{3} Q_e \left([PM]_e - \frac{\rho_e}{\rho_i}[PM]_i \right) \times 10^{-6} \times \frac{T_{std}}{T_a} \times \frac{P_a}{P_{std}} \qquad [2]$$

where ER_G = Gaseous emission rate for the house (g hr^{-1} house^{-1})

ER_{PM} = PM emission rate for the house (g hr^{-1} house^{-1})

Q_e = ventilation rate of the portion of the house at location "e" (SW1, SW3 or TE) at field temperature and barometric pressure (m^3 hr^{-1} house^{-1})

$[G]_i$ = Gaseous concentration of incoming house ventilation air, parts per million by volume (ppm$_v$)

$[G]_e$ = Gaseous concentration of exhaust house ventilation air of the portion of the house at location "e" (ppm_v)

$[PM]_i$ = PM concentration of incoming house ventilation air (ug/m^3)

$[PM]_e$ = PM concentration of exhaust house ventilation air of the portion of the house at location "e" (ug/m^3)

w_m = molar weight of air pollutants, 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_e = air density at exhaust fan location "e", kg dry air m^{-3} moist air

ρ_i = air density at outside conditions, kg dry air m^{-3} moist air

As can be seen from equations [1] and [2] and description of the variables shown above, multiple measurements are required to determine the gaseous or PM ER.

System Checks
Accuracy is defined as the degree of agreement between an observed value and an accepted reference value. For a given measurement system, it includes combination of random error (precision) and systematic error (bias). In this study, the following accuracy checks were implemented:

- Gas analyzers
- Exhaust fan flow rates
- TEOM PM monitors
- Static pressure sensors
- Temperature and RH sensors
- Barometric pressure sensor
- PP-GSS leakage and pump flow rates

After installation of the monitoring systems, and prior to the initiation of formal data collection, a series of system checks were conducted to insure that the monitoring system was operating correctly and that collected data would be representative of the emissions from the broiler houses during operation. The dynamic response times of the analyzers were evaluated in the lab prior to installation in the field. Among the lab tests, the response time of NH_3 measurement from INNOVA 1412 was longest as compared to gaseous measurements (CO_2 from INNOVA 1412, H_2S from API 101E, and NMHC from VIG 200). The actual on-site performance of the sampling system was also tested. Tests were performed by injecting ammonia span gas into the in-house sampling port of the longest sampling line (tunnel end, see Figure 11). The results of

INNOVA 1412 analyzers from both houses are shown in Figures 12 and 13. For both sampling systems, the fourth ammonia concentration reading (30 s X 4=120 s) reached 96% and 97% of the span concentration.
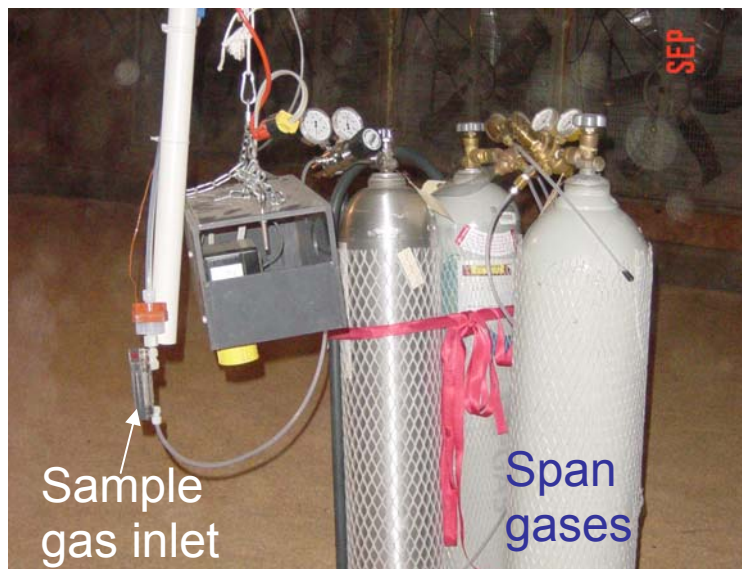

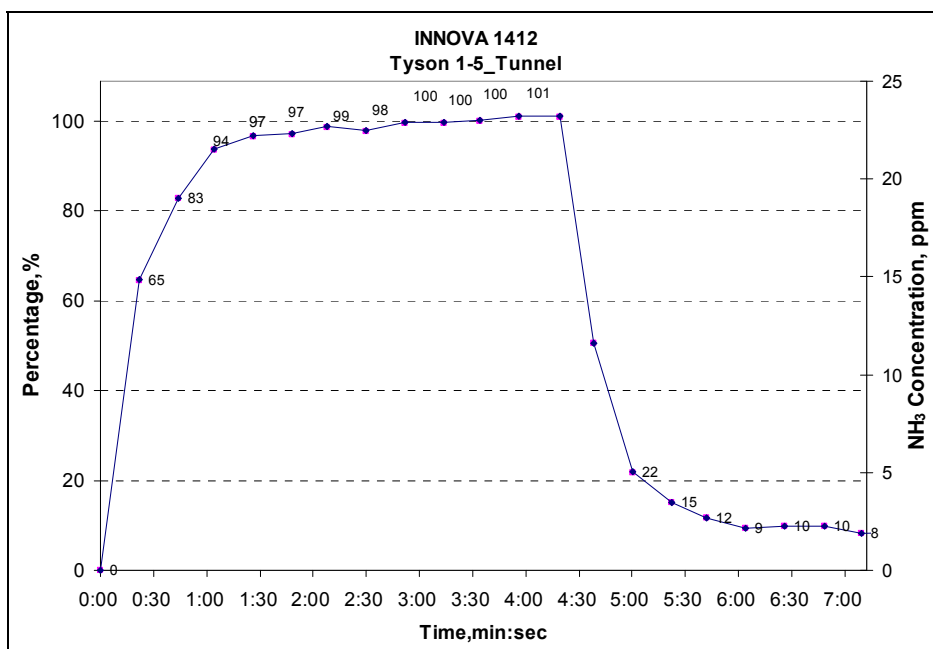**Figure 11. Picture of span gas injection at the in-house sampling point.**

Figure 12. Response time check of the sampling system and INNOVA analyzer at Tyson 1-5.
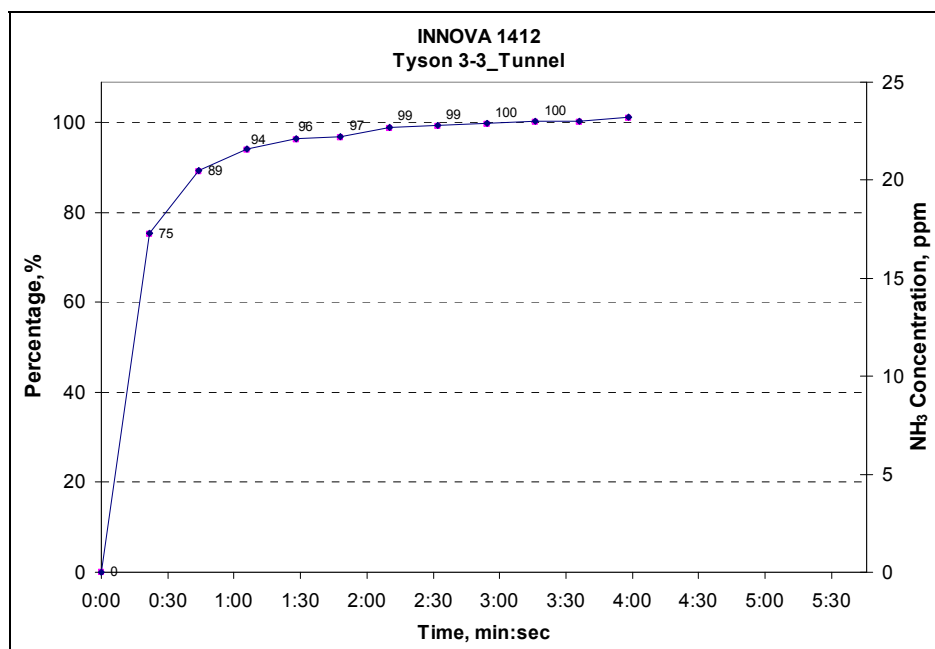
Figure 13. Response time check of the sampling system and INNOVA analyzer at Tyson 3-3.

In addition to a span gas challenge of the entire system at the farthest in-house sampling location, tests were conducted to compare the readings of a calibrated INNOVA 1412 analyzer located inside the monitoring trailer with three other calibrated INNOVA 1412 analyzers located at three sampling locations in the broiler house (SW1, SW3 and TE). The three in-house INNOVA 1412 analyzers continuously took samples during the entire testing period (Figure 14). All INNOVA 1412 analyzers were synchronized and calibrated with the same NH_3 calibration gases before the test.

Figure 14. One of the three in-house INNOVA analyzers used to compare readings to its counterpart inside the MAEMU.

To further evaluate the INNOVA's dynamic response, the number of sampling cycles for the INNOVA in the MAEMU per location was set to 4, 6 or 8 cycles per location (30s per sampling cycle). The NH_3 readings by the INNOVA 1412 in the MAEMU were compared with the respective readings by the three in-house INNOVA 1412s (Figure 15). Only the last readings from the MAEMU in each sampling cycle for each location were compared with the most recent readings from the INNOVAs in the house. Five pairs of readings for each sampling cycle setting at each location were taken. A two-way ANOVA test was conducted on the difference between in-house and MAEMU analyzer concentration readings with number of cycles per location and location in the house taken as main effects. There was neither a sampling number effect (P = 0.17) nor a location effect (P = 0.24). Table 2 provides a summary comparison of continuous in-house NH_3 concentration readings with those obtained from location cycling by the MAEMU INNOVA at 4, 6, and 8 sampling iterations for Tyson 1-5. The results indicate that the NH_3 reading in the MAEMU matched the reading in the house at all three locations and there was no difference in using 4, 6 and 8 sampling iterations at each location. Hence, four sampling iterations were chosen to maximize the sampling frequency for each location. Because the fan operation period could be as short as 30 s while the birds were young and during cold weather, it was essential to quickly move between the sample locations to capture the temporal variability in ammonia concentration arising from the intermittent (on/off) operation of the fans. Since the NH_3 reading in the MAEMU matched the reading in the house at each location, it indicated that there was no leakage in the entire sampling system. The same test was conducted for Tyson 3-3 and yielded the same results.

During weekly field visits, the integrity of each sampling line was checked by connecting a flow meter at the pump-end and blocking the in-house sampling port (Figure 16). If the flow meter read zero, it indicated no leakage in the sampling line under the negative pressure (from the in-house sampling port to the corresponding sampling pump inside the MAEMU). No leakage was detected throughout the monitoring period.

Table 2. Comparison of in-house NH_3 concentration readings (ppm) by respective INNOVA analyzers with those obtained from location cycling by the INNOVA analyzer inside the MAEMU.

No. of Sampling Iterations	$NH_{3(in-house)} - NH_{3(MAEMU)}$ For sampling locations of			(ppm) Mean (S.E.)
	SW1	SW3	Tunnel	Mean
4	0.72 (0.45)	0.20 (0.19)	0.31 (0.08)	0.41[a] (0.10)
6	0.26 (0.17)	0.08 (0.10)	-0.19 (0.22)	0.05[a] (0.10)
8	0.18 (0.20)	-0.02 (0.16)	0.46 (0.12)	0.20[a] (0.17)
Mean	0.39[b] (0.17)	0.09[b] (0.09)	0.19[b] (0.11)	

*Column or row means with the same superscript letter are not significantly different (P>0.10)
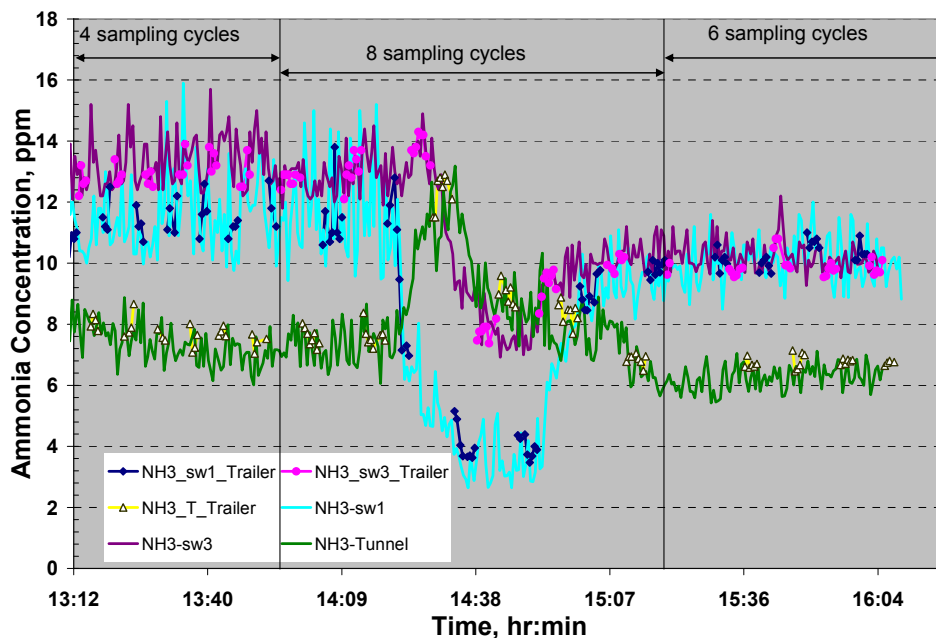
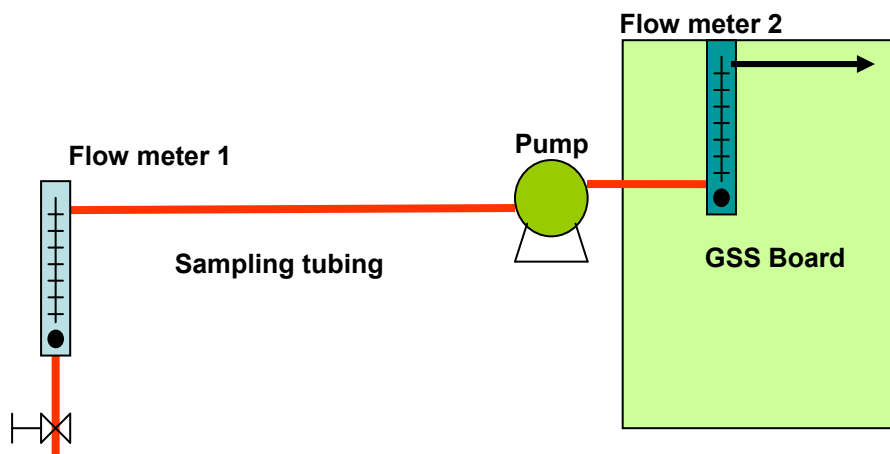**Figure 15. Comparison of ammonia readings from the MAEMU and in-house INNOVAs.**

Figure 16. Schematic representation of the gas sampling system (GSS) integrity (leakage) check.

Non-methane Hydrocarbon (NMHC) Speciation (EPA Method TO-15/17)

The EPA air consent agreement with animal feeding operations (AFOs) specifies the use of EPA TO-15 for the speciation of NMHC emitted from these facilities. Sorbent tube sampling may be a more effective technique in the speciation of NMHCs from AFOs due to its ability to capture both volatile and highly polar compounds. Stainless steel canisters (Entech Instruments, Inc., Simi Valley, CA) were used to collect the air samples from the two broiler houses; a gas chromatograph – mass spectrophotometer (GC-MS) method was used to speciate the NMHC compounds. A solid sorbent method (TO-17) was used simultaneously to collect the air samples on glass sorbent tubes containing Carbopack X and Carbopack C (2:1

packing volume) custom-made by Supelco, Inc. (Bellafonte, PA) with a GS 301 gas sampler (Gerstel, Inc., Baltimore, MD). Two collection and speciation trials were conducted on April 19, 2006 at Tyson 3-3 (empty house) and Feb 6, 2007 at Tyson 1-5 (with birds in house). The air samples were collected from nine different locations throughout the whole house, including each air sampling location (Figure 17). The top 25 compounds were speciated with the TO-15 & TO-17 methods.
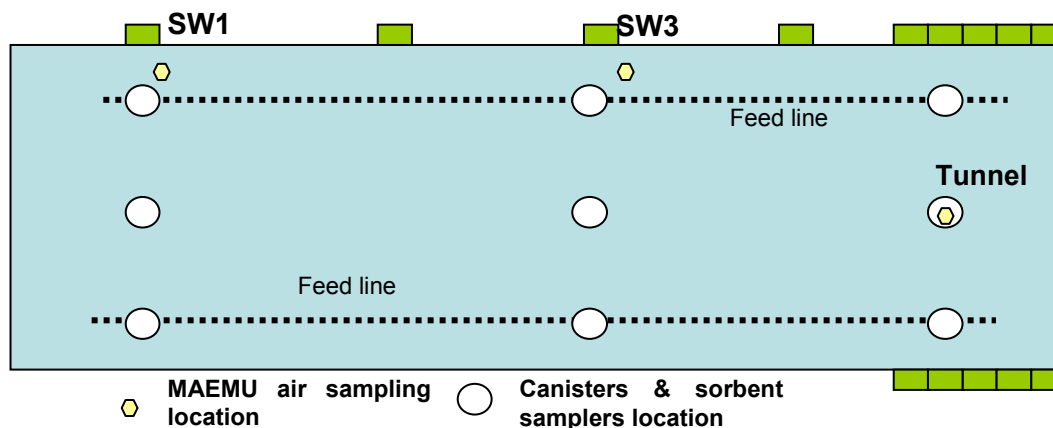
Figure 17. Schematic layout of air sampling locations for NMHC speciation.

Quality Assurance/Quality Control of Data Collection and Analysis

Strict Quality Assurance/Quality Control (QA/QC) procedures were followed throughout the data collection and data analysis processes. All measurement instruments underwent initial checks and calibrations, followed by regular operational checks and follow-up calibrations as specified by the quality assurance project plan (QAPP) (Moody et al., 2007). The frequency of each check/calibration depended on the instruments. For instance, the NH_3 gas analyzer was checked with calibration gases weekly or semi-weekly, even though our past experience had indicated that this type of photoacoustic NH_3 analyzer has excellent stability. Calibration gases were certified with concentration of 22.6, 22.8, or 25 ppm ammonia (balanced in air, certified grade with 2% accuracy, Matheson Tri-gas, PA). The INNOVA 1412 analyzers were checked once a week before February 2006 and then were checked twice a week after February 2006 to meet our data quality goal. The QC standard of instrument calibration was 5%. Internal technical system performance evaluations were performed between flocks.

In general, the broiler houses had approximately two weeks of downtime between flocks. However, the downtime at Tyson 3-3 was 41 days after the first flock due to change of the managerial personnel at the site. During each downtime, ISU and UK project personnel conducted a thorough internal technical systems audit at each site. This audit included a visual inspection of all system components, and a flow check at each of the four sample points. During the system performance evaluation, the INNOVA 1412, API 101E, and VIG 200 analyzers were recalibrated. All TEOMs were checked for leakage. The flow rate of TEOMs was audited every six months and the mass balances of TEOMs were verified after the one-year monitoring using

a mass standard (TEOM Operation Manual). All temperature sensors were checked against a certified thermometer after every flock. The RH sensors and pressure sensors were checked or calibrated against a calibrated sensor or a RH sensor calibration kit (HMK 15, Vaisala, Woburn, MA) every six months. If the check result fell outside of 5% QC standard, recalibration was performed and the corresponding data were corrected, following a linear relationship between values from the previous check and current check.

The performance curves of the ventilation fans were checked after each flock. All exhaust fans were cleaned before the start of a new flock. An uninterrupted power supply (UPS) was used for the DAQ system to avoid loss of data due to power outage.

As described in the QAPP (Moody et al., 2007), a data processing program was run daily to process the data collected on the previous day. This program calculated data completeness and automatically flagged out-of-range data. A sample qualifier or a result qualifier consists of three alphanumeric characters, which act as indicators of the fact and the reason that the data value (a) did not produce a numeric result, (b) produced a numeric result, but it is qualified in some respect relating to the type or validity of the result. Qualifiers are used both in the field and in the laboratory to signify data that may be suspect due to contamination, special events, or failure of QC limits. Appendix I in the QAPP (Moody et al., 2007) contains a complete list of the data qualifiers for the field and laboratory activities. Almost all monitored parameters have simple range checks programmed. For example, valid times must be between 00:00 and 23:59, summer temperatures must be between 10 and 50 degrees Celsius, etc. The data operator is notified immediately when data are out of range. The operator has the option of correcting the entry or overriding the range limit. The specific values used for range checks vary depending on season. The default range values for data acceptance are provided in standard operation procedures (SOPs). The response action to data flagged as out of range were to investigate and document the reason that the data were flagged and to follow-up with a site visit if any data flags were the result of equipment malfunction and correct the problem. Once problems were identified, the data could be corrected or invalidated, and corrective actions were taken for field or laboratory operations. The ISU project personnel reviewed the flagged data within two working days to confirm that the data were either invalid and should be excluded or valid and should be kept. To avoid errors introduced into determination of average values due to partial data days, which would result in biased time weights, only complete-data days (CDD) that included over 75% valid data were used in calculating average daily means (ADM). Based on the on-site surveillance and daily data flagging/review, daily data completeness for each variable was calculated.

Two external technical systems audits were conducted by independent personnel during the project. Battelle personnel (commissioned by EPA) audited the systems and QAPP on September 25-26, 2006 and agricultural air monitoring experts, Drs. Larry Jacobson and David Parker, (commissioned by the study PI's) audited the measurement methods on January 8 – 10, 2007. Both audits found that the QAPP was being fully and successfully implemented at both sites.

Uncertainty Analysis of Emission Rate

Component error analysis is used to quantify uncertainty when a quantity such as daily emission rate is calculated from multiple measurements, each with its own degree of uncertainty. A component error analysis (Doeblin, 1990) provides statistical meaning to a statement on the magnitude of error in the calculation of daily ER. This analysis had been performed for an earlier project that measured broiler house ammonia emissions and documented in a copyrighted Ph.D. dissertation (Casey, 2005), a journal article arising from this project (Gates et al, 2009), and a manuscript in preparation (Casey et al., 2009). The uncertainty analysis of ER for this study is described in detail in the project QAPP and Gates et al. (2009). The resultant ER uncertainty was 10% or less based on the accuracies of the associated measurement component uncertainties and operating ranges for ventilation fans. Consequently, data quality objectives (DQOs) and measurement quality objectives (MQOs) were developed in the QAPP to guide the achievement of 10% or less ER uncertainty.

Results and Discussion

Data Completeness

According to USEPA (2002): "Data completeness is a measure of the amount of valid data obtained from a measurement system, expressed as a percentage of the number of valid measurements that should have been collected". In this study, a data completeness goal of 75% of the scheduled sampling was established. The data completeness is primarily affected by unpredictable field events, including instrument malfunction, power outages due to adverse weather, and broiler house maintenance. When any of these events occurred, the corresponding emission data were flagged. After one-year monitoring (Mar 14, 2007 for Tyson 1-5 and Mar 5, 2007 for Tyson 3-3), six full flocks had been monitored at Tyson 1-5; the 6th flock had been monitored for 22 days (0.4 flock) for Tyson 3-3. The complete data days (CDD) for each flock and between flocks are summarized in Table 1 for each constituent.

The weather conditions for the period are reported in Table 3. The range of daily average ambient temperatures was 14 to 86 ^{o}F for the two sites.

Table 3. Daily average temperature and relative humidity (RH) summary for Tyson 1-5 and Tyson 3-3 over the one-year period from Feb 2006 to March 2007. (S.D. = standard deviation)

	Outside Temp., ^{o}F		Outside RH, %		Inside Temp., ^{o}F		Inside RH, %	
	T1-5	T3-3	T1-5	T3-3	T1-5	T3-3	T1-5	T3-3
Mean	57.8	57.1	73.3	72.7	72.1	73.1	60.6	62.1
S.D.	17.0	17.4	12.4	11.6	9.4	9.1	10.9	11.5
Max	85.6	85.9	99.7	97.4	101.7	89.7	89.0	94.7
Min	14.1	15.8	37.4	37.3	42.2	39.6	30.8	30.8

Ammonia (NH$_3$): For the 365-d annual emission calculation, the complete-data days (CDDs) were 353 out of 365 days (96.7% data completeness or DC) and 323 out of 365 days (88.5% DC) for Tyson 1-5 and Tyson 3-3, respectively. By the end of the monitoring, the CDDs were 381 out of 394 days (97.6% DC) for Tyson 1-5 and 337 out of 379 days (88.9% DC) for Tyson 3-3. The 718 house-day (11.4 flocks) emission data were used for calculating the ER of daily

mean, daily maximum, flock total, and during downtime. The CDDs for each flock and downtime are summarized in Table 1.

Hydrogen sulfide (H$_2$S): For the 365-d annual emission calculation, the CDDs were 314 out of 365 days (86.0% DC) and 260 out of 365 days (71.2% DC), respectively, for Tyson 1-5 and Tyson 3-3. By the end of the six flocks, the CDDs were 342 out of 394 days (86.8% DC) for Tyson 1-5 and 274 out of 379 days (72.3% DC) for Tyson 3-3. The 616 house-days (11.4 flocks) emission data were used for calculating the ER of daily mean, daily maximum, flock total, and during downtime.

Nonmethane hydrocarbon (NMHC): For the 365-d annual emission calculation, the CDDs were 250 out of 365 days (68.5% DC) and 201 out of 365 days (55.1% DC), respectively, for Tyson 1-5 and Tyson 3-3. By the end of the six flocks, the CDDs were 268 out of 394 days (68.0% DC) for Tyson 1-5 and 203 out of 379 days (53.6% DC) for Tyson 3-3. The 471 house-days (11.4 flocks) emission data were used for calculating the emission rate of daily mean, daily maximum, flock total, and during downtime.

TSP: For the 365-d annual emission calculation, the CDDs were 281 out of 365 days (77.0% DC) and 295 out of 365 days (80.8% DC), respectively, for Tyson 1-5 and Tyson 3-3. By the end of the six flocks, the CDDs were 304 out of 394 days (77.2% DC) for Tyson 1-5 and 298 out of 379 days (78.6% DC) for Tyson 3-3. The 602 house-days (11.4 flocks) emission data were used for calculating the emission rate of daily mean, daily maximum, flock total, and during downtime.

PM$_{10}$: For the 365-d annual emission calculation, the CDDs were 272 out of 365 days (74.5% DC) and 298 out of 365 days (81.6% DC), respectively, for Tyson 1-5 and Tyson 3-3. By the end of the six flocks, the CDDs were 295 out of 394 days (74.9% DC) for Tyson 1-5 and 301 out of 379 days (79.4% DC) for Tyson 3-3. The 596 house-days (11.4 flocks) emission data were used for calculating the ER of daily mean, daily maximum, flock total, and during downtime.

PM$_{2.5}$: For the 365-d annual emission calculation, the CDDs were 256 out of 365 days (70.1% data completeness) and 296 out of 365 days (81.1% data completeness), respectively, for Tyson 1-5 and Tyson 3-3. By the end of the six flocks, the CDDs were 279 out of 394 days (70.8% data completeness) for Tyson 1-5 and 299 out of 379 days (78.9% data completeness) for Tyson 3-3. The 578 house-days (11.4 flocks) emission data were used for calculating the ER of daily mean, daily maximum, flock total, and during downtime.

Carbon dioxide (CO$_2$): For the 365-d annual emission calculation, the complete-data days (CDDs) were 353 out of 365 days (96.7% DC) and 319 out of 365 days (87.4% DC) for Tyson 1-5 and Tyson 3-3, respectively. By the end of the monitoring, the CDDs were 381 out of 394 days (97.6% DC) for Tyson 1-5 and 333 out of 379 days (87.9% DC) for Tyson 3-3. The 714 house-days (11.4 flocks) emission data were used for calculating the ER of daily mean, daily maximum, flock total, and during downtime.

Bird Growth Data

The bird growth data from the two houses were collected for every flock. A bird growth curve was derived using the 11 full flocks of data (Figure 18). The daily bird weights at the two separate houses were compared and there was no significant difference between the two sites (P = 0.88). Therefore, the single curve was used to represent the growth during the 52-day growth cycle for both sites.
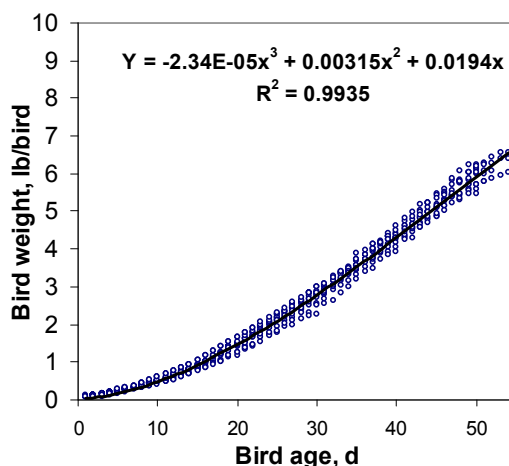

Figure showing: $Y = -2.34\text{E-}05x^3 + 0.00315x^2 + 0.0194x$, $R^2 = 0.9935$

Figure 18. Broiler growth curve for 11 flocks from Tyson 1-5 and Tyson 3-3

Emission Rate (ER)

The daily ER of each house was calculated based on the gaseous and PM concentrations and the building ventilation rates. Regression was used to test for significance of bird age, ventilation rate (VR), bedding status, house temperature and RH. Regression equation was used to predict gaseous or PM ER vs. the significant independent variables.

NH₃ Emission

NH₃ ER Estimation/Prediction

Ammonia emission from the flocks with new bedding and bird age less than 7 d was significantly lower than later periods in the flock production cycle. Therefore, the ERs of the first 6 d with new bedding would not fit the relationship of ER vs. bird age, body weight, VR, air temperature and RH. For the flocks with built-up litter and bird age older than 6-d with new bedding, the relationship of ER, bird age, body weight, VR, air temperature and RH was investigated.

Ammonia ER was highly correlated to bird age, body weight and VR, but was weakly correlated with inside RH and not correlated with outside temperature, outside RH or inside temperature. Moreover, a strong positive relationship was found among bird age, body weight and VR. Among the three variables, bird age was the predominant factor affecting NH₃ ER. Because of unusually high mortality in flock 6 at Tyson 1-5, this flock was not used in ER prediction. The

NH₃ ER per house or per bird from all data (except flock 6 at Tyson 1-5), as shown in Figures 19 and 20, may be described using the following regression equations:

$$NH_3\ ER,\ lb\ d^{-1}\ house^{-1} = a + b\ X + c\ X^2 + d\ X^3 \qquad [3]$$

where

X = bird age, d, if built-up litter is used;

X = (bird age – 6) if new bedding is used or bird age is ≥ 7 d;

$NH_3\ ER$ = 0.55 lb/d-house if bird age < 7 d for new bedding

Table 4 provides the prediction parameter estimates for the two houses, individually, and averaged over the 11.4 flocks. The correlation coefficients (r^2) of prediction models vary from 0.64 to 0.80 and show the strongest relationship between ER and bird age.

Table 4. Coefficient Estimates of ammonia ER prediction models for the houses, Tyson 1-5 and Tyson 3-3 (ER is not included when bird age is < 7d with new bedding) (S.E. = standard error)

House	S.E. (lb/d-house)	a (± S.E.)	b (± S.E.)	c (± S.E.)	d (± S.E.)	r^2
T1-5	9.70	7.9 (± 1.27)	N/S	0.063 (± 4.9 e^{-03})	-1.02 e^{-03} (± 1 e^{-04})	0.64
T3-3	9.09	12.7 (± 2.49)	-1.34 (± 0.40)	0.138 (± 0.017)	-2 e^{-03} (±2 e^{-04})	0.80
Overall	9.94	12.2 (± 1.91)	-0.97 (± 0.285)	0.1115 (± 0.016)	-1.6 e^{-03} (± 1.7 e^{-04})	0.71

For the flocks on new bedding, there was no clear effect of bird age, VR, air temperature, or RH on ER. Therefore, the first 6-d ERs could be estimated by using the average ER (± S.D.), 0.55 lb/d-house (± 0.42) measured for the first 6-d ERs from three flocks on new bedding.
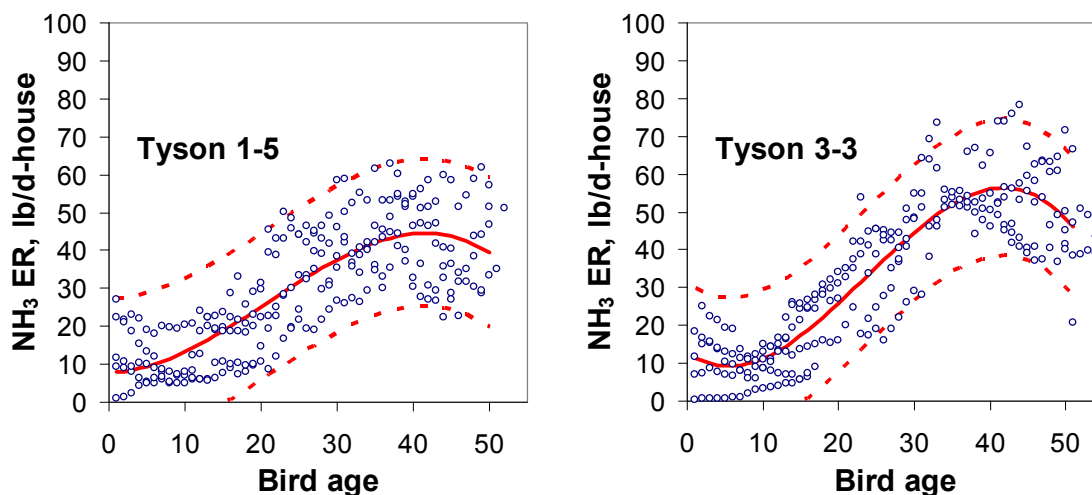
Figure 19. NH$_3$ emission rate (ER) per house vs. bird age for Tyson 1-5 and Tyson 3-3. The solid line is the regression line and the dash lines are 95% prediction limits.
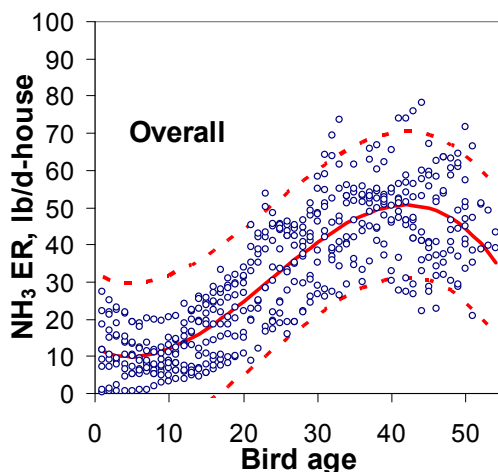
Figure 20. NH$_3$ emission rate (ER) per house vs. bird age. The solid line is the regression line and the dash lines are 95% prediction limits.

Figure 21 provides the daily NH$_3$ ER for the two houses for the entire monitoring period of 11.4 flocks and downtime between flocks. The daily ER varied from 0 to 98.6 lb/d-house (0 to 44.7 kg/d-house). When the houses were occupied by birds, the highest ER was 67.4 and 78.2 lb/d-house (30.6 and 35.5 kg/d-house) for Tyson 1-5 and Tyson 3-3, respectively. The highest daily emission of 98.6 lb/d-house (44.7 kg/d-house) occurred at Tyson 1-5 between flock 2 and flock 3. The highest emission happened on April 6, 2006 when the litter was disturbed during a between-flock litter decaking operation. Note that the emissions between the vertical dashed lines in Figure 21 represent periods between flocks when no birds were in the houses (i.e., downtime). The average ER for Tyson 1-5 over the six flocks was 29.5 ± 12.9 lb/d-house (13.4 ± 5.9 kg/d-house) which was not significantly different from 32.2 ± 15.9 lb/d-house (14.6 ± 7.2 kg/d-house) for Tyson 3-3 (P=0.35). The average ER of 11.4 flocks was 31.4 ± 14.9 lb/d-house (14.2 ± 6.8 kg/d-house).
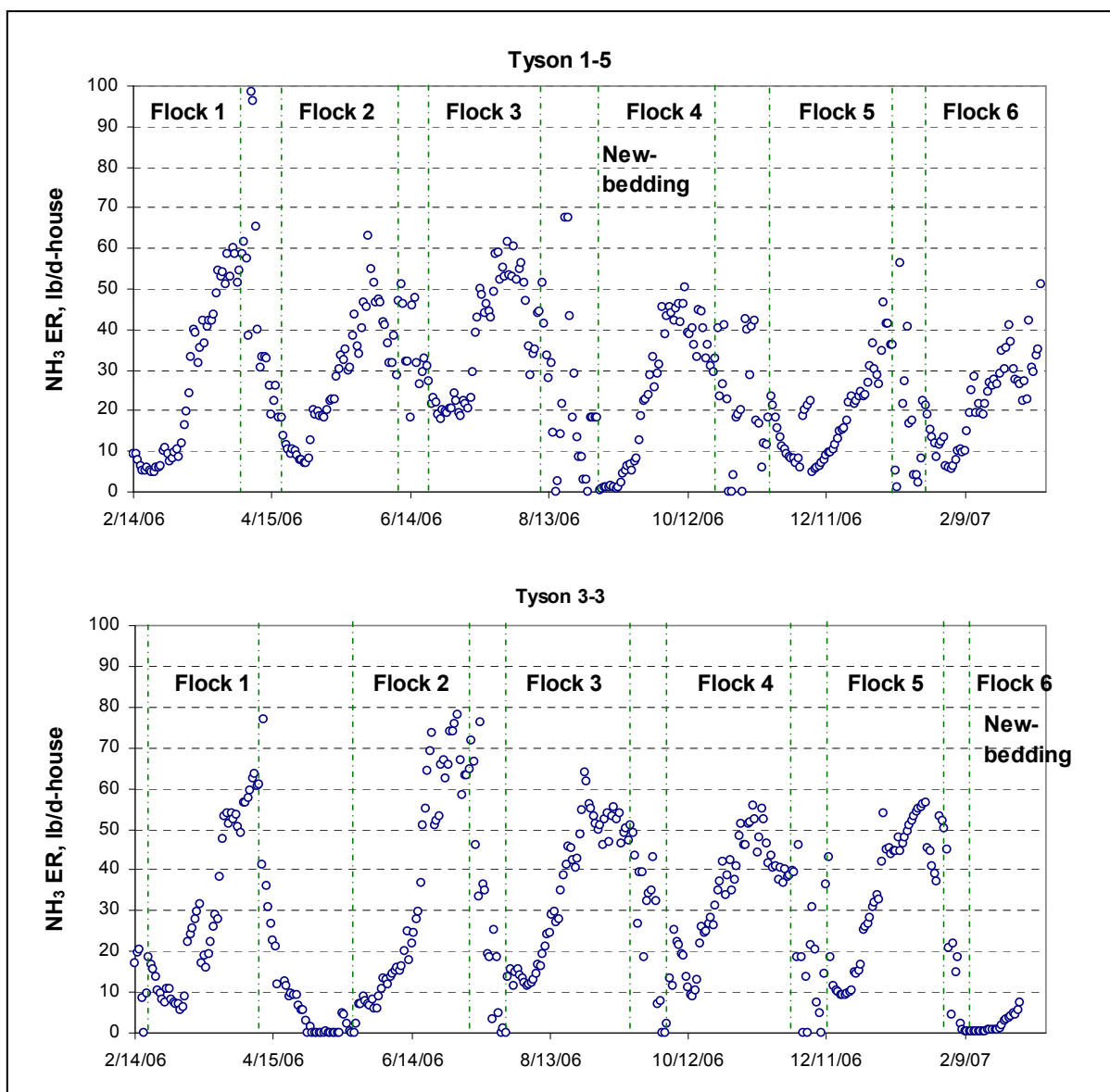
Figure 21. Daily NH$_3$ emission over the 11.4 flocks for Tyson 1-5 and Tyson 3-3.

NH$_3$ ER during Downtime between Flocks

Ammonia emissions from the two houses were continuously monitored when the houses were empty between flocks or during downtime. Ventilation rate (VR) of the houses had a significant impact on the ER when VR was lower than 80,000 cfm (135,900 m^3/hr) (Figure 22). However, it was also related to the litter management practice, e.g. litter decaking. The average ER for the two houses during downtime was 18.5 ± 17.8 lb/d-house (8.39 ± 8.1 kg/d-house), which was approximately two-thirds of the mean ER when birds were present in the houses.

The NH_3 ER per house during downtime could be described using the following regression equation:

$$NH_3\ ER,\ lb\ d^{-1}\ house^{-1} = 0.0006\ VR \qquad [4]$$

where

VR = Ventilation rate, cfm house^{-1}

$NH_3\ ER$ = 41.2 lb/d-house if VR ≥ 80000 cfm
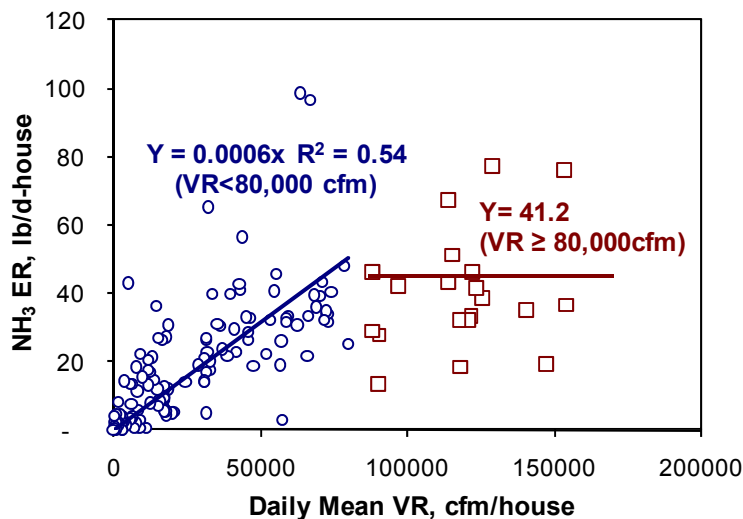
Figure 22. NH_3 emission rate(ER) vs. ventilation rate (VR) during downtime.

NH_3 ER per Animal Unit (AU)

Figures 23 and 24 present NH_3 ER in terms of 500 kg AU (kg/AU-d) for all 11.4 flocks from the two houses. The ER per AU versus bird age shows the different trends for the flocks with new bedding and built-up litter. The ER per AU of two flocks with new bedding (Tyson 1-5 flock 4, Sept to Oct, 2006, and Tyson 3-3 flock 6, Feb, 2007) was relatively low. The ER per AU of the flocks with built-up litter started high but trended downward in the first week and stabilized with bird growth. There was no significant difference between Tyson 1-5 and Tyson 3-3 in ER per AU (P=0.73). The daily ER per AU (± S.D.) was 0.48 ± 0.60 and 0.48 ± 0.48 kg/d-AU for Tyson 1-5 and Tyson 3-3, respectively. The overall daily ER per AU was 0.48 ± 0.53 kg/d-AU.
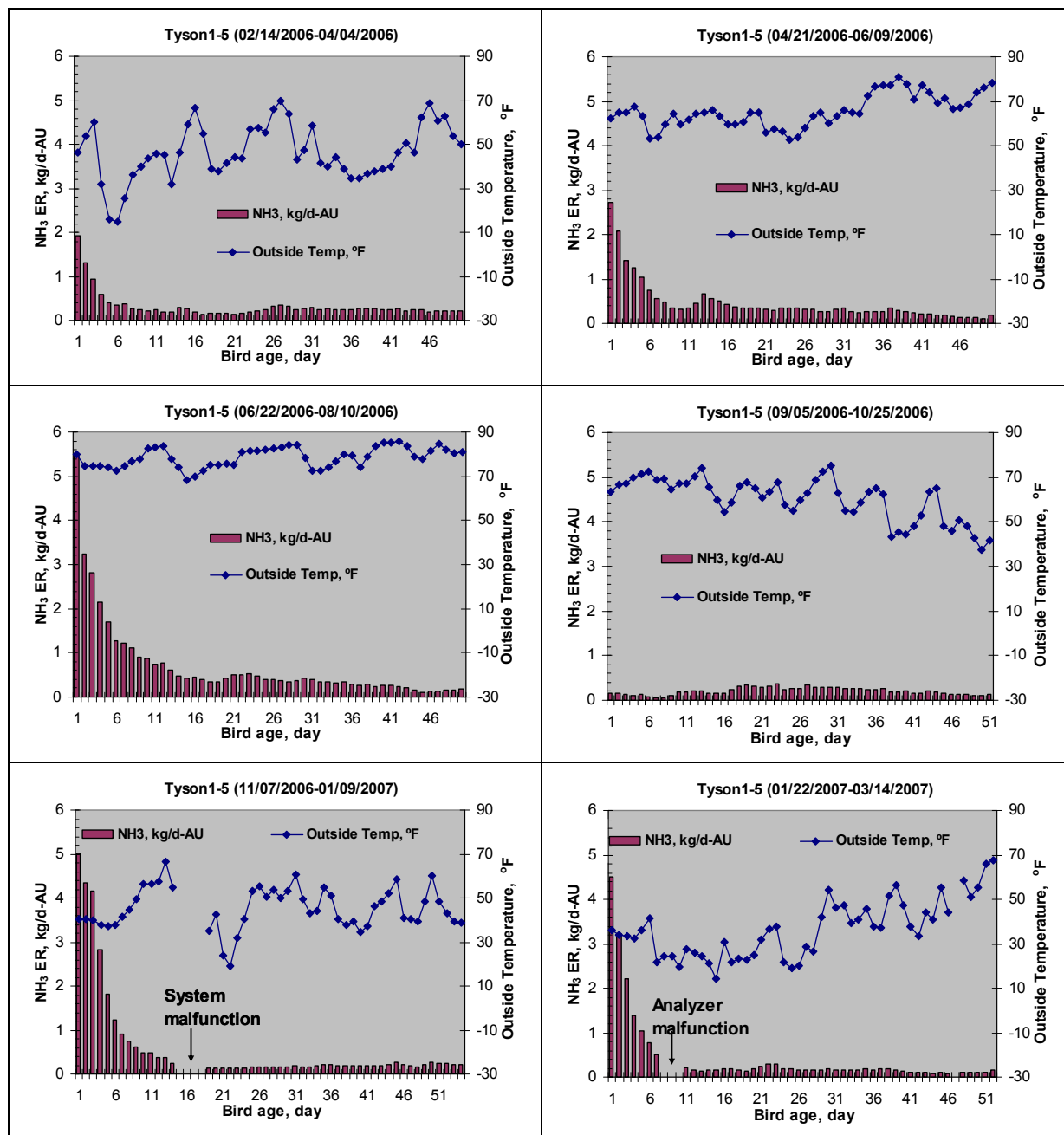
Figure 23. Tyson 1-5 NH$_3$ ER per AU (500 kg) mean outside temperature vs. bird age
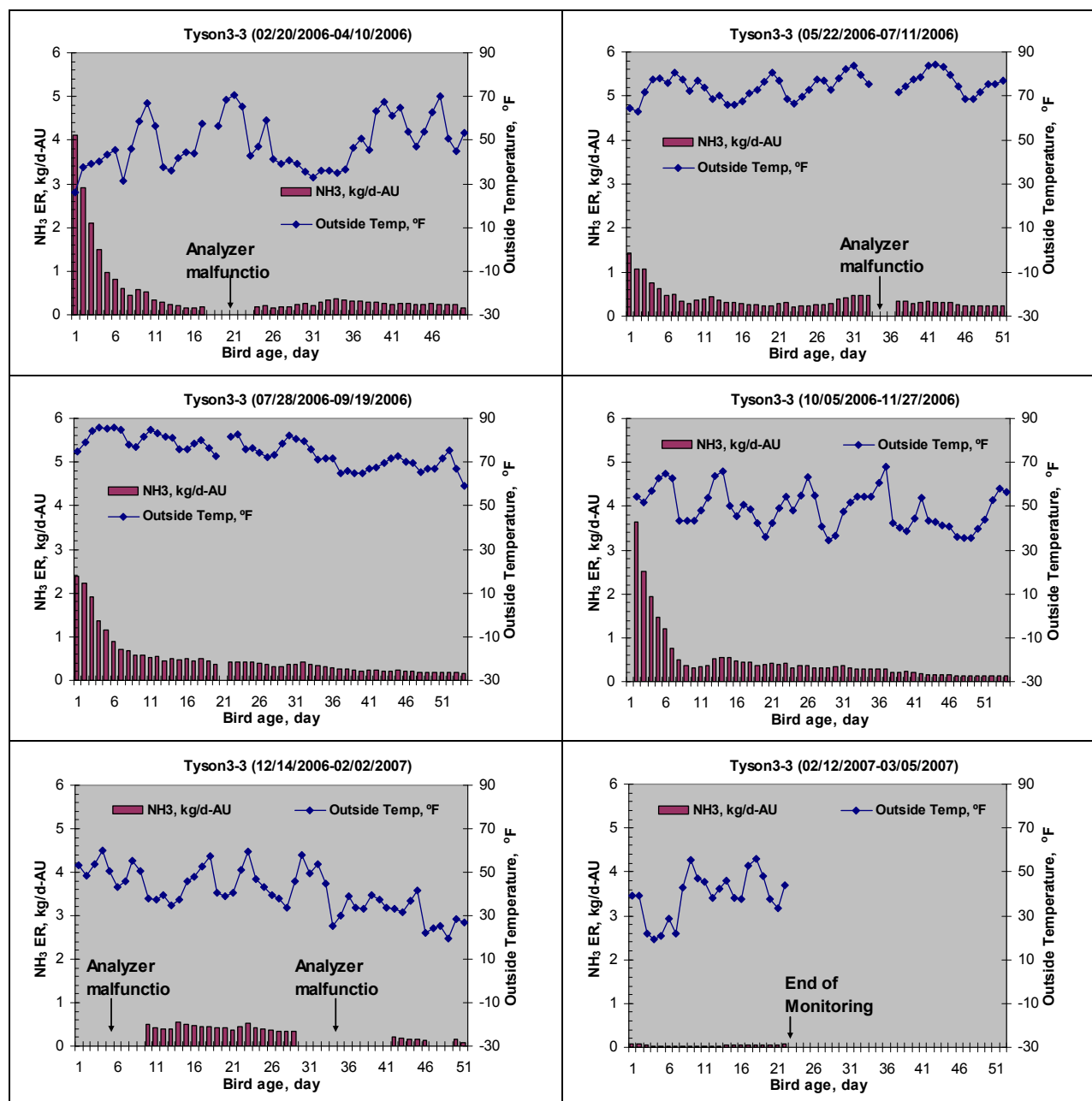
Figure 24. Tyson 3-3 NH$_3$ emission rate (ER) per animal unit (AU, 500 kg live body weight) and mean outside temperature vs. bird age

Effects of Environmental Variables on NH$_3$ ER

To assess the impact of environmental variables on the NH$_3$ emission from the two broiler houses, a multiple regression analysis was performed to relate NH$_3$ ER (lb/d-house) to bird age (d), interior temperature ($^{\circ}$F), RH (%), VR (cfm/bird) and bedding status (0 for new bedding; 1 for built-up litter). The daily mean values of the above variables were used for the regression analysis. The results of the regression analysis are shown in Table 5. House RH and VR had significant effects on NH$_3$ ER at $\alpha = 0.05$. As RH and VR increased, so did NH$_3$ ER (lb/d-house).

Table 5. Multiple regression analysis of daily NH_3 ER with bird age (d), RH (%), and litter status (LS) as inputs (R^2=0.76)

NH_3 ER, lb d^{-1} house^{-1}= β_0 + β_1x Age+ β_2 x Age^2+ β_3 x Age^3+ β_4 x RH_i+ β_5 x VR+ β_6 x LS

Term	Estimate	S.E	t Ratio	Prob>|t|
β_0= Intercept	-0.95	2.88	-0.33	0.74
β_1= Bird age, d	-0.87	0.261	-3.32	0.0009
β_2= Bird age^2, d^2	0.11	0.012	9.26	<.0001
β_3= Bird age^3, d^3	- 1.6 e^{-03}	1.5 e^{-04}	-10.9	<.0001
β_4= Inside RH, %	0.18	0.045	4.11	<.0001
β_5= VR, cfm/bird	2.82	0.407	6.93	<.0001
β_6= LS, 0 or 1	N/S			

Annual NH_3 Emission

The annual NH_3 emission from each house is the accumulation of daily ERs over 365 days. However, some daily emissions were missing due to various reasons (for example, power outage from adverse weather and instrument malfunctions). Based on the regression of the ER vs. bird age from Equation [3], the annual emissions were 4.9 and 5.3 US tons (4.4 and 4.8 metric ton) for Tyson 1-5 and Tyson 3-3, respectively. On the basis of birds marketed the average ammonia emissions over a six-flock period were 75.2 and 81.0 lb per 1,000 birds marketed (34.1 and 36.7 g/bird-marketed) for Tyson 1-5 and Tyson 3-3, respectively. Combining both houses, the average annual ammonia emission (± S.E.) was 5.1 ± 0.19 US tons per house or 78.1 ± 3.1 lb per 1,000 birds marketed (4.6 metric tons per house or 35.4 ± 1.32 g per bird marketed).

H_2S Emission

H_2S ER Estimation/Prediction

H_2S ER was correlated to the bird age, body weight and VR, weakly correlated with inside RH and not correlated with outside temperature, outside RH or inside temperature. Among the variables, bird age was most predominant. For the flocks on new bedding, there was no clear bedding effect on H_2S ER. Because of the unusually high mortality in flock 5 at Tyson 1-5, this flock was not used to predict the ER. The H_2S ER per house or per bird from all data except for the flock 5 ERs at Tyson 1-5, as shown in Figures 25 and 26, could be described using the following regression equation:

$$\sqrt{H_2S\ ER} = a + b\,X + c\,X^2 + d\,X^3 \qquad [5]$$

where

        $H_2S\ ER$ = lb/d-house;

      X = bird age.

Table 6 provides the prediction parameter estimates for the two houses, individually, and over all 11.4 flocks. The correlation coefficients (r^2) of prediction models vary from 0.72 to 0.78 and show the strongest relationship between ER and bird age (Figure 25 and 26).

Table 6. Coefficient estimates of H$_2$S ER prediction models for houses Tyson 1-5 and Tyson 3-3

House	a (± S.E.)	b (± S.E.)	c (± S.E.)	d (± S.E.)	r^2
T1-5	0.102 (± 0.011)	0.009 (± 0.0004)	N/S	N/S	0.72
T3-3	0.056 (± 0.015)	0.016 (± 0.001)	$- 1.4\ e^{-04}$ (± $2.3\ e^{-05}$)	N/S	0.81
Overall	0.065 (± 0.011)	0.015 (± 0.001)	$- 1.0\ e^{-04}$ (± $1.8\ e^{-05}$)	N/S	0.76
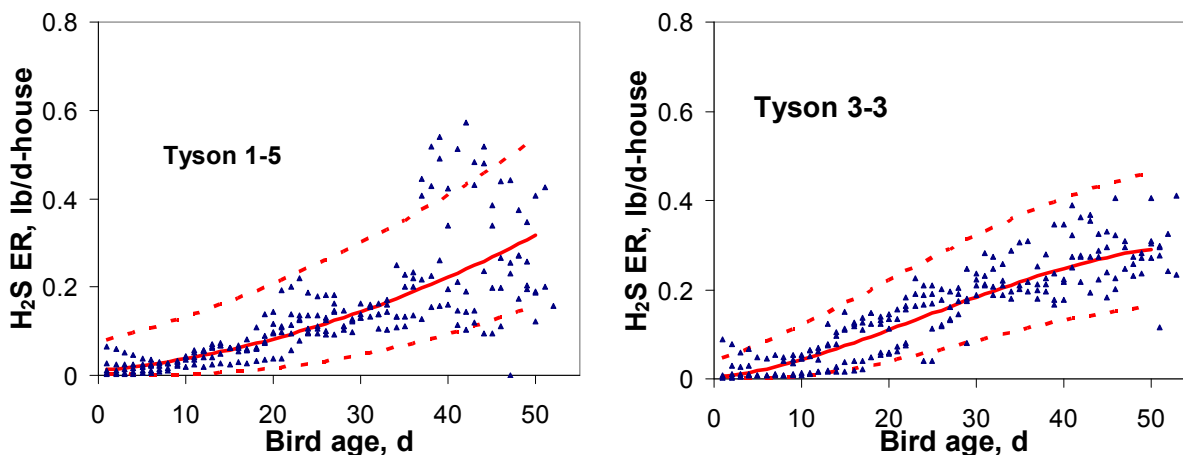
Figure 25. H$_2$S emission rate (ER) per house vs. bird age for Tyson 1-5 and Tyson 3-3. The solid line is the regression line and the dash lines are 95% prediction limits.
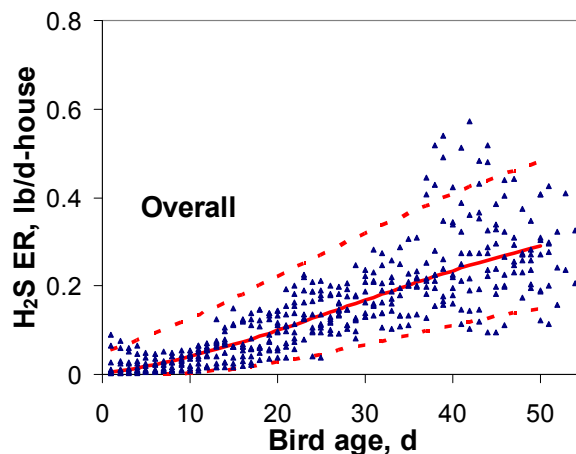
Figure 26. H$_2$S emission rate (ER) per house vs. bird age. The solid line is the regression line and the dash lines are 95% prediction limits.

Figure 27 provides the daily H$_2$S ER for the two houses for the entire monitoring period with 11.4 flocks and downtime between flocks. The daily ER varied from 0 to 0.57 lb/d-house (0 to 259.5 g/d-house). The highest ER was 0.57 and 0.41 lb/d-house (259.5 and 186.3 g/d-house) for Tyson 1-5 and Tyson 3-3, respectively. Note that the emissions between the vertical dashed lines represent periods between flocks when no birds were in the houses (i.e., downtime). There was no significant difference between the flocks with new bedding and those with built-up litter (P = 0.1) at α= 0.05. The average ER for Tyson 1-5 over the six flocks was 0.14 ± 0.10 lb/d-house (63.3 ± 44.7 g/d-house) which is not significantly different from 0.15 ± 0.10 lb/d-house (70 ± 43.6 g/d-house) for Tyson 3-3 (P=0.49). The average ER of 11.4 flocks was 0.14 ± 0.09 lb/d-house (65.7 ± 42 g/d-house).
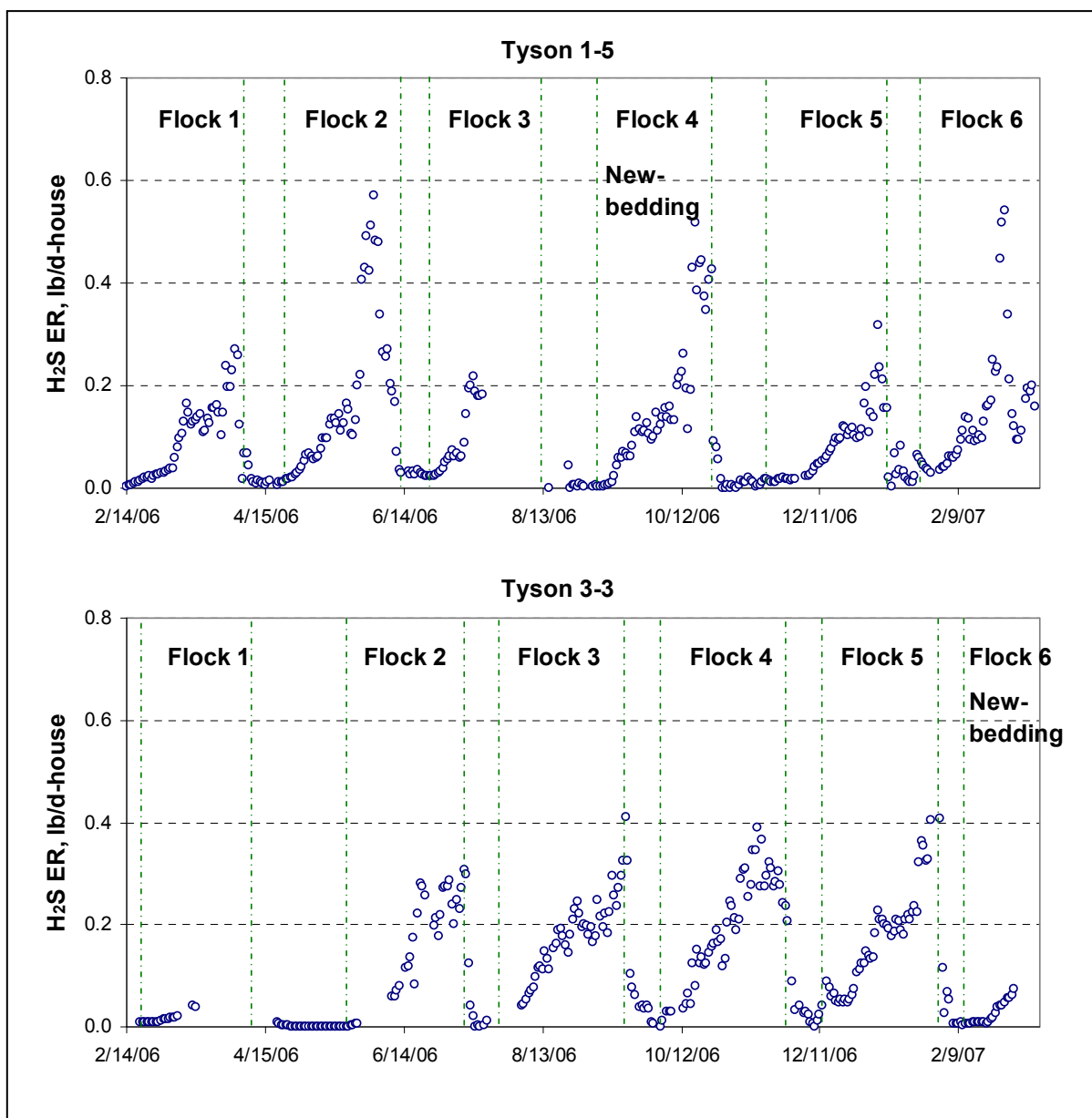
Figure 27. Daily H$_2$S emission over the 11.4 flocks for Tyson 1-5 and Tyson 3-3.

H$_2$S ER during Downtime between Flocks

The H$_2$S ER during the downtime was tested to determine the effects of environmental variables. However, no significant effects were found. VR of the houses had a significant impact on the NH$_3$ ER, but not so on H$_2$S ER (Figure 28). The average H$_2$S ER for Tyson 1-5 and Tyson 3-3 downtime was 0.023 ± 0.03 and 0.016 ± 0.026 lb/d-house (10.5 ± 13.4 and 7.3 ± 11.8 g/d-house), respectively. The average ER for the two houses during downtime was 0.020 ± 0.028 lb/d-house (9.0 ± 12.5 g/d-house).
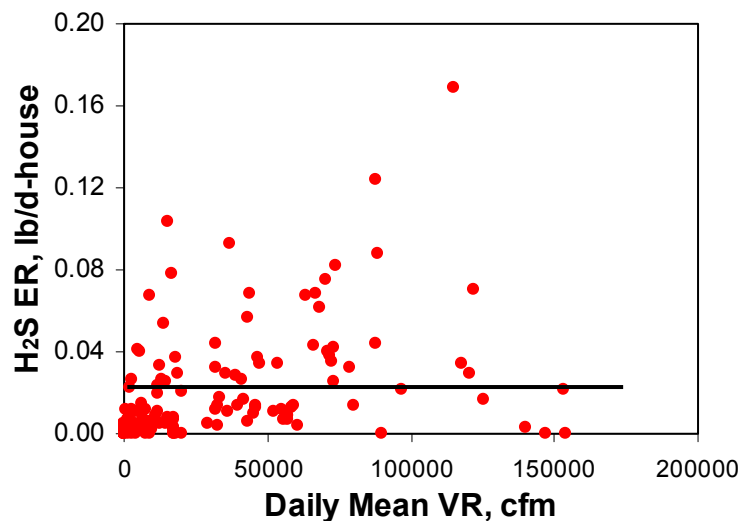
Figure 28. H$_2$S emission rate(ER) vs. ventilation rate (VR) during downtime.

H$_2$S ER per Animal Unit (AU)

Figures 29, 30, and 31 present H$_2$S ER in terms of 500 kg AU (g/d-AU) for all 11.4 flocks from the two houses. The ER per AU versus bird age showed different trends for the flocks with new bedding and built-up litter. During the first 10-d, the 1 ½ flocks new bedding (Tyson 1-5 flock 5, Sep to Oct 2006, and Tyson 3-3 flock 6, Feb 2007) had much lower ER per AU than the flocks with built-up litter. The H$_2$S ERs per AU of the flocks with built-up litter started high but trended to a low level with bird growth. No strong linear or other relationship was found between ER per AU and bird age. Therefore, daily H$_2$S ER per AU was expressed as 1.47 ± 1.53 g/d-AU. There was no significant difference between Tyson 1-5 and Tyson 3-3 in ER per AU (P=0.4).
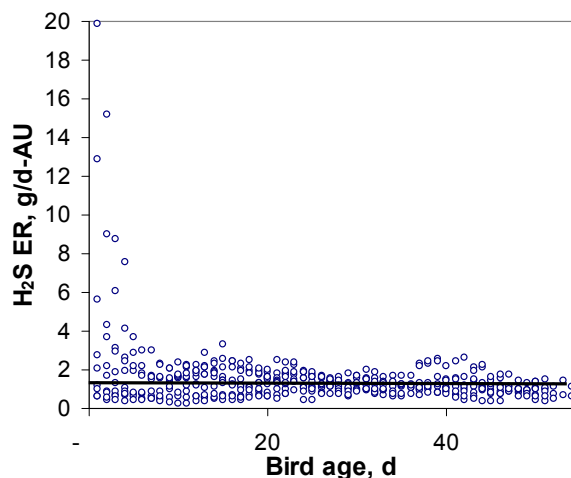
Figure 29. Relationship between H$_2$S ER per animal unit (AU, 500 kg) vs. bird age.
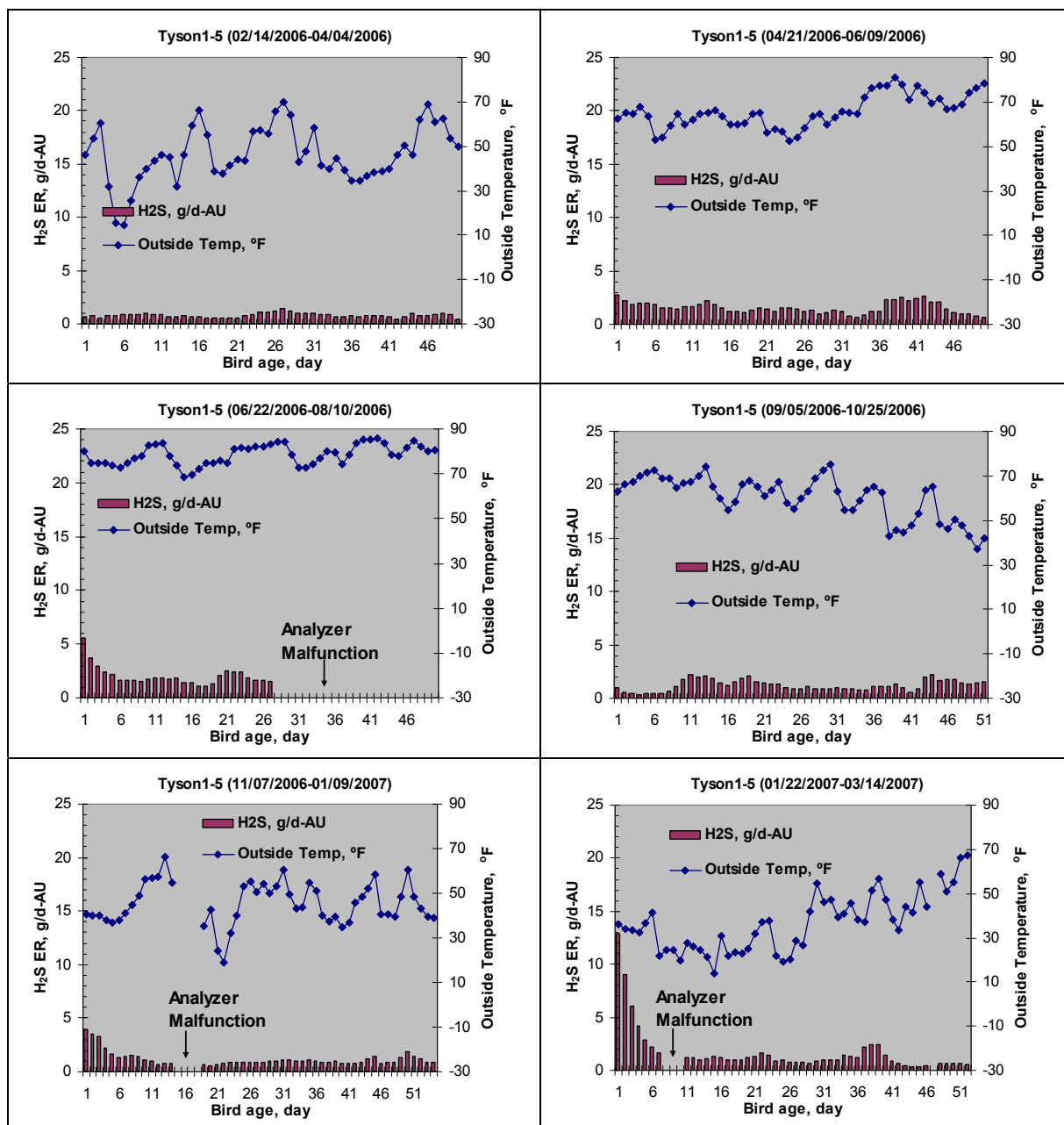
Figure 30. Tyson 1-5 H$_2$S ER per animal unit (AU, 500 kg) and outside temperature vs. bird age
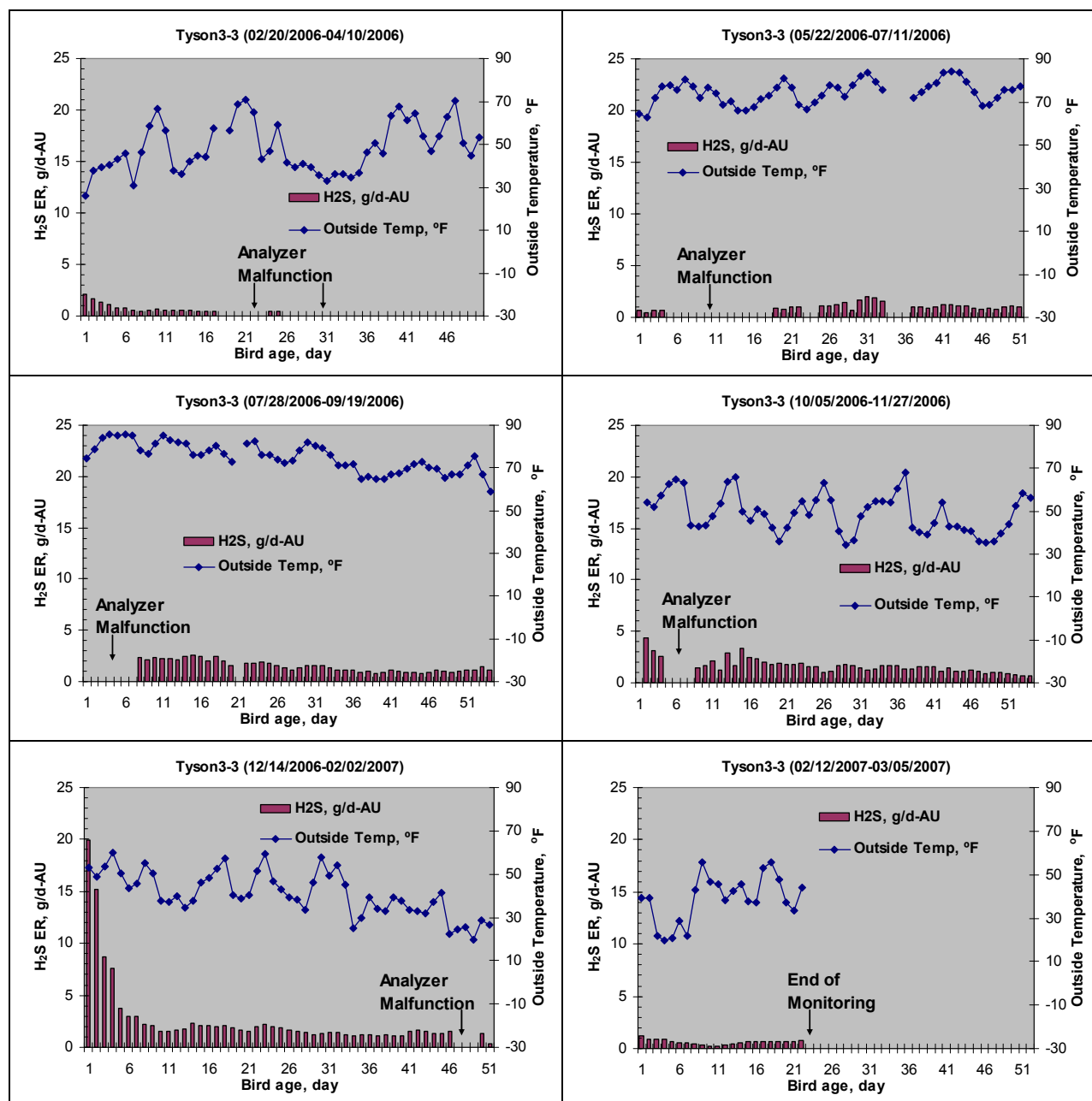
Figure 31. Tyson 3-3 H$_2$S ER per AU (500 kg) mean outside temperature vs. bird age

Effects of Environmental Variables on H$_2$S Emission Rate

To assess the impact of environmental variables on H$_2$S emission from the two broiler houses, a multiple regression analysis was performed to relate daily H$_2$S ER to bird age (d), interior temperature (^{o}F), RH (%), VR (cfm/bird) and litter status (0 for new bedding; 1 for built-up litter). The daily mean values of the above variables were used for the regression analysis. The results of the regression analysis are shown in Table 7. The interior RH had a significant effect on H$_2$S ER at α = 0.05. As RH increased, so did H$_2$S ER (lb/d-house).

Table 7. Multiple regression analysis of H_2S emission to bird age (d), interior temperature, RH (%), and litter status (LS) (R^2=0.66)

$$H_2S \text{ ER, lb d}^{-1} \text{ house}^{-1}= \beta_0 + \beta_1 x \text{ Age} + \beta_2 x T_i + \beta_3 x RH_i + \beta_4 x VR + \beta_5 x LS$$

Term	Estimate	S.E	t Ratio	Prob>|t|
β_0= Intercept	-0.272	0.034	-7.94	<.0001
β_1= Bird age, d	0.0058	0.00034	16.8	<.0001
β_2= Inside Temp., ºF	N/S			
β_3= Inside RH, %	0.0046	0.00061	7.54	<.0001
β_4= VR, cfm/bird	N/S			
β_5= LS, 0 or 1	N/S			

Annual H_2S Emission

The annual H_2S emission from each house is the accumulation of daily ERs over 365 days. However, some daily emissions were missing due to various reasons (for example, power outage from adverse weather and instrument malfunctions). When 5.4 flocks were grown for an average of 52 d and the average flock cumulative ER was 7.53 lb/flock (3.42 kg/flock), the annual emission (± S.E.) was 42.3 ± 2.1 lb/yr-house (19.2 ± 0.92 kg/yr-house). On the basis of per 1,000 birds marketed the annual average H_2S emission (± S.E.) was 147 ± 7.1 g.

NMHC Emission

In this report, the NMHC emission rate is expressed using propane (C_3H_8) as a reference. For instance, the unit of lb-NMHC /d-house represents lb-C_3H_8 per day per house.

NMHC ER Estimation/Prediction

NMHC ER was correlated to the bird age, body weight and VR, was weakly correlated with inside RH, and was not correlated with outside temperature, RH, or inside temperature. Among the three variables, bird age was most predominant. For flocks on new bedding, there was no clear bedding effect on NMHC ER. Due to the unusually high mortality in flock 5 at Tyson 1-5, this flock was not used in the ER prediction. The NMHC ER per house or per bird from all data except for the flock 5 ERs at Tyson 1-5, as shown in Figures 32 and 33, could be described using the following regression equation:

$$NMHC \text{ ER, lb } d^{-1} \text{ house}^{-1} = a + b X + c X^2 + d X^3 \qquad [6]$$

where

   X= bird age.

Table 8 provides the prediction parameter estimates for the two houses, individually, and overall 11.4 flocks. The correlation coefficients (r^2) of prediction models vary from 0.63 to 0.65 and show the strongest relationship between ER and bird age.

Table 8. Coefficient Estimates of NMHC ER regression for houses Tyson 1-5 and Tyson 3-3 (ER is not included when bird age is < 7d with new bedding)

House	a (± S.E.)	b (± S.E.)	c (± S.E.)	d (± S.E.)	r^2
T1-5	0.22 (± 0.25)	0.133 (± 0.04)	$-5.7\,e^{-4}$ ($\pm 1.7\,e^{-03}$)	$9.4\,e^{-5}$ ($\pm 2.2\,e^{-5}$)	0.65
T3-3	0.70 (± 0.097)	$-4.0\,e^{-03}$ ($\pm 9.0\,e^{-03}$)	$9.0\,e^{-4}$ ($\pm 1.8\,e^{-4}$)	N/S	0.65
Overall	0.39 (± 0.15)	-0.078 (± 0.0244)	$3.0\,e^{-03}$ ($\pm 1.0\,e^{-03}$)	$5.8\,e^{-5}$ ($\pm 1.3\,e^{-5}$)	0.63
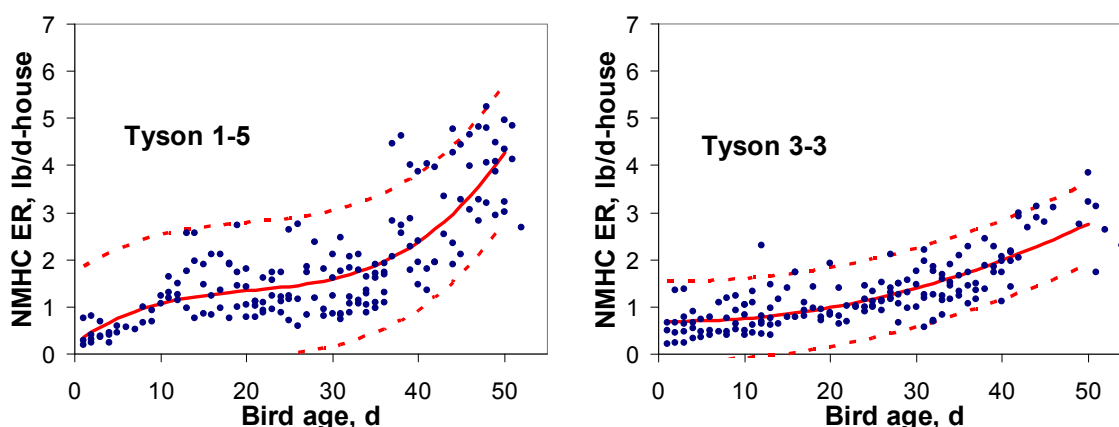
Figure 32. NMHC emission rate (ER) per house vs. bird age for Tyson 1-5 and Tyson 3-3. The solid line is the regression line and the dash lines are 95% prediction limits.
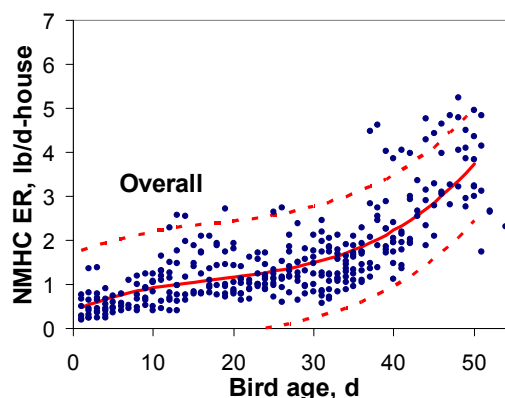
Figure 33. NMHC emission rate (ER) per house vs. bird age. The solid line is the regression line and the dash lines are 95% prediction limits.

Figure 34 provides the daily NMHC ER for the two houses for the entire monitoring period with 11.4 flocks and downtime between flocks. The daily ER varied from 0 to 5.24 lb/d-house (0 to

2.4 kg/d-house). The highest ER was 5.24 and 3.84 lb/d-house (2.4 and 1.7 kg/d-house) for Tyson 1-5 and Tyson 3-3, respectively. The average ER for Tyson 1-5 over the six flocks was 1.86 ± 1.07 lb/d-house (0.8 ± 0.5 kg/d-house) which is significantly different from 1.43 ± 0.69 lb/d-house (0.6 ± 0.3 kg/d-house) for Tyson 3-3 (P=0.017) at α =0.05. The average ER of 11.4 flocks was 1.68 ± 0.94 lb/d-house (0.8 ± 0.4 kg/d-house).
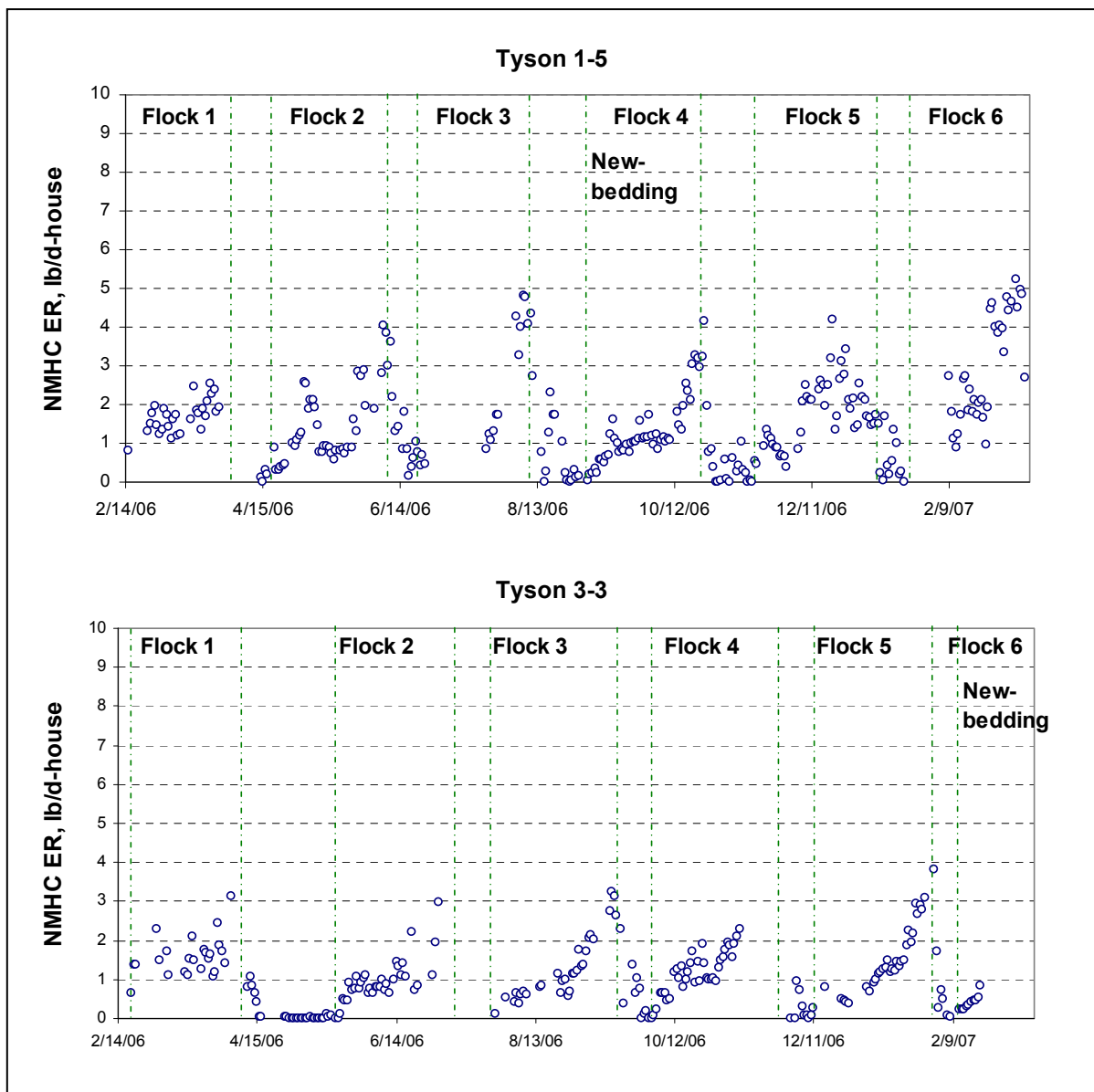

Figure 34. Daily NMHC emission rate (ER) over the 11.4 flocks for Tyson 1-5 and Tyson 3-3.

NMHC ER during Downtime between Flocks

The NMHC ER during the downtime was tested for the environmental variables effect. VR of the houses had a linear relationship with NMHC ER (Figure 35). The average NMHC ER for the two houses during downtime was 0.45 ± 0.64 lb/d-house (0.2 ± 0.3 kg/d-house).

$$Y = 1E\text{-}05x$$
$$R^2 = 0.5237$$
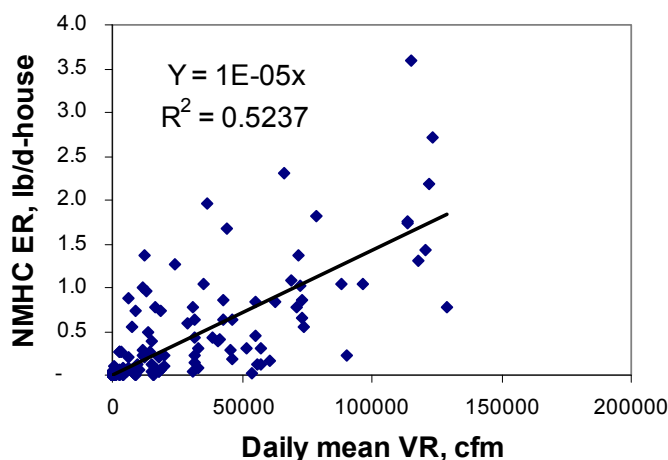
Figure 35. NMHC emission rate(ER) vs. ventilation rate (VR) during downtime.

NMHC ER per Animal Unit (AU)

Figures 36, 37, and 38 present NMHC ER in terms of 500 kg animal unit (kg/d-AU) for all 11.4 flocks from the two houses. The ER per AU versus bird age showed different trends for the flocks with new bedding and built-up litter. ER decreased with bird age. The ER per AU of the flocks with built-up litter started high for the first three weeks but trended downward in the forth week and stabilized to be stable with bird growth. There was no significant difference between Tyson 1-5 and Tyson 3-3 in ER per AU (P=0.4). The daily ER per AU was 0.024 ± 0.022 and 0.28 ± 0.51 kg/d-AU for Tyson 1-5 and Tyson 3-3, respectively. The overall ER per AU was 0.25 ± 0.33 kg/ d-AU.
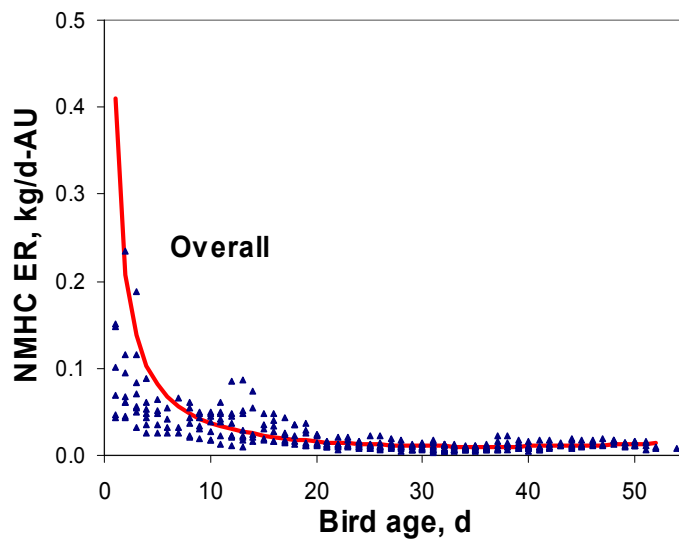
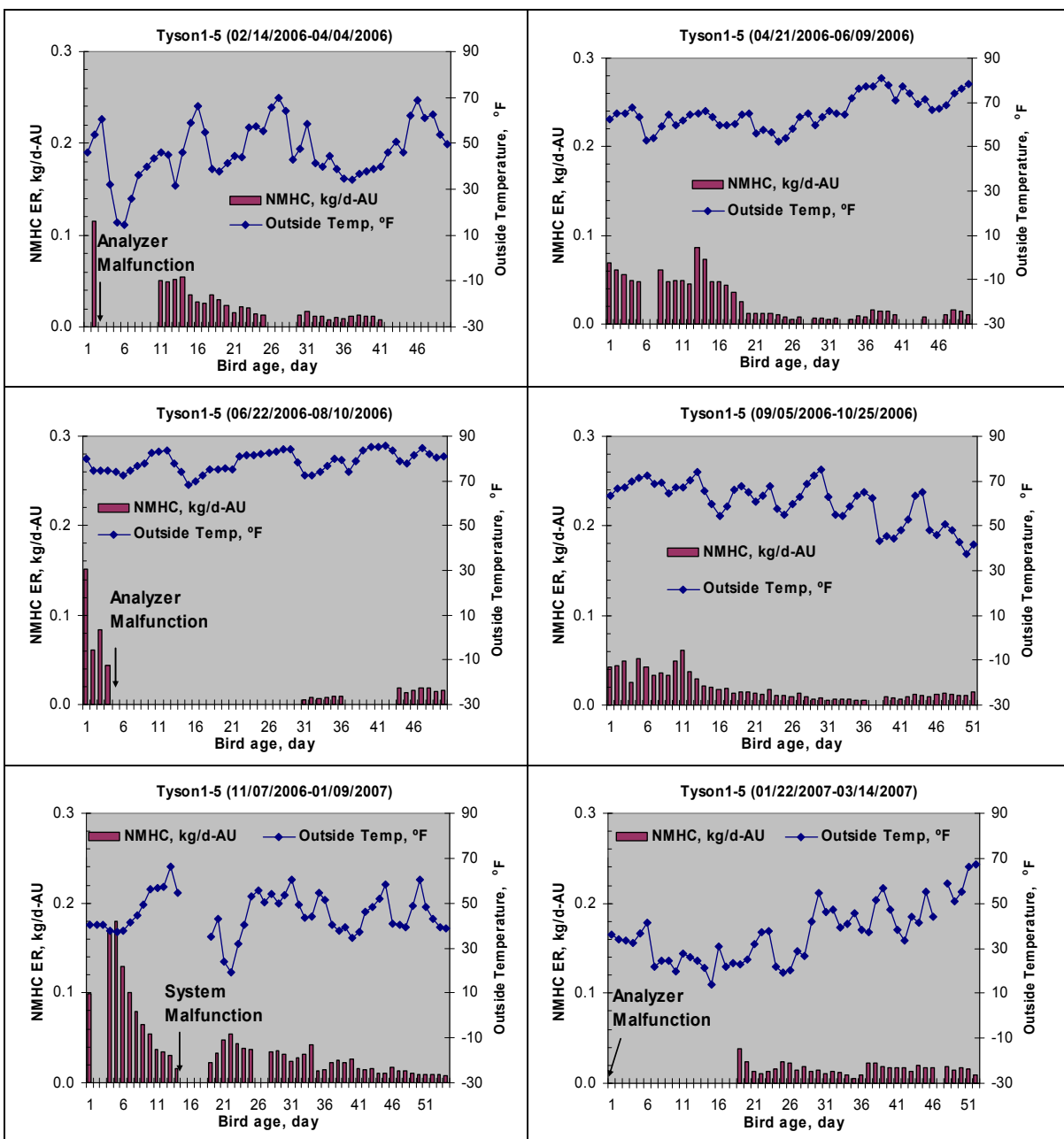Figure 36. Relationship between NMHC ER per AU (500 kg) vs. bird age.

Figure 37. Tyson 1-5 NMHC emission rate (ER) per animal unit (AU, 500 kg) and mean outside temperature vs. bird age
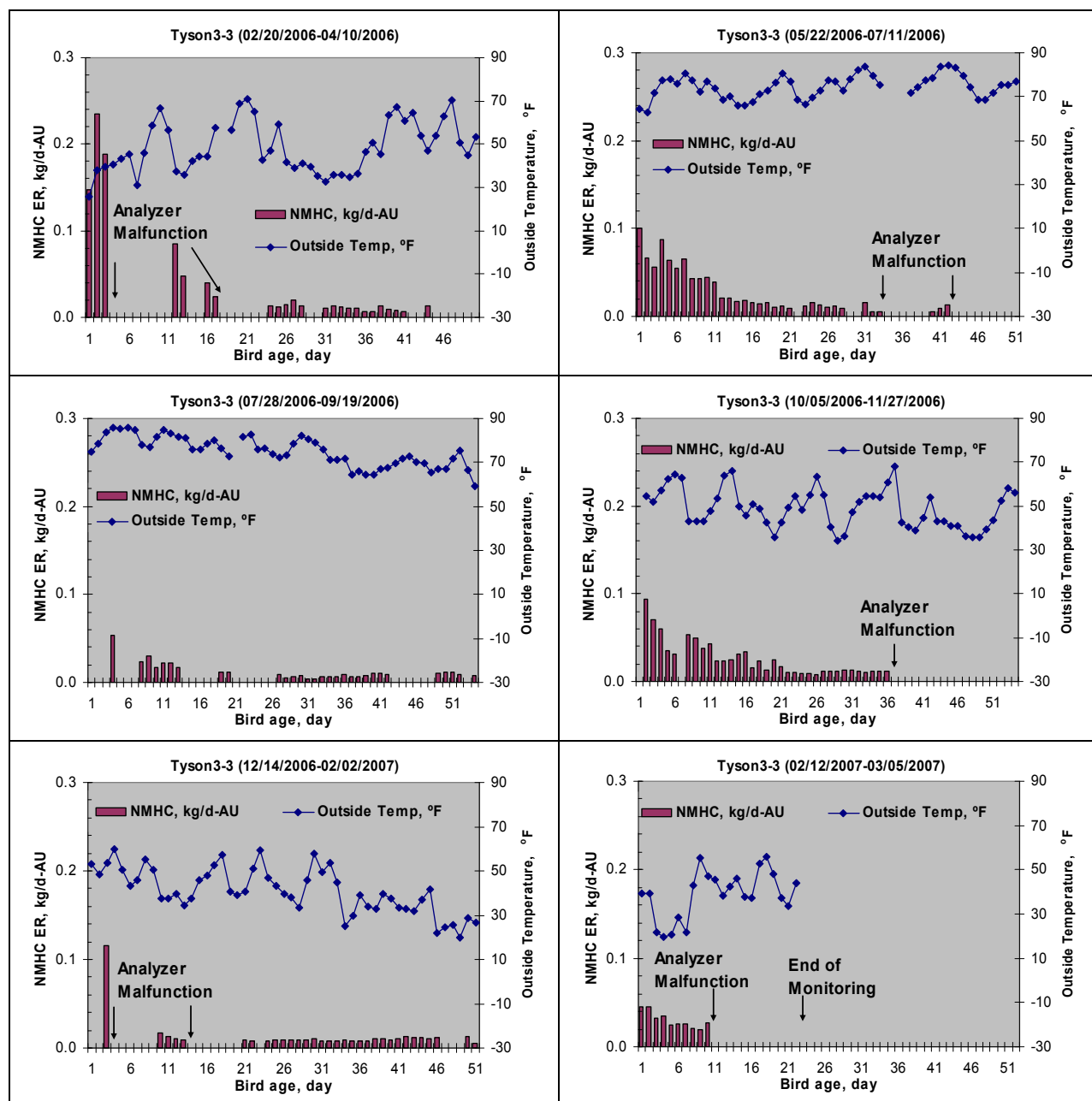
Figure 38. Tyson 3-3 NMHC emission rate (ER) per animal unit (AU, 500 kg) and mean outside temperature vs. bird age

Environmental Effect on NMHC ER

To assess the impact of environmental variables on the NMHC emission from the broiler houses, a multiple regression analysis was performed to relate NMHC ER (lb/d-house) to bird age (d), interior temperature (^{o}F), RH (%), VR (cfm/bird) and litter status (0 for new bedding; 1 for built-up litter). Daily mean values of the above variables were used for the regression analysis, and the results are shown in Table 9. Interior RH and litter status showed significant

effects on NMHC (P=0.003), with RH negatively related to NMHC ER and new bedding leading to lower NMHC ER.

Table 9. Multiple regression analysis of NMHC ER (lb/d-house) to bird age (d), interior temperature, RH (%), and litter status (LS) (R^2=0.68)

NMHC ER, lb d^{-1} house^{-1}= β_0 + β_1x Age+ β_2 x Age^2+ β_3 x Age^3+ β_4 x T$_i$ + β_5 x RH$_i$+ β_6 x VR+ β_7 x LS

Term	Estimate	S.E	Prob>|t|
β_0= Intercept	1.58	0.25	<0.001
β_1= Bird age	0.079	0.022	<0.001
β_2= Bird age^2, d^2	- 3.0 e^{-03}	1.0 e^{-03}	<0.001
β_3= Bird age^3, d^3	5.7 e^{-05}	1.2 e^{-05}	<0.001
β_4= Inside Temp., ºF	N/S		
β_5= Inside RH, %	-0.026	3.8 e^{-03}	<0.001
β_6= VR, cfm/bird	N/S		
β_7= LS, 0 or 1	0.31	0.086	0.003

Annual NMHC Emission

The annual NMHC emission from each house is the accumulation of daily ERs over 365 days. When 5.4 flocks were grown for an average of 52 d and the average flock cumulative emission was 87.5 lb/flock (39.7 kg/flock), the annual emission (± S.E.) was 510 ± 59.6 lb/yr-house (231 ± 27.0 kg/yr-house). On the basis of number of birds marketed the annual average NMHC emission (± S.E.) was 3.9 ± 0.45 lb per 1,000 birds marketed or 1.77 ± 0.21 g per bird marketed.

NMHC Speciation

Ambient background was not sampled for NMHC. It was assumed that background ambient air consisted of the same NMHC compounds emitted from the houses. Also, it was assumed that the empty house and occupied house had similar chemical profiles for detectable compounds, but the concentrations would change between the empty or occupied house. Air samples from three different sections of empty and occupied houses were speciated (Figure 17). Table 10 provides a list of net concentration levels for the combined top 25 NMHCs from the samples collected in the empty and the occupied house. This table also includes the mass conversion coefficient for all compounds that were identified and quantified. The ER of all the compounds can be calculated by multiplying the NMHC ER with the corresponding mass conversion coefficient provided in Table 10.

Table 10. Top-25 speciated NMHC concentration levels (ppb) and mass conversion coefficients (lb/lb-C$_3$H$_8$) for samples collected in the empty and occupied broiler house

Compound	Empty house		Occupied house	
	Sample concentration, ppb	Conversion Coefficient, lb/lb·C$_3$H$_8$	Sample concentration, ppb	Conversion Coefficient, lb/lb·C$_3$H$_8$
2,3-Butanedione	4.6	0.010	260.7	0.480
2-Pentanone	5.7	0.015	6.5	0.015
2-Butanone	N/A	N/A	14.9	0.023
2-Methyl propanoic acid	N/A	N/A	7.7	0.014
2-Methyl-3-Pentanone	N/A	N/A	12.4	0.040
3-Hydroxy-2-Butanone	3.5	0.007	15.8	0.030
3-Methylindole	1.8	0.013	N/A	N/A
3-Methyl butanoic acid	N/A	N/A	9.4	0.026
4-Ethylphenol	1.8	0.011	N/A	N/A
4-Methylphenol	7.1	0.032	N/A	N/A
Acetamide	N/A	N/A	10.1	0.006
Acetic acid	67.6	0.049	344.1	0.221
Acetone	30.1	0.032	40.9	0.038
Acetonitrile	N/A	N/A	13.5	0.006
Benzalaldehyde	10.7	0.048	N/A	N/A
Benzoic acid	8.2	0.043	N/A	N/A
Butanoic acid	3.3	0.007	18.9	0.036
Butanol	301.2	0.542	39.3	0.062
Dimethyl disulfide	7.2	0.008	7.8	0.008
Dimethyl sulfone	6.9	0.008	4.6	0.005
Ethanol	28.6	0.016	120.1	0.059
Hexane	22.6	0.071	10.5	0.029
Indole	N/A	N/A	3.9	0.020
Isoprene	8.3	0.017	N/A	N/A
Methanol	63.8	0.012	160.4	0.028
Pentane	N/A	N/A	9.0	0.017
Phenol	18.3	0.063	N/A	N/A
Propanoic acid	5.5	0.007	14.4	0.017
Propanol	5.6	0.006	15.6	0.015
Propene	N/A	N/A	10.9	0.007
Sulfolane	1.7	0.005	N/A	N/A
Tetra methyl pyrazine	N/A	N/A	3.4	0.027
Toluene	50.2	0.197	N/A	N/A
Triethyl citrate	14.0	0.282	N/A	N/A
Trimethyl oxazalone	N/A	N/A	5.1	0.018
Unknown compound	10.5	0.122	N/A	N/A

TSP Emission

TSP ER Estimation/Prediction

TSP ER was correlated to the bird age, body weight and VR, was weakly correlated with inside RH and was not correlated with outside temperature, RH, or inside temperature. Moreover, there existed a very strong positive relationship among bird age, body weight and VR. Among the three variables, bird age is the most predominant influencing factor. For the flocks on new bedding, there was no clear bedding effect on TSP ER. Because of the unusually high mortality in flock 5 at Tyson 1-5, this flock was not used in the ER prediction. The TSP ER per house or per bird from all data except for the flock 5 ERs at Tyson 1-5, as shown in Figures 39 and 40, may be described using the following regression equation:

$$\sqrt[3]{TSP\ ER} = a + b\ X + c\ X^2 \qquad [7]$$

where

$TSP\ ER$ = lb d^{-1} house^{-1};

X = bird age.

Table 11 provides the prediction parameter estimates for the two houses, individually, and overall 11.4 flocks. The correlation coefficients (r^2) of prediction models vary from 0.82 to 0.88 and show the strongest relationship between ER and bird age.

Table 11. Coefficient Estimates of TSP ER regressions for broiler houses Tyson 1-5 and Tyson 3-3

House	a (± S.E.)	b (± S.E.)	c (± S.E.)	r^2
1-5	0.48 (± 0.042)	0.061 (± 4.0 e^{-03})	- 4.7 e^{-4} (±7.8 e^{-5})	0.87
3-3	0.34 (± 0.040)	0.086 (± 4.0 e^{-03})	- 9.7 e^{-4} (±6.9 e^{-5})	0.88
Overall	0.40 (± 0.030)	0.074 (± 3.0 e^{-03})	- 7.5 e^{-4} (±5.3 e^{-5})	0.86
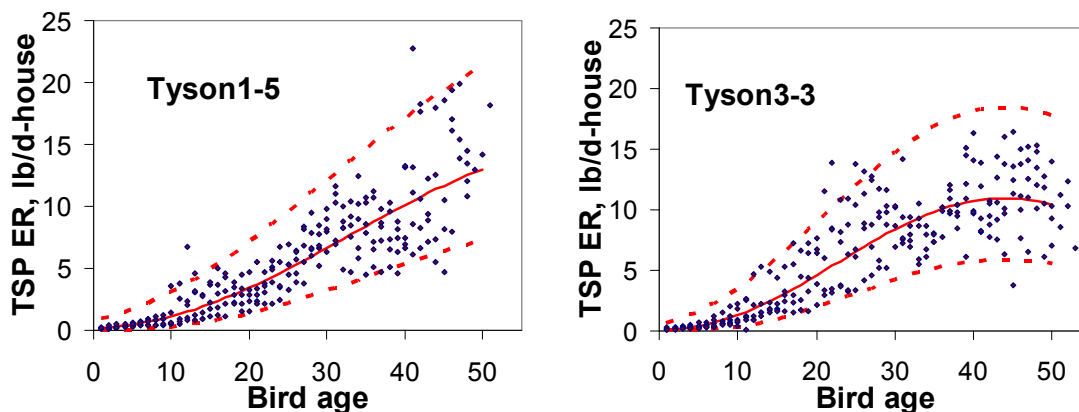
Figure 39. TSP emission rate (ER) per house vs. bird age for Tyson 1-5 and Tyson 3-3. The solid line is the regression line and the dash lines are 95% prediction limits.
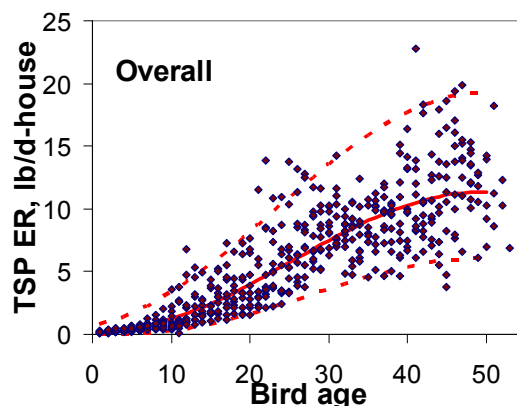

Figure 40. TSP emission rate (ER) per house vs. bird age. The solid line is the regression line; dash lines are 95% prediction limits.

Figure 41 provides the daily TSP ER for the two houses for the entire monitoring period with 11.4 flocks and downtime between flocks. The daily ER varied from 0 to 22.8 lb/d-house (0 to 10.3 kg/d-house). The highest ER was 22.8 and 16.3 lb/d-house (10.3 and 7.3 kg/d-house) for Tyson 1-5 and Tyson 3-3, respectively. Note that the emissions between the vertical dashed lines in Figure 41 represent periods between flocks when no birds were in the houses (i.e., downtime). The average ER was 5.92 ± 4.33 lb/d-house (2.69 ± 1.96 kg/d-house) for Tyson 1-5 and 6.34 ± 4.03 lb/d-house (2.88 ± 1.83 kg/d-house) for Tyson 3-3. The average ER of all 11.4 flocks was 6.13 ± 4.13 lb/d-house (2.78 ± 1.87 kg/d-house).
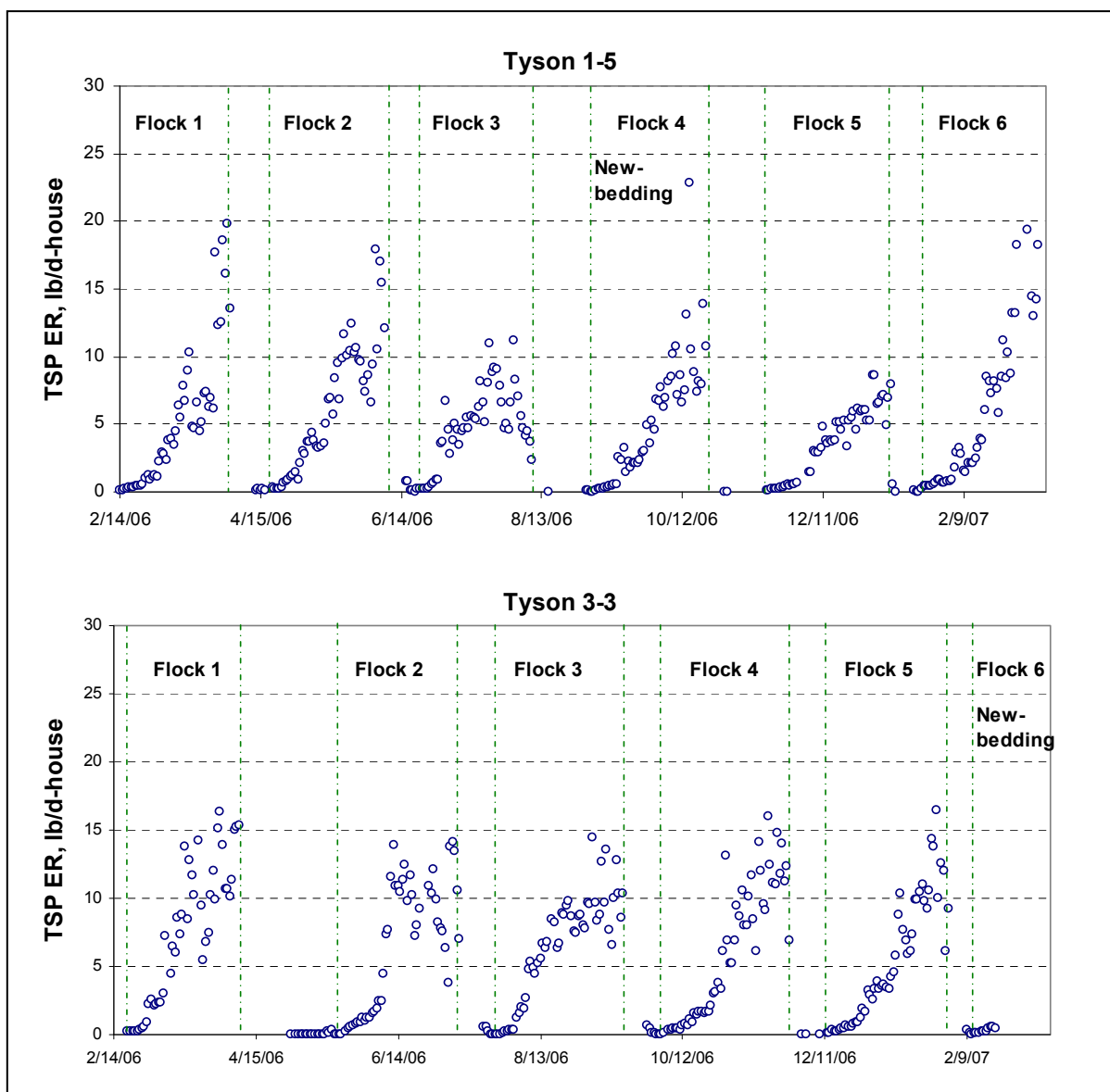
Figure 41. Daily TSP emission rate (ER) over the 11.4 flocks for Tyson 1-5 and Tyson 3-3.

TSP ER during Downtime between Flocks

The TSP ER during the downtime was tested for the environmental variables effect. VR of the houses had a linear relationship with TSP ER (Figure 42). The average TSP ER for the two houses during downtime was 0.12 ± 0.19 lb/d-house (0.05 ± 0.086 kg/d-house).
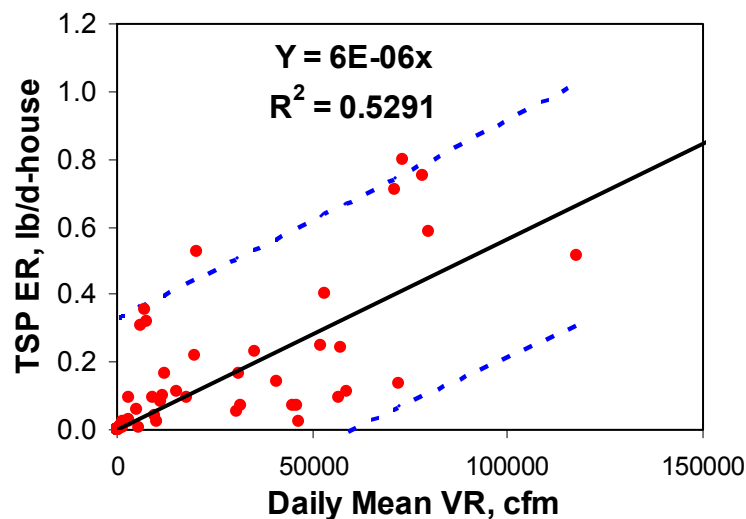
Figure 42. TSP emission rate (ER) vs. ventilation rate (VR) during downtime. The solid line is the regression line; dash lines are 95% prediction limits.

TSP ER per Animal Unit (AU)

Figures 43, 44, and 45 present TSP ER in terms of 500 kg animal unit (kg/d-AU) for all 11.4 flocks from the two houses. There was no clear trend between the ER per AU and bird age (Figure 43). ER per AU of Tyson 1-5 was significantly different to the ER of Tyson 3-3 with P=0.024 at α = 0.05. The daily ER per AU was 0.50 ± 0.13 and 0.54 ± 0.01 kg/d-AU for Tyson 1-5 and Tyson 3-3, respectively. The overall ER per AU was 0.52 ± 0.01 kg/ d-AU.
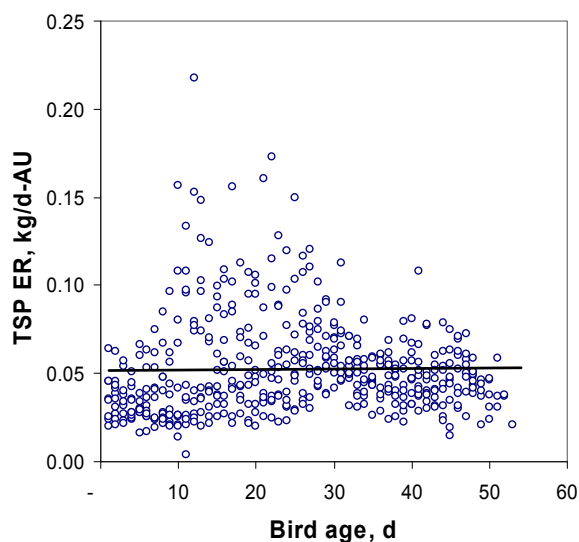
Figure 43. TSP emission rate (ER) per day per AU (500kg) vs. bird age for the two houses over one year period
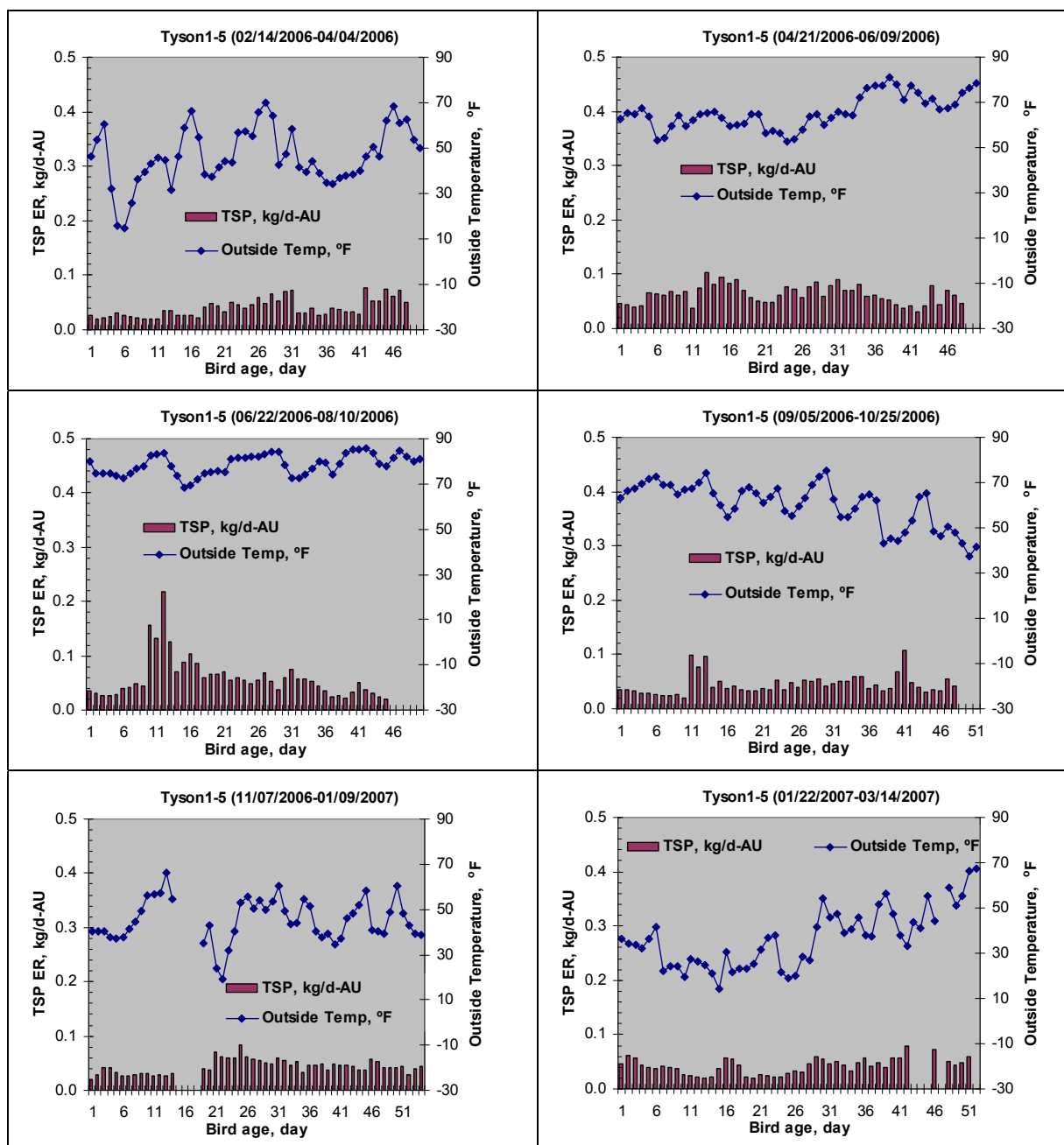
Figure 44. Tyson 1-5 TSP emission rate (ER) per animal unit (AU, 500 kg) and mean outside temperature vs. bird age.
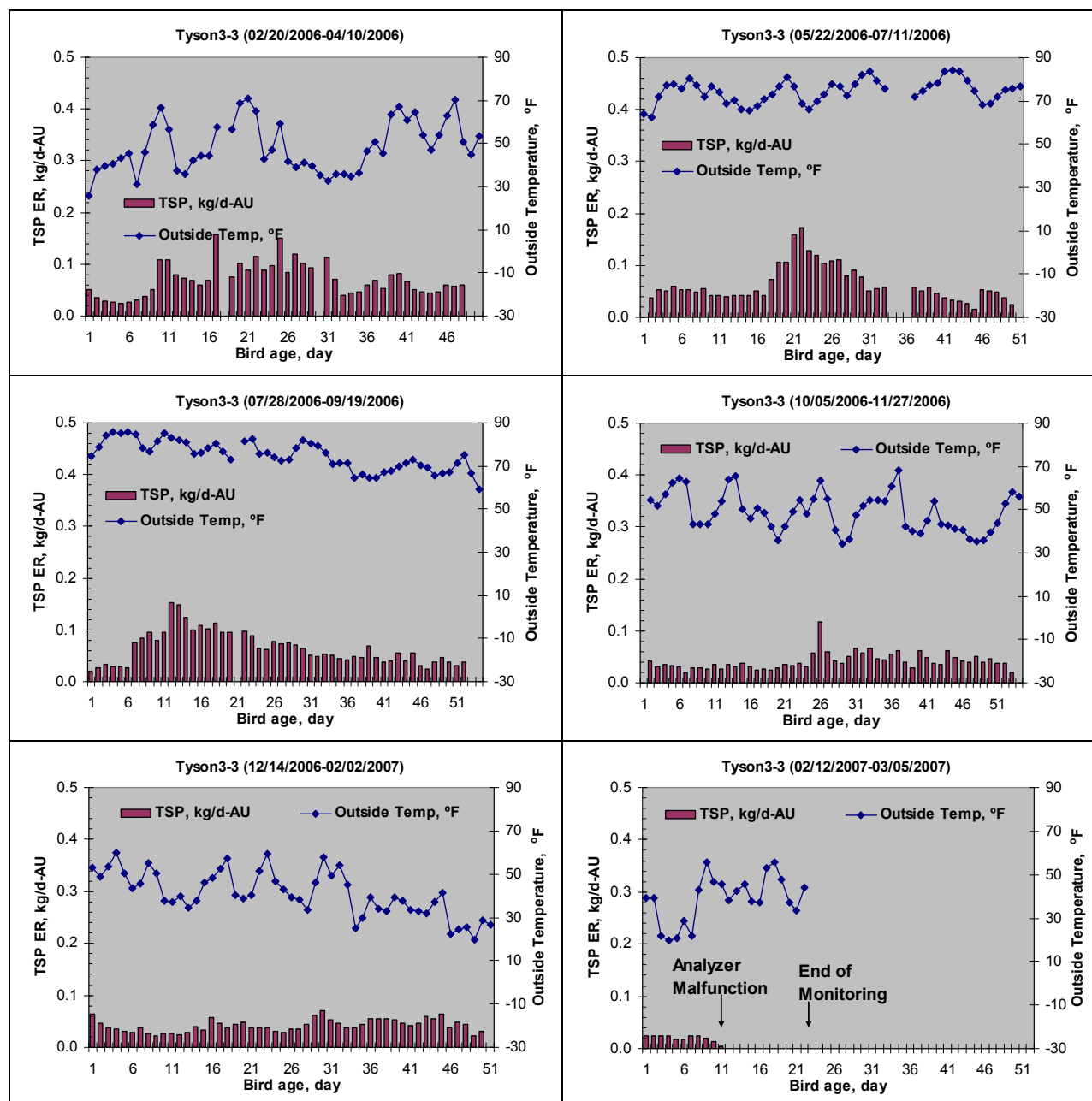
Figure 45. Tyson 3-3 TSP emission rate (ER) per animal unit (AU, 500 kg) and mean outside temperature vs. bird age.

Effects of Environmental Variables on TSP ER

To assess the impact of environmental variables on TSP emission from the two broiler houses, a multiple regression analysis was performed to relate TSP ER to bird age (d), interior temperature (^{o}F), RH (%), VR (cfm/bird) and litter status (0 for new bedding; 1 for built-up litter). The results of the regression analysis are shown in Table 12. Except for interior temperature and litter status, all variables were significant for TSP ER at α = 0.05. The TSP ER (lb/d-house) was positively correlated to temperature and RH.

Table 12. Multiple regression analysis of TSP to bird age, interior temperature, RH, Ventilation rate (VR), and litter status (LS) (R^2=0.87)

$$\sqrt[3]{TSP\ ER} = \beta_0 + \beta_1 x\ Age + \beta_2\ x\ Age^2 + \beta_3\ x\ T_i + \beta_4\ x\ RH_i + \beta_5\ x\ VR + \beta_6\ x\ LS$$

Term	Estimate	S.E	Prob>|t|
β_0= Intercept	1.19	0.092	<.0001
β_1= Bird age, d	0.066	$3.5e^{-3}$	<.0001
β_2= Bird age^2, d^2	0.00	$7.0e^{-5}$	<.0001
β_3= Inside Temp., ºF	N/S		
β_4= Inside RH, %	-0.014	0.002	<.0001
β_5= VR, cfm/bird	0.058	0.0122	0.0018
β_6= LS, 0 or 1	N/S		

Annual TSP Emission

The annual TSP emission from each house is the accumulation of daily ERs over 365 days. When 5.4 flocks were grown for 52 days and the average flock cumulative emission rate was 319 lb/flock (145 kg/flock), the annual emission rate (± S.E.) was 1,731 ± 58.6 lb/year-house (785 ± 26.6 kg/year-house). On the basis of number of birds marketed the annual average TSP emission (± S.E.) was 13.2 ± 0.46 lb per 1,000 birds marketed or 6.01± 0.21 g per bird marketed.

PM_{10} Emission

PM_{10} ER Estimation/Prediction

PM_{10} ER was correlated to bird age, body weight and VR, was weakly correlated with inside RH and not correlated with outside temperature, RH, or inside temperature. Among the three influencing variables, bird age was most predominant. For flocks on new bedding, there was no clear bedding effect on PM_{10} ER. Because of the unusually high mortality in flock 5 at Tyson 1-5, this flock was not used in the ER prediction. The PM_{10} ER per house or per bird from all data except for the flock 5 ER at Tyson 1-5, as shown in Figures 46 and 47, may be described using the following regression equation:

$$\sqrt[3]{PM_{10}\ ER} = a + b\ X + c\ X^2 \qquad [8]$$

where

$PM_{10}\ ER$ = lb d^{-1} house^{-1};

X= bird age.

Table 13 provides the prediction parameter estimates for the two houses, individually, and over all 11.4 flocks. The correlation coefficients (r^2) of prediction models vary from 0.86 to 0.88 and show the strongest relationship between ER and bird age.

Table 13. Coefficient Estimates of PM$_{10}$ ER prediction models for the houses, Tyson 1-5 and Tyson 3-3.

House	a (± S.E.)	b (± S.E.)	c (± S.E.)	r^2
T1-5	0.3 (± 0.034)	0.043 (± 0.003)	- 2.6 e^{-4} (±6.1 e^{-5})	0.88
T3-3	0.27 (± 0.031)	0.060 (± 0.003)	- 6.3 e^{-4} (±5.3 e^{-5})	0.87
Overall	0.29 (± 0.024)	0.052 (± 0.002)	- 4.5 e^{-4} (±4.2 e^{-5})	0.86
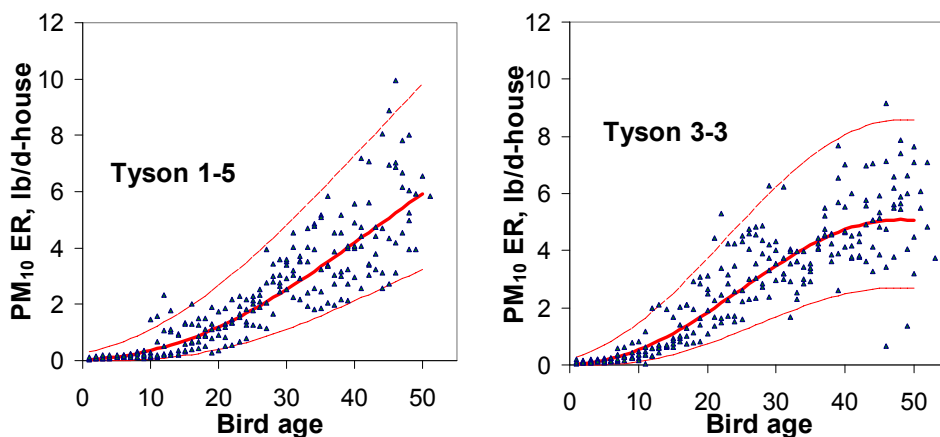
Figure 46. Relationship between PM$_{10}$ ER per house vs. bird age for Tyson 1-5 and Tyson 3-3. The solid line is the regression line; dash lines are 95% prediction limits.
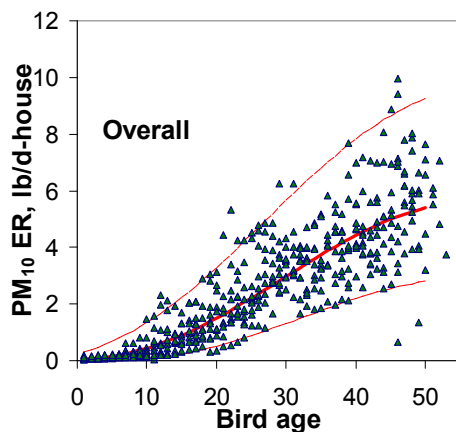
Figure 47. Relationship between PM$_{10}$ ER per house vs. bird age. The solid line is the regression line; dash lines are 95% prediction limit.

Figure 48 provides the daily PM_{10} ER for the two houses for the entire monitoring period with 11.4 flocks and downtime between flocks. The daily ER varied from 0 to 9.95 lb/d-house (0 to 4.5 kg/d-house). The highest ER was 9.95 and 9.43 lb/d-house (4.5 and 4.3 kg/d-house) for Tyson 1-5 and Tyson 3-3, respectively. Note that the emissions between the vertical dashed lines in Figures 48 represent periods between flocks when no birds were in the houses (i.e., downtime). The average ER were 2.43 ± 1.98 lb/d-house (1.10 ± 0.9 kg/d-house) for Tyson 1-5 and 3.1 ± 2.02 lb/d-house (1.4 ± 0.92 kg/d-house) for Tyson 3-3. The average ER of all 11.4 flocks was 2.57 ± 1.88 lb/d-house (1.16 ± 0.85 kg/d-house).
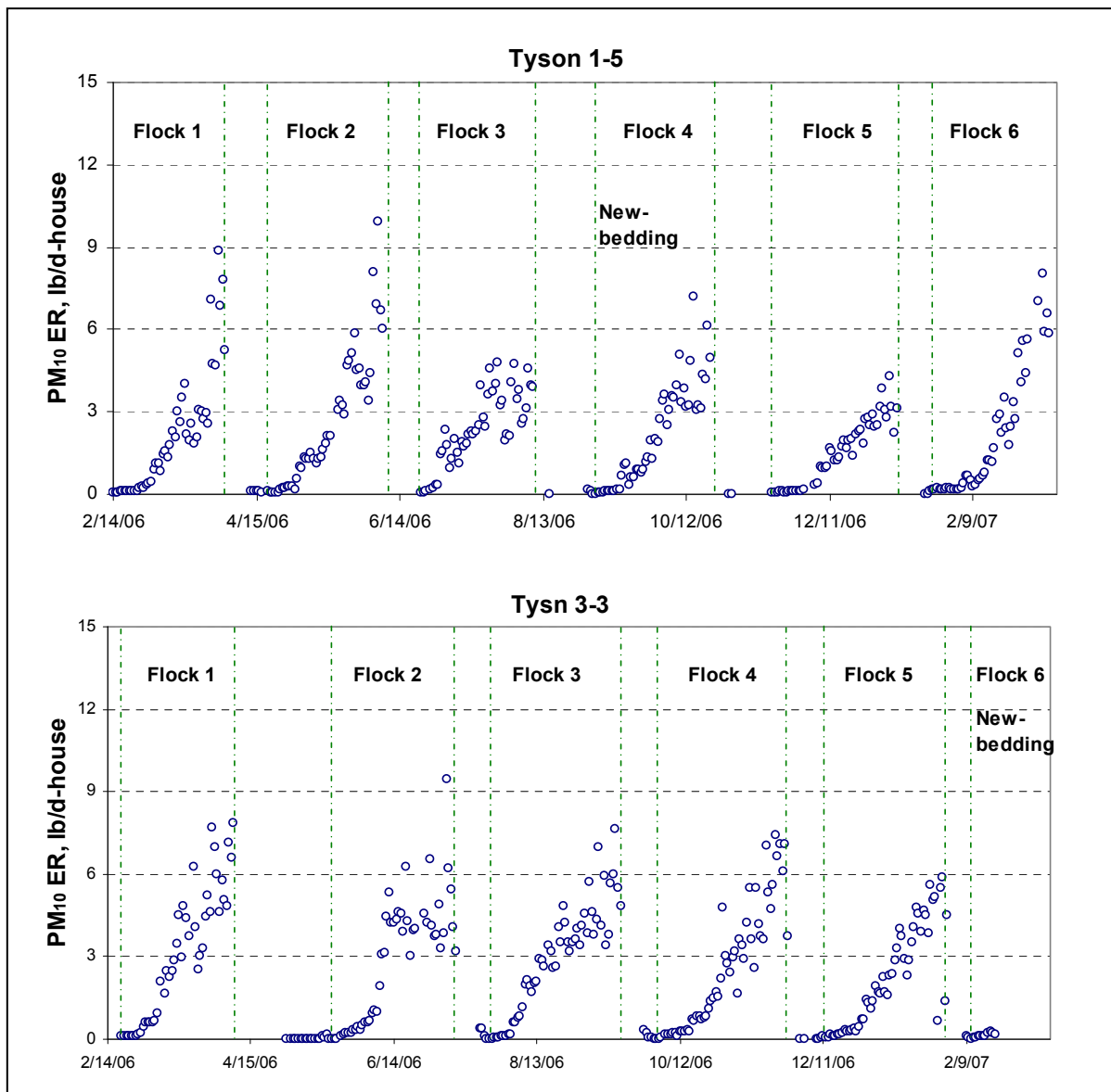
Figure 48. Daily PM_{10} emission over the 11.4 flocks for Tyson 1-5 and Tyson 3-3.

PM$_{10}$ ER during Downtime between Flocks

The PM$_{10}$ ER during the downtime was tested for the environmental variables effect. VR of the houses had a linear relationship with PM$_{10}$ ER (Figure 49). The average PM$_{10}$ ER for the two houses during downtime was 0.052 ± 0.085 lb/d-house (0.024 ± 0.039 kg/d-house).
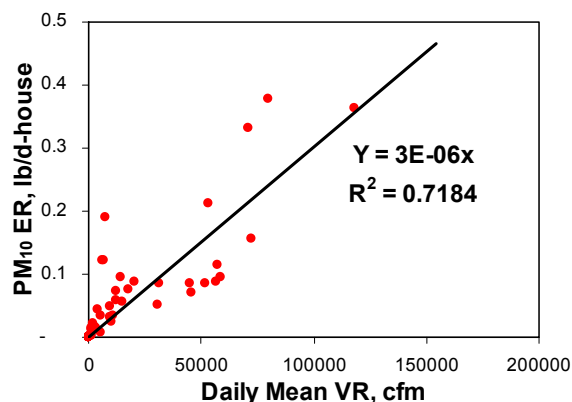

Figure 49. PM$_{10}$ emission rate (ER) vs. ventilation rate (VR) during downtime.

PM$_{10}$ ER per Animal Unit (AU)

Figures 50, 51, and 52 present PM$_{10}$ ER in terms of 500 kg animal unit (g/d-AU) for 11.4 flocks from the two houses. There was no clear trend between the PM$_{10}$ ER per AU and bird age (Figure 50). There was significant difference between Tyson 1-5 and Tyson 3-3 in ER per AU with P<0.0001 at α = 0.05. The daily ER per AU was 18.2 ± 3.34 and 26.7 ± 4.65 g/d-AU for Tyson 1-5 and Tyson 3-3, respectively. The overall ER per AU was 20.3 ± 2.34 g/d-AU.
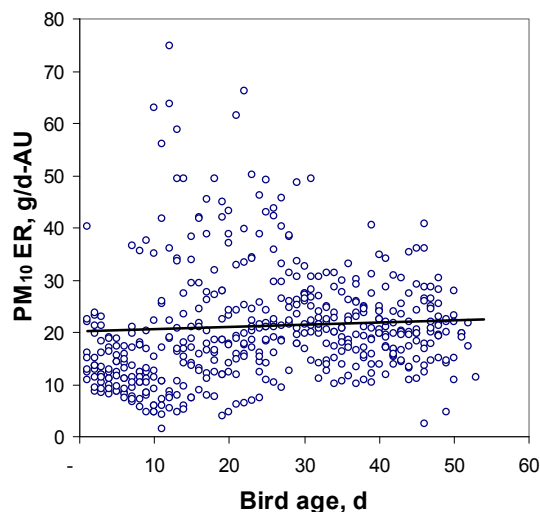

Figure 50. PM$_{10}$ emission rate (ER) per day per animal unit (AU, 500kg) vs. bird age for the two houses over one year period.
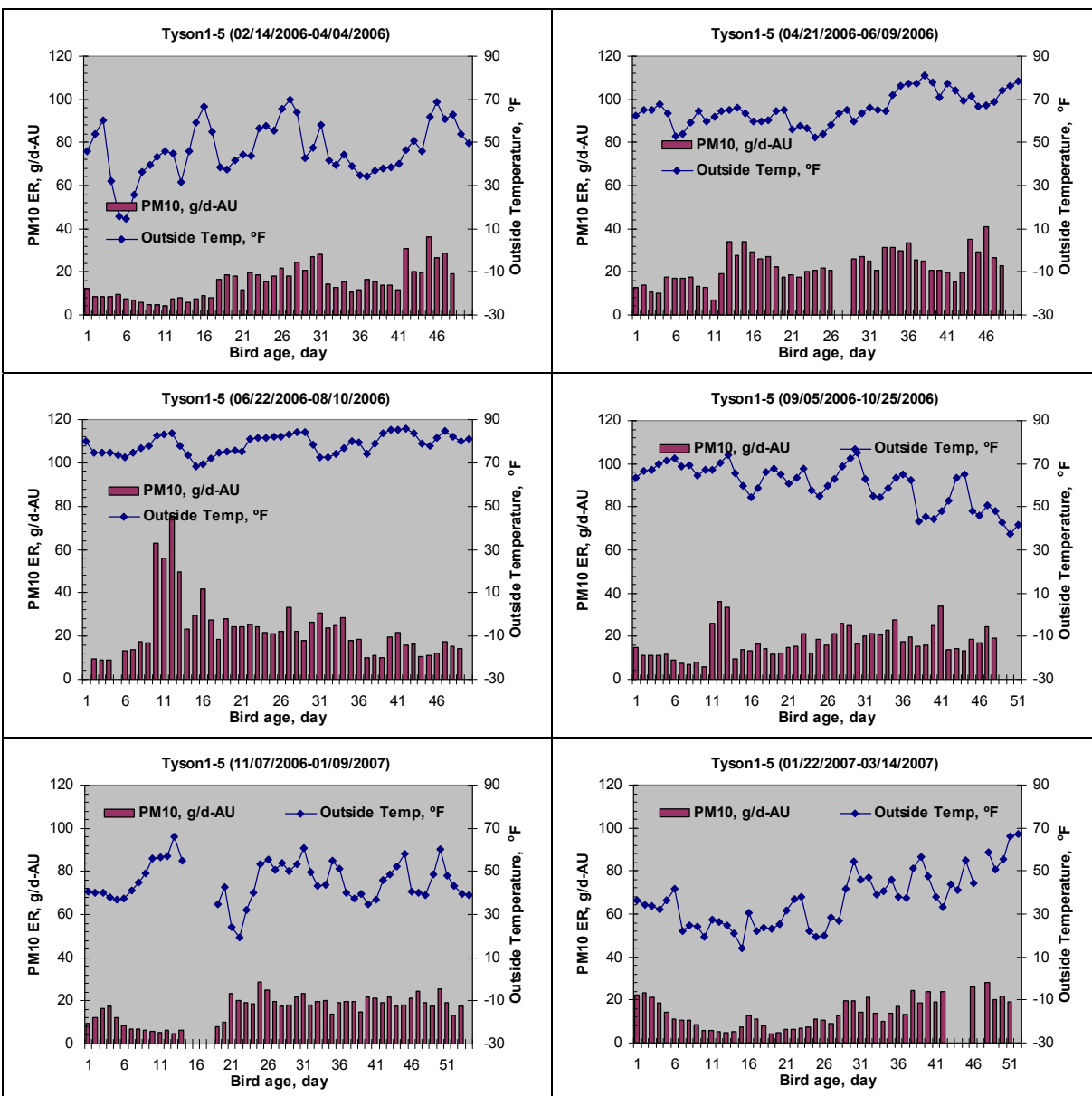
Figure 51. Tyson 1-5 PM$_{10}$ emission rate (ER) per animal unit (AU,≈500 kg) and mean outside temperature vs. bird age.
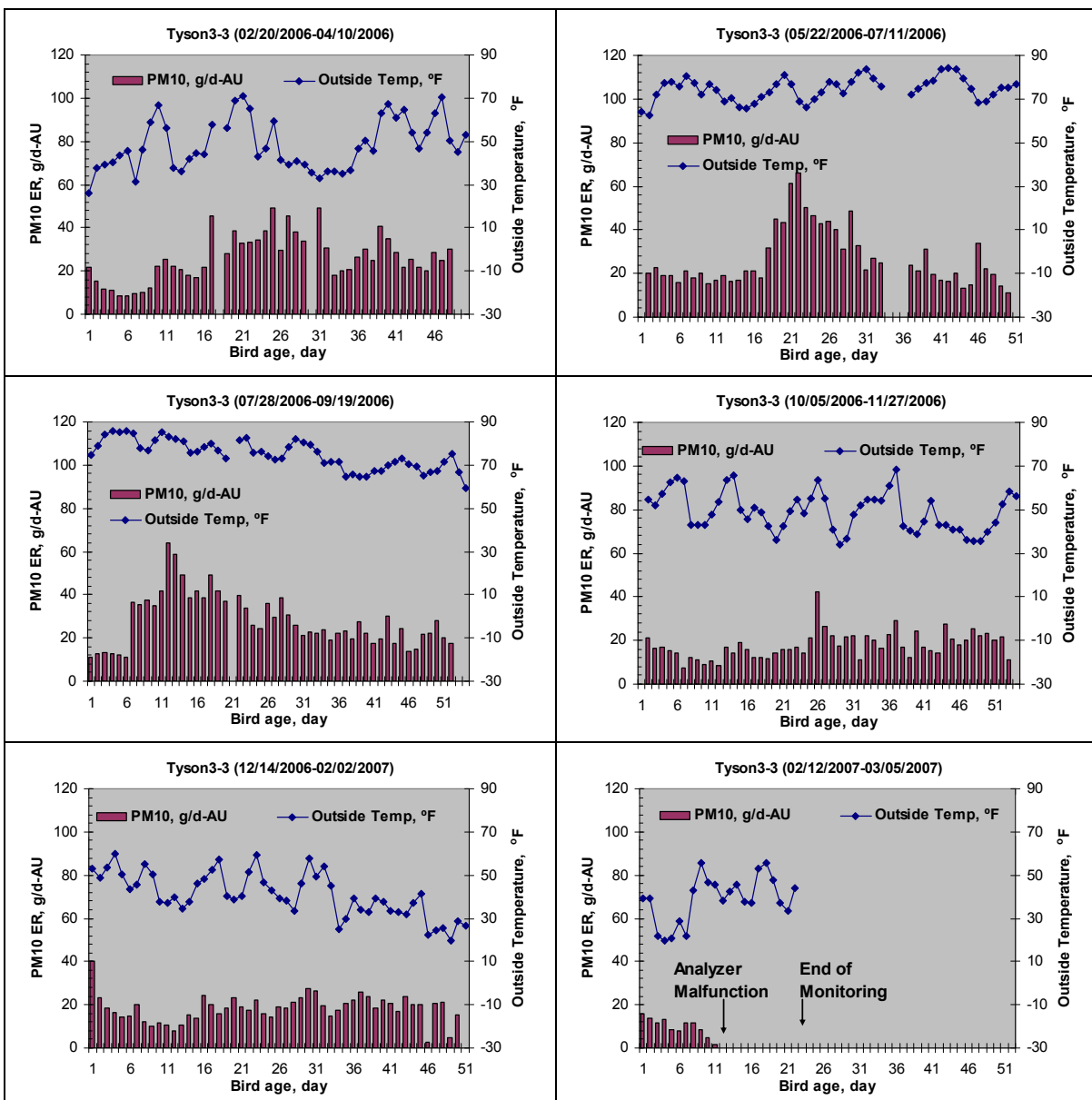
Figure 52. Tyson 3-3 PM$_{10}$ emission rate (ER) per animal unit (AU, 500 kg) and mean outside temperature vs. bird age.

Effects of Environmental Variables on PM$_{10}$ ER

To assess the impact of environmental variables on the PM$_{10}$ emission from the two broiler houses with birds, a multiple regression analysis was performed to relate PM$_{10}$ ER to bird age (d), interior temperature (^{o}F), RH (%), VR (cfm/bird) and litter status (0 for new bedding; 1 for built-up litter). The daily mean values of the above variables were used for the regression analysis. The results of the regression analysis are shown in Table 14. Except for interior temperature and litter status, all variables were significant for PM$_{10}$ ER at α = 0.05. The PM$_{10}$ ER (lb/d-house) was positively correlated with temperature and RH.

Table 14. Multiple regression analysis of PM_{10} for bird age, interior temperature, RH, Ventilation rate (VR), and litter status (LS) (R^2=0.88)

$$\sqrt[3]{PM_{10}\ ER} = \beta_0 + \beta_1 \times Age + \beta_2 \times Age^2 + \beta_3 \times T_i + \beta_4 \times RH_i + \beta_5 \times VR + \beta_6 \times LS$$

Term	Estimate	S.E	Prob>|t|
β_0= Intercept	0.29	0.10	0.0042
β_1= Bird age, d	0.05	0.0022	<.0001
β_2= Bird age^2, d^2	-4.5 e^{-4}	4.47e^{-5}	<.0001
β_3= Inside Temp., ºF	N/S		
β_4= Inside RH, %	-0.006	0.00095	<.0001
β_5= VR, cfm/bird	0.049	0.0088	<.0001
β_6= LS, 0 or 1	N/S		

Annual PM_{10} Emission

The annual PM_{10} emission from each house is the accumulation of daily ERs over 365 days. When 5.4 flocks were grown to 52 days of age and the average flock cumulative ER was 133.8 lb/flock (60.7 kg/flock), the annual emission (± S.E.) was 727 ± 93.4 lb/yr-house (330 ± e42.3 kg/yr-house). On the basis of number of birds marketed the annual average PM_{10} emission (± S.E.) was 5.56 ± 0.71 lb per 1,000 birds marketed or 2.52 ± 0.33 g per bird marketed.

$PM_{2.5}$ Emission

$PM_{2.5}$ ER Estimation/Prediction

$PM_{2.5}$ ER was correlated to the bird age, body weight and VR, was weakly correlated with inside RH and not correlated with outside temperature, RH, and inside temperature. Among the three influencing variables, bird age is most predominant. For the flocks on new bedding, there was no clear bedding effect on $PM_{2.5}$ ER. Because of the unusually high mortality in flock 5 at Tyson 1-5, this flock was not used to predict the ER. The $PM_{2.5}$ ER per house or per bird from all data except for the flock 5 ERs at Tyson 1-5, as shown in Figures 53 and 54, may be described using the following regression equation:

$$\sqrt[3]{PM_{2.5}\ ER} = a + b\,X + c\,X^2 \qquad [9]$$

where

$PM_{2.5}\ ER$ = lb d^{-1} house^{-1};

X= bird age.

Table 15 provides the prediction parameter estimates for the two houses, individually, and over all 11.4 flocks. The correlation coefficients (r^2) of prediction models vary from 0.86 to 0.88 and show the strongest relationship between ER and bird age.

Table 15. Coefficient Estimates of PM$_{2.5}$ ER prediction models for broiler houses Tyson 1-5 and Tyson 3-3

House	a (± S.E.)	b (± S.E.)	c (± S.E.)	r^2
T1-5	0.147 (± 0.0107)	0.0147 (±3.6 e^{-04})	N/S	0.89
T3-3	0.216 (± 0.009)	0.0136 (±3.0 e^{-04})	N/S	0.88
Overall	0.187 (± 0.007)	0.014 (±2.0 e^{-04})	N/S	0.88
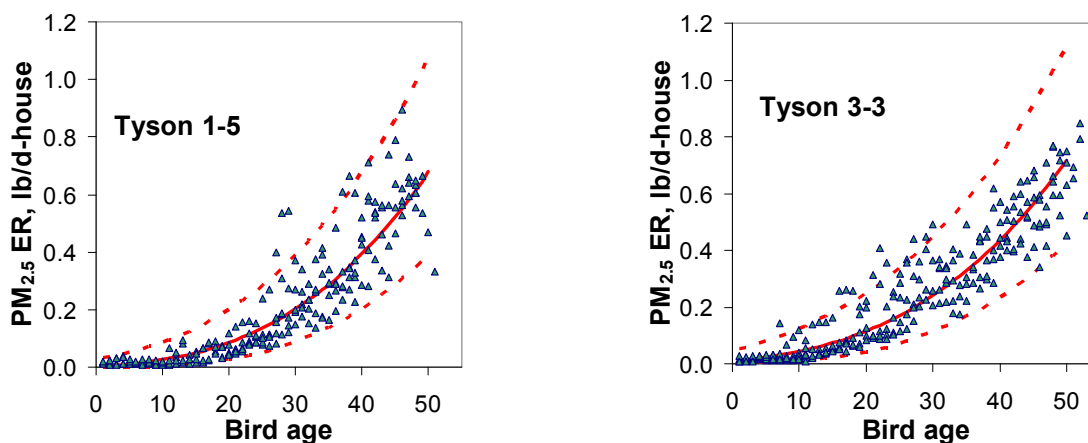
Figure 53. PM$_{2.5}$ emission rate (ER) per house vs. bird age for Tyson 1-5 and Tyson 3-3. The solid line is the regression line; dash lines are 95% prediction limits.
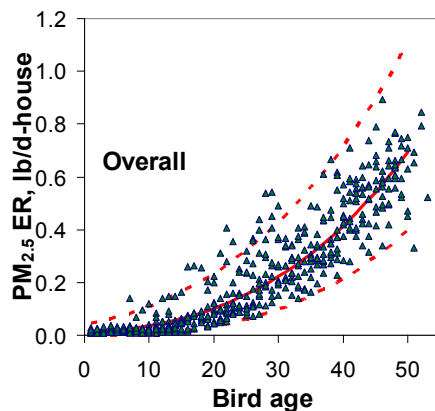
Figure 54. PM$_{2.5}$ emission rate (ER) per house vs. bird age. The solid line is the regression line; dash lines are 95% prediction limits.

Figure 55 provides the daily PM$_{2.5}$ ER for the two houses for the entire monitoring period with 11.4 flocks and downtime between flocks. The daily ER varied from 0 to 0.89 lb/d-house (0 to 0.40 kg/d-house). The highest PM$_{2.5}$ ER was 0.89 and 0.85 lb/d-house (0.40 and 0.39 kg/d-house) for Tyson 1-5 and Tyson 3-3, respectively. Note that the emissions between the vertical

dashed lines in Figure 55 represent periods between flocks when no birds were in the houses (i.e., downtime). The daily mean values of the above variables were used for the regression analysis. The average ER was 0.23 ± 0.22 lb/d-house (0.10 ± 0.10 kg/d-house) for Tyson 1-5 and 0.26 ± 0.23 lb/d-house (0.12 and 0.10 kg/d-house) for Tyson 3-3. The average ER of 11.4 flocks was 0.25 ± 0.22 lb/d-house (0.11 and 0.10 kg/d-house).
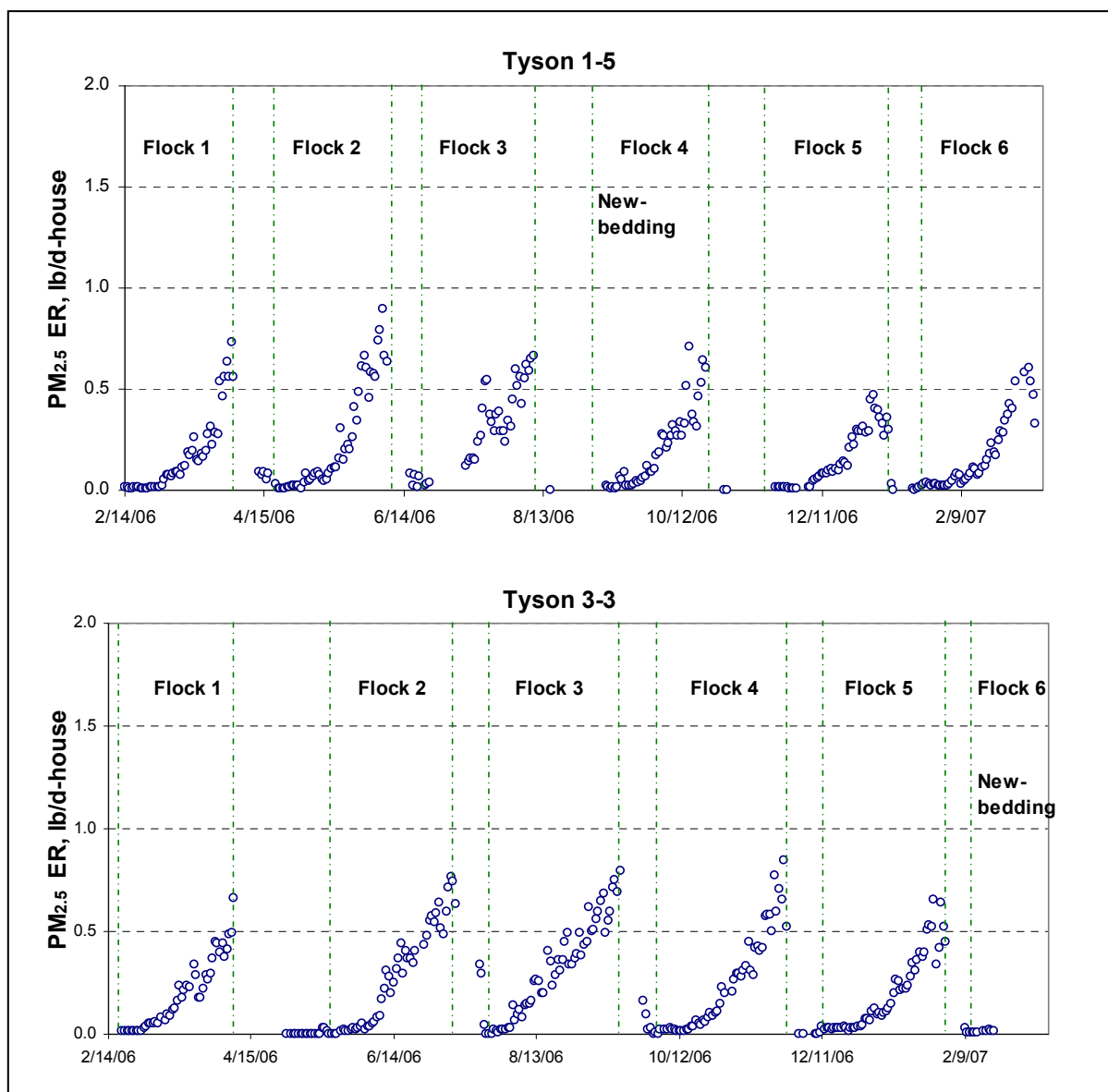
Figure 55. Daily PM$_{2.5}$ emission over the 11.4 flocks for Tyson 1-5 and Tyson 3-3.

PM$_{2.5}$ ER during Downtime between Flocks

The PM$_{2.5}$ ER during the downtime was tested for the environmental variables effect. VR of the houses had a linear relationship with PM$_{2.5}$ ER (Figure 56). The average PM$_{2.5}$ ER for the two houses during downtime was 0.03 ± 0.06 lb/d-house (0.014 ± 0.027 kg/d-house).
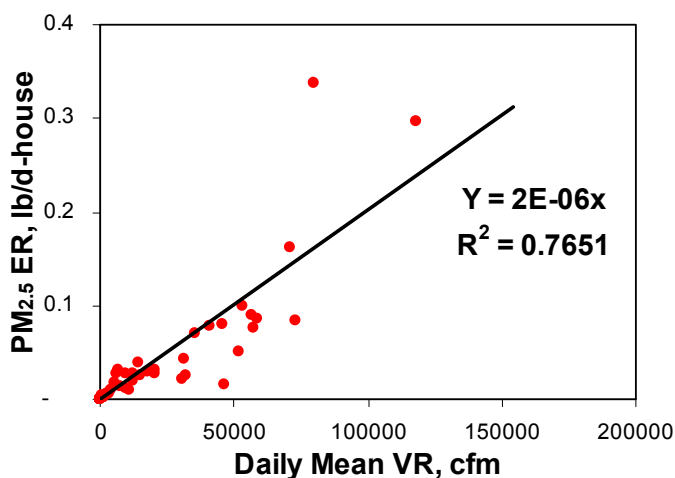

$$Y = 2E\text{-}06x$$
$$R^2 = 0.7651$$

Figure 56. PM$_{2.5}$ emission rate(ER) vs. ventilation rate (VR) during downtime.

PM$_{2.5}$ ER per Animal Unit (AU)

Figures 57, 58, and 59 present PM$_{2.5}$ ER in terms of 500 kg animal unit (g/d-AU) for all 11.4 flocks from the two houses. There was a clear trend between the ER and bird age (Figure 57); the PM$_{2.5}$ ER per AU decreased during the first 11-d and increased slightly afterwards. There was a significant difference between Tyson 1-5 and Tyson 3-3 in ER per AU (P=0.0023). The daily ER per AU was 1.59 ± 0.54 and 2.22 ± 1.35 g/d-AU for Tyson 1-5 and Tyson 3-3, respectively. The overall ER per AU was 1.91 ± 0.86 g/ d-AU.
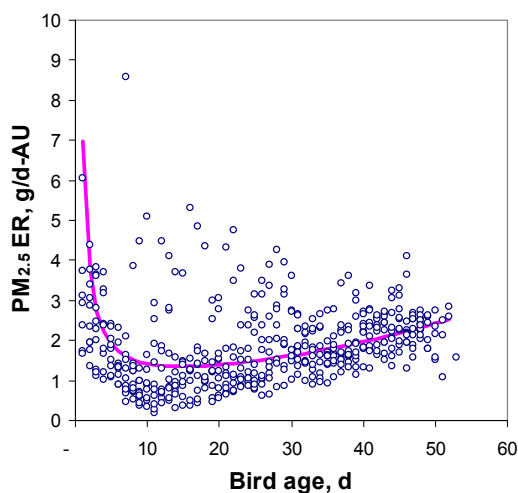

Figure 57. PM$_{2.5}$ emission rate (ER) per day per animal unit (AU, 500kg) vs. bird age for the two houses over one year period.
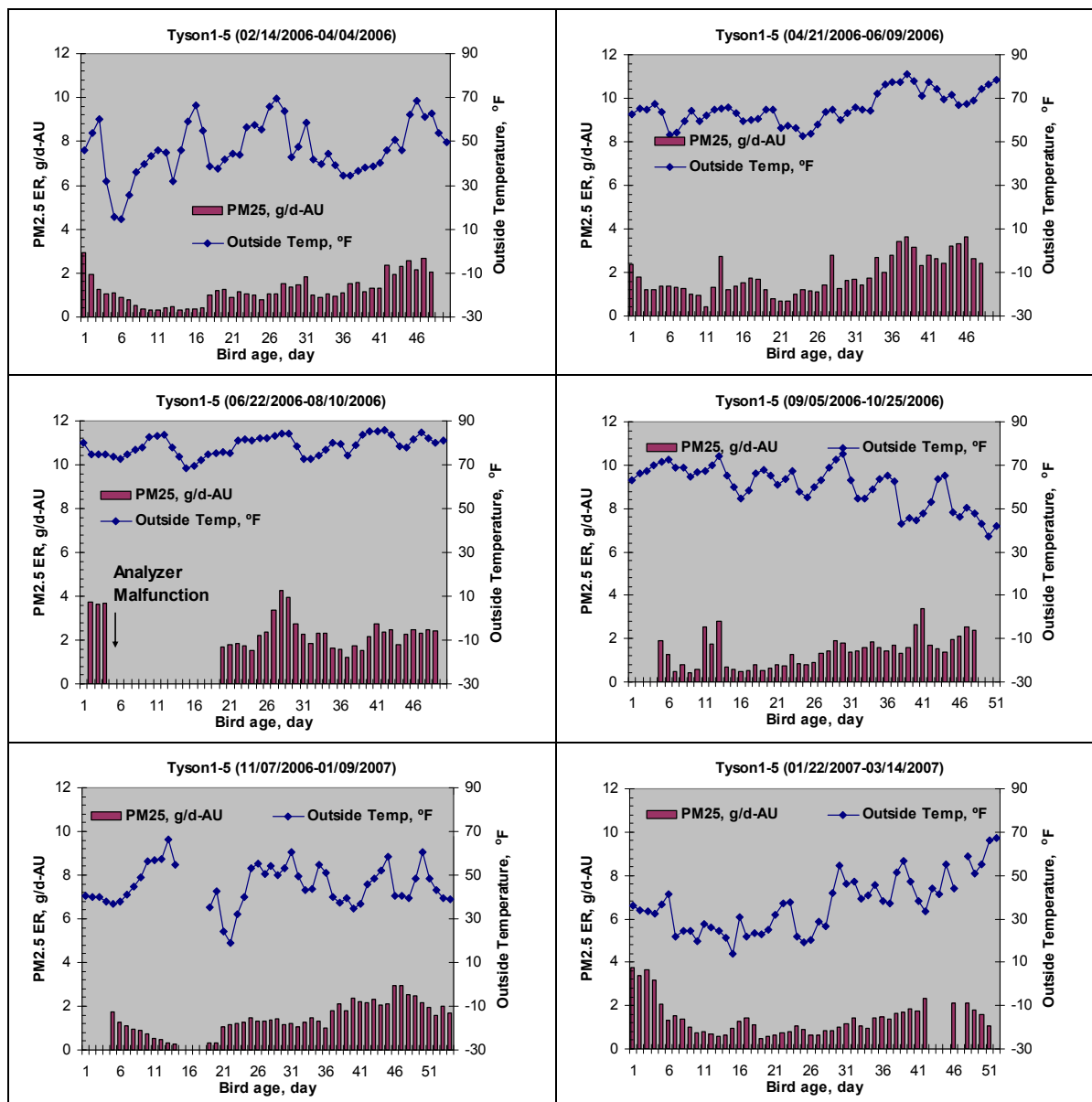
Figure 58. Tyson 1-5 PM$_{2.5}$ emission rate (ER) per animal unit (AU, 500 kg) and mean outside temperature vs. bird age.
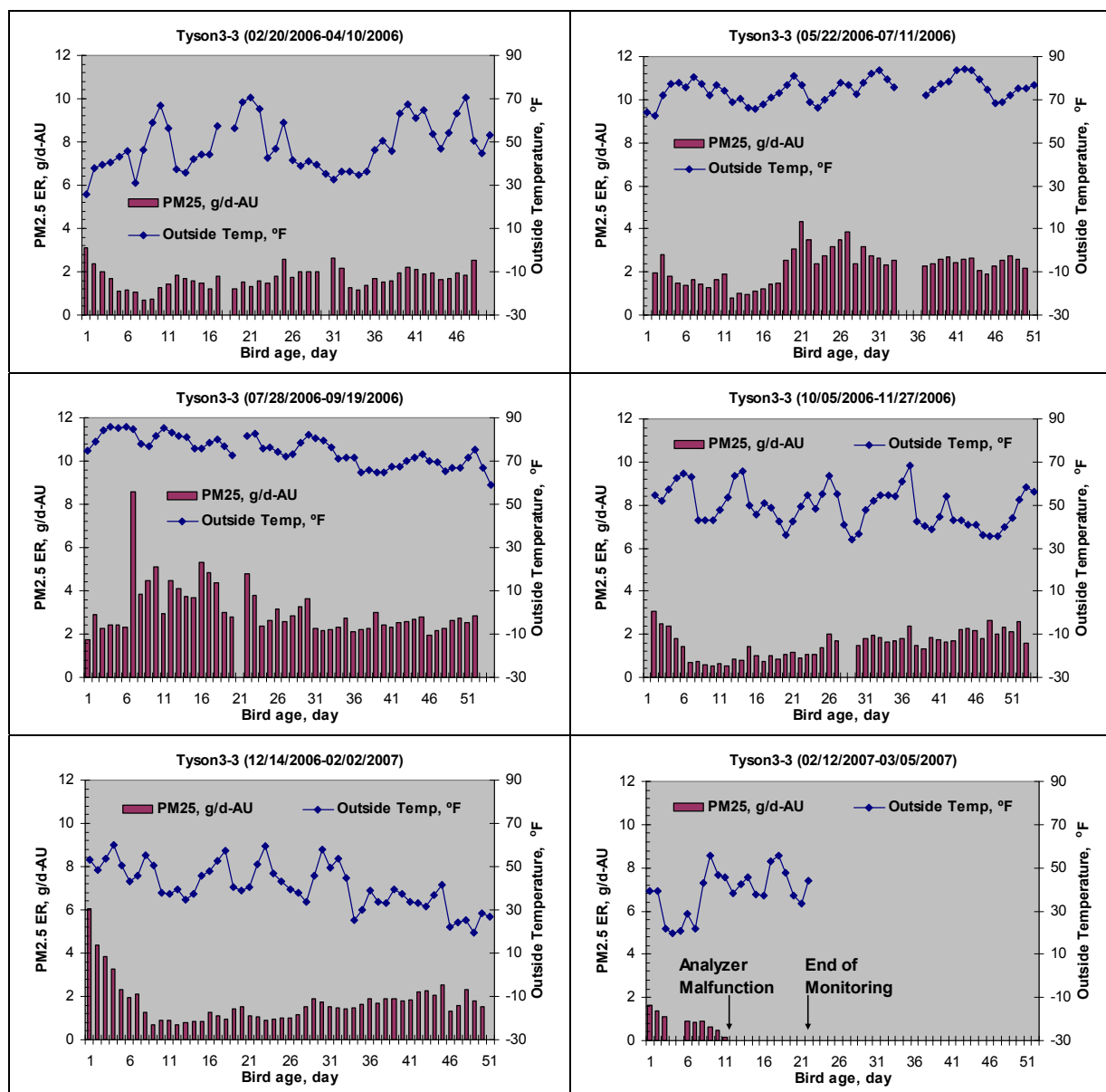
Figure 59. Tyson 3-3 PM$_{2.5}$ emission rate (ER) per animal unit (AU, 500 kg) and mean outside temperature vs. bird age.

Effects of Environmental Variables on PM$_{2.5}$ ER

To assess the impact of environmental variables on the PM$_{2.5}$ emission from the two broiler houses, a multiple regression analysis was performed to relate PM$_{2.5}$ ER to bird age (d), interior temperature (^{o}F), RH (%), VR (cfm/bird) and litter status (0 for new bedding; 1 for built-up litter). The results of the regression analysis are shown in Table 16. Except for interior temperature and bedding, all variables were significant for PM$_{2.5}$ ER at $\alpha = 0.05$. The PM$_{2.5}$ ER (lb/d-house) was positively correlated with temperature and RH.

Table 16. Multiple regression analysis of $PM_{2.5}$ for bird age, interior temperature, RH, ventilation rate (VR), and litter status (LS) (R^2=0.92)

$$\sqrt[3]{PM_{2.5}\ ER} = \beta_0 + \beta_1 \times Age + \beta_2 \times Age^2 + \beta_3 \times T_i + \beta_4 \times RH_i + \beta_5 \times VR + \beta_6 \times LS$$

Term	Estimate	S.E	Prob>|t|
β_0= Intercept	0.158	0.010	<.0001
β_1= Bird age, d	0.012	0.000	<.0001
β_2= Bird age^2, d^2	N/S		
β_3= Inside Temp., ºF	N/S		
β_4= Inside RH, %	N/S		
β_5= VR, cfm/bird	0.039	0.003	<.0001
β_6= LS, 0 or 1	0.034	0.009	0.0001

Annual $PM_{2.5}$ Emission

The annual $PM_{2.5}$ emission from each house is the accumulation of daily ERs over 365 days. When 5.4 flocks were grown to 52 days of age and the average flock cumulative ER is 12.8 lb/flock (5.8 kg/flock), the annual emission (± S.E.) was 71.7 ± 4.4 lb/yr-house (32.5 ± 2.0 kg/yr-house). On the basis of number of birds marketed the annual average $PM_{2.5}$ emission (± S.E.) was 0.55 ± 0.04 lb/1,000 birds marketed or 0.25 ± 0.01 g/bird-marketed.

Relationship among TSP, PM_{10}, and $PM_{2.5}$

The ratios of $PM_{2.5}/PM_{10}$, $PM_{2.5}/TSP$, and PM_{10}/TSP were calculated from daily ERs of TSP, PM_{10}, and $PM_{2.5}$. All three ratios had similar pattern with bird age or growth (Figures 60, 61, and 62). $PM_{2.5}/PM_{10}$ ratio rapidly dropped from ~0.17 to ~ 0.06 during the first 17-d period, then the ratio increased to ~0.12 at the end of the 52-d growth period. $PM_{2.5}/TSP$ and PM_{10}/TSP ratios had similar trends, with the ratio decreasing during the first 12 d and increasing afterwards. The overall average ratios from the two broiler houses were 0.038, 0.093, and 0.40 for $PM_{2.5}/TSP$, $PM_{2.5}/PM_{10}$, and PM_{10}/TSP, respectively. Fine particulates are thus a small fraction of TSP.
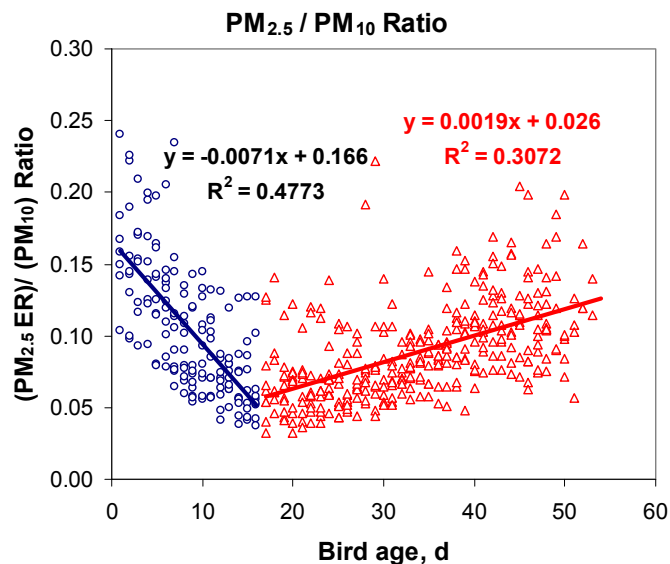
PM$_{2.5}$ / PM$_{10}$ Ratio

y = 0.0019x + 0.026
R^2 = 0.3072

y = -0.0071x + 0.166
R^2 = 0.4773

Figure 60. PM$_{2.5}$/PM$_{10}$ ratio vs. bird age.

PM$_{2.5}$ / TSP Ratio

y = -0.0054x + 0.0801
R^2 = 0.4851

y = 0.0011x + 0.002
R^2 = 0.4212
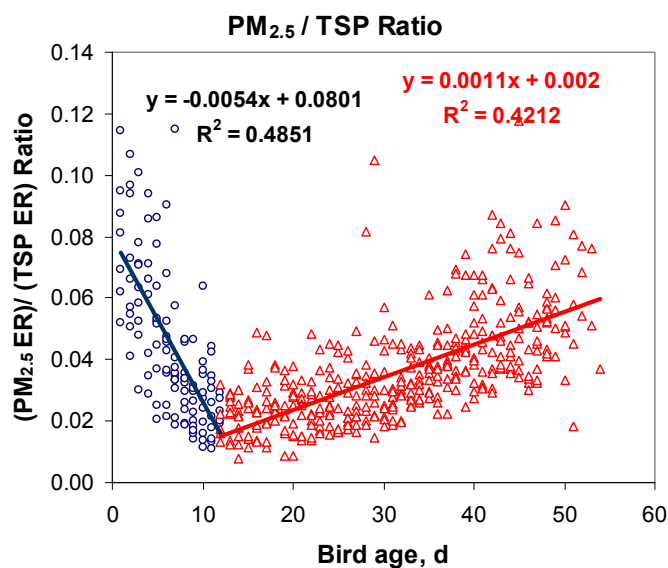
Figure 60. PM$_{2.5}$/TSP ratio vs. bird age.

PM$_{10}$ / TSP Ratio

$y = -0.0145x + 0.4627$
$R^2 = 0.2244$

$y = 0.0062x + 0.21$
$R^2 = 0.1538$
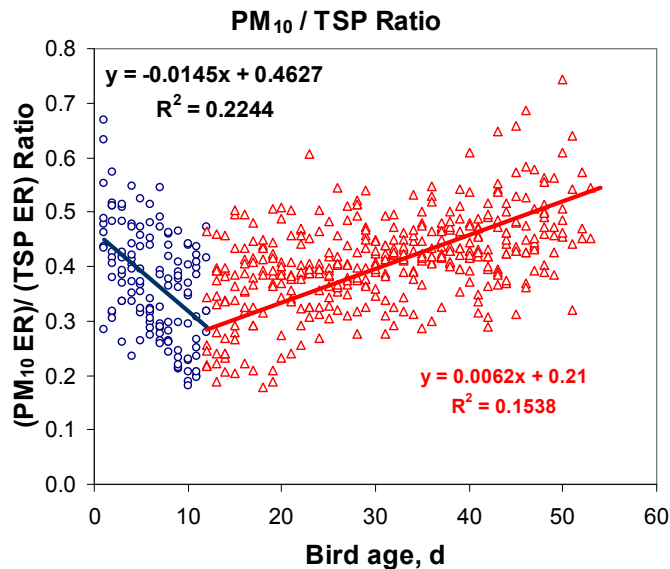
Figure 62. PM$_{10}$/TSP ratio vs. bird age.

CO$_2$ Emissions

CO$_2$ ER Estimation/Prediction

The CO$_2$ emissions reported in this study represent the combined total of both bird respiration and manure generated CO$_2$. The carbon dioxide ER was highly correlated to the bird age. The CO$_2$ ER per house or per bird from all data except for flock 6 at Tyson 1-5, as shown in Figures 63 and 64, may be estimated using the following regression equations:

$$CO_2 \ ER, \ US\text{-}ton \ d^{-1} \ house^{-1} = a + b \ X \qquad [10]$$

where

X = bird age, d.

Table 17 provides the prediction parameter estimates for the two houses, individually, and over all 11.4 flocks. The correlation coefficients (r^2) of prediction models vary from 0.64 to 0.80 and show the strongest relationship between ER and bird age.

Table 17. Coefficient estimates of CO$_2$ ER regressions for broiler houses Tyson 1-5 and Tyson 3-3 (ER is not included when bird age is < 7 d with new bedding)

House	a (± S.E.)	b (± S.E.)	r^2
T1-5	0.25 (± 0.063)	0.085 (± 0.0021)	0.87
T3-3	0.22 (± 0.065)	0.092 (± 0.0023)	0.83
Overall	0.25	0.087	0.87

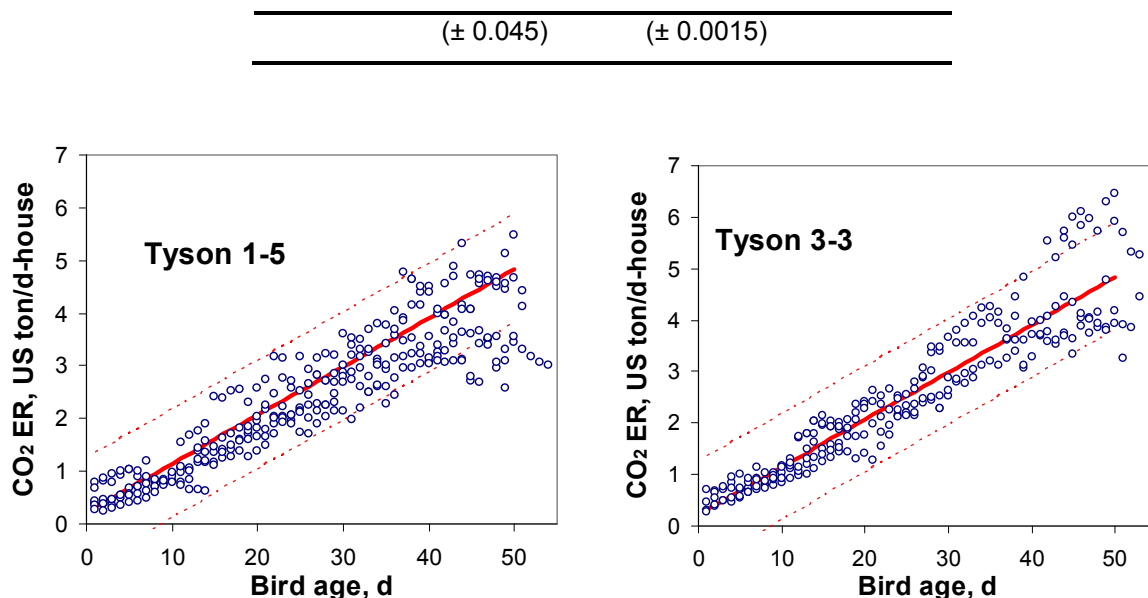(± 0.045)   (± 0.0015)

Figure 63. CO$_2$ emission rate (ER) per house vs. bird age for Tyson 1-5 and Tyson 3-3. The solid line is the regression line; dash lines are 95% prediction limits.
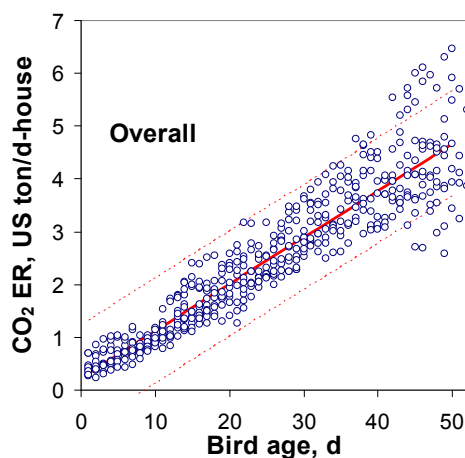

Figure 64. CO$_2$ emission rate (ER) per house vs. bird age. The solid line is the regression line; dash lines are 95% prediction limits.

Figure 65 provides the daily CO$_2$ ER for the two houses for the entire monitoring period with 11.4 flocks and downtime between flocks. The daily ER (lb/d-house) varied from 0 to 6.47 US-ton/d-house (0 to 5.87 metric ton/d-house). When the houses were occupied by birds, the highest ER was 5.51 and 6.47 US-ton/d-house (5.0 to 5.87 metric ton/d-house) for Tyson 1-5 and Tyson 3-3, respectively. The average ER for Tyson 1-5 over the six flocks was 2.51 ± 1.29 US-ton/d-house (2.28 ± 1.27 metric ton/d-house) which was not significantly different from 2.66 ± 1.4 US-ton/d-house (2.41 ± 1.27 metric ton/d-house) for Tyson 3-3 (P=0.32). The average ER of 11.4 flocks was 2.55 ± 1.32 US-ton/d-house (2.31 ± 1.2 metric ton/d-house).
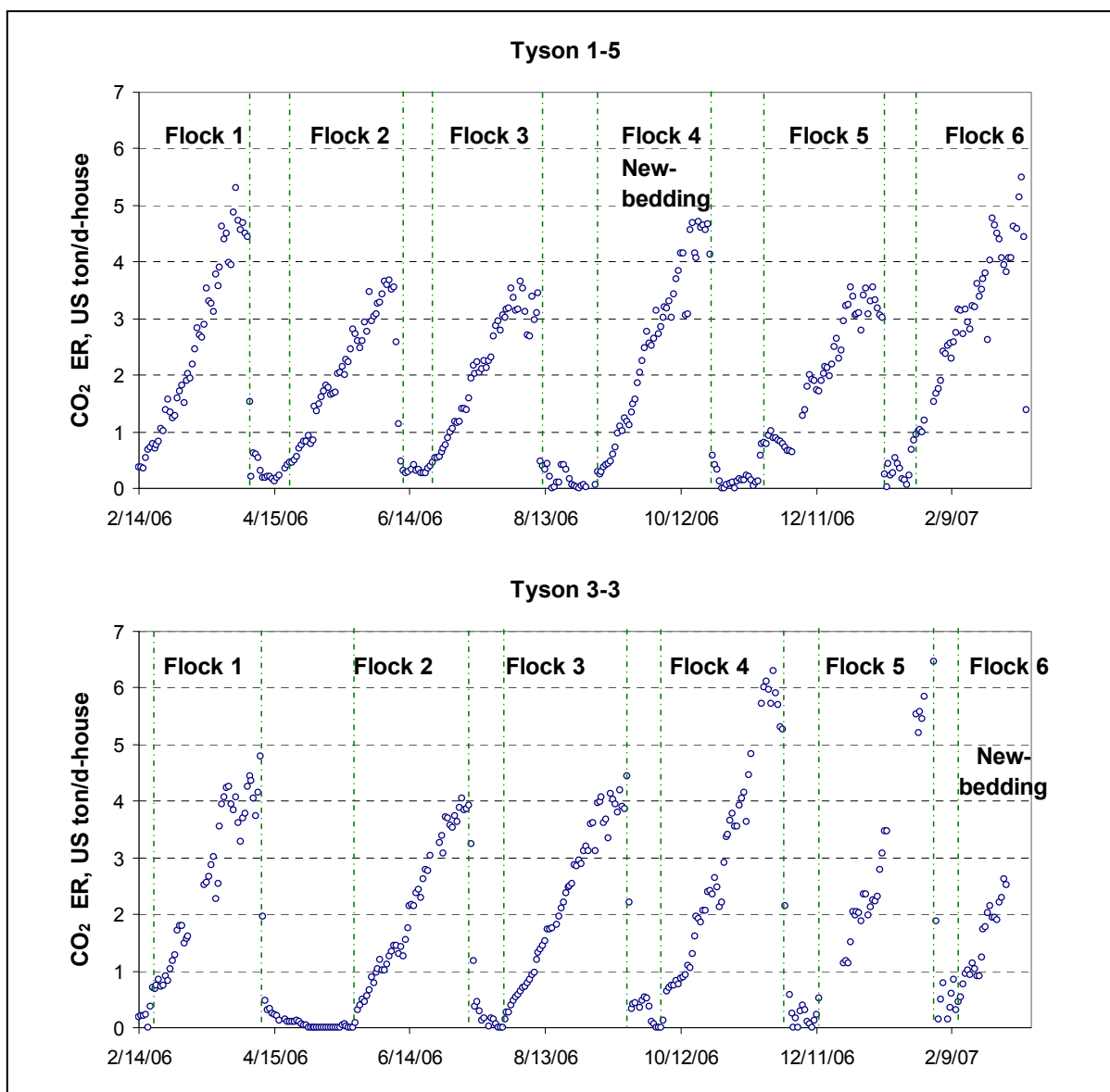
Figure 65. Daily CO$_2$ emission over the 11.4 flocks for Tyson 1-5 and Tyson 3-3.

CO$_2$ ER during Downtime between Flocks

CO$_2$ emissions from the two houses were continuously monitored when the houses were empty between flocks or during downtime. There was no significant relationship between ER and VR (Figure 66). The average daily ER for the two houses during downtime was 0.21 ± 0.20 US-ton/d-house (0.19 ± 0.18 metric ton/d-house).
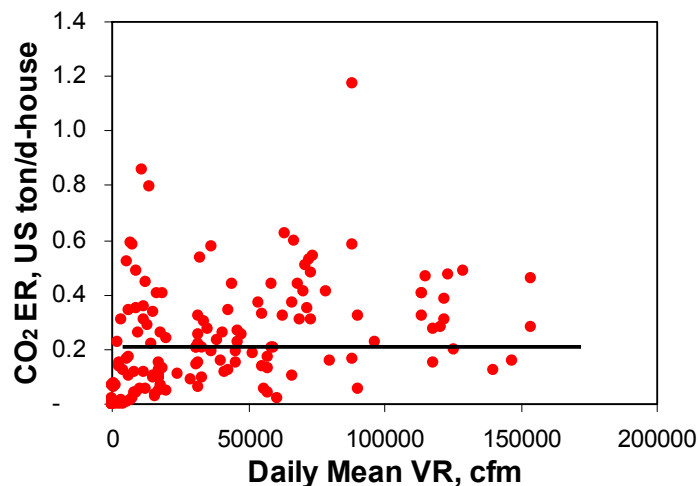
Figure 66. CO_2 emission rate(ER) vs. ventilation rate (VR) during downtime.

CO_2 ER per Animal Unit (AU)

Figures 67 and 68 present CO_2 ER in terms of 500 kg animal unit (kg/AU-d) for 11.4 flocks from the two houses. The ER per AU versus bird age showed that the ER decreased with the bird growth and became relatively stable after 30 d. The ER was higher during wintertime than during summertime due to additional CO_2 contribution from the brooder and space heaters. There was no significant difference between Tyson 1-5 and Tyson 3-3 in ER per AU (P=0.96). The daily ER per AU was 58.9 ± 37.1 and 63.3 ± 41.2 kg/d-AU for Tyson 1-5 and Tyson 3-3, respectively. The overall ER per AU was 61.9 ± 40.1 kg/ d-AU.
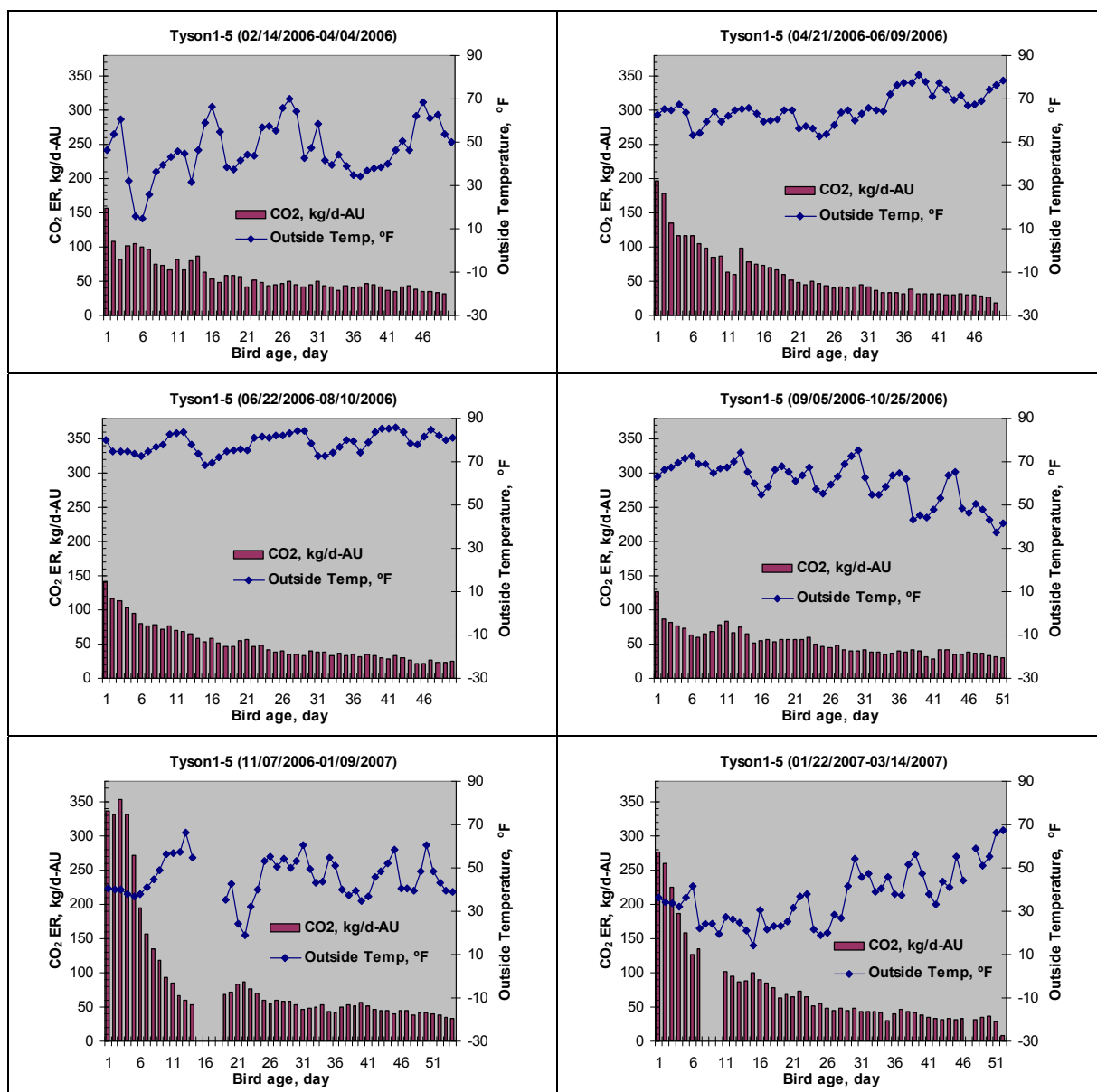
Figure 67. Tyson 1-5 CO_2 emission rate (ER) per animal unit (AU, 500 kg) and mean outside temperature vs. bird age.
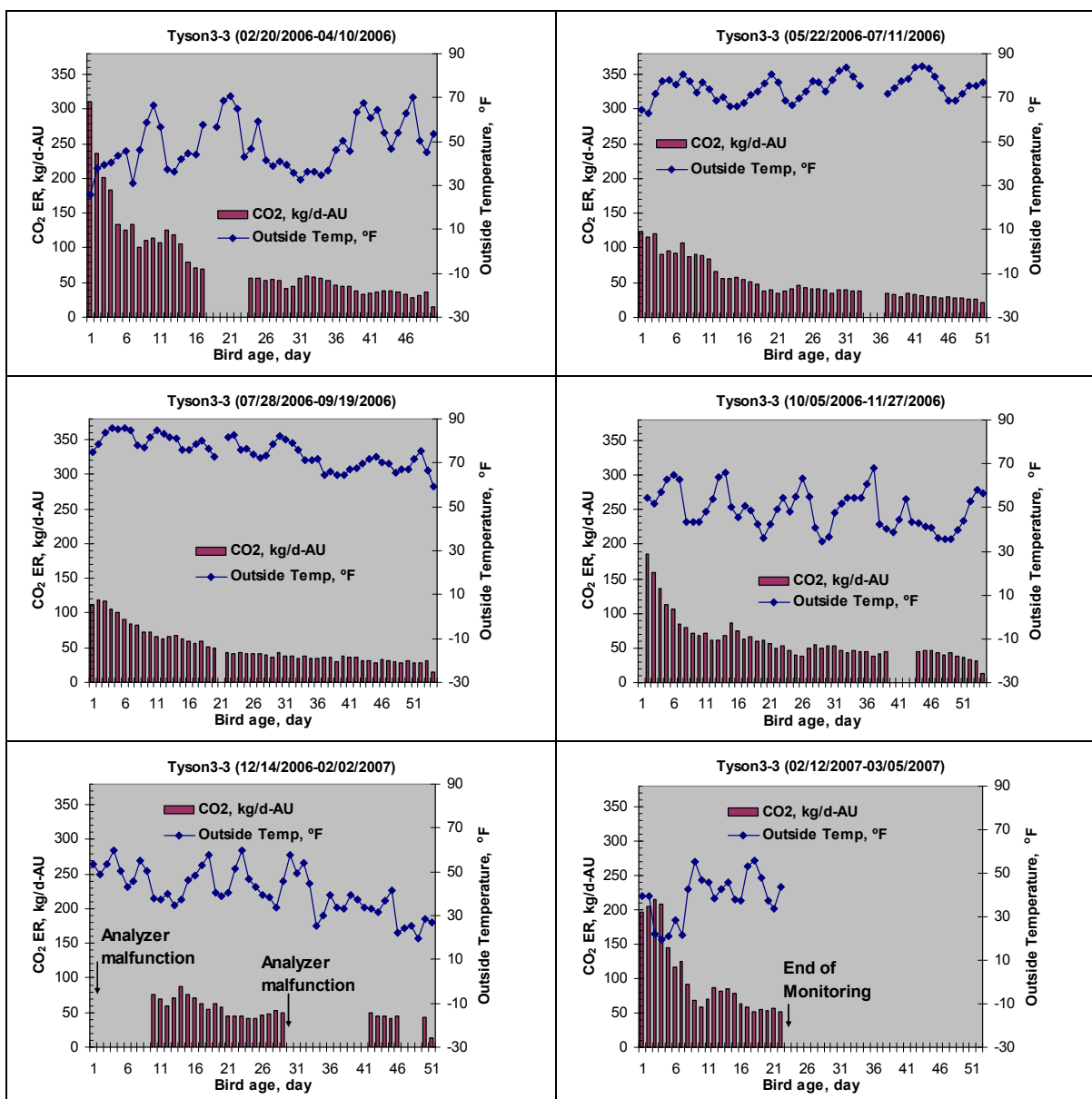
Figure 68. Tyson 3-3 CO_2 emission rate (ER) per animal unit (AU, 500 kg) and mean outside temperature vs. bird age.

Effects of Environmental Variables on CO_2 ER

To assess the impact of environmental variables on the CO_2 emission from the broiler houses, a multiple regression analysis was performed to relate CO_2 ER to bird age (d), outside temperature (^{o}F), RH (%), VR (cfm/bird) and litter status (0 for new bedding; 1 for built-up litter). The results of the regression analysis are shown in Table 18. The outside temperature and VR had significant effect on CO_2 ER at $\alpha = 0.05$. As outside temperature and VR increased, the CO_2 ER (ton/d-house) decreased because less CO_2 were from supplemental heating devices. During the cold season CO_2 emissions increased because additional CO_2 was generated by the brooder heaters and space heaters.

Table 18. Multiple regression analysis of CO_2 emission to bird age (d), ventilation rate (VR, cfm/bird), and litter status (LS) ($R^2=0.93$)

CO_2 ER us-ton d^{-1} house^{-1} $= \beta_0 + \beta_1 \times$ Age $+ \beta_2 \times T_o + \beta_3 \times RH_i + \beta_4 \times VR + \beta_5 \times LS$

Term	Estimate	S.E	t Ratio	Prob>|t|
β_0= Intercept	0.73	0.099	7.41	<.0001
β_1= Bird age, d	0.099	0.002	51.3	<.0001
β_2= Outside Temp, ^{o}F	-0.0087	0.0017	-5.21	<.0001
β_3= Inside RH, %	N/S			
β_4= VR, cfm/bird	-0.169	0.0262	-6.45	<.0001
β_5= LS, 0 or 1	N/S			

Annual CO_2 Emission

The annual CO_2 emission from each house is the accumulation of daily ERs over 365 days. Based on the regression of the ER on bird age from Equation [2], the average flock ER was 132.8 US tons per house per flock (120.5 metric ton per house per flock). The annual CO_2 emission rate (± S.E.) was 718 ± 21.6 US tons per house per year (651 ± 9.8 metric ton per house per flock). The annual mean emission of 5.49 ± 0.16 US tons per 1,000 birds marketed (including downtime emissions) obtained from this study is equivalent to an ER (± S.E.) of 4.98 ± 0.15 kg/bird-marketed.

Comparison of ER Values with Literature Data

Comparison of the reported ammonia ER (g/bird-d) for broiler production houses (occupied with birds) in the United States is given in Table 19. The data from this study tend to be on the lower side of all values reported, but match closely with the earlier Kentucky data obtained for different farms and with different instrumentation. Table 20 lists comparison of PM_{10} emissions from broiler operations, with data from this study being nearly double that of the only other published data (1.3 vs. 2.52 g/bird-marketed). There is currently a lack of published emission data for the comparison of H_2S and NMHC.

Table 19. Comparison of ammonia emission rates (ER, g/bird-d) of commercial broiler houses among various U.S. studies

Reference	Growth Period, d	Stocking Density, birds/m^2	Stocking Density, birds/ft^2	Flocks	Litter	Mean ER, g/bird-d	Location
This study	52	12.7	1.18	3	New	0.49 ± 0.37	Kentucky
This study	52	12.2	1.13	9	Built-up	0.62 ± 0.38	
Wheeler et al. (2006)	42	14.7	1.37	10	New	0.47	Kentucky and Pennsylvania
	42	14.7	1.37	12	Built-up	0.65	
	49	13.4	1.24	24	Built-up	0.76	
	63	10.8	1.00	20	Built-up	0.98	
Burns et al. (2003)	42	16.1	1.50	9	Built-up	0.92	Tennessee
Lacey et al. (2003)	49	13.5	1.25	12	Built-up	0.63	Texas
Seifert et al. (2004)	42	20	1.86	1	Built-up	1.18	Delaware

Table 20. Comparison of PM$_{10}$ emission rate (ER) of commercial broiler houses among various U.S. studies

Reference	Growth Period, d	Vent.	Stocking Density, birds/ft^2	Flocks	Litter	Mean ER, mg/bird-d	ER, g/bird - marketed	Location
Lacey et al. (2003)	49	Tunnel	1.25	12	Built-up	26.5	1.3	Texas
This study	52	Cross + Tunnel	1.15	12	Mixed	48.2	2.52	Kentucky

Summary and Conclusions

Gaseous and particulate matter (PM) emissions from two representative broiler houses in western Kentucky were continuously measured for 12.5 to 13 months, involving a total of 11 complete and two partial grow-out flocks. Each house had 5.4 straight-run flocks per year and averaged 24,200 birds grown on new or built-up litter to 52 days of age. The gaseous and PM emissions were expressed in various units to meet different purposes of the data application, as following: a) annual total emission per house, b) daily mean emission per house, c) daily maximum emission per house, d) annual average emission per bird marketed, and e) annual average emission per animal unit (AU = 500 kg or 1,100 lb live body weight) marketed. All values included downtime emission, presented as mean ± standard error (S.E.) or standard deviation (S.D.). The data from this comprehensive and extensive monitoring of production houses are expected to enhance the national emissions inventory on animal feeding operations.

The following conclusions and observations were made from this study:

- There exist functional relationships between the gaseous and PM emissions and bird age. Empirical regression equations were developed to delineate the relationships.

- Annual total emission per house (mean ± S.E.): 5.1 ± 0.19 US tons (4620 ± 171 kg) NH_3, 42.3 ± 2.1 lb (19.2 ± 0.92 kg) H_2S, 510 lb ± 59.6 (231 ± 27 kg) NMHC, 1731 ± 58.6 lb (785 ± 26.6 kg) TSP, 727 ± 93.4 lb (330 ± 42.3 kg) PM_{10}, 71.7 ± 4.4 lb (32.5 ± 2.0 kg) $PM_{2.5}$, and 718 ± 21.6 US ton (651 ± 9.8 metric ton) CO_2.

- Annual average emission per 1,000 birds marketed (mean ± S.E.): 78.1 ± 3.1 lb NH_3, 0.32 ± 0.01 lb H_2S, 3.9 ± 0.45 lb NMHC, 13.2 ± 0.46 lb TSP, 5.56 ± 0.71 lb PM_{10}, 0.55 ± 0.04 lb $PM_{2.5}$, and 5.49 ± 0.16 US ton CO_2. Expressed on a per-bird-marketed basis, the annual average emissions were: 35.4 ± 1.32 g NH_3, 0.147 ± 0.01 g H_2S, 1.77 ± 0.21 g NMHC, 6.01 ± 0.21 g TSP, 2.52 ± 0.33 g PM_{10}, 0.25 ± 0.01 g $PM_{2.5}$, and 4.98 ± 0.15 kg CO_2.

- Annual average emission per AU marketed (mean ± S.E.): 6.25 ± 0.23 kg of NH_3, 26.0 ± 1.26 g of H_2S, 0.29 ± 0.03 kg NMHC, 1.06 ± 0.04 kg TSP, 0.45 ± 0.06 kg PM_{10}, 0.044 ± 0.003 kg $PM_{2.5}$, and 881 ± 26.5 kg CO_2.

- Daily mean emission per house (mean ± S.D.): 31.4 ± 14.9 lb (14.2 ± 6.8 kg) NH_3, 0.14 ± 0.09 lb (65.7 ± 42 g) H_2S, 1.68 ± 0.94 lb (0.8 ± 0.4 kg) NMHC, 6.13 ± 4.13 lb (2.78 ± 1.87 kg) TSP, 2.57 ± 1.88 lb (1.16 ± 0.85 kg) PM_{10}, 0.25 ± 0.22 lb (0.11 and 0.10 kg) $PM_{2.5}$, 2.55 ± 1.32 us-ton (2.31 ± 1.2 mton) CO_2. For the downtime between flocks, the daily mean emission per house were: 18.5 ± 17.8 lb (8.39 ± 8.1 kg) NH_3, 0.020 ± 0.028 lb (9.0 ± 12.5 g) H_2S, 0.45 ± 0.64 lb (0.2 ± 0.3 kg) NMHC, 0.12 ± 0.19 lb (0.05 ± 0.086 kg) TSP, 0.052 ± 0.085 lb (0.024 ± 0.039 kg) PM_{10}, 0.03 ± 0.06 lb (0.014 ± 0.027 kg) $PM_{2.5}$, 0.21 ± 0.20 US-ton (0.19 ± 0.18 metric ton) CO_2.

Acknowledgements

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