Development of Emissions Estimating Methodologies for Animal Feeding Operations
Volume 3: Broilers

Draft

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This report is an external draft for review purposes only and does constitute U.S. Environmental Protection Agency (EPA) policy.

Table of Contents

List of Tables

List of Figures

GLOSSARY / ACRONYMS

-2LogL	negative twice the likelihood
ADMs	average daily means
AFO	animal feeding operation
AIC	Akaike information criterion
AICc	adjusted Akaike information criterion
BIC	Schwarz Bayesian Information Criterion
FANS	Fan Assessment Numeration System
H_2S	hydrogen sulfide
LAW	live animal weight
MB	mean bias
ME	mean error
NAEMS	National Air Emissions Monitoring Study
NH_3	ammonia
NMB	normalized mean bias
NME	normalized mean error
PI	Principal Investigator
PM	particulate matter
PM_{10}	particulate matter with aerodynamic diameters less than 10 micrometers
$PM_{2.5}$	PM with aerodynamic diameters less than 2.5 micrometers
QAPP	quality assurance project plan
QC	quality control
TAN	total ammoniacal nitrogen
TEOM	tapered element oscillating microbalance
TKN	total Kjeldahl nitrogen
TSP	total suspended particulate
USDA	U.S. Department of Agriculture

1.0 INTRODUCTION

1.1 Site descriptions

There were four broiler houses (confinement sites) monitored for the NAEMS. One site location was in California (CA1B) with two houses and two locations were in Kentucky (KY1B-1 and KY1B-2). Table 1-1 summarizes sites and the structures monitored. The following section provides additional details on the sites. Appendix A provides a table that summarizes details about the monitoring locations.

Table 1-1. Broiler confinement sites monitored under NAEMS.

Site	Site Type	Measurement Period	Number of Units Measured	Ventilation Type	Manure Storage
CA1B	Litter on floor	9/1/07 - 10/31/09	2	MV (tunnel)	None
KY1B-1	Litter on floor	2/14/06 - 3/14/07	1	MV (tunnel)	None
KY1B-2	Litter on floor	2/20/06 - 3/5/07	1	MV (tunnel)	None

1.1.1 CA1B

This 336,000-bird broiler ranch (CA1B) was located in California and consisted of 16 mechanically-ventilated houses that were oriented east-west. Figure 1-1 shows the overall layout of the site, with the two monitored houses (Houses 10 and 12) highlighted (Cortus et al., 2010). The houses are 125 m (410 ft) long x 12.2 m (40 ft) wide, arranged in an east-to west orientation, and are spaced 12.2 m (40 ft) apart. The house roofs have a 4:12 slope with sidewall heights of 2.3 m (7.5 ft).

Each house contains 21,000 birds (per flock) for a total farm capacity of 336,000 birds. Six to seven flocks of birds are raised in each house every year, and all houses are operated on the same grow-out and litter clean-out cycles. The birds housed at the facility over the course of the NAEMS were a 60/40 split between Cobb and Ross genetic varieties and were raised from approximately 0.05 to 2.41 kg (1.1 to 5.3 lb) with an average grow-out period of 47 days. The birds were concentrated in the east (front) end of the houses during the first 10 days of each brooding phase of the grow-out period.

Between each flock, the top 20 to 25 percent of the litter was removed from the entire length of the house (i.e., decaking) using a commercial poultry litter removal machine. After decaking, the remaining litter at the front (east end) of the house was moved to the back (west end) of the house and 34.4 m^3 (1,214.8 ft^3) of rice hulls were placed in the front of the house.

After three flocks, all litter from the houses was removed (i.e., full litter clean-out). Litter removed from the houses during decaking and full litter clean-out activities was placed in short term storage piles for two to three days before being taken off site to a fertilizer plant. (Cortus et al., 2010)

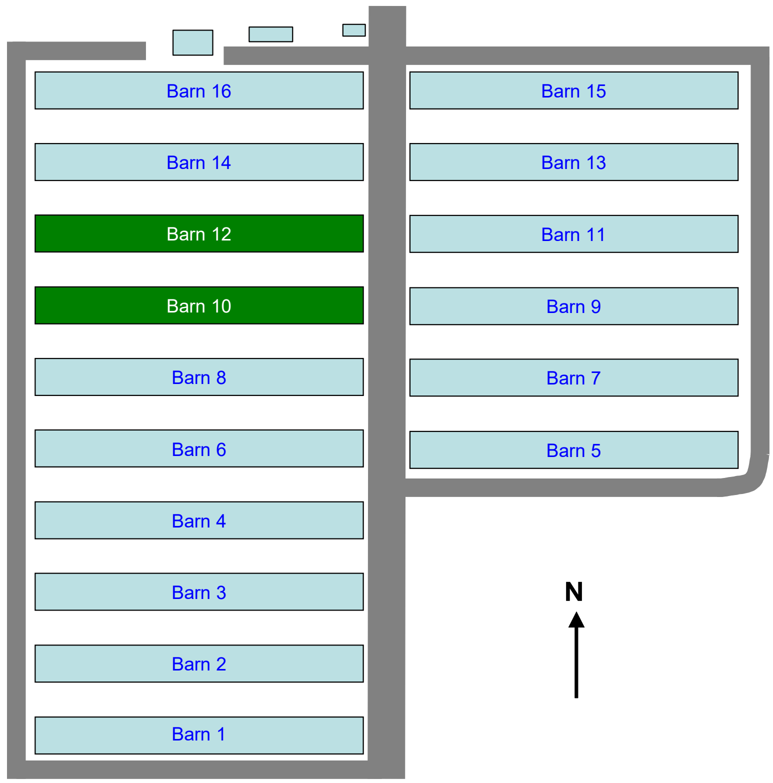

Figure 1-1. CA2B Farm layout.

1.1.2 KY1B-1 and KY1B-2

Although not funded through the Air Compliance Agreement, the EPA considered a study conducted by Tyson Foods at two broiler farms in Kentucky (sites KY1B-1 and KY1B-2) from 2006 to 2007 to be an integral part of, and ultimately included in, the NAEMS dataset because the researchers at Iowa State University and the University of Kentucky (Burns et al, 2006) developed the quality assurance project plan (QAPP) for the Tyson study (Moody et al. 2008) to be consistent with NAEMS QAPP.

The two broiler farms, designated as KY1B-1 and KY1B-2, are located in western Kentucky. The KY1B-1 farm has 8 broiler houses and has a total maximum winter capacity of 206,400 birds. The KY1B-2 farm has 24 broiler houses and a total maximum winter capacity of 619,200 birds. Figure 1-2 shows the location of the monitored facilities within Kentucky. The aerial photographs in Figure 1-3 shows the locations of the monitored houses at each site (Burns et al, 2010).

One broiler confinement house at each farm (designated as KY1B-1 House 5 and KY1B-2 House 3) was monitored. Built in the early 1990s, the two houses each measured 13.1 m x 155.5 m (43 ft x 510 ft). The birds housed during the monitoring period were Cobb-Cobb straight-run (mixed sex) broilers. During the winter, the houses were stocked with an initial placement of 25,800 birds. The initial placement during the summer was 24,400 birds. Typically, the birds were grown to 53 days of market age and an average bird weight of 2.75 kg (6.1 lb).

Each house had insulated drop ceilings, 26 box air inlets [15 x 66 cm (6 x 26 inch)] along each sidewall (see Figure 3-7), 26 pancake brood heaters [8.8 kW (30,000 Btu/hr) each], three space furnaces [65.9 kW (225,000 Btu/hr) each], four 91-cm (36-inch) diameter sidewall exhaust fans spaced approximately 36.6 m (120 ft) apart, and 10, 123-cm (48-inch) diameter tunnel fans.

A single 91-cm (36-inch) fan used for minimum ventilation was located in the brooding end of each house. Two evaporative cooling pads (24-m (80-ft) sections) were located at the opposite end of the houses 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. Each house was decaked and topped off with fresh litter after every flock, with a full litter clean-out occurring once per year.

Figure 1-2. Locations of Kentucky broiler sites.

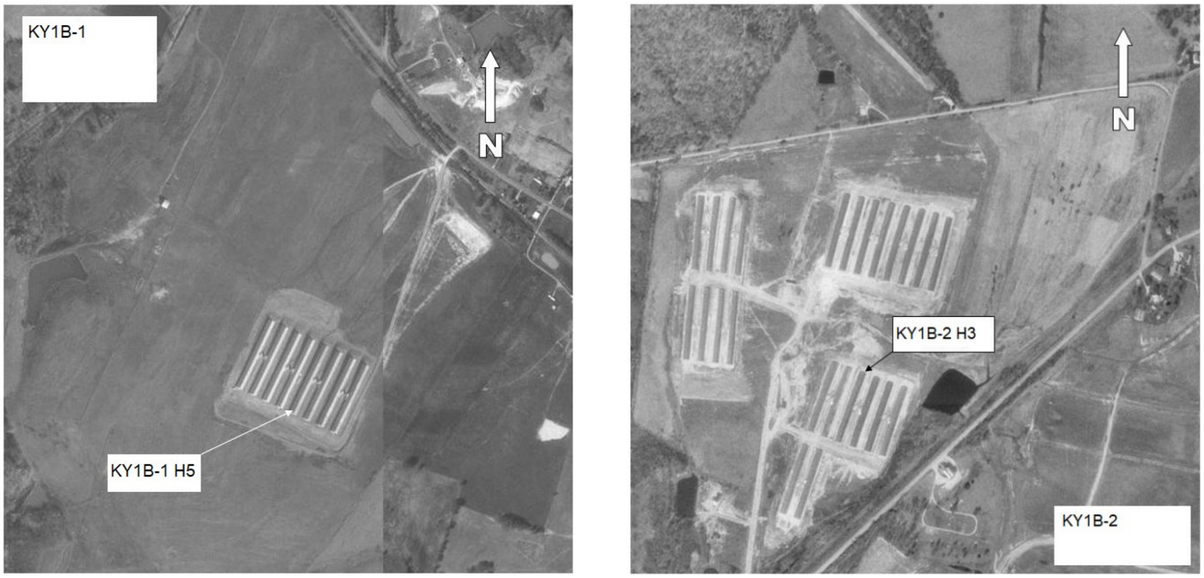

Figure 1-3. Aerial pictures indicating the locations of each monitored broiler house.

1.2 Data Sampled

NAEMS collected a host of data from the sites. Data collected included gaseous pollutant samples, particulate matter (PM) samples, meteorological data, confinement parameters, and biomaterial samples. All procedures for CA1B were outlined in the project Quality Assurance Project Plan (QAPP) (Heber, 2008) and are summarized in Section 4 of the Overview Report. The following sections outline any collection specific to the broiler sites.

1.2.1 Particulate Matter

For CA1B, at any one time, the sampled PM size class was either PM_{10}, $PM_{2.5}$ or total suspended particulate (TSP). Appendix A contains a summary table which notes the PM sampling schedules for CA1B. The Kentucky site monitored PM_{10}, $PM_{2.5}$, and TSP continuously over the study period.

1.2.2 Animal Husbandry

For both the California and Kentucky sites, the producer recorded data on animal inventory and mortalities manually on a daily basis and provided this information to the NAEMS PI.

1.2.3 Biomaterials Sampling Methods and Schedule

1.2.3.1 CA1B

An independent laboratory, Midwest Laboratories, Omaha, NE, performed all analyses of biomaterials. Samples of the rice hull bedding material were collected in duplicate from each house and analyzed for nitrogen and solids.

Three types of manure samples were collected: surface litter, decaked litter, and litter removed during full clean-out. Surface litter samples were collected over the grow-out period from 16 random locations per house, including eight samples from the front of the house with relatively fresh litter and eight from the back of the house with the older litter. The two groups together were considered representative of the house litter. At each sampling point, all litter within a 0.6-m radius was brought to the center of the sampling location and mixed thoroughly. Composite samples from the mixtures were analyzed for pH, solids, total ammoniacal nitrogen, and total Kjeldahl nitrogen (TKN). Decaking and complete litter clean-out samples were collected from 12 random locations in each house during litter decaking and clean-out, respectively, and analyzed for ash (after December 2, 2008), nitrogen and solids.

1.2.3.2 KY1B-1 and KY1B-2

Biomaterial sampling for the Tyson portion of the study was limited to litter sampling. All litter samples were processed by the Agricultural Waste Management Laboratory in the Department of Agricultural and Biosystems Engineering at Iowa State University.

Litter from the production houses was sampled after the removal of each flock and analyzed for TKN. Analyzed samples, in conjunction with litter mass removed during clean-out, were used to estimate nongaseous nitrogen movement in and out of the house.

Two types of litter samples were collected - loadout litter and decaked litter. For total litter sampling, the broiler house was divided into two main zones: non-brooding and brooding zone. Each zone was then subdivided into three sections. Twenty random samples were collected from each section and pooled together to form one composite sample per section (three composite samples per zone). Decaked litter samples were also collected by taking shovel samples from each load of removed cake and combining them to form two 20-L samples.

2.0 REVISIONS TO DATA SET AND EMISSIONS DATA SUMMARY

The section catalogs the changes made to the broiler dataset prior to model development (Section 2.1), considers further changes to the data completeness criteria (Section 2.2), and finally compares the model development dataset to the initial dataset received in 2010 (Section 2.3) and published literature (Section 2.4) to determine the effect of the data revisions.

2.1 Revisions to the 2010 Data Set

As described in Section 4.2 of the Overview Report, the NAEMS monitoring data were submitted to EPA in 2010, with revisions submitted in 2015. Revisions included an adjustment to methodology to determine barn gas inlet concentrations. In addition to the revision noted in the Overview Report, a few flagging errors associated with the gas emissions were corrected for CA1B. Appendix B summarizes the data processing steps applied to the NAEMS broiler data.

No revised data were provided for the KY1B-1 and KY1B-2 sites as this these data were part of a separate effort (Tyson study) with different PIs. For the KY1B sites, inventory values were not provided during flock replacement events. To include the emissions during flock replacement events in modeling, an inventory value of zero (0) was added to these periods by the EPA. This resulted in 87 and 97 days of zero inventory being added to the KY1B-1 and KY1B-2 data sets, respectively.

2.2 Data Completeness Criteria for the Revised Data Set

The appropriate data completeness criteria to use in a study depends on the size of the dataset and the accuracy needed. A study by Grant et al. (2013), in which NH_3 emissions were modeled from swine lagoons based on NAEMS data, investigated data completeness and associated accuracy. The swine lagoon NH_3 emissions dataset had limited data availability at a data completeness of 75%. Grant et al. (2013) explored how much the data completeness criteria could be relaxed but still result in data with acceptable error. The study suggested an error of ±25% to be acceptable and determined that a daily data completeness of 52% (or 25 out of 48 30-minute periods) gave less than ±25% error (see Figure 2-1). Using this revised daily completeness criteria resulted in a substantial increase in the size of the dataset.

Based on Figure 2-1 from the Grant et al. (2013) study, it can be observed that a daily completeness criterion of 75% (36 out of 48 30-minute periods) would give an error of approximately 10%. If it is assumed that the relationship between data completeness and error from the Grant et al. (2013) study is representative of other NAEMS datasets, the effect of relaxed data completeness criteria can be investigated for other NAEMS sources.

The project Science Advisor provided EPA with additional analysis that examined the effect of different completeness criteria by comparing the number of valid average daily means (ADM). EPA reviewed this data for the CA1B site and retained the 75% completeness criterion. The full analysis can be found in Appendix C.

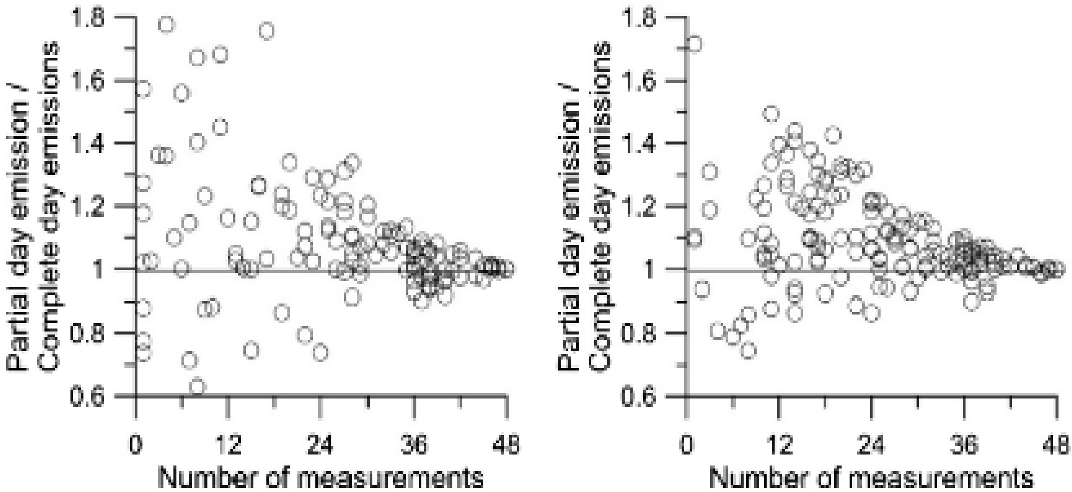

Figure 2-1. Ratio of mean predicted emissions for portion of day with valid emissions measurements to mean predicted emissions for the complete day at the finishing (A) and sow (B) farm. Error plotted against number of valid 30-minute measurements (from Grant et al., 2013).

2.3 Comparison between the 2010 and Revised Data Sets

The influence of the previously described corrections on the revised CA1B data set can be observed by comparing the number of valid ADM and mean emissions values (at 75% data completeness) between the 2010 dataset, as summarized in the final site reports, and the revised data set. The influence of the previously described corrections on the revised data set can be observed by comparing the number of valid ADM and mean emissions values (at 75% data completeness) between the 2010 and revised datasets for CA1B H10 (Table 2-1) and CA1B H12 (Table 2-2). At CA1B H10 (Table 2-1), the number of valid ADM increased by less than 1% for both NH_3 and hydrogen sulfide (H_2S). These changes in the number of ADM available only resulted in an overall ADM increase of 0.1% for NH_3 and a 0.3% decrease for H_2S. For CA1B H12 (Table 2-2), the number of valid ADM increased by 1.1% for NH_3 and 0.3% for H_2S. These changes in the number of ADM available only resulted in an overall ADM decrease of 0.2% for NH_3 and a 0.2% increase for H_2S.

Table 2-1. Number of valid ADM and mean NH_3 emissions values (at 75% data completeness) between the 2010 and revised CA1B H10 dataset.

Dataset	Statistic	NH_3 (kg d^{-1})	H_2S (g d^{-1})	PM_{10} (g d^{-1})	$PM_{2.5}$ (g d^{-1})	TSP (g d^{-1})
2010	n of ADM	467	592	352	53	37

Dataset	Statistic	NH_3 (kg d^{-1})	H_2S (g d^{-1})	PM_{10} (g d^{-1})	$PM_{2.5}$ (g d^{-1})	TSP (g d^{-1})
2010	Overall ADM	10.2	52.9	873	99	2,652
Revised	n of ADM	472	596	352	53	37
Revised	Overall ADM	10.21	52.73	873.3	98.8	2,652.4

Table 2-2. Number of valid ADM and mean NH_3 emissions values (at 75% data completeness) between the 2010 and revised CA1B H12 datasets.

Dataset	Statistic	NH_3 (kg d^{-1})	H_2S (g d^{-1})	PM_{10} (g d^{-1})	$PM_{2.5}$ (g d^{-1})	TSP (g d^{-1})
2010	n of ADM	466	590	376	43	39
2010	Overall ADM	9.0	50.3	879	124	2,270
Revised	n of ADM	471	592	376	43	39
Revised	Overall ADM	8.98	50.41	879.2	124.4	2,269.8

2.4 Comparison Between the Revised Data Sets and NAEMS Datasets Used in Peer-reviewed Published Papers

Where possible, EPA compared the revised dataset developed for this report to values presented in peer reviewed journals and reports to quantify any differences due to the application of the revised calculation methods and other adjustments discussed in Section 2.1. Summaries of the emissions from CA1B and the KY1B broiler houses have been published in peer-reviewed journal articles (Lin et al., 2012) or final project reports (Burns et al., 2007 and Burns et al., 2009). A simple comparison of the summary statistics presented in these papers and the summary statistics of the dataset used to develop the emissions models is presented in the following sections for each of the pollutants. For the PM size fractions, the revisions made for the model development dataset are minor and the dataset is still fairly consistent with versions previously published. For NH_3 and H_2S, the model development dataset contains a few larger values than included in published literature for the CA1B houses. Overall, any data revisions applied to the model development dataset are consistent with revision applied by the PIs in published reports and literature.

2.4.1 NH_3

The summary of the NH_3 emissions is presented in Table 2-3. For CA1B, the model dataset has 21 and 24 more ADM than the published datasets at H10 and H12, respectively. This resulted in a 16% and 17% difference in the mean ADM at H10 and H12, respectively. The substantial difference in the maximum values between the datasets suggests some larger values have been retained in the modeling data set that were removed for the publication dataset. For KY1B-1 and KY1B-2, differences in the means are minor (less than 2%) despite a decrease of 54 and 77 daily means at KY1B-1 H5 and KY1B-2 H3, respectively.

Table 2-3. Comparison of NH_3 emissions in the model dataset to published datasets.

Site	Emissions Units	Statistic	Model Dataset	Published Studies	Study
CA1B H10	g day^{-1} hd^{-1}	Number of ADM	391	370	Lin et al., 2012
CA1B H10	g day^{-1} hd^{-1}	Mean	0.62	0.54	Lin et al., 2012
CA1B H10	g day^{-1} hd^{-1}	Standard Deviation	1.10	0.45	Lin et al., 2012
CA1B H10	g day^{-1} hd^{-1}	Max	19.33	1.50	Lin et al., 2012
CA1B H12	g day^{-1} hd^{-1}	Number of ADM	393	369	Lin et al., 2012
CA1B H12	g day^{-1} hd^{-1}	Mean	0.55	0.47	Lin et al., 2012
CA1B H12	g day^{-1} hd^{-1}	Standard Deviation	1.04	0.42	Lin et al., 2012
CA1B H12	g day^{-1} hd^{-1}	Max	18.50	1.47	Lin et al., 2012
KY1B-1 H5	g day^{-1} hd^{-1}	Number of ADM	299	353	Burns et al., 2007
KY1B-1 H5	g day^{-1} hd^{-1}	Mean	0.54	0.55	Burns et al., 2007
KY1B-1 H5	g day^{-1} hd^{-1}	Standard Deviation	0.33	0.34	Burns et al., 2007
KY1B-2 H3	g day^{-1} hd^{-1}	Number of ADM	246	323	Burns et al., 2007
KY1B-2 H3	g day^{-1} hd^{-1}	Mean	0.60	0.59	Burns et al., 2007
KY1B-2 H3	g day^{-1} hd^{-1}	Standard Deviation	0.38	0.38	Burns et al., 2007

2.4.1 H_2S

The summary of the H_2S emissions is presented in Table 2-4. For CA1B, the model dataset has 22 more ADM than the published datasets at both H10 and H12. This resulted in a 2% difference in the mean at both H10 and H12. There are substantial differences in the maximum values between the datasets, which suggests some larger values have been retained in the modeling data set that were removed for the publication dataset. For the Kentucky sites, Burns (2009) reports the overall number of ADM, or days that passed quality checks, but presents separate emissions rates for normal operation and when birds are present. The averages presented in Table 2-4 represent times when birds were present in the house. KY1B-1 has an 11% lower overall mean ADM, and KY1B-2 matches fairly well. Without the exact count of days used in the average, it is tricky to determine the difference. One possibility for the differences is the flock 6 at KY1B-1 has an unexpectedly high mortality and was omitted from some of the analysis presented in the report. While not explicitly stated, this flock may have been omitted from the summary statistics pulled for this exercise.

2.4.2 PM_{10}

The summary of the PM_{10} emissions is presented in Table 2-5. For CA1B, the model dataset has 6 and 12 more ADM than the published dataset at H10 and H12, respectively. This resulted in a 2% decrease in the mean ADM at both H10 and H12. For the KY1B sites, the modeling dataset had 29 and 7 more ADM than the published dataset at KY1B-1 H5 and KY1B-

2 H3, respectively. These differences in ADM result in a decrease of 16% and 26% in the mean ADM at KY1B-1 H5 and KY1B-2 H3, respectively.

Table 2-4. Comparison of H_2S emissions in the EEM dataset to published datasets.

Site	Emissions Units	Statistic	EEM Dataset	Published Studies	Study
CA1B H10	mg day^{-1} hd^{-1}	Number of ADM	511	489	Lin et al., 2012
CA1B H10	mg day^{-1} hd^{-1}	Mean	3.01	2.95	Lin et al., 2012
CA1B H10	mg day^{-1} hd^{-1}	Standard Deviation	2.7	2.5	Lin et al., 2012
CA1B H10	mg day^{-1} hd^{-1}	Max	22.7	8.91	Lin et al., 2012
CA1B H12	mg day^{-1} hd^{-1}	Number of ADM	510	488	Lin et al., 2012
CA1B H12	mg day^{-1} hd^{-1}	Mean	2.89	2.82	Lin et al., 2012
CA1B H12	mg day^{-1} hd^{-1}	Standard Deviation	2.78	2.53	Lin et al., 2012
CA1B H12	mg day^{-1} hd^{-1}	Max	22.1	8.91	Lin et al., 2012
KY1B-1 H5	g day^{-1}	Number of ADM	-	-	Burns et al., 2009
KY1B-1 H5	g day^{-1}	Mean	56.48	63.3	Burns et al., 2009
KY1B-1 H5	g day^{-1}	Standard Deviation	52.90	44.7	Burns et al., 2009
KY1B-1 H5	g day^{-1}	Max	259.45	259.5	Burns et al., 2009
KY1B-2 H3	g day^{-1}	Number of ADM	-	-	Burns et al., 2009
KY1B-2 H3	g day^{-1}	Mean	69.55	70	Burns et al., 2009
KY1B-2 H3	g day^{-1}	Standard Deviation	48.42	43.6	Burns et al., 2009
KY1B-2 H3	g day^{-1}	Max	186.33	186.3	Burns et al., 2009

Table 2-5. Comparison of PM_{10} emissions in the EEM dataset to published datasets.

Site	Emissions Units	Statistic	EEM Dataset	Published Studies	Study
CA1B H10	g day^{-1} hd^{-1}	Number of ADM	334	328	Lin et al., 2012
CA1B H10	g day^{-1} hd^{-1}	Mean	44.6	45.4	Lin et al., 2012
CA1B H10	g day^{-1} hd^{-1}	Standard Deviation	40.3	40.1	Lin et al., 2012
CA1B H10	g day^{-1} hd^{-1}	Max	171	170	Lin et al., 2012
CA1B H12	g day^{-1} hd^{-1}	Number of ADM	366	354	Lin et al., 2012
CA1B H12	g day^{-1} hd^{-1}	Mean	43.7	44.6	Lin et al., 2012
CA1B H12	g day^{-1} hd^{-1}	Standard Deviation	37.7	37.9	Lin et al., 2012
CA1B H12	g day^{-1} hd^{-1}	Max	169	169	Lin et al., 2012
KY1B-1 H5	kg day^{-1}	Number of ADM	301	272	Burns et al., 2009
KY1B-1 H5	kg day^{-1}	Mean	0.92	1.1	Burns et al., 2009
KY1B-1 H5	kg day^{-1}	Standard Deviation	0.9	0.9	Burns et al., 2009
KY1B-1 H5	kg day^{-1}	Max	4.5	4.5	Burns et al., 2009
KY1B-2 H3	kg day^{-1}	Number of ADM	305	298	Burns et al., 2009
KY1B-2 H3	kg day^{-1}	Mean	1.0	1.4	Burns et al., 2009
KY1B-2 H3	kg day^{-1}	Standard Deviation	1.00	0.92	Burns et al., 2009
KY1B-2 H3	kg day^{-1}	Max	4.1	4.3	Burns et al., 2009

2.4.3 $PM_{2.5}$

The summary of the $PM_{2.5}$ emissions is presented in Table 2-6. For CA1B, the modeling dataset has the same number of available ADM as the published literature. However, the datasets do have slightly different means, with a 6% decrease at CA1B H10 and a less than 1% decrease at CA1B H12. For KY1B-1 and KY1B-2, differences in the means are minor despite an increase of 54 and 77 daily means at KY1B-1 H5 and KY1B-2 H3, respectively.

Table 2-6. Comparison of $PM_{2.5}$ emissions in the EEM dataset to published datasets.

Site	Emissions Units	Statistic	EEM Dataset	Published Studies	Study
CA1B H10	g day^{-1} hd^{-1}	Number of ADM	53	53	Lin et al., 2012
CA1B H10	g day^{-1} hd^{-1}	Mean	4.48	4.77	Lin et al., 2012
CA1B H10	g day^{-1} hd^{-1}	Standard Deviation	3.06	3.04	Lin et al., 2012
CA1B H10	g day^{-1} hd^{-1}	Max	11.9	11.8	Lin et al., 2012
CA1B H12	g day^{-1} hd^{-1}	Number of ADM	43	43	Lin et al., 2012
CA1B H12	g day^{-1} hd^{-1}	Mean	6.00	6.01	Lin et al., 2012
CA1B H12	g day^{-1} hd^{-1}	Standard Deviation	2.31	2.33	Lin et al., 2012
CA1B H12	g day^{-1} hd^{-1}	Max	11.4	11.5	Lin et al., 2012
KY1B-1 H5	kg day^{-1}	Number of ADM	286	256	Burns et al., 2009
KY1B-1 H5	kg day^{-1}	Mean	0.1	0.1	Burns et al., 2009
KY1B-1 H5	kg day^{-1}	Standard Deviation	0.1	0.1	Burns et al., 2009
KY1B-1 H5	kg day^{-1}	Max	0.4	0.4	Burns et al., 2009
KY1B-2 H3	kg day^{-1}	Number of ADM	301	296	Burns et al., 2009
KY1B-2 H3	kg day^{-1}	Mean	0.10	0.12	Burns et al., 2009
KY1B-2 H3	kg day^{-1}	Standard Deviation	0.10	0.01	Burns et al., 2009
KY1B-2 H3	kg day^{-1}	Max	0.38	0.39	Burns et al., 2009

2.4.1 TSP

The summary of the TSP emissions is presented in Table 2-7. For CA1B, the modeling dataset has the same number of ADM available as the published literature. There is a 2% decrease in the mean at H10, and no difference in the overall mean at H12. The difference in the mean ADM at H10 might be the result of a rounding and truncation difference between the two sources. For the KY1B sites, there are 34 and 6 more ADM than the published datasets for KY1B-1 H5 and KY1B-2 H3, respectively. This results in a mean ADM that is 19 and 16% lower at KY1B-1 H5 and KY1B-2 H3, respectively.

Table 2-7. Comparison of TSP emissions in the EEM dataset to published datasets.

Site	Emissions Units	Statistic	EEM Dataset	Published Studies	Study
CA1B H10	g day^{-1} hd^{-1}	Number of ADM	37	37	Lin et al., 2012
CA1B H10	g day^{-1} hd^{-1}	Mean	128	130	Lin et al., 2012
CA1B H10	g day^{-1} hd^{-1}	Standard Deviation	41.3	40.6	Lin et al., 2012
CA1B H10	g day^{-1} hd^{-1}	Max	228	229	Lin et al., 2012
CA1B H12	g day^{-1} hd^{-1}	Number of ADM	39	39	Lin et al., 2012
CA1B H12	g day^{-1} hd^{-1}	Mean	109	109	Lin et al., 2012
CA1B H12	g day^{-1} hd^{-1}	Standard Deviation	76.4	76.3	Lin et al., 2012
CA1B H12	g day^{-1} hd^{-1}	Max	298	297	Lin et al., 2012
KY1B-1 H5	kg day^{-1}	Number of ADM	315	281	Burns et al., 2009
KY1B-1 H5	kg day^{-1}	Mean	2.17	2.69	Burns et al., 2009
KY1B-1 H5	kg day^{-1}	Standard Deviation	2.02	1.96	Burns et al., 2009
KY1B-1 H5	kg day^{-1}	Max	10.3	10.3	Burns et al., 2009
KY1B-2 H3	kg day^{-1}	Number of ADM	301	295	Burns et al., 2009
KY1B-2 H3	kg day^{-1}	Mean	2.41	2.88	Burns et al., 2009
KY1B-2 H3	kg day^{-1}	Standard Deviation	2.20	1.83	Burns et al., 2009
KY1B-2 H3	kg day^{-1}	Max	7.5	7.3	Burns et al., 2009

3.0 RELATIONSHIPS ESTABLISHED IN LITERATURE

Developing EEMs for AFOs is complex as many variables potentially influence emissions. Therefore, to be efficient in this study, a focused approach was used. The focused approach involved developing models based on variables that could potentially have a major influence on air emissions. This assessment was made based on theoretical considerations and observations reported by previous studies that have investigated the influence of variables on emissions from broiler AFOs.

3.1 NH_3 and H_2S Emissions from Houses

The microbial degradation of urea, undigested proteins, and amino acids results in the generation of NH_3 and H_2S in poultry manure (Elliott and Collins, 1982; Saksrithai and King, 2018), which then can be released or emitted into the air. Accordingly, the amount of manure produced at a broiler house will be an important factor that influences emissions. Proxies for the amount of fresh manure produced at a broiler house are live animal weight (LAW) and inventory. Similar to EEMs developed for other animal types, LAW and inventory were selected as predictor variables. This allows the influence of these variables to be quantified and will consider the periods where the relationship between emissions and fresh manure production are not as strongly related. For example, during a flock replacement event there will be zero inventory and LAW, but emissions are non-zero during litter removal and also while there is litter or manure in the house. Furthermore, the LAW predictor variable can potentially represent the effects of other flock characteristics such as bird age, feed consumption and retention efficiency due to the relationship between these variables. LAW is a function of bird age and therefore increases with increasing bird age. As LAW increases, feed consumption will increase, however retention efficiency may change with increasing bird age. A variable named ‘flock age’ was created to represent bird age (i.e., number of days since birds were introduced to the house) with zero values used for flock age when the house was empty. The ‘flock age’ variable in addition to LAW and inventory was selected for further investigation. Various previous studies have observed that NH_3 and H_2S emissions increase with bird age and growth (Wheeler et al. 2006a; Calvet et al. 2011; Lin et al. 2012; Li et al. 2008)

In broiler houses, broilers reside on top of bedding that is on the floor of the house. Bedding type can influence gas emissions (Wood and Van Heyst, 2016; Van Harn et al. 2012), however, in NAEMS, all three sites used rice hull bedding, therefore this factor could not be investigated further. Manure excreted by birds, deposits onto the bedding, which is thereafter referred to as litter. Litter characteristics such as nutrient content, solid and moisture content and pH can influence NH_3 emissions (Liu et al. 2007; Carey et al. 2004) and H_2S emissions. Common measurements of nutrient content that relate to NH_3 and H_2S emissions are TKN (NH_3-

N + organic N), total ammoniacal nitrogen (TAN; NH_3-N), and sulfide. Higher litter nutrient content can result in higher NH_3 emissions (Liu et al. 2009) and presumably H_2S emissions. Within a flock cycle, litter nitrogen and sulfur content are likely to increase with litter age as more manure is contributed to the litter (Liu et al. 2007), thus increasing gas emissions. Litter pH is an important factor in influencing litter NH_3 and H_2S concentrations and thus the potential for emissions. The pH of the litter effects the chemical equilibrium between NH_3 and NH_4^+ and HS^- and H_2S, respectively (Liang et al. 2014; Saksrithal and King, 2018).

Litter moisture can influence NH_3 generation by promoting microbial degradation of uric acid, amino acids, and undigested proteins (Liu et al. 2007; Elliott and Collins, 1982). Moisture content in litter can be influenced by the bird's consumption of water, which may be higher in warmer conditions, and also by misting systems and the efficiency of broiler drinking systems (Liu et al. 2007; Carey et al. 2004). Within a flock cycle, litter moisture content is expected to increase as more manure is excreted to the litter surface. At CA1B, litter floor samples were taken for six of the fourteen flocks that were present during the two-year monitoring period. For four of these six flocks, one sample was taken. For the other two flocks, weekly sampling was conducted throughout the broiler cycle. All litter samples were analyzed for TAN, pH, and solids content (inverse of moisture content), but sulfide was only measured in three samples at each house and TKN was not measured at all. At KY1B-1 and KY1B-2, no litter floor samples were taken. The litter solids content, pH, and TAN data at CA1B were selected for further investigation.

Management activities can influence gas emissions from broiler houses (Carey et al. 2004). During flock emptying and replacement, there will be different numbers of broilers in the house, which will influence the amount of fresh manure in the house. In addition, in-between flock cycles the litter is either partially or completely removed. While the litter is being removed, there is the potential for increases in NH_3, and particularly H_2S, emissions due to manure disturbance (Ni et al. 2009). The influence of flock emptying and replacement, and litter removal was investigated by assigning a status of full (F), empty (E), or transition to empty or full (T). The date(s) of litter removal were not provided; however, it is assumed that the litter removal occurred on some or all of the days when the house was empty. Therefore, the E status also represents the effects of litter removal.

As stated, at the end of each flock cycle the litter is either partially or completely removed. Partial removal of litter is known as decaking, and the number of times litter is decaked before complete litter removal occurs can vary. When litter is decaked as opposed to being completely removed, it is probable that the nitrogen and sulfur content of the remaining 'built-up' litter will be higher than fresh bedding and thus could have higher gas emissions. Observational studies support that emissions from built-up litter are higher, however the reported increase varies greatly from study to study (Brewer and Costello, 1999; Wheeler et al. 2006a; Lin et al. 2012; Burns et al. 2007). To investigate the influence of litter age, a numerical variable was created that represented the age (in days) of the litter. In addition, categorical variables were developed that represented the status of litter usage.

Airflow caused by house ventilation can influence gas emissions. The transfer rate of NH_3 from litter to the house air is dependent on the mass transfer coefficient, which is a function of air velocity (Elliot and Collins, 1982) and thus the transfer rate will increase as air velocity or air flow increases. However, higher house ventilation can dry the litter, resulting in less NH_3 generation and thus reduced emissions (Lin et al. 2012; Calvet et al. 2011). It is expected that airflow will have a similar effect on H_2S emissions. Accordingly, airflow was selected for further investigation.

Temperature is an important factor in many of the processes that influence gas emissions from litter. Temperature can influence microbial activity and thus the generation of NH_3 from uric acid as temperature increases to around 35ºC (Elliot and Collins, 1982). An increasing litter temperature will increase the dissociation constant and Henry's law constant for NH_3 (Liang et al. 2014; Liu et al. 2009), increasing the potential amount that can be released into the air. For H_2S, increasing litter temperature will increase the dissociation constant and Henry's law constant similarly. However, an increasing dissociation constant results in less availability of H_2S due to its effect on the chemical equilibrium (Rumsey and Aneja, 2014), therefore the influence of litter temperature on H_2S may be weaker than that for NH_3. Temperature can also potentially influence the transfer of NH_3 and H_2S across the litter-air interface, however the effect of temperature on NH_3 mass transfer is not clear as two studies that have examined this closely (Elliot and Collins, 1982; Liu et al. 2008) report different (i.e., positive versus negative) effects. The effect of temperature on gas emissions from broiler litter is further complicated by the effect of temperature on mechanical ventilation rate, as higher temperatures will result in higher ventilation rates, which as previously described, can reduce the moisture content of the litter, resulting in reduced gas emissions. Continuous measurements of barn exhaust temperature and ambient temperature were made during NAEMS and both were selected for further investigation.

Relative humidity (RH) may affect gas emissions from broiler litter due to its effect on litter moisture/solid content. As was described for layer manure (Ni et al. 2017), higher RH may similarly reduce the evaporation of water from the litter surface, resulting in higher moisture content. This influence of RH on NH_3 emissions was identified by Weaver and Meijerhof (1991), in which they found relative humidity to generally increase NH_3 levels in broiler litter. Continuous measurements of barn exhaust RH and ambient RH were made during NAEMS and both were selected for further investigation.

3.2 PM Emissions from Houses

The release of PM into broiler house air is caused by the physical suspension of different source materials including feathers, feed, manure, and bedding (Cambra-Lopez et al. 2011; Redwine et al. 2002; Winkel, 2016). The amount of source materials increases with increasing LAW and bird age (Roumeliotis et al. 2010a). Similar to the gases, the variables inventory, LAW, and flock age were selected as predictor variables for further investigation.

Physical suspension of PM from house surfaces can be caused by animal activity, human activity, and air flow (Aarnink and Ellen, 2007). Activity measurements were not provided to the EPA; however, broiler activity has been reported to increase with bird age and weight (Redwine et al. 2002), which means using these variables as predictor variables may partly consider their influence. Air flow or ventilation rate can influence PM emissions by facilitating PM suspension from litter (Lin et al. 2012). As mentioned, mechanical ventilation rates are related to ambient and house temperature, thus meaning that temperature could be a potential surrogate variable that represents airflow. Factors that can influence the physical suspension of PM in house air include house air moisture content. A study by Takai et al. (1998) examined PM emissions from a variety of livestock types including broiler and reported that RH greater than 70% contributed to particles aggregating together and thus reducing emissions. Accordingly, for broiler houses the variables airflow, ambient temperature, barn exhaust temperature, ambient RH, and barn RH were selected for further investigation. Litter moisture content, which as previously described can be influenced by numerous factors, may also affect the physical suspension of PM. Accordingly, litter solid content (inverse of moisture content) was selected for further investigation.

Management activities can also influence PM emissions from broiler houses (Patterson and Adrizal, 2005). Flock replacement and litter removal events will increase the disturbance of PM source materials, resulting in increased PM emissions. Similar to gases, the influence of flock emptying and replacement, and litter removal was investigated by assigning a management status of full (F), empty (E), transition to empty or full (T) to the appropriate days. As previously mentioned, the E status also represents the effects of litter removal.

Another management activity that may influence PM emissions is the bedding type (Wood and Van Heyst, 2016; Van Harn et al. 2012). In NAEMS, all three sites used rice hull bedding, therefore this factor could not be investigated further. However, the type of litter removal (i.e., de-caking or complete removal) theoretically influences litter characteristics and thus the potential for the litter to be suspended. Similar to gases, the influence of litter age was investigated using a numerical variable and also through categorical variables that represented the status of litter usage.

4.0 SITE COMPARISON, TRENDS, AND ANALYSIS

Before developing the emissions models, EPA evaluated NAEMS data for each pollutant to identify patterns and trends in the emissions data using a combination of summary statistics (mean, standard deviation, number of data values, median, minimum, maximum, coefficient of variation, and number of data values less than zero) and time series plots. Section 4.1 summarizes the emissions trends from the sites, while Appendix D contains the tables of summary statistics. Appendix E presents the time series plots of the site-specific emissions, environmental and production parameters, and manure data collected under NAEMS.

Based on the analysis described in Section 3.0, EPA identified the key environmental and manure parameters that potentially affect emissions from broiler houses. Parameters of particular interest include inventory, LAW, flock age, barn conditions (exhaust temperature, exhaust relative humidity, and airflow), ambient temperature, ambient relative humidity, litter age and status, litter moisture, litter pH, litter total ammoniacal nitrogen (TAN), and litter TKN.

The next step of the analysis was to look at the key environmental and manure parameters compared to emissions trends. The exploratory data analysis was conducted to confirm that the variables were selected based on the following criteria: (1) data analysis in this study and in the literature suggested that these variables had an influence on emissions; (2) the variables should be easy to measure; and (3) the variables were already in the daily average NAEMS data and were available for most days of monitored emissions. This third selection criterion particularly applies to the manure parameters, such as moisture content and TAN concentration, which were infrequent due to the intensive collection and analysis methods. Additional time could be taken to develop an appropriate methodology for interpolating between the few data points available for these parameters in the dataset. However, these parameters are difficult to acquire as they require chemical analysis from a laboratory.

The exploratory data analysis was also used to explore whether additional parameters could be included to explain trends. To further explore the trends between the predictor variables and emissions and determine whether the parameter should be included in developing an EEM, EPA prepared scatter plots of emissions versus the process, environmental, and manure parameters and conducted least squares regression analysis to assess the influence of each variable on emissions. For the linear regressions, EPA classified the linear relationships based on the ranges in Table 4-1.

A summary of this analysis for environmental parameters is discussed in Section 4.2, and the manure parameters are presented in Section 4.3. Appendix D contains summary statistics,

Appendix E contains the relevant time series plots, and Appendix F contains the least squares regression analyses between the identified parameters and emissions.

Table 4-1. Relationship classification based on R^2 values.

Range of R^2	Relationship Strength
$R^2 \leq 0.001$	None
$0.001 < R^2 \leq 0.2$	Slight or weak
$0.2 < R^2 \leq 0.4$	Modest
$0.4 < R^2 \leq 0.6$	Moderate
$0.6 < R^2 \leq 0.8$	Moderately strong
$R^2 > 0.8$	Strong

4.1 Emissions Data

Appendix D, Table D-1 presents the summary statistics for daily average emissions of NH_3 for the broiler sites. From the table, the emissions are fairly consistent across sites with average daily emissions of 8.98 at CA1b H12 to 12.37 kg d^{-1} at KY1B-2 H3. Appendix E, Figure E-1 shows that the emissions follow a cycle that is likely linked to bird age and size. The figure also reiterates that the range of average daily emissions is consistent between sites. There were only 2 negative emissions values in the NH_3 dataset, both of which occurred at CA1B H12.

Appendix D, Table D-2 presents the summary statistics for daily average emissions of H_2S for the broiler sites. From the table, the emissions are fairly consistent across sites with average daily emissions of 47.70 at KY1B-1 H5 to 53.50 g d^{-1} at KY1B-2 H3 Appendix E, Figure E-2 shows that the emissions again follow a cycle that is likely linked to the growing cycle. The figure supports that the range of average daily emissions is consistent between sites but does show a tendency for higher values at KY1B-1 H5. There were 18 negative values in the H_2S dataset for both CA1B houses, and only one negative value at KY1B-1 H5.

Appendix D, Table D-3 presents the summary statistics for daily average emissions of PM_{10} for the broiler sites. From the table, the emissions are fairly consistent across sites with average daily emissions of 873.30 g d^{-1} at CA1B H10 to 1040.05 g d^{-1} KY1B-2 H3. Appendix E, Figure E-3 shows that the emissions again follow a cycle that is likely linked to the growing cycle. The figure visually demonstrates the range of average daily emissions values is consistent between sites. There were 4 negative values in the PM_{10} dataset, which occurred at CA1B houses.

Appendix D, Table D-4 presents the summary statistics for daily average emissions of $PM_{2.5}$ for the broiler sites. From the table, the emissions are fairly consistent across sites with average daily emissions of 89.60 g d^{-1} at KY1B-1 H5 to 124.39 g d^{-1} at CA1B H12. Appendix E,

Figure E-4 shows that the emissions again follow a cycle that is likely linked to the growing cycle at the Kentucky sites. The CA1B houses practiced a limited monitoring schedule, which limits the ability to detect a similar trend. However, the data available shows increasing emissions for successive days in the growing cycle. There were no negative values in the $PM_{2.5}$ dataset.

Appendix D, Table D-5 presents the summary statistics for daily average emissions of TSP for the broiler sites. From the table, the emissions are fairly consistent across sites with average daily emissions of 2.16 kg d^{-1} at KY1B-1 H5 to 2.65 kg d^{-1} at CA1B H10. As with $PM_{2.5}$, the time series plot in Appendix E, Figure E-5 shows the limited nature of the TSP observations from the CA1B houses compared to the Kentucky sites. There is still the indication of increased emissions as birds progress through the growing cycle across all houses. There were no negative values in the TSP.

4.2 Environmental Parameters

The statistical summary of the environmental parameters associated with broiler houses are presented in Appendix D, Table D-6. The inventory was similar across the sites, with CA1B having just under 17,000 birds in each house to KY1B-2 H3 with just over 18,000 birds. Appendix E, Figure E-6 shows that the number of birds present over the course of NAEMS was fairly consistent, except during periods of bird removal and cleaning after each cycle. Appendix F, Figures F-1 through F-5 show the scatter plots of inventory versus each pollutant. A summary of the findings is provided in Table 4-2. In general, there is a weak positive relationship with inventory across all pollutants.

Bird weight and LAW (i.e., inventory * bird weight) are fairly consistent across the houses with the average bird weight ranging from 1.04 to 1.14 kg. Appendix E, Figure E-7 shows the weight steadily increasing through the growing cycle, which is also reflected in the plot of LAW (Appendix E, Figure E-8). The regression analysis for average weight (Appendix F, Figures F-6 through F-10) and LAW (Appendix F, Figures F-11 through F-15) showed moderately strong correlations with all the pollutants.

Table 4-2. Bird specific parameters regression analysis.

Pollutant	Parameter	R^2	Strength	Figure
NH_3	Inventory (head)	0.0399	Slight or weak	Appendix F, F-1
H_2S	Inventory (head)	0.1271	Slight or weak	Appendix F, F-2
PM_{10}	Inventory (head)	0.0775	Slight or weak	Appendix F, F-3
$PM_{2.5}$	Inventory (head)	0.0691	Slight or weak	Appendix F, F-4
TSP	Inventory (head)	0.1179	Slight or weak	Appendix F, F-5
NH_3	Average bird weight (kg)	0.7282	Moderately strong	Appendix F, F-6
H_2S	Average bird weight (kg)	0.6921	Moderately strong	Appendix F, F-7

Pollutant	Parameter	R^2	Strength	Figure
PM_{10}	Average bird weight (kg)	0.7058	Moderately strong	Appendix F, F-8
$PM_{2.5}$	Average bird weight (kg)	0.7715	Moderately strong	Appendix F, F-9
TSP	Average bird weight (kg)	0.6364	Moderately strong	Appendix F, F-10
NH_3	LAW (kg)	0.5844	Moderate	Appendix F, F-11
H_2S	LAW (kg)	0.7242	Moderately strong	Appendix F, F-12
PM_{10}	LAW (kg)	0.7467	Moderately strong	Appendix F, F-13
$PM_{2.5}$	LAW (kg)	0.8122	Strong	Appendix F, F-14
TSP	LAW (kg)	0.7241	Moderately strong	Appendix F, F-15
NH_3	Flock Age (days, 0 between flocks)	0.4989	Moderate	Appendix F, F-16
H_2S	Flock Age (days, 0 between flocks)	0.6781	Moderately strong	Appendix F, F-17
PM_{10}	Flock Age (days, 0 between flocks)	0.7343	Moderately strong	Appendix F, F-18
$PM_{2.5}$	Flock Age (days, 0 between flocks)	0.7246	Moderately strong	Appendix F, F-19
TSP	Flock Age (days, 0 between flocks)	0.7070	Moderately strong	Appendix F, F-20
NH_3	Flock age (continuous between flocks)	0.1209	Slight or weak	Appendix F, F-21
H_2S	Flock age (continuous between flocks)	0.0757	Slight or weak	Appendix F, F-22
PM_{10}	Flock age (continuous between flocks)	0.1924	Slight or weak	Appendix F, F-23
$PM_{2.5}$	Flock age (continuous between flocks)	0.1411	Slight or weak	Appendix F, F-24
TSP	Flock age (continuous between flocks)	0.0778	Slight or weak	Appendix F, F-25
NH_3	Bird age (days)	0.6886	Moderately strong	Appendix F, F-26
H_2S	Bird age (days)	0.6656	Moderately strong	Appendix F, F-27
PM_{10}	Bird age (days)	0.7150	Moderately strong	Appendix F, F-28
$PM_{2.5}$	Bird age (days)	0.7337	Moderately strong	Appendix F, F-29
TSP	Bird age (days)	0.6632	Moderately strong	Appendix F, F-30

To capture the cyclical nature of the emissions at broiler farms, EPA explored three different variations on age parameters: 1) flock age, where age was set to zero between flocks (Appendix E, Figure E-9); 2) flock age, where age increased between flocks (Appendix E, Figure E-10); and 3) bird age, which only included periods when birds were in the house (Appendix E, Figure E-11). Both the flock age, where age was zero between flocks (Appendix F, Figures F-16 through F-20), and bird age (Appendix F, Figures F-26 through F-30) showed moderately strong correlations with each pollutant, which were consistent with the weight correlations. Since broilers are grown, weight and age will be correlated and should show similar correlations with emissions. The regression analysis for flock age, where age increased between flocks (Appendix F, Figures F-21 through F-25) only showed weak correlations with emissions.

Appendix D, Table D-7 provides the summary statistic for the house environmental parameters. The mean daily house temperature actually varies across the growth cycle, with temperatures ranging from as low as 4.24 to 24.99 °C. This wide range of temperatures was seen at each of the houses. The time series (Appendix E, Table E-12) shows the trend of increasing temperatures as the birds grow, followed by decreasing temperature during periods between flocks. The regression analysis in Appendix F Figures F-31 through F-35, summarized in Table 4-3, shows only a weak relationship between house temperature and each pollutant.

Table 4-3. House specific parameters regression analysis.

Pollutant	Parameter	R^2	Strength	Figure
NH_3	Exhaust temperature	0.0081	Slight or weak	Appendix F, F-31
H_2S	Exhaust temperature	0.0000	Slight or weak	Appendix F, F-32
PM_{10}	Exhaust temperature	0.0007	Slight or weak	Appendix F, F-33
$PM_{2.5}$	Exhaust temperature	0.0084	Slight or weak	Appendix F, F-34
TSP	Exhaust temperature	0.0111	Slight or weak	Appendix F, F-35
NH_3	House relative humidity	0.0733	Slight or weak	Appendix F, F-36
H_2S	House relative humidity	0.0124	Slight or weak	Appendix F, F-37
PM_{10}	House relative humidity	0.0012	Slight or weak	Appendix F, F-38
$PM_{2.5}$	House relative humidity	0.0628	Slight or weak	Appendix F, F-39
TSP	House relative humidity	0.0023	Slight or weak	Appendix F, F-40
NH_3	Airflow	0.4285	Moderate	Appendix F, F-41
H_2S	Airflow	0.3537	Modest	Appendix F, F-42
PM_{10}	Airflow	0.4568	Moderate	Appendix F, F-43
$PM_{2.5}$	Airflow	0.5757	Moderate	Appendix F, F-44
TSP	Airflow	0.2667	Modest	Appendix F, F-45

The summary statistics (Appendix D, Table D-7) show all the houses maintained a similar range of relative humidities across the study. The trends in house relative humidity shown in Appendix E, Figure E-13 appear to have some seasonality, although it varies at the two locations. The Kentucky sites have higher barn relative humidities in the summer, and the California houses have higher relative humidities in the winter. Regression analysis (Appendix F, Figures F-36 through F-40) shows a weak relationship with house relative humidity and pollutant emissions.

The summary statistics (Appendix D, Table D-7) show airflow for the houses spanned a wide range, which was fairly consistent across the houses. Appendix E, Figure E-14 shows a similar pattern to house temperatures, with increased airflow rates roughly corresponding to increasing bird age and size, with decreasing values after the birds are removed. The regression analysis (Appendix F, Figures F-41 through F-15) indicates a modest linear relationship between airflow and any of the pollutants.

The statistical summary of the ambient parameters for the broiler sites is presented in Appendix D, Table D-8. The table shows that the average daily temperature is lowest at KY1B-2 followed by KY1B-1, and CA1B. The sites did have variation in the range of temperatures covered, as CA1B was not exposed to freezing temperatures, but both KY1B-1 and KY1B-2 were. The temporal trend in ambient temperature is as expected, with Appendix E, Figure E-15 showing peaks in the July timeframe and lows after the new year. The regression analysis, shown in Appendix F, Figures F-46 through F-50 and summarized in Table 4-4, note ambient temperature had a weak relationship to pollutant emissions.

The summary statistics (Appendix D, Table D-8) show that while the sites had different mean ambient relative humidities, they were subject to approximately the same range of values across the study. Appendix E, Figure E-16 shows some seasonality to the relative humidity measurements, but these patterns vary between the sites. CA1B peaks at the start of the year, with lows occurring midyear. KY1B-1 and KY1B-2 have peak relative humidity in the summer, and generally more variability than CA1B. The regression analysis (Appendix F Figures F-51 through F-55) showed ambient relative humidity had a weak linear relationship with each pollutant.

Table 4-4. Ambient parameters regression analysis.

Pollutant	Parameter	R^2	Strength	Figure
NH_3	Ambient temperature	0.0131	Slight or weak	Appendix F, F-46
H_2S	Ambient temperature	0.0105	Slight or weak	Appendix F, F-47
PM_{10}	Ambient temperature	0.0411	Slight or weak	Appendix F, F-48
$PM_{2.5}$	Ambient temperature	0.0526	Slight or weak	Appendix F, F-49
TSP	Ambient temperature	0.0059	Slight or weak	Appendix F, F-50
NH_3	Ambient relative humidity	0.0120	Slight or weak	Appendix F, F-51
H_2S	Ambient relative humidity	0.0000	Slight or weak	Appendix F, F-52
PM_{10}	Ambient relative humidity	0.0092	Slight or weak	Appendix F, F-53
$PM_{2.5}$	Ambient relative humidity	3E-05	Slight or weak	Appendix F, F-54
TSP	Ambient relative humidity	0.0139	Slight or weak	Appendix F, F-55

4.3 Litter Parameters

For broilers, litter age can affect emissions rates in the house. While all the houses decaked litter (i.e., removed the top layer) between flock, full litter clean out happened less frequently and at different rates across the sites. CA1B had a full litter clean out after every third flock, while KY1B-1 and KY1B-2 only performed a full clean out once a year. During the study, KY1B-1 raised 4 flocks before a full litter clean out and KY1B-2 raised 7 flocks on the same litter. To account for this, EPA tested five parameters to account for the age of the litter:

- Litter age: continuous variable that indicates the number of days since litter removal.
- Litter Status (0-1, continuous between flocks): discrete variable to indicate whether the flock was the first flock raised on fresh litter (0) or if it was not fresh litter (1). The value is held during transition periods between flocks.
- Litter Status (0-3, continuous between flocks): discrete variable to indicate the number of flocks since litter removal, where 0 indicates the first flock raised on fresh litter, up to 3 to indicate four or more flocks had been raised on the litter. The value is held during transition periods between flocks.

- Litter Status (0-6, continuous between flocks): discrete variable to indicate the number of flocks since litter removal, where 0 indicates the first flock raised on fresh litter and up to 6 to indicate the up to seven (7) flocks raised on the litter before a full clean out. The value is held during transition periods between flocks.

- Litter Status (0-6; empty between flocks): discrete variable to indicate the number of flocks since litter removal, where 0 indicates the first flock raised on fresh litter and up to 6 to indicate the up to seven (7) flocks raised on the litter before a full clean out. The value set to "null" during transition periods between flocks.

The four 'Litter Status' categorical variables were considered experimental by EPA since an appropriate methodology for their evaluation and application has not been finalized. The data has been included in the report to note all the options EPA explored.

The summary statistics for the litter age parameters is provided in Appendix D, Table D-9, which reiterates litter was removed more frequently at CA1B than KY1B-1 and KY1B-2. The time series in Appendix E, Figure E-17 through E-22 shows the more frequent cleaning at CA1B, and less frequent clean outs at KY1B-1 and KY1B-2. The figures also show the limited data available for older litter, with only one instance each of 5, 6 and 7 flocks raised on the litter. Appendix F Figures F-56 through F-80, with the results summarized in Table 4-5, show the scatter plots of the various litter age parameters versus each pollutant. The analysis shows only a weak linear relationship with any of the litter ages and the emissions of each pollutant.

Table 4-5. Litter age parameters regression analysis.

Pollutant	Parameter	R^2	Strength	Figure
NH_3	Litter age	0.0466	Slight or weak	Appendix F, F-56
H_2S	Litter age	0.0266	Slight or weak	Appendix F, F-57
PM_{10}	Litter age	0.0262	Slight or weak	Appendix F, F-58
$PM_{2.5}$	Litter age	0.0227	Slight or weak	Appendix F, F-59
TSP	Litter age	0.0131	Slight or weak	Appendix F, F-60
NH_3	Litter Status (0-1, continuous)	0.0031	Slight or weak	Appendix F, F-61
H_2S	Litter Status (0-1, continuous)	0.0005	Slight or weak	Appendix F, F-62
PM_{10}	Litter Status (0-1, continuous)	0.0002	Slight or weak	Appendix F, F-63
$PM_{2.5}$	Litter Status (0-1, continuous)	0.0132	Slight or weak	Appendix F, F-64
TSP	Litter Status (0-1, continuous)	0.001	Slight or weak	Appendix F, F-65
NH_3	Litter Status (0-3, continuous)	0.0167	Slight or weak	Appendix F, F-66
H_2S	Litter Status (0-3, continuous)	0.0100	Slight or weak	Appendix F, F-67
PM_{10}	Litter Status (0-3, continuous)	0.0105	Slight or weak	Appendix F, F-68
$PM_{2.5}$	Litter Status (0-3, continuous)	0.0253	Slight or weak	Appendix F, F-69
TSP	Litter Status (0-3, continuous)	0.0047	Slight or weak	Appendix F, F-70
NH_3	Litter status (0-6, continuous between flocks)	0.0203	Slight or weak	Appendix F, F-71
H_2S	Litter status (0-6, continuous between flocks)	0.0145	Slight or weak	Appendix F, F-72

Pollutant	Parameter	R^2	Strength	Figure
PM_{10}	Litter status (0-6, continuous between flocks)	0.0089	Slight or weak	Appendix F, F-73
$PM_{2.5}$	Litter status (0-6, continuous between flocks)	0.0123	Slight or weak	Appendix F, F-74
TSP	Litter status (0-6, continuous between flocks)	0.0055	Slight or weak	Appendix F, F-75
NH_3	Litter Status (0-6; empty between flocks)	0.0379	Slight or weak	Appendix F, F-76
H_2S	Litter Status (0-6; empty between flocks)	0.0285	Slight or weak	Appendix F, F-77
PM_{10}	Litter Status (0-6; empty between flocks)	0.0181	Slight or weak	Appendix F, F-78
$PM_{2.5}$	Litter Status (0-6; empty between flocks)	0.0196	Slight or weak	Appendix F, F-79
TSP	Litter Status (0-6; empty between flocks)	0.0081	Slight or weak	Appendix F, F-80

Several samples of the floor litter were taken and analyzed for litter moisture/solids content, litter TAN, litter TKN, and litter pH. These samples were taken several different times during the litter cycle, including litter from the house floor, fresh litter after it was added to the house, decaked litter removed from the house, and full load-out litter.

The summary statistics of the litter samples is provided in Appendix D, Table D-10. For measurements taken of litter from the house floor, the table shows the only measurements available were from CA1B. The solids, TAN content, and pH were similar between the two houses at Ca1B. When plotted (Appendix E, Figures E-22, E-23, E-33), the sparse nature of the measurements makes it difficult to discern any seasonal trends. However, the plots do show the samples were generally comparable between the two houses. The regression analysis (Appendix F, Figures F-81 through F-90, F-113, and F-114), summarized in Table 4-6, do show moderate to moderately strong linear relationships between both solids content and TAN content with the emissions of NH_3, H_2S, and $PM_{2.5}$. There was only a weak relationship between the PM_{10} emissions data and either solids content or TAN content. For TSP emissions, there was not sufficient measurement data to conduct a linear regression analysis. For pH, there was a modest relationship with NH_3 and H_2S emissions.

Table 4-6. House litter parameters regression analysis.

Pollutant	Parameter	R^2	Strength	Figure
NH_3	Solid Content Litter Floor	0.6680	Moderately strong	Appendix F, F-81
H_2S	Solid Content Litter Floor	0.6031	Moderately strong	Appendix F, F-82
PM_{10}	Solid Content Litter Floor	0.1038	Slight or weak	Appendix F, F-83
$PM_{2.5}$	Solid Content Litter Floor	0.6169	Moderately strong	Appendix F, F-84
TSP	Solid Content Litter Floor	a	a	Appendix F, F-85
NH_3	TAN Litter floor	0.7529	Moderately strong	Appendix F, F-86
H_2S	TAN Litter floor	0.5696	Moderate	Appendix F, F-87
PM_{10}	TAN Litter floor	0.1387	Slight or weak	Appendix F, F-88
$PM_{2.5}$	TAN Litter floor	0.7906	Moderately strong	Appendix F, F-89
TSP	TAN Litter floor	a	a	Appendix F, F-90
NH_3	pH Litter floor	0.2799	Modest	Appendix F, F-113
H_2S	pH Litter floor	0.3918	Modest	Appendix F, F-114

[a] EPA did not have sufficient measurement data from NAEMS to conduct a linear regression analysis (i.e., two or fewer observations were taken).

For new litter samples, fewer samples were taken over the course of the study. The summary statistics provided in Appendix D, Table D-10 show there were no new litter measurements at KY1B-2, and only one sample taken at KY1B-1. The summary table also shows that the samples were analyzed differently between the sites, as CA1B provided values on a wet weight basis and the KY1B sites provided both wet and dry weight basis. The time series for TKN (Appendix E, Figures E-24 and E-25) and solids content (Appendix E, Figure E-26) show the sparse nature of the measurements, which makes it difficult to discern any trends. The regression analysis for TKN (Appendix F, Figures F-91 through F-94) and solids content (Appendix F, Figures F-95 and F-96), summarized in Table 4-7, show some relationship to NH_3 and H_2S emissions. However, with only four samples in the regression, there is not a lot of confidence in the relationship. For PM_{10}, $PM_{2.5}$ and TSP, none of the new litter samples coincided with emissions observations.

For decaked litter samples, there were only a few samples taken over the course of the study. The summary statistics provided in Table D-10 of Appendix D show there were no solids analysis on decaked litter samples at the KY1B sites. Again, the summary table shows the samples were analyzed differently between the sites, as CA1B provided values only on a wet weight basis and the KY1B sites provided both wet and dry weight basis. The time series for TKN (Appendix E, Figures E-27 and E-28) and solids content (Appendix E, Figure E-29) show the sparse nature of the measurements, which makes it difficult to discern any trends. The regression analysis for TKN (Appendix F, Figures F-97 through F-104) and solids content (Appendix F, Figures F-105 and F-106), summarized in Table 4-8, show modest linear relationships with NH_3 and H_2S emission. For PM_{10}, $PM_{2.5}$, and TSP, none of the decaked litter samples coincided with emissions observations.

Table 4-7. New litter parameters regression analysis.

Pollutant	Parameter	R^2	Strength	Figure
NH_3	TKN Content, new litter (wet basis)	0.0486	Slight or weak	Appendix F, F-91
H_2S	TKN Content, new litter (wet basis)	0.3807	Modest	Appendix F, F-92
PM_{10}	TKN Content, new litter (wet basis)	b	b	b
$PM_{2.5}$	TKN Content, new litter (wet basis)	b	b	b
TSP	TKN Content, new litter (wet basis)	b	b	b
NH_3	TKN Content, new litter, (dry basis)	a	a	Appendix F, F-93
H_2S	TKN Content, new litter, (dry basis)	a	a	Appendix F, F-94
PM_{10}	TKN Content, new litter, (dry basis)	b	b	b
$PM_{2.5}$	TKN Content, new litter, (dry basis)	b	b	b
TSP	TKN Content, new litter, (dry basis)	b	b	b
NH_3	Solids content, new litter	0.9236	Strong	Appendix F, F-95
H_2S	Solids content, new litter	0.3331	Modest	Appendix F, F-96
PM_{10}	Solids content, new litter	b	b	b
$PM_{2.5}$	Solids content, new litter	b	b	b
TSP	Solids content, new litter	b	b	b

[a] EPA did not have sufficient measurement data from NAEMS to conduct a linear regression analysis (i.e., two or fewer observations were taken).
[b] No observations were collected that coincided with emissions observations.

Table 4-8. Decaked litter parameters regression analysis.

Pollutant	Parameter	R^2	Strength	Figure
NH_3	TKN, decaked litter (wet weight basis)	0.0718	Slight or weak	Appendix F, F-97
H_2S	TKN, decaked litter (wet weight basis)	0.2384	Modest	Appendix F, F-98
PM_{10}	TKN, decaked litter (wet weight basis)	b	b	b
$PM_{2.5}$	TKN, decaked litter (wet weight basis)	a	a	Appendix F, F-99
TSP	TKN, decaked litter (wet weight basis)	a	a	Appendix F, F-100
NH_3	TKN content, decaked litter (dry weight basis)	0.3342	Modest	Appendix F, F-101
H_2S	TKN content, decaked litter (dry weight basis)	0.1887	Slight or weak	Appendix F, F-102
PM_{10}	TKN content, decaked litter (dry weight basis)	b	b	b
$PM_{2.5}$	TKN content, decaked litter (dry weight basis)	a	a	Appendix F, F-103
TSP	TKN content, decaked litter (dry weight basis)	a	a	Appendix F, F-104
NH_3	Solids Content, decaked litter	0.3014	Modest	Appendix F, F-105
H_2S	Solids Content, decaked litter	0.4653	Moderate	Appendix F, F-106
PM_{10}	Solids Content, decaked litter	b	b	b
$PM_{2.5}$	Solids Content, decaked litter	b	b	b
TSP	Solids Content, decaked litter	b	b	b

[a] EPA did not have sufficient measurement data from NAEMS to conduct a linear regression analysis (i.e., two or fewer observations were taken).
[b] No observations were collected that coincided with emissions observations.

For loadout litter samples, there were only limited samples taken over the course of the study. The summary statistics provided in Appendix D, Table D-10, show there were no solids analysis on decaked litter samples at the KY1B sites. Again, the summary tables show the samples were analyzed differently between the sites, as CA1B provided values only on a wet weight basis and the KY1B sites provided both wet and dry weight basis. The time series for TKN (Appendix E, Figures E-30 and E-31) and solids content (Appendix E, Figure E-30) reiterate the sparse nature of the measurements, which makes it difficult to discern any trends. The figures show that measurements are similar across the sites. The regression analysis for TKN (Appendix F, Figures F-107 through F-110) and solids content (Appendix F, Figures F-111 and F-112), summarized in Table 4-9, show modest linear relationships with NH_3 and H_2S emissions. For PM_{10}, $PM_{2.5}$ and TSP, none of the decaked litter samples coincided with emissions observations.

Table 4-9. Loadout litter parameters regression analysis.

Pollutant	Parameter	R^2	Strength	Figure
NH_3	TKN, loadout litter (wet weight basis)	0.3979	Modest	Appendix F, F-107
H_2S	TKN, loadout litter (wet weight basis)	0.3621	Modest	Appendix F, F-108
PM_{10}	TKN, loadout litter (wet weight basis)	b	b	b
$PM_{2.5}$	TKN, loadout litter (wet weight basis)	b	b	b
TSP	TKN, loadout litter (wet weight basis)	b	b	b

Pollutant	Parameter	R^2	Strength	Figure
NH_3	TKN content, loadout litter (dry weight basis)	a		Appendix F, F-109
H_2S	TKN content, loadout litter (dry weight basis)	a		Appendix F, F-110
PM_{10}	TKN content, loadout litter (dry weight basis)	b	b	b
$PM_{2.5}$	TKN content, loadout litter (dry weight basis)	b	b	b
TSP	TKN content, loadout litter (dry weight basis)	b	b	b
NH_3	Solids content, loadout litter	0.3348	Modest	Appendix F, F-111
H_2S	Solids content, loadout litter	0.0454	Slight or weak	Appendix F, F-112
PM_{10}	Solids content, loadout litter	b	b	b
$PM_{2.5}$	Solids content, loadout litter	b	b	b
TSP	Solids content, loadout litter	b	b	b

[a] EPA did not have sufficient measurement data from NAEMS to conduct a linear regression analysis (i.e., two or fewer observations were taken).
[b] No observations were collected that coincided with emissions observations.

4.4 Parameter selection

The exploratory data analysis was conducted to confirm that the variables were selected based on the following criteria: (1) data analysis in this study and/or literature suggested that these variables had an influence on emissions; (2) the variables should be easy to measure; and (3) the variables were already in the daily average NAEMS data and were available for most days of monitored emissions. These selection criteria particularly apply to the manure parameters, such as moisture content and TAN concentration, which were infrequent due to the intensive collection and analysis methods. Additional time could be taken to develop an appropriate methodology for interpolating between the few data points available for these parameters in the dataset. However, these parameters are difficult to acquire as they require chemical analysis from a laboratory. The exploratory data analysis was also used to explore whether additional parameters, such as bird age, could be included to explain trends.

Based on both the literature review (Section 3) and exploratory data analysis in this section, the EPA selected ambient temperature, exhaust temperature, ambient relative humidity, exhaust relative humidity, management phase, litter age and status, bird age, inventory, and LAW as parameters to consider for emissions model development.

5.0 DEVELOPMENT AND SELECTION OF MODELS FOR DAILY EMISSIONS

Based on the literature review (Section 3) and exploratory data analysis (Section 4) EPA selected ambient temperature, exhaust temperature, ambient relative humidity, exhaust relative humidity, management phase, litter age and status, bird age, inventory, and LAW in the development of the emissions models for broiler houses. The 26 combinations of these parameters were used as test models, which are listed in Table 5-1.

Models 19 through 26 are slightly different due to the inclusion of a categorical variable to account for either the management phase or the number of flocks raised on the litter. These models do have merit, as both the management phase and the number of flocks raised on the litter will affect emissions. However, EPA is still considering these models as experimental since an appropriate methodology for their evaluation and application has not been finalized. The models have been included in the tables to note all the options EPA explored, but were not considered as potential models at this time.

The final PM_{10}, $PM_{2.5}$, and TSP models are not based on log transformed emissions data like with the gaseous pollutant or other animal types. During the model development, it was found that better model performance was achieved with non-transformed data. Only the results for the non-transformed PM models are presented in this report. Section 8 will provide an example calculation for PM to show how these calculations differ from the gaseous pollutant that use transformed data.

Table 5-1. Parameter combinations evaluated as models for NH_3 and H_2S emissions.

Model	Parameter
1	Intercept, Inventory, Flock age
2	Intercept, Inventory, Flock age, Ambient temperature
3	Intercept, Inventory, Flock age, Ambient relative humidity
4	Intercept, Inventory, Flock age, Exhaust temperature
5	Intercept, Inventory, Flock age, Exhaust humidity
6	Intercept, Inventory, Flock age, Ambient temperature, Ambient relative humidity
7	Intercept, Inventory, Flock age, Exhaust temperature, Exhaust relative humidity
8	Intercept, Inventory, Flock age, Litter age
9	Intercept, Inventory, Flock age, Litter age, Ambient temperature
10	Intercept, LAW
11	Intercept, LAW, Ambient temperature
12	Intercept, LAW, Ambient relative humidity
13	Intercept, LAW, Exhaust temperature
14	Intercept, LAW, Exhaust humidity

Model	Parameter
15	Intercept, LAW, Ambient temperature, Ambient relative humidity
16	Intercept, LAW, Exhaust temperature, Exhaust relative humidity
17	Intercept, LAW, Litter age
18	Intercept, LAW, Litter age, Ambient temperature
19*	Intercept, Inventory, Flock age, Ambient temperature, Ambient relative humidity, House status (Empty (E), Full (F), Transition (T))
20*	Intercept, LAW, Ambient temperature, Ambient relative humidity, House status (Empty (E), Full (F), Transition (T))
21*	Intercept, Inventory, Flock age, Ambient temperature, Ambient relative humidity, Litter status (0-3, continuous between flocks)
22*	Intercept, LAW, Ambient temperature, Ambient relative humidity, Litter status (0-3, continuous between flocks)
23*	Intercept, Inventory, Flock age, Ambient temperature, Ambient relative humidity, Litter status (0-6, continuous between flocks)
24*	Intercept, LAW, Ambient temperature, Ambient relative humidity, Litter status (0-6, continuous between flocks)
25*	Intercept, Inventory, Flock age, Ambient temperature, Ambient relative humidity, Litter status (0-1, continuous between flocks)
26*	Intercept, LAW, Ambient temperature, Ambient relative humidity, Litter status (0-1, continuous between flocks)

Of the models evaluated for NH_3 (Appendix G, Table G-2), models 1 through 8, 14, 17, and 18 had terms that were not statistically significant ($p > 0.05$) and were removed from further consideration. The model fit (-2 log likelihood, AIC, AICc, and BIC) and evaluation statistics (ME, NME, MB, NMB) for NH_3 (Appendix G, Table G-3) indicate the remaining models had comparable performance, which suggested using ambient parameters was as effective as house parameters. The model performance plots (Appendix G, Figures G-1 through G-3) also indicated nominal performance differences between the remaining models. Therefore, EPA considered the potential ease of data collection and concluded that a model using ambient temperature and relative humidity would be preferable to one with exhaust temperature and relative humidity and eliminated models with the barn specific parameters. EPA also wanted to include temperature in the model to account for regional emissions variability due to climate. EPA also verified the relationship indicated by the coefficients (i.e., negative, or positive relationship with emissions) were consistent with literature. Of the remaining models that used ambient temperature (9, 11, and 15), EPA selected model 15 for further analysis for NH_3 as it had marginally lower error than the remaining models. The final form of these models is presented in Table 5-2.

For H_2S (Appendix G, Table G-4), only models 17 and 18 had terms that were not statistically significant ($p > 0.05$) and were removed from further consideration. The model fit (-2 log likelihood, AIC, AICc, and BIC) and evaluation statistics (ME, NME, MB, NMB) for H_2S (Appendix G, Table G-5) indicate the remaining models had comparable performance, which suggested using ambient parameters was as effective as house parameters. The model performance plots (Appendix G, Figures G-4 through G-6) also indicated nominal performance differences between the remaining models. After a review of the consistency of the model relationships compared to literature, EPA considered the potential ease of data collection and concluded that a model using ambient temperature and relative humidity would be preferable to one with exhaust temperature and relative humidity. As with NH_3, EPA wanted to include temperature in the H_2S model to account for regional emissions variability due to climate. Of the remaining models that used ambient parameters (2, 6, 9, 11, and 15), EPA selected model 15 for further analysis for H_2S as it had marginally lower error than the remaining models. The final form of these models is presented in Table 5-2.

For PM_{10} (Appendix G, Table G-6), models 5, 10, 11, 12, 13, 14, and 15 were comprised entirely of terms that were statistically significant and moved forward for further consideration. The model fit and evaluation statistics for PM_{10} (Appendix G, Table G-7) indicate the remaining models were comparable, which suggested using ambient parameters was as effective as house parameters. The model performance plots (Appendix G, Figures G-7 through G-9) also indicated nominal performance differences between the remaining models. After a review of the consistency of the model relationships compared to literature, EPA considered the potential ease of data collection and concluded that ambient temperature and relative humidity would be preferable to one with exhaust temperature and relative humidity and eliminated models with the barn specific parameters. Of the remaining models that used ambient parameters (12 and 15), EPA selected model 15 for further analysis as it had marginally better fit statistics than model 12. The full form of the model is presented in Table 5-2.

As noted in Section 6.4 of the Overview Report, the PM model selection starts with the PM_{10} due to the greater quantity of emissions data. Because of the continuous monitoring of $PM_{2.5}$ and TSP at the KY1B-1 and KY1B-2 sites, the number of daily emissions values is much greater than for other animal types in NAEMS. The PM_{10} models had between 1,296 and 1,334 daily ADM values for model development, depending on the completeness of the various predictive parameters. For $PM_{2.5}$ and TSP, the number of daily predicted values ranged between 681 – 683 for $PM_{2.5}$ and 688 – 692 for TSP. For broilers, there is more $PM_{2.5}$ and TSP observations than the other animal types. This increase means that the $PM_{2.5}$ and TSP observations cover a wide range of conditions, similar to the PM_{10} data. The consistency in broiler $PM_{2.5}$ and TSP model results, in comparison with the PM_{10} model results, support the approach used for model selection for other animal types, where PM_{10} model selection was used in determining TSP and $PM_{2.5}$ model selection.

Even with the increased data for $PM_{2.5}$ and TSP, the model's consistency with the PM_{10} results, build confidence in supported using the same model form for all the PM species.

For $PM_{2.5}$ (Appendix G, Table G-8), only four models were comprised of significant parameters (11, 12, 14, 15) and moved forward for further consideration. These models were also considered for PM_{10}, and the relationships were consistent with the PM_{10} models and literature. The model performance statistics for $PM_{2.5}$ (Appendix G, Table G-9) suggested comparable performance between ambient and house parameters. The model performance plots (Appendix G, Figures G-10 through G-12) also indicated nominal performance differences between the remaining models. Again, EPA considered the ease of data collection and focused on the remaining models that utilized ambient parameters, and verified the relationship indicated by the coefficient was consistent with literature. Of the remaining models (11, 12, and 15), EPA selected model 15 for further analysis as it had marginally better fit statistics and was consistent with the model selected for PM_{10}. The full form of the model is presented in Table 5-2.

TSP (Appendix G, Table G-10) has six significant models (10, 11, 12, 13, 14, and 15). Again, these were similar to the set of models considered for PM_{10}. The relationships in the TSP models were consistent with the PM_{10} models and literature, except the intercept in model 11 was positive for TSP. Overall, the model statistics for TSP (Appendix G, Table G-11) suggested comparable performance between ambient and house parameters. The model performance plots (Appendix G, Figures G-13 through G-15) also indicated nominal performance differences between the remaining models. Again, EPA considered the ease of data collection and focused on the remaining models that utilized ambient parameters. Of the remaining models (11, 12, and 15), EPA selected model 15 for further analysis as it had marginally better fit statistics and was consistent with the model selected for PM_{10}. The full form of the model is presented in Table 5-2.

Table 5-2. Selected daily models for broiler houses.

Pollutant	Formula	Equation Number
NH_3	$ln(NH_3) = 1.60581 + 0.008532 * LAW + 0.020739 * Amb_T + 0.004038 * Amb_{RH}$	Equation 1
H_2S	$ln(H_2S) = 2.824278 + 0.016214 * LAW + 0.015048 * Amb_T + 0.004429 * Amb_{RH}$	Equation 2
PM_{10}	$PM_{10} = 397.28057 + 40.872002 * LAW + 10.401892 * Amb_T - 6.584463 * Amb_{RH}$	Equation 3
$PM_{2.5}$	$PM_{2.5} = 15.776704 + 4.087002 * LAW + 1.308433 * Amb_T - 0.464143 * Amb_{RH}$	Equation 4
TSP	$TSP = 1518.9199 + 85.598315 * LAW + 22.632906 * Amb_T - 21.28833 * Amb_{RH}$	Equation 5

6.0 MODEL COEFFICENT EVALUATION

To ensure reliable prediction of the emissions, the model coefficients were evaluated with the jackknife method (Christensen et al., 2016; Leeden et al., 2008), which examined the cumulative effect on coefficient estimates of multiple “minus-one” runs. The jackknife approach called for removing one of the independent sample units from the dataset. For NAEMS, the individual barns at each site and the monitored lagoons are the mutually exclusive independent sample units. EPA then determined the associated parameter estimates for the selected model based on this dataset. This was repeated for each of the sample units. These results were then compared to the model coefficients based on the full dataset (full model). For each jackknife model, the ME, NME, MB, and NMB were calculated, based on the equations outlined in Section 6 of the Overview Report, to facilitate comparison.

EPA also prepared plots showing the variation in coefficients and standard errors for the selected model and compared them to each of the jackknife models. EPA interpreted these plots similar to the Tukey confidence interval plots in that, if the result for the jackknife model overlapped the results for the full model (i.e., the area highlighted in gray on the figures), then the model coefficients are not inconsistent with one another. If the omission of one monitoring unit (e.g., a barn or lagoon) resulted in a coefficient that was outside ± 1 standard error of the full model, the sample unit was reviewed to determine if a specific characteristic of that unit (e.g., animal placement strategy, manure handling system) might have caused the inconsistency. If the difference could not be ascribed to an operational characteristic of the unit, the data were reviewed for outliers that could be trimmed, and other potential remediation measures considered.

6.1 NH_3 Model Evaluation

Table 6-1 and Figure 6-1 show the variation in coefficients and standard errors for the selected model (“None”) and each of the jackknife models. The model coefficients from the jackknife approach were comparable across the withheld sets (Table 6-1) and remained significant across all models. The plots in Figure 6-1 show that the results for all jackknife models overlap the full model estimate ± 1 standard error. In comparison to the full model, that is where the house removed is “None”, the maximum percentage differences for parameter estimates across the three models were 7%, 6%, 4%, and 13% for intercept, inventory, ambient temperature, and ambient relative humidity, respectively. Across all models, the difference in NME and NMB (Table 6-2) in comparison to the selected model were minor, with NME values differing by less than 6.20% and NMB by less than 0.81%.

Table 6-1. Model coefficients developed using the jackknife approach for NH_3 emissions from broiler houses.

House Out	Effect	Estimate	Standard Error	p-value
None	Intercept	1.60581	0.10407	<.0001
None	LAW	0.008532	0.00094	<.0001
None	Ambient temperature	0.020739	0.0024	<.0001
None	Ambient relative humidity	0.004038	0.00081	<.0001
CA1B H10	Intercept	1.663708	0.10922	<.0001
CA1B H10	LAW	0.008131	0.00113	<.0001
CA1B H10	Ambient temperature	0.020722	0.00268	<.0001
CA1B H10	Ambient relative humidity	0.003718	0.00092	<.0001
CA1B H12	Intercept	1.662263	0.10958	<.0001
CA1B H12	LAW	0.008731	0.00114	<.0001
CA1B H12	Ambient temperature	0.019854	0.00272	<.0001
CA1B H12	Ambient relative humidity	0.003844	0.00093	<.0001
KY1B-1 H5	Intercept	1.498738	0.14664	<.0001
KY1B-1 H5	LAW	0.008223	0.00105	<.0001
KY1B-1 H5	Ambient temperature	0.021704	0.00297	<.0001
KY1B-1 H5	Ambient relative humidity	0.004087	0.00099	<.0001
KY1B-2 H3	Intercept	1.543183	0.12071	<.0001
KY1B-2 H3	LAW	0.009042	0.00105	<.0001
KY1B-2 H3	Ambient temperature	0.020961	0.00277	<.0001
KY1B-2 H3	Ambient relative humidity	0.004549	0.00093	<.0001

Table 6-2. Model fit statistics for the broiler house NH_3 jackknife.

House Out	n	LNME[a] (%)	NME[b] (%)	ME[b] ($kg\ d^{-1}$)	MB[b] ($kg\ d^{-1}$)	NMB[b] (%)	Corr.
None	1602	26.067	56.78	5.984	-0.599	-5.681	0.662
CA1B H10	1157	24.948	54.351	5.89	-0.555	-5.123	0.654
CA1B H12	1159	24.267	52.335	5.91	-0.587	-5.199	0.664
KY1B-1 H5	1224	28.902	62.982	6.328	-0.652	-6.493	0.672
KY1B-2 H3	1266	25.816	57.057	5.736	-0.583	-5.799	0.658

[a] Based on transformed data (i.e., $\ln(NH_3)$).
[b] Based on back-transformed data.

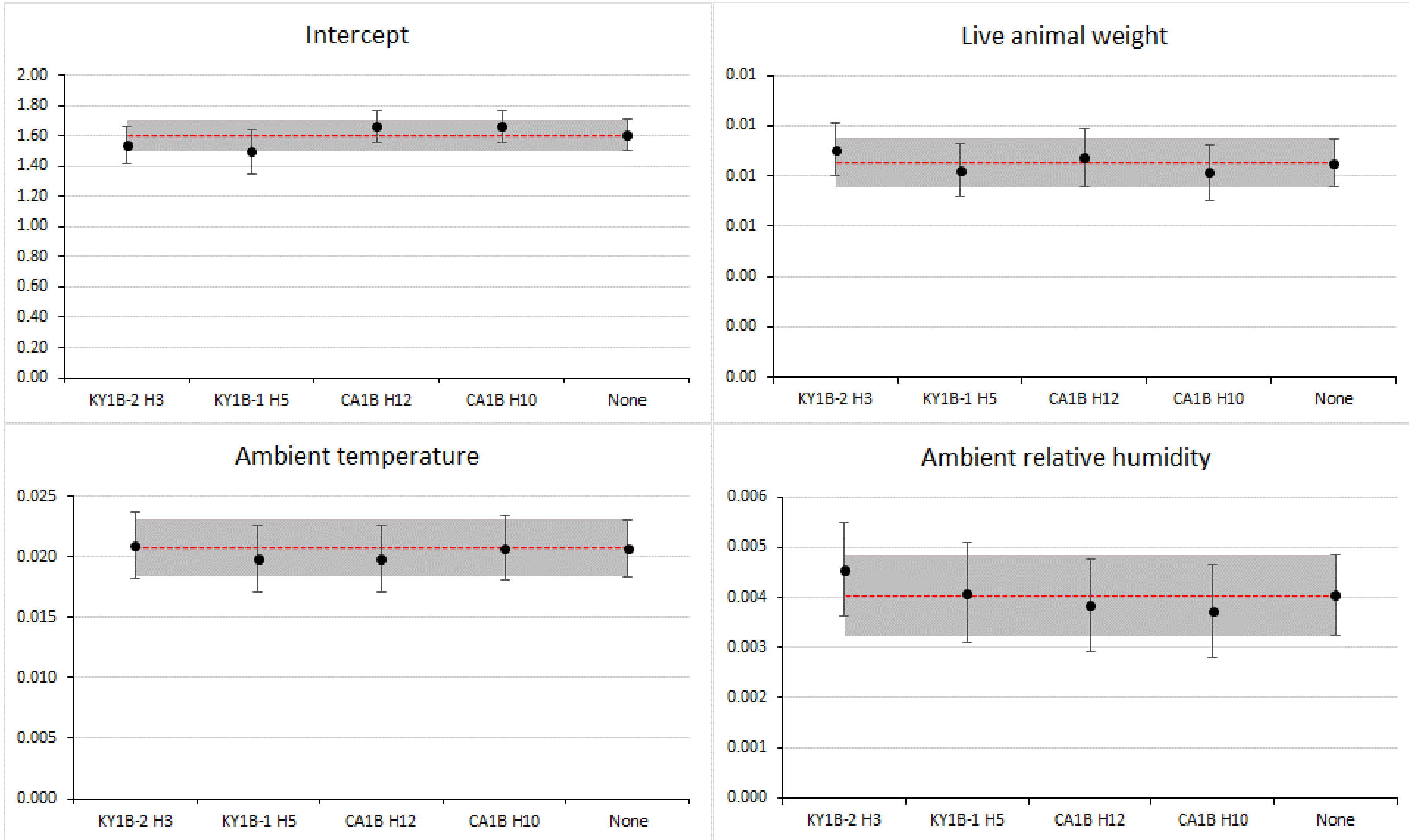

Figure 6-1. Comparison of variation in coefficients and standard errors for NH_3 broiler house model.
Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected TSP belted battery house model coefficient ("None", gray band for ± SE) for each model parameter.

6.2 H_2S Model Evaluation

Table 6-3 and Figure 6-2 show the variation in coefficients and standard errors for the selected model ("None") and each of the jackknife models. The model coefficients from the jackknife approach were comparable across the withheld sets (Table 6-3) and remained significant across all models. The plots in Figure 6-2 show that the results for all jackknife models overlap the full model estimate ± 1 standard error, except for ambient temperature at KY1B-2 H3. In comparison to the full model, that is where the house removed is "None", the maximum percentage differences for parameter estimates across the three models were 4%, 5%, 28%, and 13% for intercept, inventory, ambient temperature, and ambient relative humidity, respectively. Across all models, the difference in NME and NMB (Table 6-4) in comparison to the selected model were minor, with NME values differing by less than 5.41% and NMB by less than 0.32%.

Table 6-3. Model coefficients developed using the jackknife approach for H_2S emissions from broiler houses.

House Out	Effect	Estimate	Standard Error	p-value
None	Intercept	2.824278	0.10483	<.0001
None	LAW	0.016214	0.0008	<.0001
None	Ambient temperature	0.015048	0.00189	<.0001
None	Ambient relative humidity	0.004429	0.00063	<.0001
CA1B H10	Intercept	2.829714	0.09394	<.0001
CA1B H10	LAW	0.017087	0.00095	<.0001
CA1B H10	Ambient temperature	0.012804	0.00206	<.0001
CA1B H10	Ambient relative humidity	0.004492	0.00069	<.0001
CA1B H12	Intercept	2.887174	0.08908	<.0001
CA1B H12	LAW	0.015657	0.00096	<.0001
CA1B H12	Ambient temperature	0.012718	0.00211	<.0001
CA1B H12	Ambient relative humidity	0.004257	0.00071	<.0001
KY1B-1 H5	Intercept	2.828938	0.13856	<.0001
KY1B-1 H5	LAW	0.01539	0.00089	<.0001
KY1B-1 H5	Ambient temperature	0.015985	0.00238	<.0001
KY1B-1 H5	Ambient relative humidity	0.004112	0.00079	<.0001
KY1B-2 H3	Intercept	2.723739	0.12561	<.0001
KY1B-2 H3	LAW	0.016739	0.0009	<.0001
KY1B-2 H3	Ambient temperature	0.019268	0.00219	<.0001
KY1B-2 H3	Ambient relative humidity	0.004991	0.00072	<.0001

Table 6-4. Model fit statistics for the broiler house H_2S jackknife.

House Out	n	LNME[a] (%)	NME[b] (%)	ME[b] ($g\ d^{-1}$)	MB[b] ($g\ d^{-1}$)	NMB[b] (%)	Corr.
None	1757	16.921	56.995	29.307	-7.107	-13.82	0.814
CA1B H10	1193	15.882	54.29	27.444	-7.245	-14.33	0.82
CA1B H12	1197	16.329	55.164	28.536	-6.93	-13.4	0.812
KY1B-1 H5	1415	18.295	59.699	31.234	-7.133	-13.63	0.815
KY1B-2 H3	1466	16.967	58.133	29.653	-7.068	-13.86	0.817

[a] Based on transformed data (i.e., $\ln(NH_3)$).
[b] Based on back-transformed data.

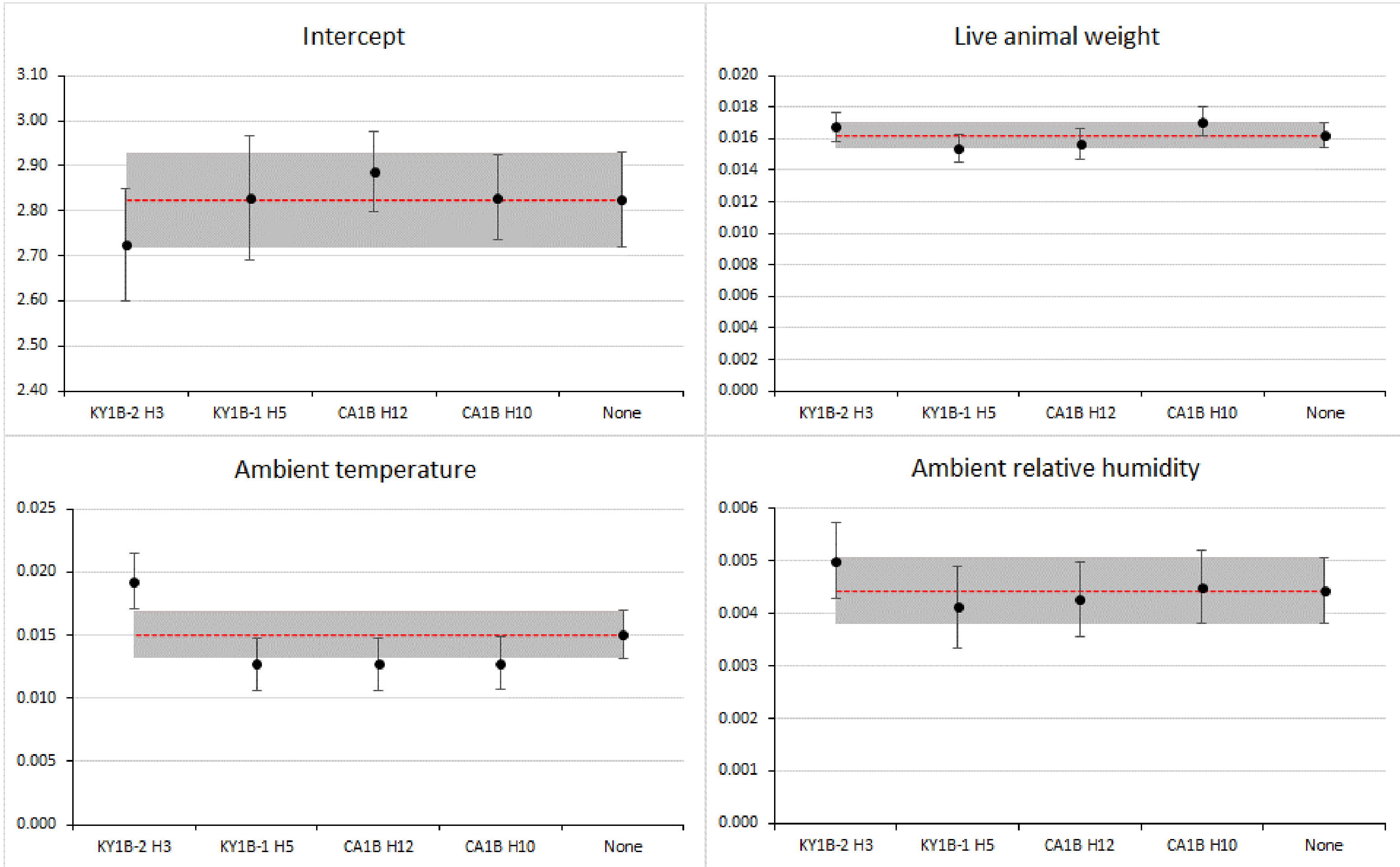

Figure 6-2. Comparison of variation in coefficients and standard errors for H_2S broiler house model.
Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected TSP belted battery house model coefficient (“None”, gray band for ± SE) for each model parameter.

6.3 PM_{10} Model Evaluation

Table 6-5 and Figure 6-3 show the variation in coefficients and standard errors for the selected model ("None") and each of the jackknife models. The model coefficients from the jackknife approach were comparable across the withheld sets (Table 6-5) and remained significant across all models. The plots in Figure 6-3 show that the results for all jackknife models overlap the full model estimate ± 1 standard error. In comparison to the full model, that is where the house removed is "None", the maximum percentage differences for parameter estimates across the three models were 21%, 4%, 34%, and 26% for intercept, inventory, ambient temperature, and ambient relative humidity, respectively. Across all models, the difference in NME and NMB (Table 6-6) in comparison to the selected model were minor, with NME values differing by less than 0.90% and NMB by less than 0.59%.

Table 6-5. Model coefficients developed using the jackknife approach for PM_{10} emissions from broiler houses.

House Out	Effect	Estimate	Standard Error	p-value
None	Intercept	397.28057	87.0688	<.0001
None	LAW	40.872002	1.23866	<.0001
None	Ambient temperature	10.401892	2.31348	<.0001
None	Ambient relative humidity	-6.584463	0.99133	<.0001
CA1B H10	Intercept	416.43351	96.5238	<.0001
CA1B H10	LAW	40.560352	1.30848	<.0001
CA1B H10	Ambient temperature	11.933339	2.46947	<.0001
CA1B H10	Ambient relative humidity	-7.181311	1.14528	<.0001
CA1B H12	Intercept	423.44921	99.3889	<.0001
CA1B H12	LAW	40.320695	1.31826	<.0001
CA1B H12	Ambient temperature	11.307166	2.51767	<.0001
CA1B H12	Ambient relative humidity	-7.119333	1.17254	<.0001
KY1B-1 H5	Intercept	315.11649	110.273	0.0044
KY1B-1 H5	LAW	41.28158	1.52787	<.0001
KY1B-1 H5	Ambient temperature	9.677985	2.94704	0.0011
KY1B-1 H5	Ambient relative humidity	-4.859073	1.22256	<.0001
KY1B-2 H3	Intercept	425.79124	97.2686	<.0001
KY1B-2 H3	LAW	42.501116	1.57997	<.0001
KY1B-2 H3	Ambient temperature	6.833973	2.73684	0.0128
KY1B-2 H3	Ambient relative humidity	-6.808038	1.03715	<.0001

Table 6-6. Model fit statistics for the broiler house PM_{10} jackknife.

House Out	n	NME (%)	ME (g d^{-1})	MB (g d^{-1})	NMB (%)	Corr.
None	1298	30.33	280.05	-2.222	-0.241	0.881
CA1B H10	963	29.435	276.74	-4.744	-0.505	0.886
CA1B H12	941	30.089	283.67	-2.064	-0.219	0.886
KY1B-1 H5	997	30.969	286.3	-3.922	-0.424	0.875
KY1B-2 H3	993	31.079	275.82	3.124	0.352	0.873

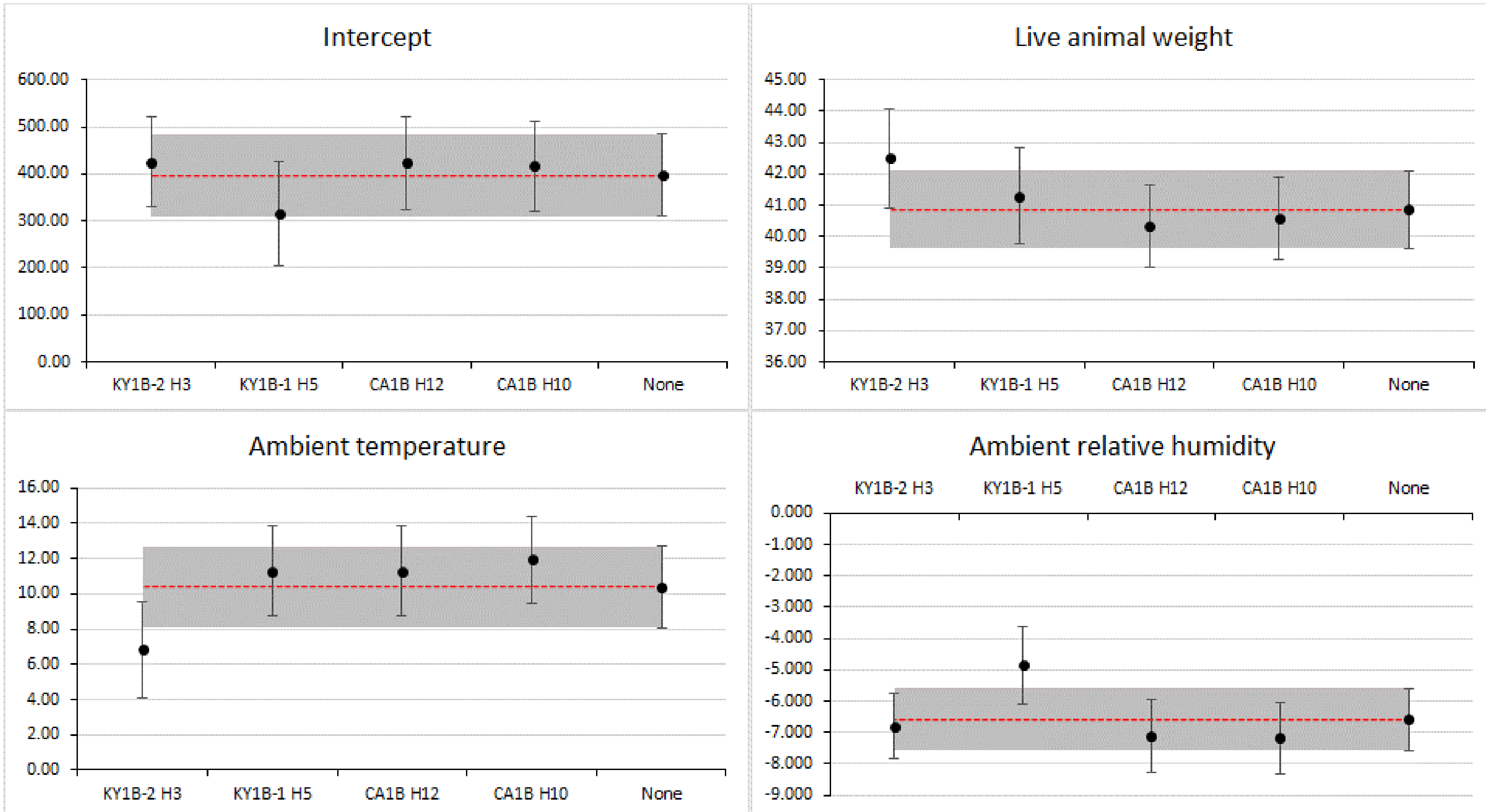

Figure 6-3. Comparison of variation in coefficients and standard errors for PM_{10} broiler house model.

Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected TSP belted battery house model coefficient ("None", gray band for ± SE) for each model parameter.

6.4 $PM_{2.5}$ Model Evaluation

Table 6-7 and Figure 6-4 show the variation in coefficients and standard errors for the selected model ("None") and each of the jackknife models. The model coefficients from the jackknife approach were comparable across the withheld sets (Table 6-7) and remained significant across all models. The plots in Figure 6-4 show that the results for all jackknife models overlap the full model estimate ± 1 standard error, except for ambient temperature at KY1B-2 H3. In comparison to the full model, that is where the house removed is "None", the maximum percentage differences for parameter estimates across the three models were 60%, 4%, 52%, and 25% for intercept, inventory, ambient temperature, and ambient relative humidity, respectively. Across all models, the difference in NME and NMB (Table 6-8) in comparison to the selected model were minor, with NME values differing by less than 3.12% and NMB by less than 4.67%.

Table 6-7. Model coefficients developed using the jackknife approach for $PM_{2.5}$ emissions from broiler houses.

House Out	Effect	Estimate	Standard Error	p-value
None	Intercept	15.776704	9.16964	0.0862
None	LAW	4.087002	0.13779	<.0001
None	Ambient temperature	1.308433	0.23488	<.0001
None	Ambient relative humidity	-0.464143	0.10162	<.0001
CA1B H10	Intercept	14.962259	9.30605	0.1087
CA1B H10	LAW	4.094488	0.13513	<.0001
CA1B H10	Ambient temperature	1.417178	0.23708	<.0001
CA1B H10	Ambient relative humidity	-0.463122	0.10522	<.0001
CA1B H12	Intercept	15.710709	9.26846	0.0909
CA1B H12	LAW	4.114284	0.13705	<.0001
CA1B H12	Ambient temperature	1.318599	0.23673	<.0001
CA1B H12	Ambient relative humidity	-0.463017	0.1044	<.0001
KY1B-1 H5	Intercept	6.333521	11.8668	0.594
KY1B-1 H5	LAW	4.173591	0.14753	<.0001
KY1B-1 H5	Ambient temperature	1.659652	0.27877	<.0001
KY1B-1 H5	Ambient relative humidity	-0.37942	0.13758	0.0061
KY1B-2 H3	Intercept	25.189723	13.5625	0.0653
KY1B-2 H3	LAW	3.911753	0.24801	<.0001
KY1B-2 H3	Ambient temperature	0.62491	0.36119	0.0851
KY1B-2 H3	Ambient relative humidity	-0.578885	0.13371	<.0001

Table 6-8. Model fit statistics for the broiler house $PM_{2.5}$ jackknife.

House Out	n	NME (%)	ME (g d^{-1})	MB (g d^{-1})	NMB (%)	Corr.
None	683	28.989	27.76	6.014	6.28	0.919
CA1B H10	630	28.965	27.663	5.17	5.413	0.923
CA1B H12	640	29.129	27.334	5.215	5.557	0.924
KY1B-1 H5	397	25.872	25.924	7.627	7.612	0.933
KY1B-2 H3	382	30.363	28.782	1.526	1.61	0.888

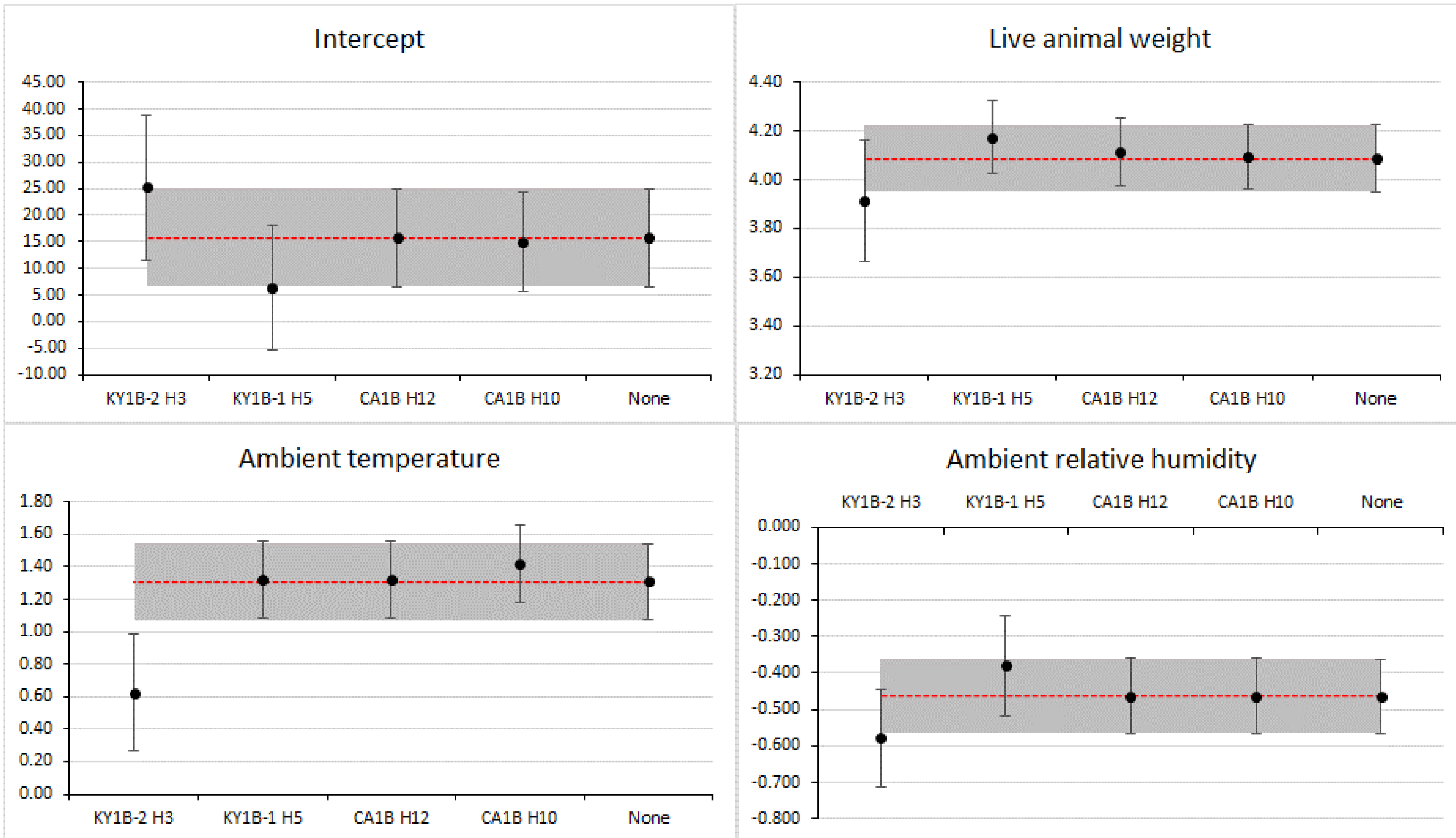

Figure 6-4. Comparison of variation in coefficients and standard errors for $PM_{2.5}$ broiler house model.

Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected TSP belted battery house model coefficient (“None”, gray band for ± SE) for each model parameter.

6.5 TSP Model Evaluation

Table 6-9 and Figure 6-5 show the variation in coefficients and standard errors for the selected model ("None") and each of the jackknife models. The model coefficients from the jackknife approach were comparable across the withheld sets (Table 6-9) and remained significant across all models. The plots in Figure 6-5 show that the results for all jackknife models overlap the full model estimate ± 1 standard error. In comparison to the full model, that is where the house removed is "None", the maximum percentage differences for parameter estimates across the three models were 9%, 6%, 53%, and 9% for intercept, inventory, ambient temperature, and ambient relative humidity, respectively. Across all models, the difference in NME and NMB (Table 6-10) in comparison to the selected model were minor, with NME values differing by less than 2.07% and NMB by less than 1.16%.

Table 6-9. Model coefficients developed using the jackknife approach for TSP emissions from broiler houses.

House Out	Effect	Estimate	Standard Error	p-value
None	Intercept	1,518.9199	267.416	<.0001
None	LAW	85.598315	4.07168	<.0001
None	Ambient temperature	22.632906	6.91714	0.0012
None	Ambient relative humidity	-21.28833	3.03384	<.0001
CA1B H10	Intercept	1,532.9567	277.153	<.0001
CA1B H10	LAW	86.095861	4.1767	<.0001
CA1B H10	Ambient temperature	23.162107	7.14728	0.0014
CA1B H10	Ambient relative humidity	-21.60906	3.16145	<.0001
CA1B H12	Intercept	1,522.2666	277.367	<.0001
CA1B H12	LAW	85.388284	4.14236	<.0001
CA1B H12	Ambient temperature	22.903337	7.11571	0.0015
CA1B H12	Ambient relative humidity	-21.04226	3.16372	<.0001
KY1B-1 H5	Intercept	1,375.9692	378.531	0.0003
KY1B-1 H5	LAW	80.604024	5.92136	<.0001
KY1B-1 H5	Ambient temperature	34.587826	9.62385	0.0004
KY1B-1 H5	Ambient relative humidity	-19.47689	4.1225	<.0001
KY1B-2 H3	Intercept	1,607.4014	331.078	<.0001
KY1B-2 H3	LAW	89.968545	5.1479	<.0001
KY1B-2 H3	Ambient temperature	10.575943	8.82671	0.233
KY1B-2 H3	Ambient relative humidity	-22.82391	3.84822	<.0001

Table 6-10. Model fit statistics for the broiler house TSP jackknife.

House Out	n	NME (%)	ME (g d^{-1})	MB (g d^{-1})	NMB (%)	Corr.
None	688	30.502	701.59	-29.46	-1.281	0.863
CA1B H10	653	30.92	705.63	-29.05	-1.273	0.864
CA1B H12	651	30.341	699.71	-31.29	-1.357	0.864
KY1B-1 H5	373	32.572	785.97	-50.92	-2.11	0.856
KY1B-2 H3	387	29.546	653.52	-2.717	-0.123	0.863

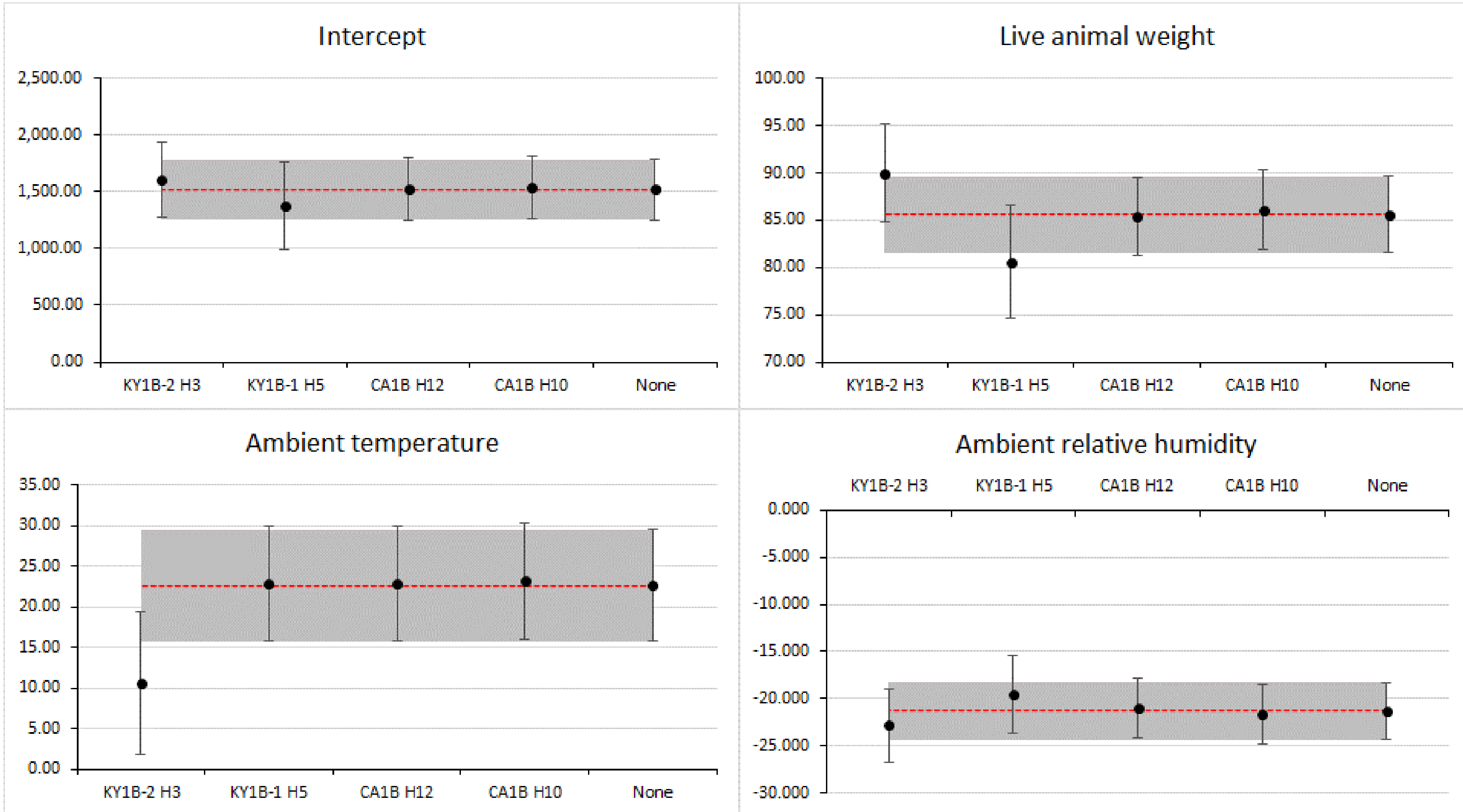

Figure 6-5. Comparison of variation in coefficients and standard errors for TSP broiler house model.

Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected TSP belted battery house model coefficient ("None", gray band for ± SE) for each model parameter

7.0 ANNUAL EMISSIONS ESTIMATES AND MODEL UNCERTAINTY

To estimate annual pollutant emissions, the results of the daily emissions models are summed over the number of operating days per year. This approach requires values for the necessary ambient and barn parameters. For an actual emissions estimate, the daily estimates are based on meteorology from nearby monitors and barn occupancy and weight records from the producer. Since the models were developed using all the available data, producers can specify downtime for cleaning or other reasons with an inventory value of zero. For farms with multiple barns, annual emissions are determined for individual barns and summed to calculate total annual farm-scale emissions.

As noted in Section 6 of the Overview Report, the model results are transformed values of the emissions. To convert to the native emissions units (e.g., kg or g), the back transformation equation (Equation 7 from Section 6 of the Overview Report) is applied using the values of $\overline{E_i}$ and C provided in Table 7-1 for each emissions model. As noted in Section 5, the PM models were developed using data that was not transformed, and do not have to be back transformed. Section 8 contains an example of the back transformation calculation.

Table 7-1. Back transformation parameters.

Animal Type	Pollutant	$\overline{E_i}$	C	Resulting Units
Broiler House	NH_3	1.10605	2	kg
Broiler House	H_2S	1.32433	10	g
Broiler House	PM_{10}	[a]	[a]	g
Broiler House	$PM_{2.5}$	[a]	[a]	g
Broiler House	TSP	[a]	[a]	g

[a] Data used to develop models was not log transformed.

EPA also developed an estimate of uncertainty for total annual emissions, characterized by the random error in the model prediction, based on parametric principles, using the Gaussian error of propagation. Under this approach, the annual standard deviation (S_{an}) for n days can be determined using the following equation:

$$S_{an} = \sqrt{(S_{r1})^2 + (S_{r2})^2 + \ldots (S_{rn})^2} \qquad \text{Equation 6}$$

where S_r is the standard deviation of the daily residual values (i.e., the difference between model-predicted and observed or measured emissions). If S_r is the same value for each day (i.e., $S_{r1} = S_{r2} = S_{rn}$), Equation 6 simplifies to:

$$S_{an} = S_r n^{0.5} \qquad \text{Equation 7}$$

Table 7-2 lists the S_r values for broiler houses by pollutant. Thus, for the broiler house NH_3 EEM with a S_r value of 7.205 kg day^{-1} and an n value of 365, S_{an} is determined as follows:

$S_{an} = 7.205 \times (365^{0.5}) = 39.05$ kg

EPA considered a 95-percent residual distribution (i.e., the range was the difference between the 97.5 and 2.5 percentiles) or equivalently 1.96 standard deviations; therefore, the annual uncertainty (U_{an}) can be approximated as:

$$U_{an} \approx 1.96\, S_{an} \quad \text{Equation 8}$$

Combining Equations 7 and 8 with an n value of 365 (representing the number of days in the annual uncertainty calculation) yields:

$$U_{an} \approx 1.96\, S_{an} \approx 1.96\, S_r n^{0.5} \approx 1.96\, S_r{*}(365)^{0.5} \approx 37.45\, S_r \quad \text{Equation 9}$$

Table 7-2. Daily residual standard deviation values for broiler houses.

Process	Pollutant	S_r	Emissions Units
Broiler House	NH_3	7.205	kg/d
Broiler House	H_2S	36.749	g/d
Broiler House	PM_{10}	414.19	g/d
Broiler House	$PM_{2.5}$	36.073	g/d
Broiler House	TSP	1,304	g/d

To propagate the uncertainty across all sources at a farm, EPA combined the estimates of absolute uncertainty for each source according to:

$$Total\ farm\ uncertainty = \sqrt{(U_{B1})^2 + \cdots + (U_{Bi})^2} \quad \text{Equation 10}$$

Where:

Total farm uncertainty = total uncertainty for the total emissions from all farm sources.
UBi = the resulting uncertainty for barns, with i representing the total number of barns on the farm.

EPA notes that the uncertainty framework described above reflects the random uncertainty (error) in the prediction of daily emissions calculated using the emissions models, which includes the random uncertainty in the measurements used to develop the equation. This framework does not, however, consider systematic error (e.g., bias) in either NAEMS measurements or the emissions model. Section 8 provides example calculations showing how the daily emissions, annual emissions, and annual uncertainty calculations are completed.

8.0 MODEL APPLICATION AND ADDITIONAL TESTING

Key to the development of any model is the demonstration of the use and practical examples of how the model behaves and replicates independent data. This section provides a series of example calculations to demonstrate the application of the models (Section 8.1), the sensitivity of the models to their inputs and possible limitations (Section 8.2), a comparison of the models developed to literature (Section 8.3), and a test of model performance against an independent data set (Section 8.4).

8.1 Model Application Example

The following sections demonstrate how the daily EEMs from Section 5 and the annual uncertainty from Section 7 are used to calculate emissions for an example farm. These example calculations demonstrate how to use the system of equations to estimate emissions.

In Section 6.4 of the Overview Report, the data were log-transformed prior to developing the models, the result would need to be back-transformed using Equation 7 from Section 6 of the Overview Report to represent emissions in units of grams or kilograms.

$$Y_{bp} = e^{\widehat{(y_p)}} * \overline{E_\iota} - C$$

Where:

Y_{bp} is the back-transformed predicted emissions.
y_p is the model predicted (log transformed) emissions.
$\overline{E_i}$ is the average residual between model-predicted and observed (or measured) emissions on the natural log scale.
C is a constant added to the data prior to the log transformation.

To complete the back transformation, users need two parameters that are specific to each model: 1) $\overline{E_\iota}$, the residual between model-predicted and observed (or measured) emissions on the natural log scale; and 2) C, which is a constant added to the data prior to the log transformation. As noted in Sections 5 and 7 of this report, the PM emissions data were not log-transformed for model development. The values for $\overline{E_\iota}$ and C for the NH_3 and H_2S broiler models are provided in Table 8-1.

Table 8-1. Back transformation parameters.

Animal Type	Pollutant	$\bar{E}_i$	C	Resulting Units
Broiler house	NH_3	1.10605	2	kg
Broiler house	H_2S	1.32433	10	g
Broiler house	PM_{10}	[a]	[a]	g
Broiler house	$PM_{2.5}$	[a]	[a]	g
Broiler house	TSP	[a]	[a]	g

[a] Data used to develop models was not log transformed.

For transparency, and to help stakeholders better understand the process of calculating emissions, this section presents example calculations to estimate NH_3 and PM_{10} emissions from a broiler house.

The examples in this section use a fictional farm located in Crow Wing County, Minnesota on January 1, 2020. The ambient weather data used in each equation can be obtained for free from several sources including the National Centers for Environmental Information (NCEI; https://www.ncdc.noaa.gov/cdo-web/). NCEI stores hourly and daily ambient data from various monitors located across the country that can be used for emissions estimation. The Brainerd Crow Wing County Airport site (GHCND:USW00094938) is a Global Historical Climatology Network (GHCN) Station located in Crow Wing County and its data file provides the values of the key meteorological parameters needed for calculations.

Additionally, the broiler model requires the LAW, which is the number of birds in the house multiplied by the average weight. For this fictious farm, an initial placement of 25,000 chicks are added to the house and have an average weight of 0.087 kg. The equations use thousands of birds, so this value will be divided by 1,000 for use in the emissions models. A summary of the input values for the example calculations for January 1, 2020, is provided in Table 8-2.

Table 8-2. Daily calculation parameter values for January 1, 2020.

Parameter	Value
Daily Average Ambient Temperature (°C)	-5.3
Daily Average Relative Humidity (%)	76
Inventory (birds)	25,000
Average bird weight (kg)	0.087
LAW (Mg)	2.16

8.1.1 NH_3 Example

Referring back to Equation 1 in Section 5, the log transformed values are calculated as follows:

$$ln(NH_3) = 1.60581 + 0.008532 * LAW + 0.020739 * Amb_T + 0.004038 * Amb_{RH}$$

$$ln(NH_3) = 1.60581 + 0.008532 * 2.16 + 0.020739 * -5.3 + 0.004038 * 76$$

$$\ln(NH_3) = 1.60581 + 0.018429 - 0.109917 + 0.306888$$

$$\ln(NH_3) = 1.82121$$

To back transform the results to NH_3 in kg, use Equation 7, from the Overview Report. For a broiler house, $\overline{E_\iota}$ is 1.106051 and C is 2.

$$NH_3 = e^{1.82121} \times 1.10605 - 2$$

This comes to 4.83 kg NH_3 for the day. This process is repeated for each day, using the daily values for the ambient parameters and daily average bird weight, which changes during the growing cycle. The individual daily emissions are added together to get an annual estimate of emissions. After considering the values for each day in 2020, the total annual emissions for the barn were calculated at 3,254.58 kg. To calculate the uncertainty associated with this estimate, use Equation 9 with the S_r value from Table 7-2. This results in an annual uncertainty of ± 269.83 kg. Thus, the final annual estimate for this barn is 3,254.58 kg ± 269.83 kg. This calculation would be repeated for any other broiler barns on the site.

8.1.2 PM_{10} Example

Referring back to Equation 3 in Section 5, the log transformed NH_3 emissions values for a broiler house is calculated as follows:

$$PM_{10} = 397.28057 + 40.872002 * LAW + 10.401892 * Amb_T - 6.584463 * Amb_{RH}$$

$$PM_{10} = 397.28057 + 40.872002 * 2.16 + 10.401892 * -5.3 - 6.584463 * 76$$

$$PM_{10} = 397.28057 + 88.283524 - 55.130028 - 500.419188$$

$$PM_{10} = -69.99\ g$$

With no back transformation necessary, the total PM_{10} emissions for the data come to -69.99 g for the day. This example demonstrates that the PM_{10} equation produces negative emissions estimates for low LAWs at low temperatures and high relative humidities. The limitations of the broiler equations are discussed further in section 8.2.1. This emissions calculation process is repeated for each day, then the daily emissions are added together to get an annual estimate of emissions. After considering the values for each day in 2020, the total annual emissions for the barn were calculated at 386.93 kg. This total does leave any negative emissions results as a negative value, as there were negative emissions values in the model development dataset.

To calculate the uncertainty associated with this estimate, use Equation 9 with an S_r value of 414.19 from Table 7-2 This results in an annual uncertainty of ± 15,511 g or ± 15.51 kg. Thus, the final annual estimate for this barn is 386.93 ± 15.51 kg. This calculation would be repeated for any other broiler barns on the site.

8.1.3 Combining Structures

To calculate total farm emissions, the emissions from each unit are added. As an example, consider a farm with two houses with a capacity of 25,000 broilers each. These houses will have the same emissions estimate for the year, 3,254.58 kg ± 1,844.90 kg. The annual farm emissions estimate is:

$$Farm\ Total\ Emissions = 3{,}254.58 + 3{,}254.58 = 6{,}509.16\ kg\ NH_3$$

To estimate the total farm uncertainty, use Equation 10:

$$Total\ Farm\ Uncertainty = \sqrt{{U_{house\ 1}}^2 + {U_{house\ 2}}^2}$$

$$Total\ Farm\ Uncertainty = \sqrt{(269.83\ )^2 + (269.83)^2}$$

$$Total\ Farm\ Uncertainty = 381.6\ \text{kg}$$

The final annual NH_3 estimate for the farm is 6,509.16 ± 381.6 kg.

8.2 Model Sensitivity Testing

To further test the models, EPA varied the model parameters to ensure the model results would vary based on these key parameters. Two different tests were conducted: 1) bird placement was increased while the meteorological parameters were held constant, and 2) bird placement was held constant while the meteorological parameters were replaced with the values for a warmer climate.

8.2.1 Sensitivity to Inventory

To test the sensitivity to the bird population, the initial placement was increased to 40,000 birds, resulting in a LAW of 3.46. Using the same meteorology from Section 8.1, the emissions for a broiler house on January 1, 2020, is as follows:

$$ln(NH_3) = 1.60581 + 0.008532 * LAW + 0.020739 * Amb_T + 0.004038 * Amb_{RH}$$

$$ln(NH_3) = 1.60581 + 0.008532 * 3.46 + 0.020739 * -5.3 + 0.004038 * 76$$

$$\ln(NH_3) = 1.60581 + 0.029521 - 0.109917 + 0.306888$$

$$\ln(NH_3) = 1.83230$$

$$NH_3 = e^{1.83230} \times 1.10605 - 2$$

This comes to 4.91 kg NH_3 for the day. This is only 0.08 kg more than a barn with a bird population of 25,000 broiler chicks for the same day. While the individual day difference at a low LAW is minimal, over a year the house with 40,000 birds is estimated to produce 3,942 kg of NH_3 compared to the 3,254.58 kg at the 25,000 head house. This annual difference of 687 kg suggests there is some model sensitivity to the number of animals in the barn. A plot of the estimated emissions over the year (Figure 8-1) shows a greater difference in emissions at the end of the growing cycle, particularly during the summer months.

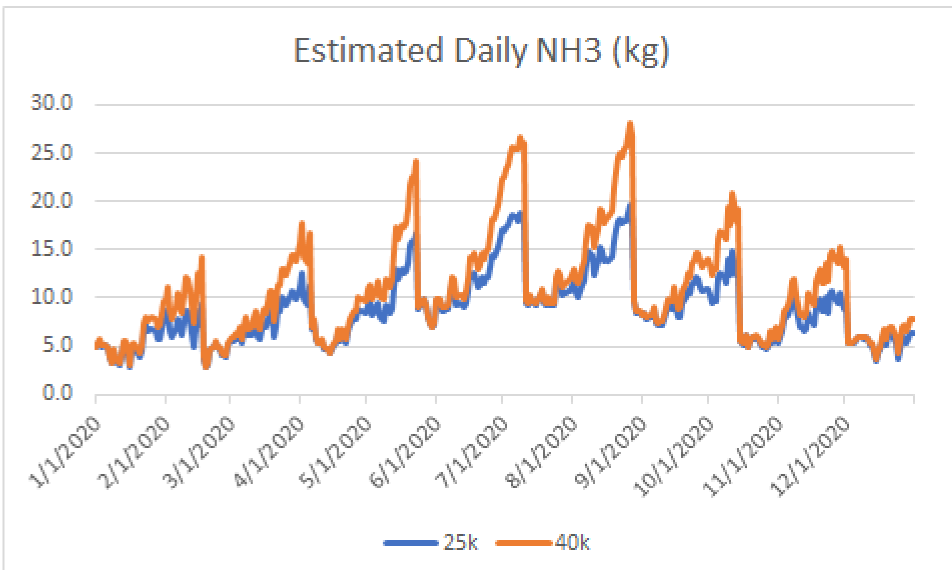

Figure 8-1. Comparison of a broiler house with initial placement of 25,000 birds and 40,000 birds.

8.2.2 Sensitivity to climate

To further test model sensitivity, specifically that climate differences were producing different emissions results, EPA calculated the emissions for the same farm in two distinctly different climate regions. The first was the theoretical farm in central Minnesota from the previous example (Section 8.1). The NH_3 emissions for this same broiler barn were calculated using meteorology from Atascosa, Texas. These locations were chosen based on 2017 Census of Agriculture data indicating areas of broiler markets (Figure 8-2).

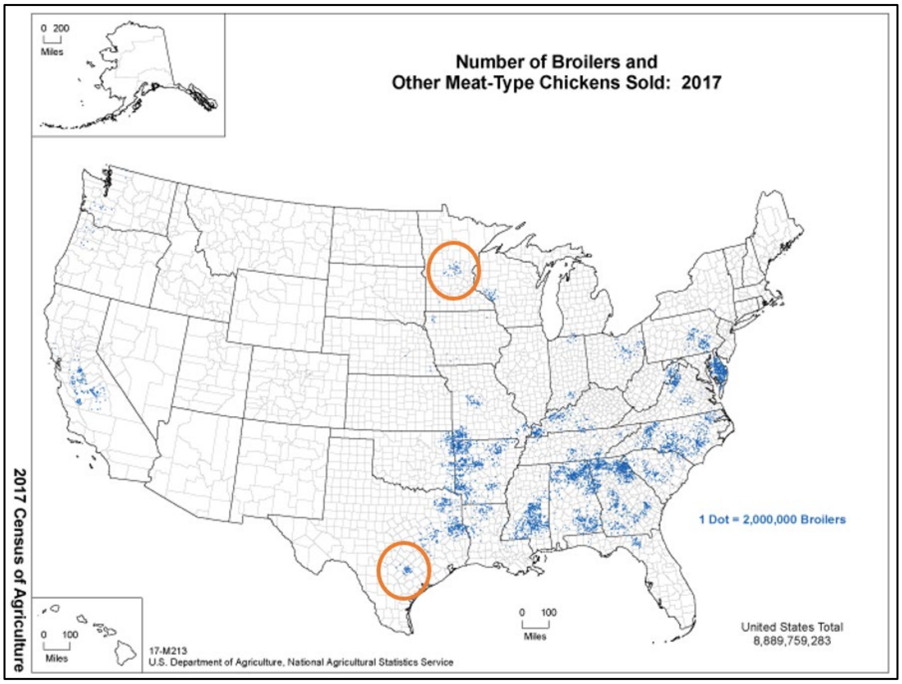

Figure 8-2. 2017 Census of Agriculture plot indicating areas of broiler sales.
Orange circles indicate approximate locations of test meteorology from Minnesota (MN) and Texas (TX).

For the test sites, the temperatures from the Minnesota (MN) site were generally less than the Texas (TX) site (Figure 8-3). On average, the temperatures in Minnesota were 15 °C less than those in Texas (Table 8-3), with difference between individual month averages varying from 4.6 to 19.7 °C lower. With respect to relative humidity, the Texas and Minnesota sites experienced a similar range of daily average relative humidities throughout the year (Figure 8-4and Table 8-4). There are a few instances in the January to March timeframe where humidities were higher in Texas.

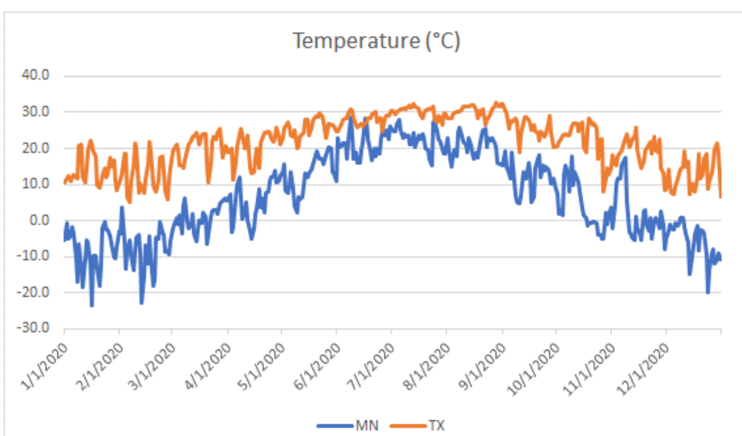

Figure 8-3. Comparison of temperatures at test locations in Minnesota (MN) and Texas (TX).

Table 8-3. Summary of temperature at the two meteorological sites.

Site	Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Overall
MN	Min	-23.5	-22.9	-6.4	-4.9	2.4	15.9	15.4	15.0	4.9	-5.1	-7.8	-20.1	-23.5
MN	Max	-0.3	3.5	6.1	13.9	20.4	28.8	28.1	25.9	19.4	18.0	17.6	0.8	28.8
MN	Average	-8.2	-8.3	0.7	5.5	12.9	21.4	22.7	20.5	12.4	4.0	1.7	-5.9	6.7
TX	Min	8.3	5.3	10.5	11.3	20.1	24.6	26.5	26.4	19.0	8.2	8.4	6.5	5.3
TX	Max	22.3	21.9	25.5	25.9	30.0	31.0	32.4	32.8	32.3	28.3	25.8	21.4	32.8
TX	Average	14.0	12.8	20.4	20.6	25.7	27.9	30.2	30.4	26.0	22.3	19.1	12.9	21.9

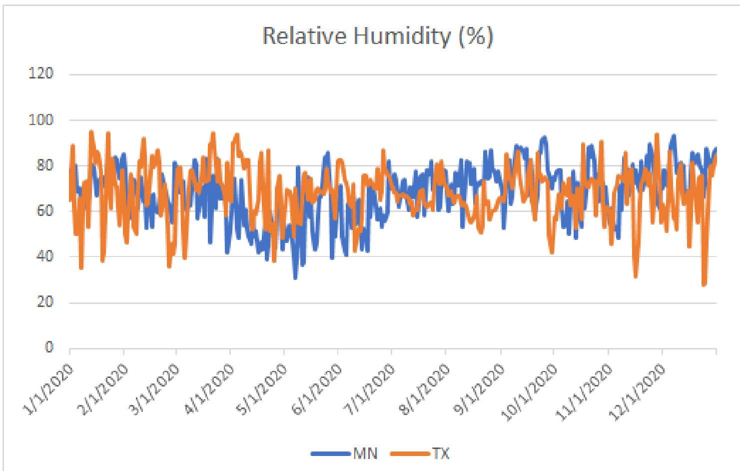

Figure 8-4. Comparison of relative humidities at test locations MT and AZ.

Table 8-4. Summary of relative humidity at the two meteorological sites.

Site	Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Overall
MN	Min	61.3	53.0	42.0	39.3	30.8	41.0	57.6	53.2	53.0	48.5	48.6	63.0	30.8
MN	Max	85.2	81.4	83.5	74.6	86.0	81.9	82.0	86.9	92.7	89.0	89.4	93.5	93.5
MN	Average	74.9	65.7	67.1	53.7	57.2	58.9	70.4	73.4	77.2	69.0	70.6	78.8	68.1
TX	Min	35.0	35.9	39.4	38.6	49.2	42.7	58.1	51.0	42.3	53.0	31.8	28.0	28.0
TX	Max	95.3	92.0	94.4	93.5	82.0	86.7	82.1	73.0	86.4	90.7	93.9	86.3	95.3
TX	Average	68.3	66.2	73.0	70.3	67.5	69.9	67.3	62.3	70.3	67.6	67.5	64.6	67.8

When the daily calculations are performed for the entire year for a broiler with 25,000 birds, the Texas site typically has higher greater daily emissions values for the gaseous pollutants than the Minnesota site (Figure 8-5). Table 8-5 has the estimated annual emissions of all the pollutants studied. The total annual NH_3 emissions estimate for the farm using meteorology from Texas was 4,622 kg, which is a 1,368 kg increase from the same broiler house with meteorology from Minnesota. A similar trend is seen across the other pollutants. This is consistent with the trend of lower temperatures and higher humidities yielding lower emissions seen during the data exploration in Section 4. Overall, this suggests that the emissions models can account for differences in temperature of the different growing regions in the results for broiler houses.

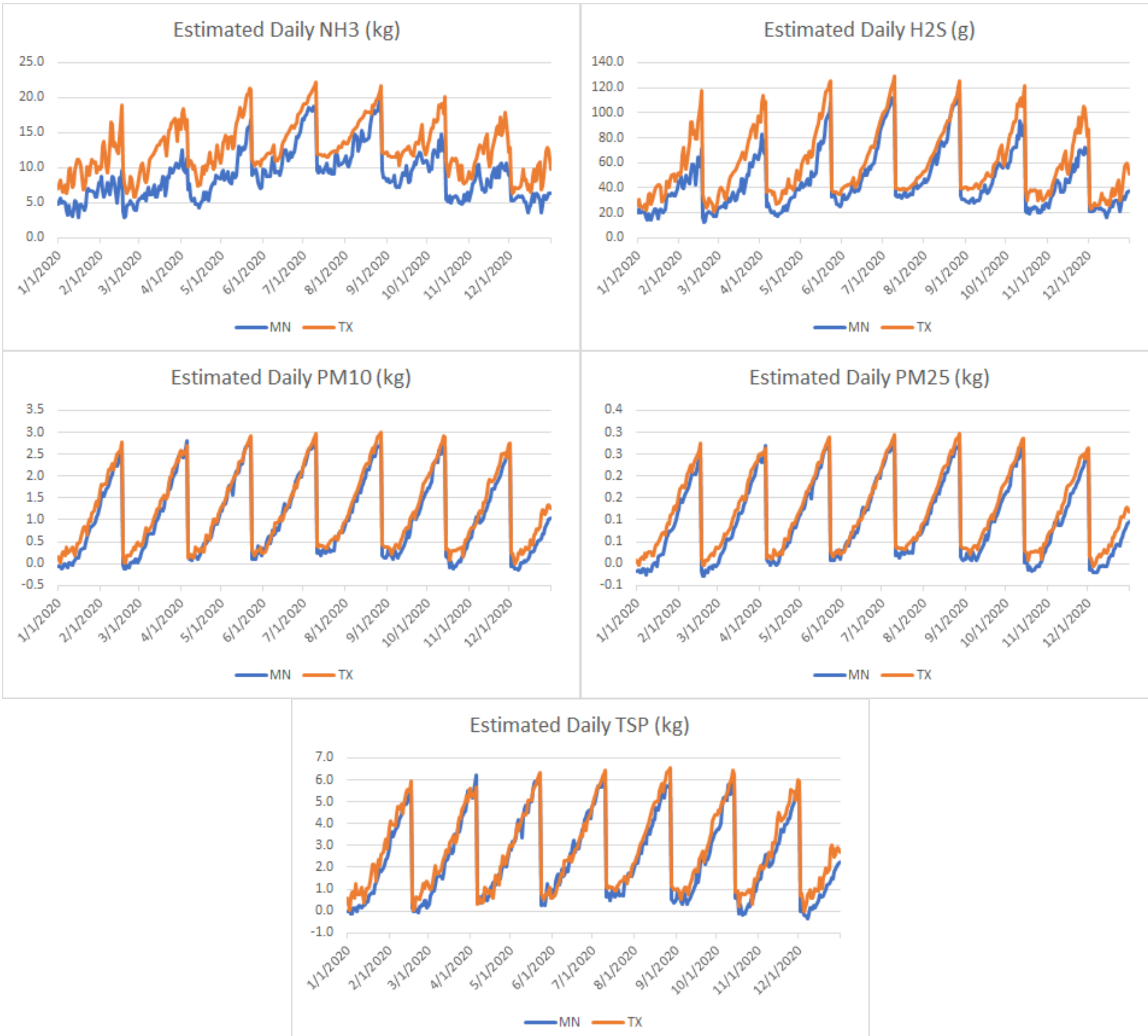

Figure 8-5. Comparison of daily emissions at test broiler locations MN and TX.

Table 8-5. Total annual emissions from the theoretical broiler barn in MN and TX.

Pollutant	MN Emissions (kg per year)	TX Emissions (kg per year)
NH_3	3,255	4,622
H_2S	16.4	21.2
PM_{10}	387	446
$PM_{2.5}$	35.4	42.8
TSP	877	1,005

8.2.3 Model Limitations

As noted in the 2013 SAB review (US EPA SAB, 2013), extrapolating beyond conditions represented in the model development dataset could produce unrealistic results. To test the limitations of the model, EPA conducted a series of emissions calculations over a range of conditions that could be seen at a farm in the US. These emissions calculations tested one parameter at a time, with the selected parameter varied by a constant value through the range. For example, ambient temperature was increased by 1 °C from the minimum value in the model development dataset up to the maximum value. While one parameter was evaluated, the remaining parameters were held constant at the average value seen in the model development dataset. The resulting emissions values were reviewed and plotted to determine if the model resulted in unrealistic emissions values, such as negative emissions or rapid increases in emissions rates.

This analysis does not account for interaction between multiple terms within an equation, which could further affect the results. For example, a broiler house with higher ambient temperatures would be able to cover a larger range of inventory before producing negative NH_3 emissions. Conversely, a house with lower ambient temperatures would cover a smaller range of inventory before producing negative NH_3 emissions values. However, the analysis does provide a general range where the model produces reasonable results. The following sections outline the analysis for each of the selected models.

The broiler equations included LAW, ambient temperature, and ambient relative humidity. The ranges of ambient parameters and average bird weight are based on the NAEMS dataset. The number of birds in a single house are based on house capacity numbers provided by consent agreement participants. The range values tested for each parameter are in Table 8-6, with the results plotted in Figure 8-6 and Figure 8-7. Neither the NH_3 nor H_2S models produce negative emissions under average conditions. For PM_{10}, $PM_{2.5}$, and TSP (Figure 8-7), none of the models produce negative emissions under average conditions.

Table 8-6. Parameter ranges evaluated for the broiler model.

Parameter	Upper Limit	Lower Limit	Average Value	Increment
Ambient temperature (°C)	31	-9	15.8	0.6
Ambient relative humidity (%)	100	32	65.3	1
Average of bird weight (kg)	3	0.00	1.1	0.045
Inventory (birds)	50,000	0	24,000	750
LAW (Mg)	150	0	25.7	0.034

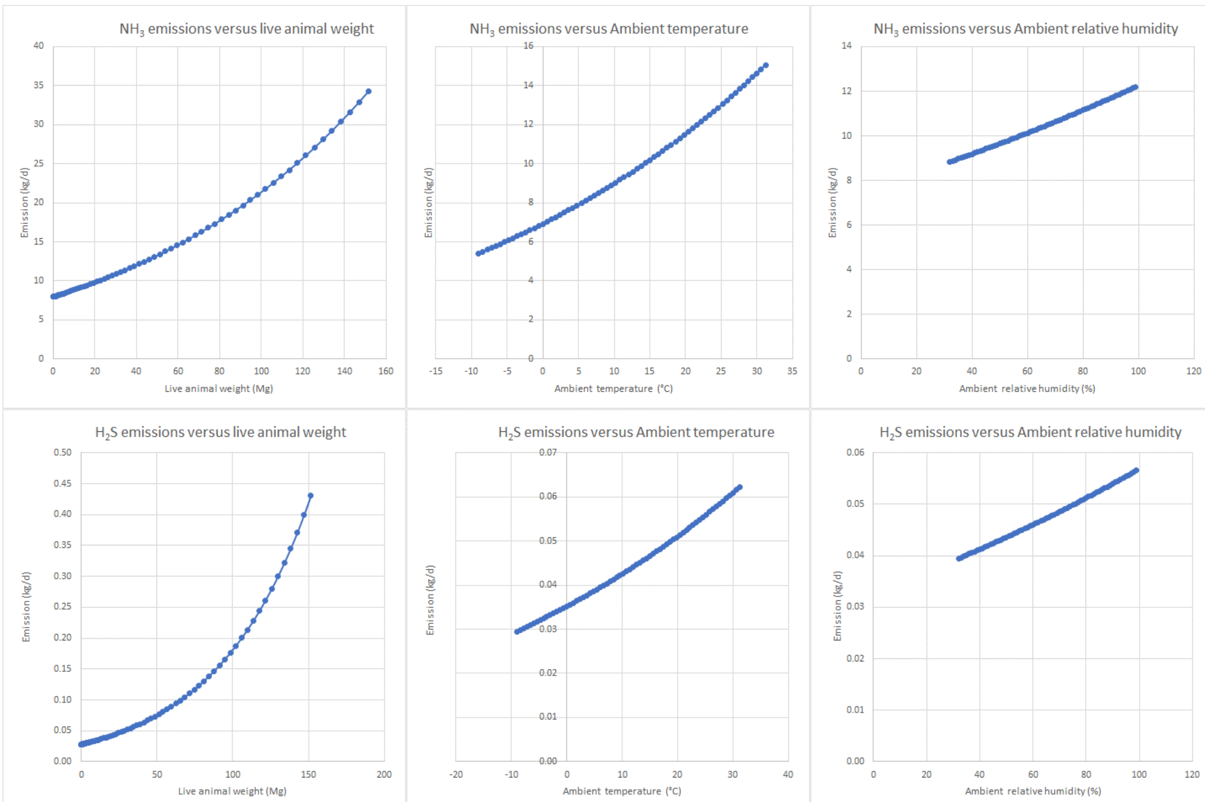

Figure 8-6. Broiler limitation tests for gaseous pollutants.
Visualization of the results for NH_3 (top row) and H_2S (bottom row) with tests LAW (left), ambient temperature (center), and relative humidity (right).

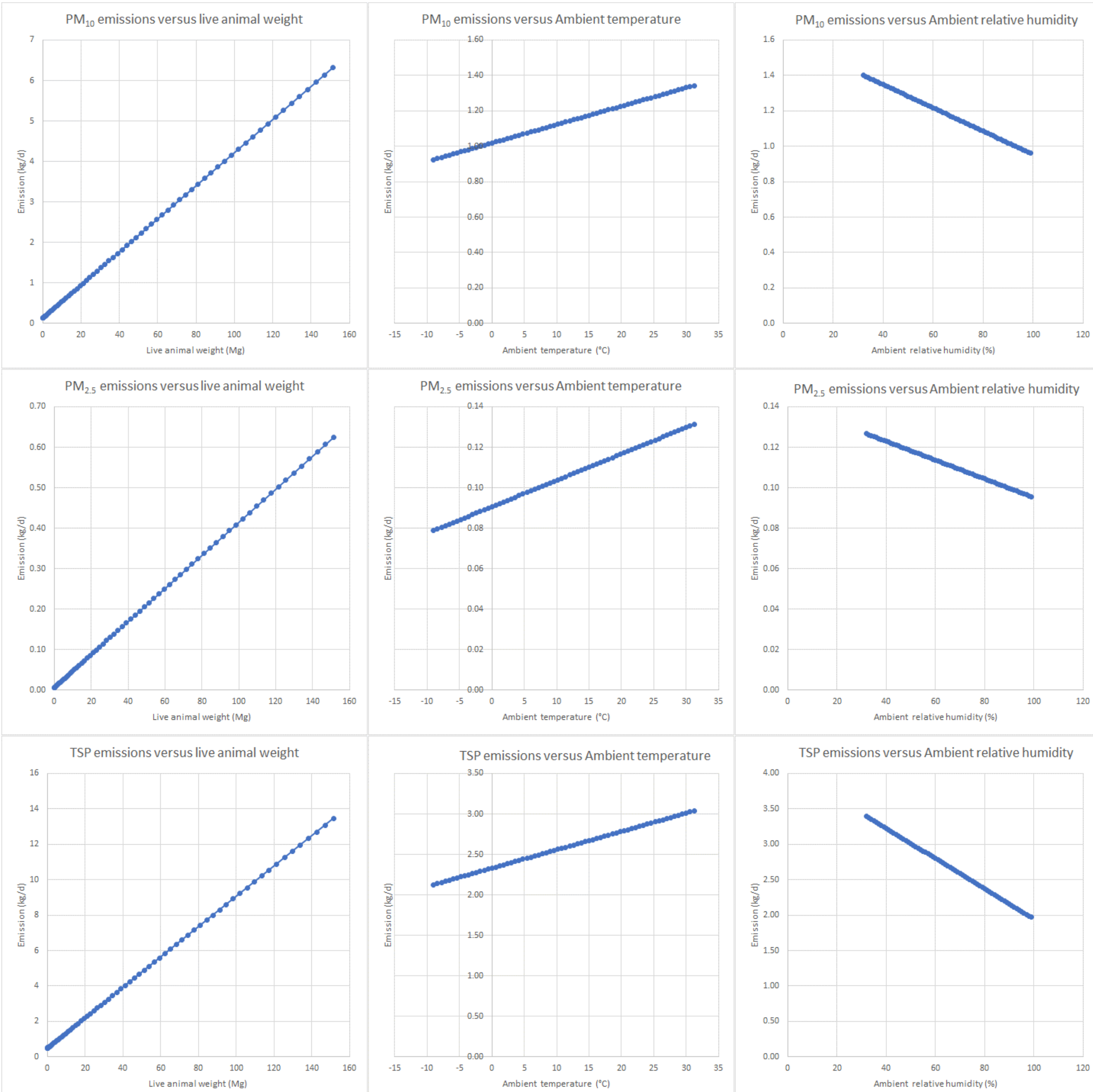

Figure 8-7. Broiler house limitation tests for PM.

Visualization of the results for PM_{10} (top row), $PM_{2.5}$ (center row), and TSP (bottom row) with tests for LAW (left), ambient temperature (center), and relative humidity (right).

To further explore any limitations in the models, emissions were calculated for 21,695,808 combinations across the range of values specified in Table 8-6. A list of all the combinations of the three inputs was created using the R statistical software. R was then used to calculate the emissions using the method shown in section 8.1. The results were then filtered down to only the results that produced negative values to generate the plots for each pollutant. Across this range of conditions, neither the NH_3 nor H_2S models produce negative emissions. The models for PM_{10}, $PM_{2.5}$, and TSP will produce negative values in instances of low LAW (<~10 thousand bird kg^{-1}) combined with high humidities and low temperatures. These conditions mostly occur when the house is empty or during the very first days of the growing cycle. The plots in Figure 8-8 are an attempt to plot the maximum values of LAW and ambient temperature that produce negative emissions at the relative humidity specified on the x-axis, but not necessarily in combination. For example, the equation for PM_{10} will produce negative emissions at 47% humidity when LAW is zero, and ambient temperature is less than or equal to -9 °C. Similarly, at 99% relative humidity, the equation can produce negative number when LAW is less than or equal to 8.46 thousand birds kg^{-1} with low temperatures, and temperatures as high as 24 °C in combination with low LAWs.

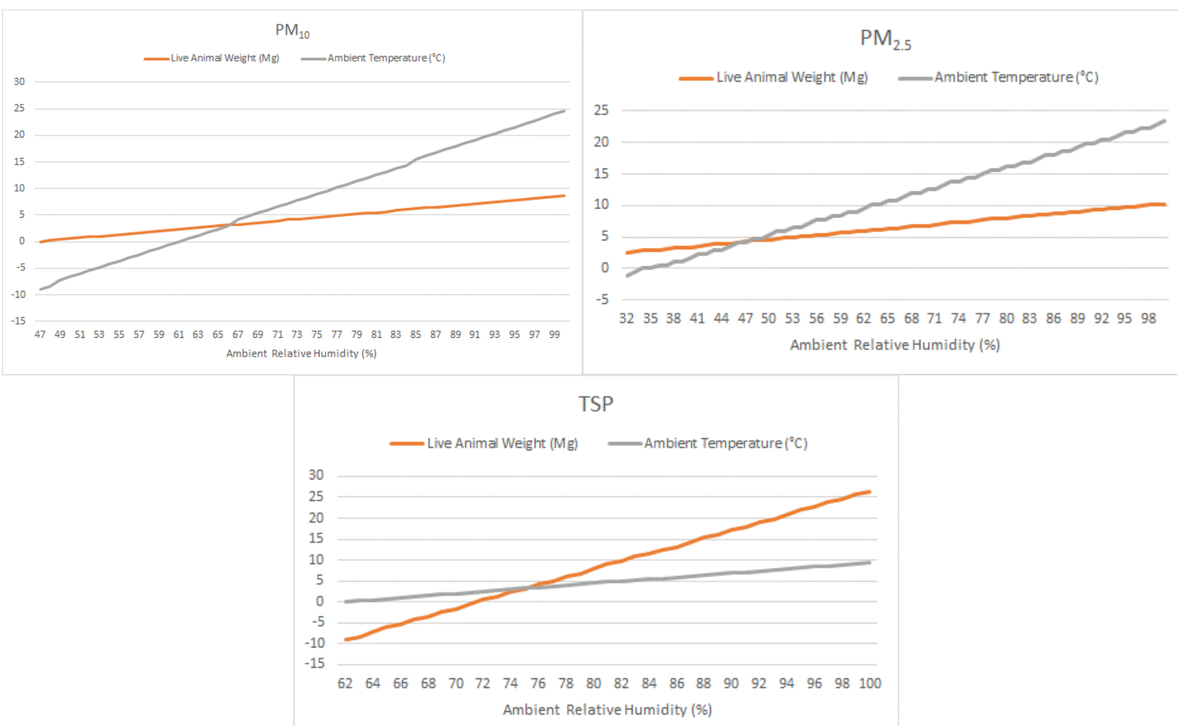

Figure 8-8. Maximum values at which the PM equations yield negative emissions.
Visualization of the results for PM_{10} (top left), $PM_{2.5}$ (top right), and TSP (bottom).

8.3 Comparison to literature

To further validate the EEMs developed under this effort, EPA compared the results for the emissions models to the emissions calculated using emissions factors found in literature. EPA scanned the literature for a variety of emissions factors for this comparison. EPA selected a variety of recent factors not derived from the NAEMS for comparison, which are summarized separately for each pollutant in Table 8-7. The original units provided in Roumeliotis et al. (2010b) were g d^{-1} AU^{-1}, based on an animal unit (AU) of 500kg, and was converted to head (hd) using an average bird weight of 1.03. For further comparison, the emissions factor included EPA's 2001 draft AP-42 chapter is included for NH_3. The emissions factor was converted from the original units of the document were lb yr^{-1} AU^{-1}, where AU was equivalent to 100 birds, to kg hd^{-1} yr^{-1}. The draft AP-42 section has a general emissions factor for PM that is not specific to size fractions and is not included here.

Table 8-7. Emissions factors for broiler houses from literature.

Source	Pollutant	mg h^{-1} 500 kg^{-1}	g d^{-1} AU^{-1}	g hd^{-1} yr^{-1}	kg hd^{-1} yr^{-1}
EPA 2001	NH_3	--	--	243	0.243
Lacey et al., 2003	NH_3	--	--	0.630 [a]	0.230
Roumeliotis et al., 2010b	NH_3	--	82[a]	--	0.062
Harper et al., 2010	NH_3	--	--	--	0.099 [a]
Miles et al., 2014	NH_3	--	--	0.540 [a]	0.197
Lacey et al., 2003	PM_{10}	536[a]	--	--	0.010
Roumeliotis et al., 2010b	PM_{10}	--	5 [a]	--	0.004
Roumeliotis et al., 2010b	$PM_{2.5}$	--	0.78 [a]	--	0.001
Lacey et al., 2003	TSP	10,210[a]	--	--	0.184

[a] As reported in source.

These emissions factors were then applied to the theoretical broiler house from the previous example calculations. Comparisons were made for an inventory of 25,000 birds and 40,000 birds for both a cold weather location (MN) and a warm weather location (TX). The results for NH_3 are presented in Table 8-8. For both inventory levels, the emissions factors from literature generally fall between the estimate produced by the emissions models for the two climate extremes. The exception is the emissions factor from Miles et al. (2014) which produces an estimate slightly higher than the warm weather estimate from the model developed for this report.

Table 8-8. Comparison of resulting broiler house NH_3 emissions (kg yr^{-1}) from various estimation methods.

Meteorology Site	Inventory (hd)	2021 Models	EPA 2001	Lacey et al., 2003	Roumeliotis et al., 2010b	Harper et al., 2010	Miles et al., 2014
MN	25,000	3,255	6,075	5,749	1,541	2,475	4,928
TX	25,000	4,469	6,075	5,749	1,541	2,475	4,928
MN	40,000	3,942	9,720	9,198	2,466	3,960	7,884
TX	40,000	5,352	9,720	9,198	2,466	3,960	7,884

The comparisons for PM_{10}, $PM_{2.5}$, and TSP are presented in Table 8-9, Table 8-10, and Table 8-11, respectively. The models developed for this report produce higher estimates for PM_{10} and $PM_{2.5}$ than the factors found in literature. For TSP, the model estimates are lower than the factors found in literature. One possible reason for the differences in emissions might be the amount of data collected. The KY1B site captures all three PM sizes for an entire year, while Lacey et al. (2003) monitored for 6 months and Roumeliotis et al. (2010b) monitored for 8 months. The Lacey et al. (2003) study does not provide an indication of the completeness of observation from its modeling period. However, the Roumeliotis et al. (2010b) study does provide a summary by season, which indicates a loss of data, particularly in the spring, that would further reduce the number of daily emissions values available to develop an emissions factor. In addition, the NAEMS models included the days between flocks in the data set used to develop the model, which do not appear to have been included in the estimates from literature. Another factor that could contribute to differences is the farms in the Lacey et al. (2003) and Roumeliotis et al. (2010b) used different bedding material (wood shavings and wheat straw) from the NAEMS sites (rice hulls).

Table 8-9. Comparison of resulting broiler house PM_{10} emissions (kg yr^{-1}) from various estimation methods.

Meteorology Site	Inventory (hd)	2021 Models	Lacey et al., 2003	Roumeliotis et al., 2010b
MN	25,000	387	242	94
TX	25,000	430	242	94
MN	40,000	615	388	150
TX	40,000	658	388	150

Table 8-10. Comparison of resulting broiler house $PM_{2.5}$ emissions ($kg\ yr^{-1}$) from various estimation methods.

Meteorology Site	Inventory (hd)	2021 Models	Roumeliotis et al., 2010b
MN	25,000	35	15
TX	25,000	41	15
MN	40,000	58	23
TX	40,000	64	23

Table 8-11. Comparison of resulting broiler house TSP emissions from various estimation methods.

Meteorology Site	Inventory (hd)	2021 Models	Lacey et al., 2003
MN	25,000	877	4,605
TX	25,000	961	4,605
MN	40,000	1,355	7,369
TX	40,000	1,439	7,369

8.4 Replication of Independent Measurements

A final test of the developed emissions models is to compare the predicted emissions to observed values from an independent study. For this test EPA obtained data from the Wheeler et al. (2006b) study, where twelve commercial broiler houses in Pennsylvania and western Kentucky were monitored for NH_3 emissions for several two day periods over the course of a year. EPA was able to obtain data for the Kentucky sites, which were comprised of two sites, where four barns were monitored. The study included houses that used a pH-reducing litter treatment to reduce ammonia (NH_3) emissions. Observations from the houses with treated litter were withheld from this comparison, as the emissions model replicates uncontrolled emissions.

The data provided included the inventory and animal weight parameters needed to estimate emissions from the barns using the developed emissions models. The additional ambient temperature and relative humidity data were obtained from the NCEI for the Paducah Barkley Regional Airport in KY (WBAN: 03816), a Local Climate Data site in western Kentucky with data available for this period. Its data file provides the values of the key meteorological parameters needed for calculations. These estimates were then compared to the observed values, when available, using the same model performance statistics noted in Section 6 of the Overview Report. The statistics for all observations are presented in Table 8-11. These statistics suggest the model has a negative bias, and under predicts NH_3 to some degree. The model performance statistics were also calculated for each season (Table 8-12). The seasonal statistics show slightly better performance in the spring and a shift to positive bias (over prediction) in the winter.

Table 8-12. Model performance evaluation statistics for broiler houses.

Pollutant	n	MB (kg)	ME (kg)	NMB (%)	NME (%)	r
NH_3	154	-5.21	11.01	-24%	51%	0.83

Table 8-13. Model performance evaluation statistics by season.

Pollutant	Season	n	MB (kg)	ME (kg)	NMB (%)	NME (%)	r
NH_3	spring (MAM)	36	-0.64	7.28	-4%	48%	0.82
NH_3	summer (JJA)	60	-10.81	13.48	-36%	45%	0.81
NH_3	autumn (SON)	40	-4.43	12.25	-22%	61%	0.74
NH_3	winter (DJF)	18	2.60	7.45	26%	75%	0.56

Scatter plots were also developed to present the ordered pairs with observations on the x-axis and the model predicted values on y-axis. These plots are useful for indicating trends of either over, or under prediction across the range of values. The plots include the 1:1 line (solid line) and the 1:0.5 and 1:2 lines (dashed lines). Points that fall on the 1:1 line were predicted correctly, and points that fall between the 1:0.5 and 1:2 are within a factor of two observations. Good model performance would be indicated by scatter contained within a factor of two of the 1:1 line, that is between the 1:0.5 and 1:2 lines. Looking for scatter confined to within a factor of two of the observation has been used as a model performance metric in air quality modeling as by EPA for some time (Chang & Hanna, 2004), and continues to be included in EPA's Atmospheric Model Evaluation Tool (Appel, et al. 2011) which is the current model evaluation platform.

The scatter plots were developed by season and color code to show the performance for each house. The NH_3 scatter plots (Figure 8-9) show that a vast majority of the predicted values fall within a factor of two of the observation for all seasons. Additional plots and statistics are available in Appendix H.

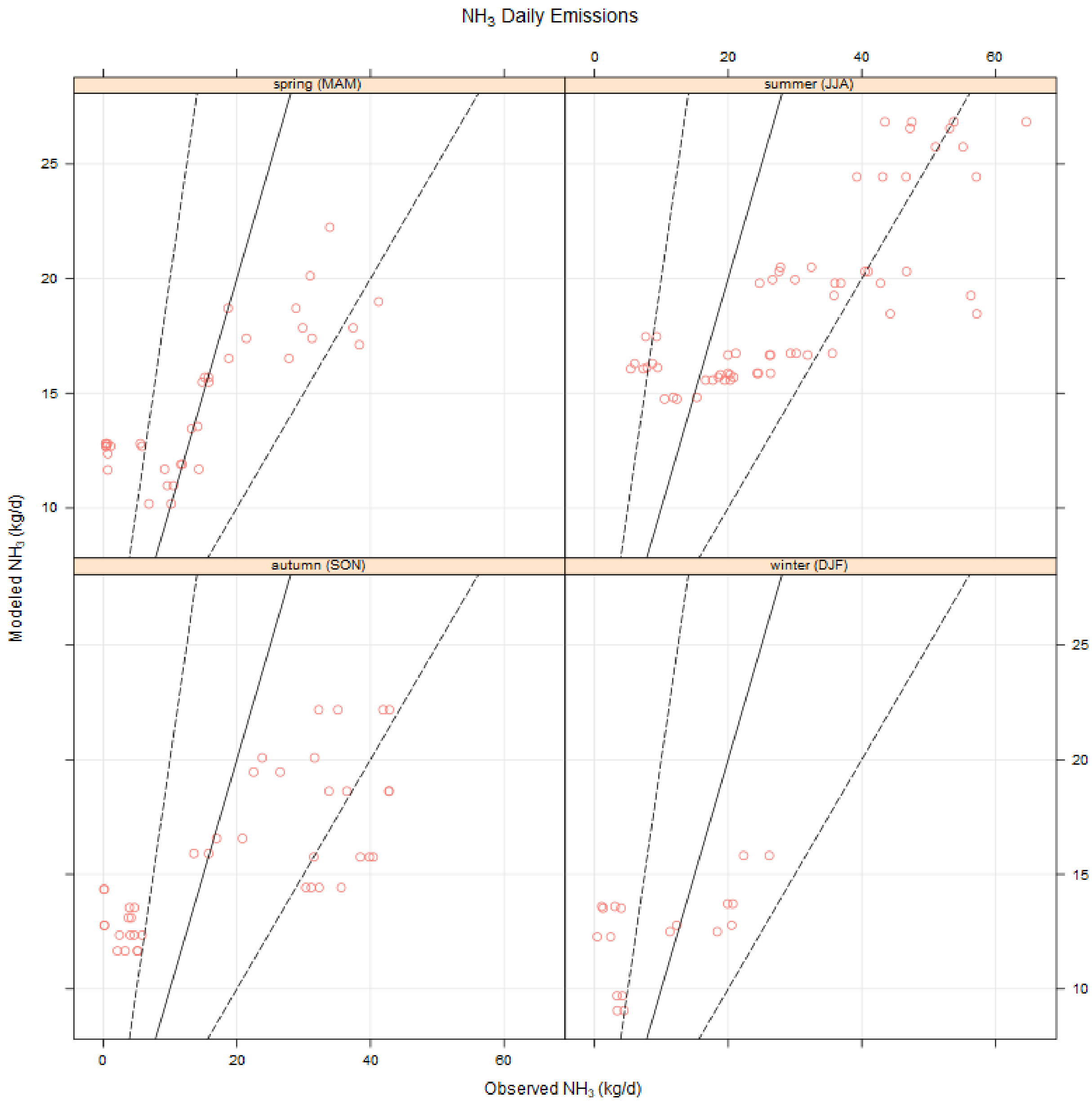

Figure 8-9. Scatter plot of the observed NH_3 emissions at the broiler house site versus the emissions model estimates.

9.0 CONCLUSIONS

Consistent with the Air Compliance Agreement with the AFO industry, EPA has developed emissions estimation methods for NH_3, H_2S, PM_{10}, $PM_{2.5}$, and TSP for confinement sources at broiler operations. These draft statistical models focus on parameters that have been identified in published peer-reviewed journals as having empirical relationships with emissions. These relationships were evaluated within the NAEMS dataset before selecting parameters for emissions model development. EPA also considered which variables could be measured or obtained with minimal effort.

The LAW (inventory*average animal weight) was identified as a key parameter and is used in all the models as a proxy for the volume of manure generated and changes during the growing cycle. Temperature and relative humidity parameters were also identified as important variables for emissions rates in the confinement house emissions models. Relative humidity parameters proved to be key for PM prediction, as the higher moisture levels keep barn materials from entraining into the air with mechanical disruptions. Confinement parameters specific to the barn, like exhaust temperature, showed promise as predictive parameters. However, these parameters are not routinely measured at farms and would therefore represent an increased burden to operators should they be required for emissions estimation. As such, all of the draft broiler emissions models put forward for potential use in this document use parameters that are already routinely collected as part of the standard farm operation (e.g., inventory and animal weight) or are ambient meteorological parameters, which are freely available from public sources such National Center for Environmental Information (NCEI, https://gis.ncdc.noaa.gov/maps/).

Overall, the method used to develop the emissions models allows for the incorporation of additional emissions and monitoring datasets from other studies, should they become available to EPA after the release of the emissions models. Revised emissions models for any individual farm type could be issued once significant additional data becomes available. Similarly, if monitoring options for house parameters become more widespread as automation options grow, future evaluations could assess whether emissions models should be developed to include these parameters.

EPA recognizes the scientific and community desire for process-based models. The data collected during NAEMS and the emissions models developed here lay the groundwork for developing these more process-related emissions estimates. EPA supports the future development of process-based models which account for the entire animal feeding process. While the interim statistical models allow estimation of emissions from confinement houses at broiler operations across the U.S., process-based models would allow producers to estimate the impacts of different management practices to reduce air emissions, helping to incentivize change.

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