Development of Emissions Estimating Methodologies for Animal Feeding Operations

Volume 4: Egg-Layers

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.

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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 eight layer houses and one manure shed monitored during NAEMS. The site locations were in California (CA2B), Indiana (IN2H/IN2B) and North Carolina (NC2B). Table 1-1 summarizes sites and the structures monitored. The following section provides additional details on the sites.

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

Site	Site Type	Monitoring Period	Ventilation type	Number of units measured	Manure Collection	Manure storage[2]
CA2B	High-rise	10/17/07 - 10/31/09	MV (sidewall)	2	DB	Inside
IN2B[1]	High-rise	6/1/07 - 5/31/09	MV (sidewall)	2	CBC	First floor
IN2B[1]	Manure belt	1/1/08 - 12/31/09	MV (sidewall)	2	Belt	Shed
IN2H	Manure shed	1/1/08 - 12/31/09	MV	1	Loader	-
NC2B	High-rise	10/17/07 - 10/31/09	MV (tunnel)	2	CBC	Inside

[1]House sites that also have measured manure shed.
[2]Characterizes type of farm, not necessarily a measurement location.
MV = mechanically ventilated.
CBC = Curtain backed cages.
DB = dropping boards under cages.

1.1.1 CA2B

The CA2B layer site was located in central California. The monitored houses, H5 and H6, were built in 2003. The cluster initially consisted of three houses built in 2003, but a fourth house was added in the summer of 2008, during the monitoring period (Heber et al., 2012). In addition, there was a storage lagoon for temporarily holding egg-wash water (not monitored in NAEMS). At this four-house layer cluster, one building (144 m long, 15 m wide, 6.7 m high sidewalls, and 9.1 m high ridge) was selected as the monitoring site (Liang, 2015), which contained two separate (distinct) and individually-ventilated high-rise houses (H5 and H6) (7.5 m wide), each of identical design, and capacity of 38,000 hens (Lohmann LSL Lite) (Cortus et al., 2010; Lin et al., 2012b). Importantly, H5 and H6 are identical in building design, feed regime, manure management, and ventilation (Lin et al., 2012b). H5 and H6 use board scraper systems for manure collection. In this system, the manure collects on dropping boards under the cages and is then scraped into the first floor, where it is stored for six to eight months. H5 and H6 are mechanically ventilated and have misting systems that are used in the summer. A schematic of CA2B and the monitored houses is provided in Figure 1-1. The particulate matter (PM) sampling schedule is provided in Appendix A, Table A-1.

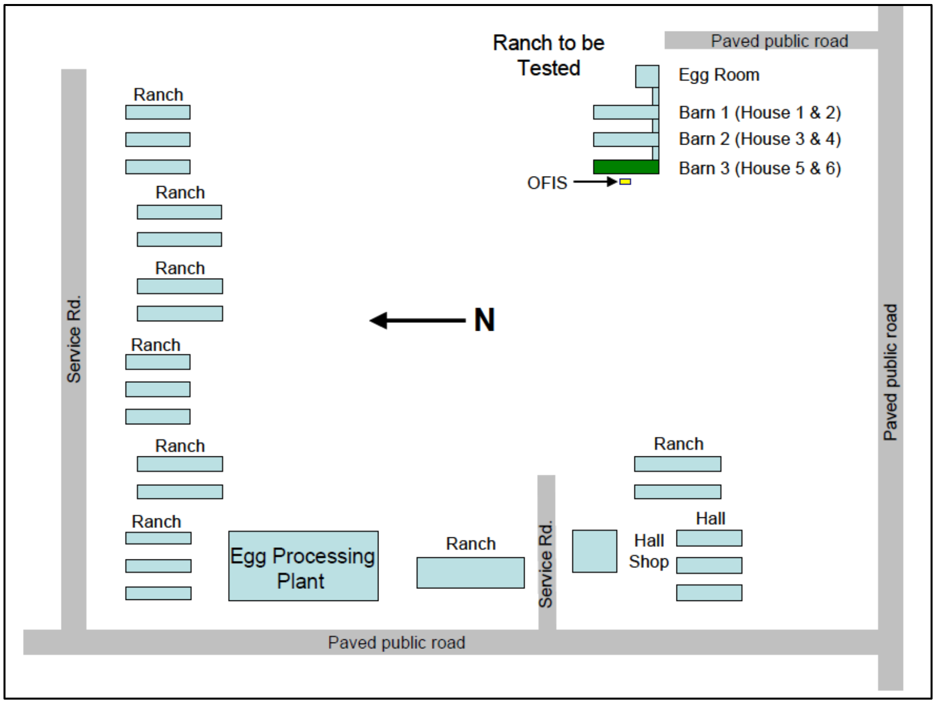

Figure 1-1. CA2B Farm layout.

1.1.2 IN2B/IN2H

The IN2H/IN2B layer site was in eastern Indiana. This site provided the unique opportunity to monitor the two most common housing and manure management types at one location. The egg production farm consists of an egg-processing plant, two high-rise caged-layer houses, seven manure belt caged-layer houses, two cage-free layer houses, and one free-standing manure shed (Ni et al., 2010a; Ni et al., 2010b; Ni et al., 2017a). A schematic of IN2H/IN2B is provided in Figure 1-2. The high rise site, IN2H, consisted of monitoring the two high rise houses, H6 and H7. The belt-battery, or manure belt system, monitoring site, IN2B, consisted of two of the farm's manure belt houses, H8 and H9, and the manure shed.

The monitored high rise houses were built in 1997. Each high-rise house is 198 m long and 30.5 m wide (Ni et al., 2010a). All houses are oriented east-west and are spaced 17 to 18 m apart (Ni et al., 2010a). The high-rise houses had a capacity of 218,050 hens in ten rows of [Big Dutchman 520N] A-frame cages (5 tiers high) on the upper floor (Ni et al., 2017a). The houses were mechanically ventilated and had a direct drop manure collection method where manure drops off slanted boards behind the cages directly into the first floor, where it is stored for up to one year. The PM sampling schedule is provided in Appendix A, Table A-2.

The monitored manure belt houses were built in 2004. The monitored houses were mechanically ventilated and measured 140 m long and 19.5 m wide, with 7-m sidewalls (Ni et al., 2010b). The houses had capacities of 280,000 birds housed in seven 10-tier rows with Hframe cages (Ni et al., 2010b). The manure shed for houses 8 and 9 was 85 m long and 30.5 m wide and naturally ventilated via two 0.6-m (2-ft) wide ventilation openings that run the length of the east and west sides (Ni et al., 2010). Manure was collected on 1.21-m wide plastic belts that were under each tier of cages. The manure belt system was manually operated for approximately 4 hours in the morning to move the manure 1/3 of the total belt length from west to east. The longest time that any manure stayed in the house was three days. The manure was then conveyed into manure drying tunnels by three belts at the east end of the house. The PM sampling schedule is provided in Appendix A, Table A-3.

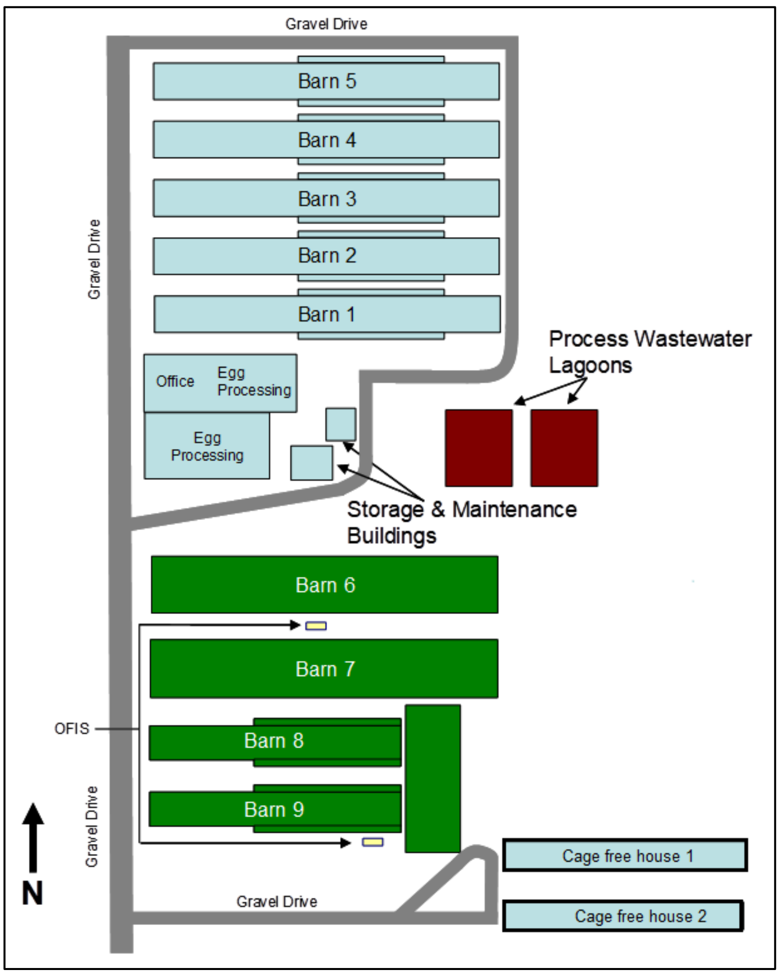

Figure 1-2. IN2B/IN2H Facility layout.

1.1.3 NC2B

The NC2B layer site was located in eastern North Carolina. The monitored houses here, H3 and H4, were built in 2002 and are 18 m wide and 175 m long. At the time of NAEMS, this farm consisted of nine egg-layer houses, one egg-processing (packing) plant, two wastewater treatment lagoons with solid traps, and a wastewater spray field (Wang-Li et al., 2013a). The aerated pond, used for temporarily holding egg-wash water at this facility, was not monitored in

NAEMS. At NC2B, two monitored tunnel-ventilated high-rise houses (H3 and H4) had an inventory of 95,000 hens and 34 exhaust fans (SW-NE) on opposite end-walls with sixteen of these exhaust fans located at the cage level (top floor) (Wang Li et al., 2013a; 2013b). Layers were placed in six rows of 4-tiered curtain-backed cages on the upper floor. Manure falls onto the curtain backed cages and then down into the first floor, where it is stored for up to one year.

The NC2B site was a comprehensive environmental management system (EMS) and complied with International Organization for Standardizations (ISO) 14000 standards (Wang-Li et al., 2013a). The ISO 14000 is a series of international, voluntary environmental management standards, guides, and technical reports (Wall et al., 2001; Feldman and Tibor, 1996). For example, the monitored houses at NC2B are controlled by a computerized environmental control system with ISO 14000 implementations (Wang et al., 2010). A schematic of NC2B is provided in Figure 1-3. The PM sampling schedule is provided in Appendix A, Table A-4.

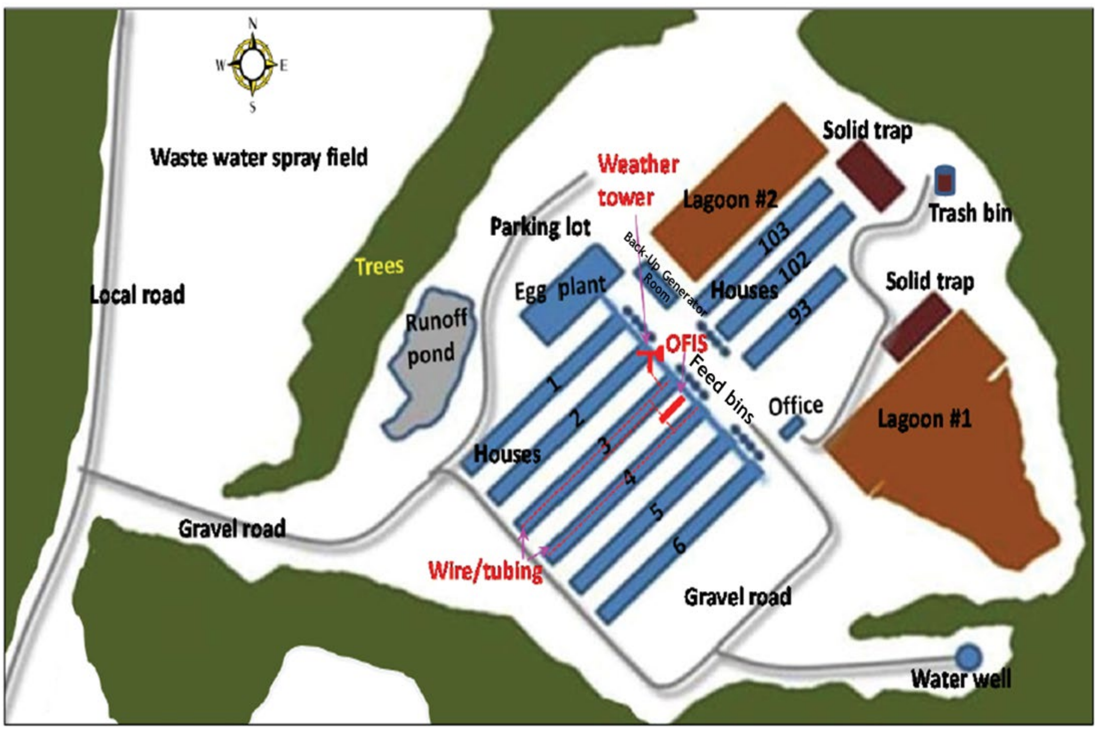

Figure 1-3. NC3B facility layout. Monitored buildings were houses 1, 2 and 3.

1.2 Data Sampled

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

1.2.1 *Animal Husbandry*

Weekly layer inventories, feed and water consumption, egg production and characteristics and bird mass data were collected from the farm's computer system for each site.

1.2.2 *Biomaterials Sampling Methods and Schedule*

Surface manure samples were collected to determine pH, moisture content and total ammoniacal nitrogen. In addition to surface manure, loadout manure was sampled during each full cleanout of the houses and were analyzed for pH, moisture content, total N, and ammoniacal N. All analyses of biomaterials were performed by an independent laboratory (Midwest Laboratories, Omaha, NE).

Sampling frequency varied between the sites. For CA2B, manure sampled from the first floor storage 5 times at H5 and 8 times at H6. Sampling of load out material occurred 3 times at CA1B H5 and 4 times at CA1B H6. At IN2H, the in-house manure sampling was approximately every three months, on a total of 8 days for each house. The load-out manure was only sampled when the manure was loaded out, which only occurred once during the two year monitoring period. For NC2B, H3 and H4 were sampled on 6 and 5 days, respectively. Dates were randomly spaced across the study period. Load out material was sampled on three different dates from each house.

For the manure belt site, IN2B, samples were collected from 5 locations: 1) the belts in the house, 2) the drying tunnel inlet, 3) the drying tunnel outlet, 4) the manure shed, and 5) the manure shed load out material. Manure from the houses, drying tunnel, and shed were sampled every 60 days. Manure from the shed load out were sampled twice during NAEMS. Per the SOP (Hanni & Bogan 2008), a block random sampling procedure was used to take the manure surface samples. Each windrow was divided into multiple sections per house. A computer program randomly selected sections to be sampled. The samples of approximately equal weight were randomly collected from each section. These samples were mixed thoroughly, and 12 to 15 samples (about ½ kg each) were taken from the mixture and sent to the lab for analysis.

Loadout manure samples were taken from random locations in the manure piles outside of each house or from the trucks used during load out event. Multiple samples were collected, and then combined and mixed. A subsample from this mixed collection sample was sent to the lab for analysis.

2.0 REVISIONS TO DATASET AND EMISSIONS DATA SUMMARY

The section catalogs the changes made to the layer 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 Dataset

As described in Section 4.2 of the Overview report, NAEMS monitoring data were submitted to EPA in 2010, with revisions submitted in 2015. Revisions included an adjustment to methodology to determine house gas inlet concentrations, which reduced the number of negative emissions calculations due to occasionally high inlet concentrations. A more detailed description of these changes can be found in the Overview report.

Further site-specific revisions include re-calculating negative emissions data at IN2H, PM concentrations and emissions at NC2B, and airflow at IN2B to dry standard conditions.

In 2018, EPA received additional data associated with the NC2B dataset from Dr. Albert Heber. At NC2B, monitoring continued for an additional three months (until 12/31/09) beyond the NAEMS monitoring dates (9/25/07 to 9/30/09) and were included since the investigators continued to follow NAEMS QA/QC procedures. In addition, revised environmental and production data were received for NC2B, which included revised values for a range of variables such as inventory, live animal weight (LAW), exhaust temperature, house temperature and ambient temperature. Revised values for inventory, LAW, exhaust temperature, house temperature and ambient temperature were also received for IN2H and CA2B. A description of the revisions is provided in Liang (2015).

EPA reviewed the datasets and removed a small amount of individual environmental data points that were erroneous. In addition, EPA corrected a small amount of production values where there was inconsistency between inventory, hen weight, LAW, and flock status. Furthermore, in 2020, EPA received additional inventory data for IN2B, which was used to fill-in blank inventory data during a flock replacement event (10/4/08 to 10/24/08) at H9. This inventory data were also used in the Ni et al. (2017b) publication and was determined based on CO_2 production (Heber, personal communication). This information was requested by EPA as there is a limited range of inventory values in the layer-manure belt dataset and this was the only flock replacement event at the monitored houses during NAEMS.

While performing the exploratory data analysis and reviewing model performance for outliers, EPA developed criteria for the removal of additional negative values from the dataset as part of an outlier analysis. Appendix B outlines the method and the number of additional data points excluded from the layer datasets.

2.2 Data Completeness Criteria for the Revised Dataset

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 ammonia (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 relaxed 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 following sections examine the effect of a reduced data completeness criterion on the number of valid average daily means (ADM) for both the layer houses and manure shed, based on additional analysis completed by Heber that examined the effect of different completeness criteria by comparing the number of valid ADM.

EPA reviewed this data for the egg-layer sites and retained the 75% completeness criterion for all sites. The full analysis can be found in Appendix D.

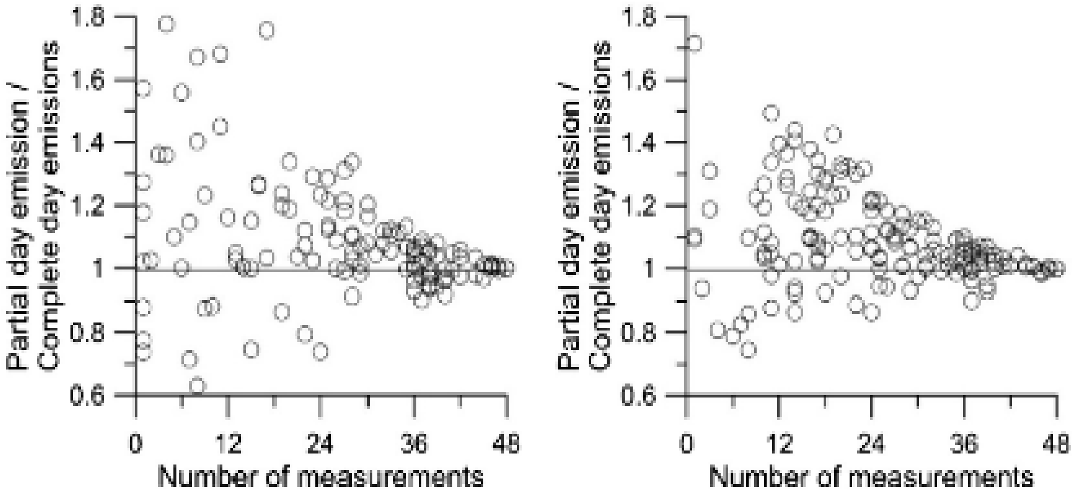

Figure 2-1. Ratio of mean predicted emissions for portion of day with valid emissions measurements to mean predicted emissions for the complete day at the finishing (A) and sow (B) farm. Error plotted against number of valid 30-minute measurements (from Grant et al., 2013c).

2.3 Comparison Between the 2010 and Revised Datasets

The influence of the previous described corrections on the revised dataset 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 dataset. The following sections describe the differences in the ADM for each pollutant between the 2010 data and the revised dataset used in this analysis.

2.3.1 NH_3 High Rise House Dataset

The influence of the previous described corrections on the revised dataset can be observed by comparing the number of valid ADM and mean emissions values (at 75% data completeness) between the 2010 and revised datasets (Table 2-1). At CA2B the number of valid ADM decreased by 13 (2.2%) for both H5 and H6 with mean NH_3 emissions increasing by 1.2% for H5 and 1.8% for H6. At NC2B the number of valid ADM increased by 102 (16.6%) and 104 (17.0%) for H3 and H4 (due to additional data, see section 2.1), respectively, with the mean emissions decreasing by 7.3% for H3 and 1.0% for H4. At IN2H, there was also an increase in number of valid ADM, with number of ADM values increasing for both houses in the revised dataset (39 (7.4%) for H6 and 58 (11.3%) for H7). In terms of the effect on mean NH_3 emissions, IN2H had the smallest changes in mean emissions with H6 increasing by 0.6% and H7 decreasing by 0.4%.

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

Dataset	Statistic	CA2B H5	CA2B H6	IN2H H6	IN2H H7	NC2B H3	NC2B H4
2010	n of ADM	583	603	525	512	613	611
2010	Overall ADM (kg d^{-1})	32.7	31.7	223.3	249.3	62.5	58.1
Revised	n of ADM	570	590	564	570	715	715
Revised	Overall ADM (kg d^{-1})	33.1	32.3	224.7	248.2	58.1	57.5

2.3.2 H_2S High Rise House Dataset

The comparison of the number of valid ADM and mean emissions values (at 75% data completeness) between the 2010 and revised datasets is provided in Table 2-2. At CA2B, the number of valid ADM decreased by 13 (2.1%) for both H5 and H6 with mean hydrogen sulfide (H_2S) emissions increasing by 0.02% for H5 and 0.4% for H6. At NC2B, the number of valid ADM increased by 21 (3.3%) and 28 (4.4%) for H3 and H4, respectively, with the mean emissions increasing by 0.6% for H3 and 3.9% for H4. At IN2H, there was the largest change in number of valid ADM with the number of ADM values increasing for both houses in the revised dataset (43 (12.0%) for H6 and 41 (11.1%) for H7).

In terms of the effect on mean H_2S emissions, IN2H had the largest changes in mean emissions with H6 increasing by 8.9% and H7 increasing by 4.8%. Additional data provided for the NC2B site increased the number of valid ADM by 39 (5.6%) and 38 (5.4%), respectively. The additional data resulted in the mean emissions decreasing by 0.2% at H3 and 4.7% at H4.

Table 2-2. Number of valid ADM and mean H_2S emissions values (at 75% data completeness) between the 2010 and revised high rise datasets.

Dataset	Statistic	CA2B H5	CA2B H6	IN2H H6	IN2H H7	NC2B H3	NC2B H4
2010	N of ADM	614	633	358	369	641	635
2010	Overall ADM (kg d^{-1})	45.40	39.80	277	257	57.10	62.80
Revised	N of ADM	601	620	401	410	662	663
Revised	Overall ADM (kg d^{-1})	45.41	39.96	301.54	269.27	57.45	65.24
Additional Data	N of ADM	-	-	-	-	701	701
Additional Data	Overall ADM (kg d^{-1})	-	-	-	-	57.36	62.31

2.3.3 PM High Rise House Dataset

Table 2-3 provides a summary of the number of valid ADM (N of ADM) and the overall ADM for PM_{10} at each site. At CA2B, the number of valid ADM remained the same for both H5 and H6 with mean PM_{10} emissions increasing by 0.2% for H5 and no change for H6. At IN2H, the number of valid ADM values increased for both H6 (6 days, 1.5%) and H7 (18 days, 4.5%). In terms of the effect on mean H_2S PM_{10} emissions, H6 decreased by 0.6% and H7 decreased by 0.9%. For NC2B, the number of valid ADM increased by 6 (1.6%) and 47 (9.1%) at H3 and H4, respectively. The additional valid ADM values resulted in the mean emissions increasing by 2.5% at H3 and decreasing by 0.9% at H4.

Table 2-3. Number of valid ADM and mean PM_{10} emissions values between the 2010 and revised high rise site datasets.

Dataset	Statistic	CA2B H5	CA2B H6	IN2H H6	IN2H H7	NC2B H3	NC2B H4
2010	N of ADM	451	527	411	403	377	518
2010	Overall ADM (g d^{-1})	1,270	960	3,702	4,944	1,486	2,219
Revised	N of ADM	451	527	417	421	383	565
Revised	Overall ADM (g d^{-1})	1,273	960	3,678	4,898	1,523	2,200

Table 2-4 provides a summary of the number of valid ADM and the overall ADM for $PM_{2.5}$ at each site. The number of valid ADM values remained the same for both houses at CA2B, H6 at IN2H, and H3 at NC2B. However, the ADM did decrease at CA2B H5 by 0.4%, IN2H H6 by 3.3%, and 38% at NC2B H3. Emissions at CA2B H6 remained the same. The number of valid ADM at IN2H H7 decreased by 1 (10%), which corresponded to a 1.9% decrease in the ADM. The largest difference occurred at NC2B H4, where the number of valid ADM values increased by 15 days (45.5%), which resulted in a 12.1% decrease in the ADM.

Table 2-4. Number of valid ADM and mean $PM_{2.5}$ emissions values between the 2010 and revised high rise site datasets.

Dataset	Statistic	CA2B H5	CA2B H6	IN2H H6	IN2H H7	NC2B H3	NC2B H4
2010	N of ADM	40	43	16	10	21	33
2010	Overall ADM (g d^{-1})	238	168	214	104	50	165
Revised	N of ADM	40	43	16	9	21	48
Revised	Overall ADM (g d^{-1})	237	168	207	102	31	145

Similar to the $PM_{2.5}$ results, the number of ADM did not change much for most of the sites (see Table 2-5). Both CA2B houses and IN2H H6 saw no change in the number of ADM available. However, there were changes in the overall ADM. CA2B H5 had a 0.1% decrease, while CA2B H6 and IN2H H6 had 0.2% and 5.3% increase, respectively. IN2H H7 and NC2B H3 had small changes in the number of ADM available, increasing by 2 (10.5%) and 1 (2.3%) days, respectively. These corresponded to a 0.9% decrease in overall ADM at IN2H H7 and a 1.3% increase at NC2B H3. The final site, NC2B H4, saw the largest change, as the number of ADM increased by 45 (40.3%) which corresponded to a 5.4% decrease in overall ADM.

Table 2-5. Number of valid ADM and mean total suspended particulate (TSP) emissions values between the 2010 and revised high rise site datasets.

Dataset	Statistic	CA2B H5	CA2B H6	IN2H H6	IN2H H7	NC2B H3	NC2B H4
2010	N of ADM	36	32	19	19	44	62
2010	Overall ADM (g d^{-1})	2,440	2,760	7,408	4,694	3,391	4,385
Revised	N of ADM	36	32	19	21	45	87
Revised	Overall ADM (g d^{-1})	2,437	2,765	7,803	4,652	3,434	4,148

2.3.4 NH_3 Manure Belt House Dataset

For NH_3 emissions at the manure belt site, the changes made in the revised dataset were relatively minor (Table 2-6). At CA2B the number of valid ADM decreased by 3 (0.5%) for both H8 while the number of valid days remained the same at H9. Mean NH_3 emissions increased by less than 1 kg at each house, for a 1.4% and 0.8% change for H8 and H9, respectively.

Table 2-6. Number of valid ADM and mean NH_3 emissions values between the 2010 and revised manure belt house datasets.

Dataset	Statistic	IN2B H8	IN2B H9
2010	N of ADM	624	629
2010	Overall ADM (kg d^{-1})	70.6	66.5
Revised	N of ADM	621	629
Revised	Overall ADM (kg d^{-1})	71.5	67.0

2.3.5 H_2S Manure Belt House Dataset

The changes in the H_2S dataset for the manure belt house made between the 2015 revision to the dataset were relatively minor (Table 2-7). At CA2B the number of valid ADM decreased by 3 (0.5%) for H8 while the number of valid days remained the same at H9. Mean H_2S emissions increased in the revised dataset by 0.6% for H3 and 0.4% for H4.

Table 2-7. Number of valid ADM and mean H_2S emissions values between the 2010 and revised manure belt house datasets.

Dataset	Statistic	IN2B H8	IN2B H9
2010	N of ADM	634	645
2010	Overall ADM (g d^{-1})	489.0	469.2
Revised	N of ADM	631	645
Revised	Overall ADM (g d^{-1})	492.1	471.1

2.3.6 PM Manure Belt House Dataset

The emissions dataset for PM_{10} (Table 2-8), $PM_{2.5}$ (Table 2-9), and TSP (Table 2-10) were unchanged between the original 2010 submission and the revision submitted in 2015 by Dr. Heber. The comparison here does not include the exclusions implemented by EPA.

Table 2-8. Number of valid ADM and mean PM_{10} emissions values between the 2010 and revised manure belt house datasets.

Dataset	Statistic	IN2B H8	IN2B H9
2010	N of ADM	346	361
2010	Overall ADM (g d^{-1})	2,209.2	6,076.2
Revised	N of ADM	346	361
Revised	Overall ADM (g d^{-1})	2,209.2	6,076.2

Table 2-9. Number of valid ADM and mean $PM_{2.5}$ emissions values between the 2010 and revised manure belt house datasets.

Dataset	Statistic	IN2B H8	IN2B H9
2010	N of ADM	25	31
2010	Overall ADM (g d^{-1})	-85.1	113.2
Revised	N of ADM	25	31
Revised	Overall ADM (g d^{-1})	-85.1	113.2

Table 2-10. Number of valid ADM and mean TSP emissions values between the 2010 and revised manure belt house datasets.

Dataset	Statistic	IN2B H8	IN2B H9
2010	N of ADM	35	34
2010	Overall ADM (g d^{-1})	8,136.3	21,871.0
Revised	N of ADM	35	34
Revised	Overall ADM (g d^{-1})	8,136.3	21,871.0

2.3.7 *Manure Shed Dataset*

The emissions dataset for manure sheds (Table 2-11) also remained unchanged between the original 2010 submission and the revision submitted in 2015 by Dr. Heber. The comparison here does not include the exclusions implemented by EPA.

Table 2-11. Number of valid ADM and mean emissions values between the 2010 and revised manure shed datasets.

Dataset	Statistic	NH_3	H_2S	PM_{10}	$PM_{2.5}$	TSP
2010	N of ADM	518	534	307	30	24
2010	Overall ADM (g d^{-1})	5	35	134	48	295
Revised	N of ADM	518	534	307	30	24
Revised	Overall ADM (g d^{-1})	5	36	134	48	295

2.4 Comparison Between the Revised Datasets 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 to quantify any differences due to the application of the revised calculation methods and other adjustments discussed in Section 2.1.

2.4.1 *High Rise Houses*

Summaries of the NH_3 emissions from CA2B, IN2H, and NC2B high rise layer houses have been published in peer-reviewed journal articles (Lin et al., 2012a; Ni et al., 2017a; Wang-Li et al. 2013b). 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 Table 2-12. For CA2B, the number of ADM is less than in the article by 2%. This resulted in a 1.3% and 2.3% difference in the mean at H5 and H6, respectively. For IN2H, differences in the means are minor (less than 1%) despite an increase of 39 and 58 daily means at H6 and H7, respectively. For NC2B, the revised EEM dataset has 64 and 56 more ADM values for H3 and H4, respectively, than in comparison to the Wang-Li et al. (2013b) study. However, the number of ADMs reported by Wang-Li et al.(2013b) is for full and active bird status only, whereas the revised EEM dataset includes ADMs for all bird status. In the revised EEM dataset, the mean ADM values were 1.5% (H3) and 4.2% (H4) higher than in the Wang-Li et al. (2013b) study.

Table 2-12. Comparison of NH_3 emissions in the EEM dataset to datasets published in peer-review journal papers.

Site	Emissions Units	Statistic	EEM Dataset	Previous Studies	Study
CA2B H5	g day^{-1} hd^{-1}	Number of ADM	570	583	Lin et al., 2012a
CA2B H5	g day^{-1} hd^{-1}	Mean	0.963	0.95	Lin et al., 2012a
CA2B H5	g day^{-1} hd^{-1}	Standard Deviation	0.494	0.49	Lin et al., 2012a
CA2B H5	g day^{-1} hd^{-1}	Max	2.34	2.28	Lin et al., 2012a
CA2B H6	g day^{-1} hd^{-1}	Number of ADM	590	602	Lin et al., 2012a
CA2B H6	g day^{-1} hd^{-1}	Mean	0.962	0.94	Lin et al., 2012a
CA2B H6	g day^{-1} hd^{-1}	Standard Deviation	0.872	0.67	Lin et al., 2012a
CA2B H6	g day^{-1} hd^{-1}	Max	3.95	3.97	Lin et al., 2012a
IN2H H6	kg day^{-1}	Number of ADM	564	525	Ni et al., 2017a
IN2H H6	kg day^{-1}	Mean	225	223	Ni et al., 2017a
IN2H H6	kg day^{-1}	Standard Deviation	90	86	Ni et al., 2017a
IN2H H7	kg day^{-1}	Number of ADM	570	512	Ni et al., 2017a
IN2H H7	kg day^{-1}	Mean	249	249	Ni et al., 2017a
IN2H H7	kg day^{-1}	Standard Deviation	90	97	Ni et al., 2017a
NC2B H3	kg day^{-1}	Number of ADM	715	651	Wang-Li et al., 2013
NC2B H3	kg day^{-1}	Mean	58.1	57.2	Wang-Li et al., 2013
NC2B H3	kg day^{-1}	Standard Deviation	20.9	19.0	Wang-Li et al., 2013
NC2B H4	kg day^{-1}	Number of ADM	715	659	Wang-Li et al., 2013
NC2B H4	kg day^{-1}	Mean	57.5	55.1	Wang-Li et al., 2013
NC2B H4	kg day^{-1}	Standard Deviation	24.4	23.3	Wang-Li et al., 2013

The H_2S emissions from NAEMS high rise layer houses have been published in peer-reviewed journal articles (Lin et al., 2012a; Ni et al., 2017a; Wang et al., 2016), which is presented in Table 2-13. For CA2B and NC2B, there are only small differences between the datasets with the difference in number of ADM ranging from 1.9-2.1% for all houses at CA2B and 6.9-7.5% at NC2B. Additionally the differences in mean and standard deviations are less than 10% for all houses at CA2B and NC2B. There is, though, a larger difference in the max values between the Lin et al. (2012b) study and this study, which have values of 3.72 (H5) and 4.26 (H6) and 3.80 (H5) and 4.99 (H6), respectively.

With respect to IN2H, there are large differences in the number of ADMs and in the standard deviation between the Ni et al. (2017a) study and this study. The number of available ADM reported in the Ni et al. (2017a) study are 27.7% (H6) and 27.3% (H7) less than this study. This 111 day difference in the daily values available has relatively small changes in the mean values: 4% and 7% for H6 and H7, respectively. However, it has a much larger influence on standard deviation, with values decreasing by 41.7% (H6) and 22.1% (H7) in comparison to the dataset used to develop the models. This suggests that some of the high or low emissions values in the dataset used in this study were not included in the dataset in the Ni et al. (2017a) study.

Table 2-13. Comparison of H_2S emissions in the EEM dataset to datasets published in peer-review journal papers.

Site	Emissions Units	Statistic	EEM Dataset	Previous Studies	Study
CA2B H5	mg day^{-1} hd^{-1}	Number of ADM	601	614	Lin et al., 2012a
CA2B H5	mg day^{-1} hd^{-1}	Mean	1.33	1.33	Lin et al., 2012a
CA2B H5	mg day^{-1} hd^{-1}	Standard Deviation	0.71	0.70	Lin et al., 2012a
CA2B H5	mg day^{-1} hd^{-1}	Max	3.80	3.72	Lin et al., 2012a
CA2B H6	mg day^{-1} hd^{-1}	Number of ADM	620	632	Lin et al., 2012a
CA2B H6	mg day^{-1} hd^{-1}	Mean	1.20	1.20	Lin et al., 2012a
CA2B H6	mg day^{-1} hd^{-1}	Standard Deviation	0.89	0.86	Lin et al., 2012a
CA2B H6	mg day^{-1} hd^{-1}	Max	4.99	4.26	Lin et al., 2012a
IN2H H6	g day^{-1}	Number of ADM	401	290	Ni et al., 2017a
IN2H H6	g day^{-1}	Mean	302	314	Ni et al., 2017a
IN2H H6	g day^{-1}	Standard Deviation	278	162	Ni et al., 2017a
IN2H H7	g day^{-1}	Number of ADM	410	298	Ni et al., 2017a
IN2H H7	g day^{-1}	Mean	269	287	Ni et al., 2017a
IN2H H7	g day^{-1}	Standard Deviation	281	219	Ni et al., 2017a
NC2B H3	g day^{-1}	Number of ADM	701	656	Wang et al., 2016
NC2B H3	g day^{-1}	Mean	57.4	59.6	Wang et al., 2016
NC2B H3	g day^{-1}	Standard Deviation	35.2	34.7	Wang et al., 2016
NC2B H3	g day^{-1}	Median	47.7	48.6	Wang et al., 2016
NC2B H4	g day^{-1}	Number of ADM	701	652	Wang et al., 2016
NC2B H4	g day^{-1}	Mean	62.3	65.4	Wang et al., 2016
NC2B H4	g day^{-1}	Standard Deviation	43.7	41.5	Wang et al., 2016
NC2B H4	g day^{-1}	Median	49.5	50.5	Wang et al., 2016

The PM_{10} emissions for all NAEMS high rise layer houses have been published in peer-reviewed journal articles (Lin et al., 2012a; Ni et al., 2017a; Li et al., 2013), which is presented in Table 2-14. The biggest departure across the houses is NC2B H4, which has 171 (30.3%) more ADM available, which translates to a 19% increase in the average value. The main reason for this difference is that Li et al. (2013) does not report daily PM summary statistics for the whole monitoring period at house 4 due to the two different PM sampling strategies used at NC2B H4. For CA2B, the modeling dataset produces summary statistics nearly identical to the Lin et al. (2012b) paper. The exception is EPA included an additional value for house 6. This value was the maximum value in the EPA dataset, and caused an 8.2% increase in the standard deviation. For IN2H houses and NC2B H3, there are only small differences between the datasets, with the difference in number of ADM ranging from 1.4-4.3% increase in the number of ADM available. This minor increase in ADM available translates to differences in the mean and standard deviation of less than 2% for these houses.

Table 2-14. Comparison of PM_{10} emissions in the EEM dataset to datasets published in peer-review journal papers.

Site	Emissions Units	Statistic	EEM Dataset	Previous Studies	Study
CA2B H5	mg day^{-1} hd^{-1}	Number of ADM	451	451	Lin et al., 2012a
CA2B H5	mg day^{-1} hd^{-1}	Mean	37.6	37.6	Lin et al., 2012a
CA2B H5	mg day^{-1} hd^{-1}	Standard Deviation	30.3	30.4	Lin et al., 2012a
CA2B H5	mg day^{-1} hd^{-1}	Max	231	231	Lin et al., 2012a
CA2B H6	mg day^{-1} hd^{-1}	Number of ADM	525	524	Lin et al., 2012a
CA2B H6	mg day^{-1} hd^{-1}	Mean	29.6	29.2	Lin et al., 2012a
CA2B H6	mg day^{-1} hd^{-1}	Standard Deviation	26.7	24.5	Lin et al., 2012a
CA2B H6	mg day^{-1} hd^{-1}	Max	276	143	Lin et al., 2012a
IN2H H6	g day^{-1}	Number of ADM	417	411	Ni et al., 2017a
IN2H H6	g day^{-1}	Mean	3,678	3,687	Ni et al., 2017a
IN2H H6	g day^{-1}	Standard Deviation	3,230	3,197	Ni et al., 2017a
IN2H H7	g day^{-1}	Number of ADM	421	403	Ni et al., 2017a
IN2H H7	g day^{-1}	Mean	4,898	4,934	Ni et al., 2017a
IN2H H7	g day^{-1}	Standard Deviation	4,004	3,982	Ni et al., 2017a
NC2B H3	g day^{-1}	Number of ADM	383	371	Li et al., 2013
NC2B H3	g day^{-1}	Mean	1,523	1,528	Li et al., 2013
NC2B H3	g day^{-1}	Standard Deviation	636	644	Li et al., 2013
NC2B H3	g day^{-1}	Median	1,481	1,501	Li et al., 2013
NC2B H4	g day^{-1}	Number of ADM	565	394	Li et al., 2013
NC2B H4	g day^{-1}	Mean	2,200	1,781	Li et al., 2013
NC2B H4	g day^{-1}	Standard Deviation	1,130	783	Li et al., 2013
NC2B H4	g day^{-1}	Median	2,016	1,693	Li et al., 2013

The $PM_{2.5}$ emissions for CA2B and NC2B houses have been published in peer-reviewed journal articles (Lin et al., 2012a; Li et al., 2013). Searches did not find articles that included summaries of the $PM_{2.5}$ emissions data from IN2H. Table 2-15 presents a summary of the model development dataset and the summary values presented in the articles. For CA2B, the modeling dataset produces summary statistics nearly identical to the Lin et al. (2012a) paper. For NC2B H4, the EEM data set has 27 days more available than the Li et al. (2013) study, which is an increase of 56.3%. This produced a 72.7% increase in the mean and an 59.3% increase in the standard deviation for the house. The main reason for the difference in the number of ADMs is that Li et al. (2013) does not report daily PM summary statistics for the whole monitoring period at house 4 due to the two different PM sampling strategies used at NC2B H4. Data for H3 at NC2B was nearly identical to the statistics presented in Li et al. (2013), with a 0.1% or less difference across all statistics.

Table 2-15. Comparison of $PM_{2.5}$ emissions in the EEM dataset to datasets published in peer-review journal papers.

Site	Units	Statistic	EEM Dataset	Previous Studies	Study
CA2B H5	mg day^{-1} hd^{-1}	Number of ADM	40	40	Lin et al., 2012a
CA2B H5	mg day^{-1} hd^{-1}	Mean	6.7	6.7	Lin et al., 2012a
CA2B H5	mg day^{-1} hd^{-1}	Standard Deviation	14.9	14.9	Lin et al., 2012a
CA2B H5	mg day^{-1} hd^{-1}	Max	53.2	53.2	Lin et al., 2012a
CA2B H6	mg day^{-1} hd^{-1}	Number of ADM	43	43	Lin et al., 2012a
CA2B H6	mg day^{-1} hd^{-1}	Mean	5.17	5.2	Lin et al., 2012a
CA2B H6	mg day^{-1} hd^{-1}	Standard Deviation	10.3	10.3	Lin et al., 2012a
CA2B H6	mg day^{-1} hd^{-1}	Max	35.2	35.2	Li et al., 2013
NC2B H3	g day^{-1}	Number of ADM	21	21	Li et al., 2013
NC2B H3	g day^{-1}	Mean	31.1	31.1	Li et al., 2013
NC2B H3	g day^{-1}	Standard Deviation	79.0	79	Li et al., 2013
NC2B H3	g day^{-1}	Median	48.9	48.9	Li et al., 2013
NC2B H4	g day^{-1}	Number of ADM	48	21	Li et al., 2013
NC2B H4	g day^{-1}	Mean	144.9	39.5	Li et al., 2013
NC2B H4	g day^{-1}	Standard Deviation	168.8	68.7	Li et al., 2013
NC2B H4	g day^{-1}	Median	81.1	72.3	Li et al., 2013

Similar to $PM_{2.5}$, TSP emissions have been published for CA2B and NC2B (Lin et al., 2012a; Li et al., 2013), and no articles were found that included summaries of the TSP emissions data from IN2H. Table 2-16 presents a summary of the model development dataset and the summary values presented in the articles. For CA2B, the modeling dataset produces summary statistics nearly identical to the Lin et al. (2012a) paper. For NC2B H4, the EEM data set has 50 more ADMs (an increase of 57.5%) available than the Li et al. (2013) study. The main reason for this difference is that Li et al. (2013) does not report daily PM summary statistics for the whole monitoring period at house 4 due to the two different PM sampling strategies used at NC2B H4. The EEM dataset had 3% lower mean and 45.6% higher standard deviation in comparison to the Li et al. (2013) study. Data for H3 at NC2B saw an 8 day (17.8%) increase in the number of daily values available, which resulted in a 7.2% decrease in the mean and 1.8% decrease in the standard deviation.

Table 2-16. Comparison of TSP emissions in the EEM dataset to datasets published in peer-review journal papers.

Site	Units	Statistic	EEM Dataset	Previous Studies	Study
CA2B H5	mg day^{-1} hd^{-1}	Number of ADM	36	36	Lin et al., 2012a
CA2B H5	mg day^{-1} hd^{-1}	Mean	71.9	71.9	Lin et al., 2012a
CA2B H5	mg day^{-1} hd^{-1}	Standard Deviation	41.0	41	Lin et al., 2012a
CA2B H5	mg day^{-1} hd^{-1}	Max	177	177	Lin et al., 2012a
CA2B H6	mg day^{-1} hd^{-1}	Number of ADM	32	32	Lin et al., 2012a
CA2B H6	mg day^{-1} hd^{-1}	Mean	84.0	84	Lin et al., 2012a
CA2B H6	mg day^{-1} hd^{-1}	Standard Deviation	44.4	44.4	Lin et al., 2012a
CA2B H6	mg day^{-1} hd^{-1}	Max	226	226	Lin et al., 2012a
NC2B H3	g day^{-1}	Number of ADM	45	37	Li et al., 2013
NC2B H3	g day^{-1}	Mean	3,434	3,680	Li et al., 2013
NC2B H3	g day^{-1}	Standard Deviation	1,515	1,543	Li et al., 2013
NC2B H3	g day^{-1}	Median	3,296	3,606	Li et al., 2013
NC2B H4	g day^{-1}	Number of ADM	87	37	Li et al., 2013
NC2B H4	g day^{-1}	Mean	4,148	4,273	Li et al., 2013
NC2B H4	g day^{-1}	Standard Deviation	2,429	1,322	Li et al., 2013
NC2B H4	g day^{-1}	Median	4,415	4,348	Li et al., 2013

2.4.2 Manure Belt Houses

Summaries of the emissions from the manure belt layer houses monitored during NAEMS have been published in a peer-reviewed journal article by Ni et al. (2017b). The model development dataset is slightly different from the summaries presented in the article, with all statistics reported in Table 2-17 varying by less than 2%.

Table 2-17. Comparison of emissions in the manure belt EEM dataset to datasets published in peer-review journal papers.

Pollutant	Site	Emissions Units	Statistic	EEM Dataset	Previous Studies	Study
NH_3	IN2B H8	kg day^{-1}	Number of ADM	621	624	Ni et al., 2017b
NH_3	IN2B H8	kg day^{-1}	Mean	71.5	70.6	Ni et al., 2017b
NH_3	IN2B H8	kg day^{-1}	Standard Deviation	37.5	36.8	Ni et al., 2017b
NH_3	IN2B H9	kg day^{-1}	Number of ADM	629	629	Ni et al., 2017b
NH_3	IN2B H9	kg day^{-1}	Mean	67.0	66.5	Ni et al., 2017b
NH_3	IN2B H9	kg day^{-1}	Standard Deviation	43.0	42.2	Ni et al., 2017b
H_2S	IN2B H8	g day^{-1}	Number of ADM	631	634	Ni et al., 2017b
H_2S	IN2B H8	g day^{-1}	Mean	492	489	Ni et al., 2017b
H_2S	IN2B H8	g day^{-1}	Standard Deviation	246	241	Ni et al., 2017b
H_2S	IN2B H9	g day^{-1}	Number of ADM	645	645	Ni et al., 2017b
H_2S	IN2B H9	g day^{-1}	Mean	471	469	Ni et al., 2017b
H_2S	IN2B H9	g day^{-1}	Standard Deviation	268	265	Ni et al., 2017b
PM_{10}	IN2B H8	g day^{-1}	Number of ADM	251	248	Ni et al., 2017b
PM_{10}	IN2B H8	g day^{-1}	Mean	3,039	3,086	Ni et al., 2017b
PM_{10}	IN2B H8	g day^{-1}	Standard Deviation	4,813	4,812	Ni et al., 2017b
PM_{10}	IN2B H9	g day^{-1}	Number of ADM	361	361	Ni et al., 2017b
PM_{10}	IN2B H9	g day^{-1}	Mean	6,076	6,076	Ni et al., 2017b
PM_{10}	IN2B H9	g day^{-1}	Standard Deviation	8,238	8,226	Ni et al., 2017b

2.4.3 Manure Shed

Searches by EPA did not find any articles that included data from the manure shed at IN2B.

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 to develop EEMs. 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 swine AFOs.

3.1 NH_3 and H_2S Emissions from Houses and Manure Sheds

The amount of manure produced at a layer house is a key factor influencing NH_3 and H_2S emissions, since this will affect the total amount of NH_3 and H_2S that is generated in the manure (due to microbial degradation of urea, undigested proteins, and amino acids (Mackie et al., 1998)) and released (e.g., movement of gas from manure into the air). Proxies for the amount of fresh manure produced at a layer house are inventory and LAW. Thus, these variables, which were determined daily, were selected for further investigation. For the layer-manure shed, there is on average a 5-day gap between manure production in the house and the manure arriving in the manure-shed. Therefore, variables were created and selected for further investigation for the layer manure shed, which represent a 5-day lag of inventory (adjusted inventory) and LAW (adjusted LAW) from the house values. For the manure-shed, inventory, LAW, adjusted LAW and adjusted inventory represented the sum of inventory and LAW from the two houses the shed was receiving manure from. The amount and content of fresh manure produced by layers can also be influenced by feed characteristics, which can be different for layers depending on their age (Wu-Hann et al. 2007; Li et al. 2013). Accordingly, hen age was selected for further investigation by creating a numeric variable that indicated how many days since the hens were brought into the house. For the layer-manure shed, this variable was the weighted average age of the hens in the two houses that the shed was receiving manure from.

In layer high rise houses, the manure is stored on the bottom floor of the house and thus the amount of manure in the house increases with time, which may influence gas emissions (Liang et al. 2005; Lin et al. 2012a; Li et al. 2013). Therefore, a variable for manure age was created with a numeric value that indicated how many days since the date of the last manure cleanout. This variable was similarly created for layer manure sheds, but not for layer-manure belt houses since this manure management system does not store the manure in the house.

Manure characteristics such as nitrogen and sulfur content, solid and moisture content and pH can influence NH_3 and H_2S emissions. Common measurement of nitrogen and sulfur content that relate to NH_3 and H_2S emissions are total Kjeldahl nitrogen (TKN; NH_3-N + organic

N), total ammoniacal nitrogen (TAN; NH_3-N), and sulfide. Higher concentrations of these nitrogen and sulfur components indicate a greater potential for NH_3 emissions (Groot Koerkamp, 1994) and H_2S emissions. Manure pH can influence emissions as it can affect both the generation of NH_3 in manure and the concentration of NH_3 in layer manure (Tong et al., 2020). Groot Koerkamp, (1994) reported that as manure pH increases above 5.5, the rate of manure degradation increases. Manure pH also influences NH_3 and H_2S concentrations due to its effect on the chemical equilibrium between NH_3 and NH_4^+ and HS^- and H_2S, respectively. Fresh layer manure is excreted with approximately 75% moisture content (Xin et al., 2011) and dries through movement of air caused by ventilation fans. The rate of drying affects the manure solid and moisture content, which influences NH_3 generation within the manure and thus influences emissions (Groot Koerkamp, 1994; Xin et al. 2011). Lower manure solid content and thus higher moisture content increase the generation of NH_3 increases due to the impact of moisture on microbe growth. It is hypothesized that moisture would have a similar effect on H_2S generation. In NAEMS, manure samples at layer sites were taken at a frequency of 2-5 months on average. Manure samples were analyzed for TAN in all samples, but TKN and sulfide were not measured in surface manure in any of the houses, with the exception of one sample taken at CA2B-H6. TAN was selected for further analysis, but TKN and sulfide could not be selected due to the low number of measurements. All collected manure samples were analyzed for solid content and pH, therefore manure solid content and pH were selected for further investigation. For the manure-shed, manure samples were regularly analyzed for TKN concentration in addition to pH, solids content and TAN. Accordingly, for the manure shed, TKN was also selected for further investigation.

House airflow or ventilation rate is a variable that can have a major influence on the emissions of NH_3 and H_2S from manure as it affects the air flow above the manure surface (Tong et al. 2020; Rumsey and Aneja, 2014). An increase in air velocity reduces the boundary layer thickness above the manure surface, thereby lowering the resistance to volatilization and causing an increase in the transfer of NH_3 and H_2S across the air-manure interface (Arogo et al. 1999; Rumsey and Aneja, 2014). However, higher ventilation rates can also dry out layer manure (i.e., increase manure solid content) resulting in lower emissions rates (Ni et al. 2017a). House air flow was measured continuously during NAEMS and was chosen for further analysis. The layer-manure shed was naturally ventilated, and therefore the airflow is not necessarily a function of temperature but could be related to wind speed (Joo et al. 2014). Accordingly, air flow and wind speed, which were measured continuously, were selected for further investigation.

Temperature plays a key role in many of the biological, physical, and chemical processes involved in NH_3 and H_2S generation and release processes, and thus influences NH_3 and H_2S emissions from layer manure. Manure temperature influences the microbial degradation of layer manure, with increasing temperatures resulting in increasing degradation rates (Groot Koerkamp, 1994; Zhao et al. 2013). Increasing manure temperature will also increase the Henry's law constant and dissociation constant for NH_3 and H_2S (Tong et al. 2020; Montes et al. 2009; Rumsey and Aneja, 2014). For NH_3, this increases the potential amount that can be released from the manure into the air. However, for H_2S, an increasing Henry's law constant and dissociation have conflicting effects on the potential amount available, meaning that the overall influence of temperature on H_2S emissions may not be as strong as for NH_3. Increasing manure temperature and air temperature can also increase the transfer of NH_3 and H_2S across the manure-air interface (Ni, 1999, and references within; Montes et al., 2009, and references within; Tong et al. 2020; Rumsey and Aneja, 2014). Note that while the release of NH_3 is controlled by the convective mass transfer release mechanism, the release of H_2S is additionally influenced by bubble-release (ebullition) mechanisms, which can be triggered by manure disturbances (Ni et al., 2009) from animal or management activities inside the house. The effect of temperature on emissions from layer manure is complicated by the relationship between temperature and ventilation rate. In mechanically ventilated houses, increasing ambient and house temperature will result in higher ventilation rates, which as previously described could reduce emissions due to drying of the manure, thus countering the effect temperature has as on other emissions processes. During NAEMS, researchers took continuous measurements of house exhaust temperature (temperature at house fan exhaust) and ambient temperature, and both were chosen for further analysis. For the layer manure-shed, no measurements of shed temperature were made, therefore only ambient temperature was selected for further analysis.

Relative humidity may influence NH_3 and H_2S emissions from layer manure through its effect on manure solids content/moisture content as a higher relative humidity may reduce the evaporation of water from the manure surface, resulting in wetter manure and thus higher NH_3 emissions (Ni et al. 2017a). This effect of relative humidity on NH_3 emissions has also been identified in broiler litter, where increasing relative humidity that varied from 40% to 80% (similar to house exhaust relative humidity measured at NAEMS sites (see Appendix D)) was found to increase NH_3 levels (Weaver and Meijerhof, 1991). It is proposed that relative humidity could affect H_2S emissions similarly. During NAEMS, researchers took continuous measurements of exhaust relative humidity and ambient relative humidity, and both were chosen for further analysis. For the layer manure-shed, no measurements of shed relative humidity were made, therefore only ambient relative humidity was selected for further analysis.

Management activities can also influence gas emissions from layer houses (Lim et al. 2003). There are three major management activities that occur in layer-HR houses: flock emptying and replacement, manure cleanouts, and molting. During flock emptying and replacement there will be different numbers of hens in the house, thus influencing the amount of fresh manure produced. Manure cleanouts involve the removal of manure from the bottom level of the house where the manure is stored. In NAEMS, the manure cleanouts did not occur during periods of flock replacement. During manure cleanouts there is the potential for increases in gas emissions due to the disturbance of manure (Ni et al. 2009). Theoretically, molting can influence NH_3 and H_2S emissions as birds can be given different amounts of feed during molting. In addition, different types of feed can be given to the birds, which could have different nutrient content, thus influencing gas emissions. The influence of flock emptying and replacement, manure cleanouts and molting on layer-HR houses was selected for further investigation. To achieve this, each day for each house was assigned a status of full (F), empty (E), transition to empty or full (T), manure cleanout (C) or molting (M). Similarly, the same statuses with the exception of C status (since manure is not stored in a manure-belt house) were assigned to each day of each house for the manure belt houses. For manure sheds, the only management event that occurs is the removal or cleanout of manure since there are no birds in the shed. Manure cleanouts only occurred for two days during the NAEMS monitoring period. However, house management activities that influence the amount and composition of manure can also potentially affect gas emissions from the manure shed once the manure arrives 5-days later. Therefore, for each day, the manure shed was assigned a status that was a combination of the statuses from 5 days beforehand at house 8 and 9. For example, if house 8 had a status of F and house 9 a status of M, the combined shed status would be FM. Accordingly, each day had a two letter status with the exception of the two days when the manure shed manure clean out occurred. On these days, the letter "C" was added to the two-letter status.

3.2 PM Emissions from House and Manure Sheds

The release of PM into layer house air is caused by the physical suspension of a range of different materials in layer houses including feed, manure, and feathers (Cambra-Lopez et al. 2011). In the manure shed, there are no birds, feed, or recently excreted manure, therefore, the deposition of manure from the belt to the manure pile is probably the main process that causes PM emissions. The amount of PM source materials being transferred from the belt to the manure pile will likely be related to house LAW and inventory, therefore these variables were explored further. Similar to the gases, in addition to the LAW and inventory values, the variables, adjusted inventory and adjusted LAW, which represent a 5-day lag of inventory and LAW from both of the houses were created for further investigation for the layer-manure sheds.

Physical suspension of PMfrom house surfaces can be caused by animal activity, human activity, and air flow (Aarnink and Ellen, 2007). However, house activity measurements were not provided to EPA, therefore the influence of this variable could not be explored further. Ventilation rate or airflow influences house PM emissions by controlling the amount of PM sedimentation in a house (Shepherd et al. 2015). In animal houses or houses, mechanical ventilation is typically a function of ambient temperature and thus house temperature, meaning that temperature could serve as a potential surrogate variable for airflow. The physical suspension of PM can also be influenced by moisture conditions and relative humidity (Cambra-Lopez et al. 2010). The moisture content of feces can be affected by bird water consumption with increased water consumption during warmer months leading to wetter feces (Shepherd et al. 2015). While there was no direct measure of this in NAEMS, measurements of manure solid content could be an indicator, therefore manure solid content was selected for investigation. As mentioned, feed characteristics can be different for layers depending on their age (Li et al. 2013). In addition, hen activity can increase with hen age after initial placement (Li et al. 2013). Both of these factors could potentially influence PM emissions; therefore, hen age was selected for further investigation.

The moisture content of the house air can also influence PM emissions. Takai et al. (1998) reported that a relative humidity greater than 70% results in a high equilibrium moisture content and may contribute to particles aggregating together, resulting in lower concentrations and emissions. However, the 70% RH value reported by Takai et al. (1998) is based on the condensation of water on barley or wheat grains, and it is not known how representative this value is for other types of PM (e.g., different types of feed, manure, and feathers/skin). House exhaust daily RH values at NAEMS layer houses varied from 31.8% to 86.2%, with ADM at different sites varying from 48.7% at IN2H to 68.4% at NC2B (see Appendix D). It should be noted that determining the influence of airflow, temperature and relative humidity on emissions is complex due the intrinsic relationship between these variables in a mechanically ventilated animal house. Accordingly, for layer houses, the continuously measured variables, house exhaust relative humidity, ambient relative humidity, house exhaust temperature, ambient temperature and airflow were selected for further investigation for PM_{10}, $PM_{2.5}$ and TSP emissions from layer houses. As mentioned for layer-manure shed, manure-shed temperature and RH were not measured, therefore only the airflow, ambient temperature and ambient relative humidity variables were selected for further investigation. As stated in Section 3.1, airflow could be related to wind speed (Joo et al. 2014), therefore wind speed was also selected for further investigation.

Management activities can also affect PM emissions from layer houses. Flock emptying and replacement will increase the disturbance of hen feathers, although there will be less birds in the house during this period. Cleaning out of manure from the house will obviously result in increased manure disturbance and thus increase PM emissions. Molting is a management activity that intrinsically involves feather loss, so that can also increase PM emissions, however, it is also a period where reduced or different feed is provided to the birds that could also influence emissions. Accordingly, the influence of management activities was investigated further for PM emissions from layer houses by assigning a status to each day (see Section 3.1 for more information on status assignments). Since there is no manure storage in manure-belt houses, only the flock emptying and replacement, and molting management activities were investigated for this house type. As mentioned previously for the manure shed (Section 3.1), the only management event that occurred during the NAEMS monitoring period was the cleanout of manure, which occurred twice for two single days. However, neither of the two manure removal days coincided with PM measurements. House management activities that influence the amount and solid content of manure can also potentially affect PM emissions from the manure shed once the manure arrives 5 days later. Therefore, the influence of management activities was selected for further investigation using the assigned two letter statuses described in Section 3.1.

4.0 SITE COMPARISON, TRENDS, AND ANALYSIS

Before developing the EEMs, 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 egg-layer houses and associated manure sheds. Parameters of particular interest included inventory, average hen weight, LAW, hen age, house conditions (exhaust temperature, exhaust relative humidity, and airflow), ambient temperature, ambient relative humidity, manure moisture, manure TAN, manure pH, and manure total Kjeldahl Nitrogen (TKN). For the manure shed, additional inventory and LAW parameters were considered that represented a five day lag to account for the average time needed for manure to move to the manure shed.

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 selection criteria issue 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, such as hen age, 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 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 a summary of the manure parameters is presented in Section 4.3. Appendix D contains summary statistics, Appendix E contains the relevant time series plots, and Appendix F contains least squares regression analysis 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

4.1.1 High Rise Houses

Appendix D, Table D-1 presents the summary statistics for daily average emissions of NH_3 for the high rise sites. Daily average NH_3 emissions ranged from 32.27 kg d^{-1} to 248.18 kg d^{-1}. The table indicates the emissions are proportional to inventory. That means the houses with the fewest birds, CA2B, have the lowest average emissions (33.11 and 32.27 kg d^{-1}) and the houses with the largest number of birds, IN2H, have the highest average emissions (224.75 and 248.18 kg d^{-1}). Appendix E, Figure E-1 shows that the emissions can be quite variable at each site, as reiterated by standard deviations that can be as much as half the average value. However, the figure also demonstrates that the houses at the same site are not always in sync with each other, with emissions from one house peaking when the second was much lower. This asynchronous behavior makes it hard to discern any temporal patterns in the data due to seasonal effects. It suggests the emissions from the emissions from individual houses are also dependent on house specific parameters, such as bird weight and ventilation rate, that are not uniform across all houses at the site. The plot of IN2H suggests a peak in emissions following the new year, but that is not consistent across sites. There were only 4 negative values in the NH_3 dataset, two days for both IN2H H6 and H7.

H_2S summary statistics are presented in Appendix D, Table D-2. Average daily H_2S emissions ranged from 39.96 g d^{-1}at CA2B H6 to 301.54 g d^{-1} at IN2H H6. Like the NH_3 emissions, the houses with the most birds (IN2H) have the highest emissions. The emissions from the IN2H houses were typically 5 to 7 times higher than the houses at other sites. Appendix E, Figure E-2 shows H_2S emissions are prone to isolated high daily averages. This can be seen in the NC2B graph in particular as values typically stay below 100 grams per day until the second half of 2008 when a few isolated days jump to emissions greater than 200 grams per day. Figure E-2 of Appendix E also highlights the H_2S dataset had several negative average daily means across all the sites. Negative emissions values can result from instrumentation drift between calibrations, instances where concentration measurements are near the minimum detection limit of the instrument, or instrument fluctuations due to ambient conditions (i.e., ambient concentrations greater than the house concentrations). Furthermore, Appendix E, Figure E-2 shows houses at the same site are not always in sync and peaks at one house do not necessarily mean the other house will peak as well. The best example is CA2B in early 2008, when H5 is experiencing near minimum values but H6 is experiencing maximum values. Appendix E, Figure E-2 does suggest that H_2S emissions peak in the summer. Appendix D, Table D-2 provides counts of the number of days with negative emissions ($N<0$), and notes CA2B H6 had the least with 1 day while IN2H H7 had the most with 24.

For PM_{10}, the summary statistics (Appendix D, Table D-3) show the average daily emission ranges from 959.86 g d^{-1} at CA2B H6 to 4,897.59 g d^{-1} at IN2H H7. The table indicates the houses with the most birds again have the highest average daily emissions. However, the difference is not as drastic as seen with H_2S or NH_3. With the gaseous pollutants, gaseous emissions from IN2H ranged from 4 to 7 times higher than other houses. For PM_{10}, the IN2H emissions dipped slightly to 2-5 times higher than the other houses. Appendix E, Figure E-3 suggests that average daily emissions see an increase in the summer months, which looks consistent across sites and houses. In Appendix E, Figure E-3 there appears to be less asynchronous behavior between the houses, with the exception of IN2H in mid-2007. Most houses had less than 10 days with negative daily emissions (Appendix D, Table D-3), except for IN2H H6, which had 30 days.

The $PM_{2.5}$ average daily emissions are more consistent across sites; compared to NH_3 and H_2S, which seemed to depend on the number of birds present. The average daily emissions for houses (Appendix D, Table D-4) are typically within a factor of two or less of each other. The exception is NC2B H3 at 144.89 g d^{-1}, which has an average daily emissions 7 times lower than the site with the highest average daily emissions, CA2B H5 at 237.47 g d^{-1}. Appendix E, Figure E-4 further supports that $PM_{2.5}$ emissions are generally more consistent, as values from houses at the same site typically have similar concentrations. The sparse temporal nature of the daily values makes it hard to determine if there is a seasonal trend to the data. The number of negative daily averages from the sites varied greatly. Both houses at IN2H had no negative values, while NC2B had 3 and 7 negative values at H3 and H4, respectively. The houses at CA2B had the most negative values with 29 and 25 at H5 and H6, respectively.

The summary statistics for TSP are available in Appendix D, Table D-5. These statistics indicate less of a disparity between houses, with the highest average daily emissions value of

7,803.04 g d^{-1} at site IN2H H6, approximately 2 to 3 times higher than the other houses. Appendix E, Figure E-5 shows some variation between houses at the same site. Similar to $PM_{2.5}$, the sparse temporal nature of the daily values makes it hard to determine if there is a seasonal trend to the data. The TSP dataset had only two negative values at NC2B H4.

4.1.2 Manure Belt Houses

Appendix D, Table D-6 presents the summary statistics for daily average emissions of NH_3 for the manure belt houses. From the table, the average daily emissions are comparable between the two houses with values of 71.54 and 67.05 kg d^{-1} at IN2B H8 and IN2B H9, respectively. Appendix E, Figure E-6 shows that the daily average emissions can be quite variable at each site, as reiterated by standard deviations that can be as much as half the average value. The figure also demonstrates that these houses are in better sync temporally than the high rise houses, with peaks of NH_3 emissions occurring at approximately the same time. The plot shows a peak in emissions at the start of 2009, which coincides with the molting phase in both houses.

H_2S summary statistics are available in Appendix D, Table D-7 and again show comparable average daily emissions, with 492.07 and 471.07 gd-1 at IN2B H8 and IN2B H9, respectively. Appendix E, Figure E-7 generally supports this but shows the highest emissions at each site occur at different times in the study. IN2B H8 saw its highest H_2S emissions over the summer of 2008 while IN2B H9 saw the highest emissions in early 2009. The management of the houses were in sync, with both houses having new flocks placed toward the start of the monitoring period and management phases occurring at similar times. Emissions during these peak periods were comparable and seem within normal operation. The dissociation of the peak emissions is likely due to a subtle management difference in the houses that was not logged or a house environmental factor, like temperature.

For PM_{10}, the summary statistics (Appendix D, Table D-8) are not as consistent as the gaseous pollutants. Average daily emissions for IN2B H8 were 3,038.68 gd^{-1}, while IN2B H9 had an average daily emissions of 6,076.17 gd^{-1}. Appendix E, Figure E-8 shows the collection of PM_{10} at IN2B H8 was not as frequent as H9. The site report indicates that the TEOM at IN2B H8 was in repair for these periods due to various failures with the unit (Ni et al., 2010b). One of the repair periods for IN2B H8 occurred while IN2B H9 had high PM_{10} emissions. It is possible that the absence of similarly high emissions at IN2B H8 at this time is the reason for the higher average emissions at IN2B H9 seen in Appendix D, Table D-8. The table also shows that more negative observations were recorded for PM_{10} than with the gaseous pollutants, possibly due to data measurement limitations discussed in Section 4.1.4. As discussed in Section 2.1 and Appendix B, EPA developed a process to evaluate data that were likely affected by outdoor events, as recommended by the Science Advisory Board review of the initial 2012 models (SAB, 2013). Through this process, erroneous negative data were removed from the final dataset for model development. However, the analysis presented here and in Appendices D through F includes these negative values.

The summary statistics for $PM_{2.5}$ (Appendix D, Table D-9) indicate that data collection for this pollutant proved challenging, as the mean for IN2B H8 is negative and over half of all the readings are negative. Appendix E, Figure E-9 shows that all the observations in the last collection period for IN2B H8 fell below zero. IN2B H9 had fewer negative observations and more observations in total, which yielded a positive average value. Valid negative readings can occur at very low concentrations near the method detection limit. Negative emissions can also occur when ambient concentrations are greater than the house concentrations. In these instances, the calculation to determine the emissions from the house subtract the ambient concentration. If the concentration in the house is lower, an erroneous negative emissions value will result. Section 4.1.4 explores additional concerns about the monitoring set up at IN2H that may contribute to the number of negative values. Similar to the PM_{10} data, EPA processed the $PM_{2.5}$ data further to exclude erroneous data from the final modeling dataset.

The TSP summary statistics (Appendix D, Table D-10) show differences in each house. IN2B H9 has an average daily emissions of 21,870.99 gd^{-1}, which is more than twice IN2B H8, as well as a higher standard deviation, which is larger than the mean. Appendix E, Figure E-10 also shows a high variability in the H9 emissions, especially compared to H8.

4.1.3 Manure Shed

For the manure shed, the emissions for all pollutants were less than the emissions in the houses that supplied manure into the shed. The summary statistics for NH_3 (Appendix D, Table D-6) and H_2S (Appendix D, Table D -7) both show large standard deviations (6.52 kg d^{-1}) compared to the average daily mean (4.74 kg d^{-1}), which suggests highly variable emissions at the manure shed. The time series plots for NH_3 (Appendix E, Figure E-11) and H_2S (Appendix E, Figure E-12) shows some periods of more limited variability around the mean, particularly summer of 2009, along with instances of greater variability paired with spikes in emissions across the monitoring period. Notably, both NH_3 and H_2S both experience their maximum values near the same time in early July 2008. This appears to coincide with wetter manure in the shed. The site report (Ni et al., 2010) notes that on June 29, 2008, a manure pile in the shed was visibly wet. As noted in Section 3.1, higher moisture content results in higher emissions.

PM_{10} (Appendix D, Table D-8; Appendix E, Figure E-13), $PM_{2.5}$ (Appendix D, Table D-9; Appendix E, Figure E-14), and TSP (Appendix D, Table D-10; Appendix E, Figure E-15) observations were also variable, with standard deviations greater than the average across the monitoring period. The time series plots show more day to day variability that the plots for the gaseous species. The variability does not have an obvious pattern but could correlate with a shed environmental factor like temperature, or coincide with movement in the shed, which was not recorded frequently.

4.2 Environmental Parameters

4.2.1 High Rise Houses

The statistical summary of the environmental parameters associated with high rise laying houses are presented in Appendix D, Table D-11. The inventory varies widely across the sites, with CA2B having just over 32,000 birds in each house to IN2H with just over 218,000 birds in each house. Appendix E, Figure E-16 shows that the number of birds present in each house over the course of NAEMS was fairly consistent. However, each house did have a restocking event during the course of the study, where the existing flock of birds was removed, the house remained empty for at least one day, and then a new flock of birds was placed in the house. 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 positive relationship with inventory across all pollutants, which is consistent with literature.

Hen weight was fairly consistent across the houses with the average hen weight ranging from 1.44 to 1.66 kg. Weight varied the most at CA2B, as the standard deviations were 0.13 and 0.12 kg for H5 and H6, respectively. The remaining houses had standard deviation values less than 0.09 kg. Appendix E, Figure E-17 shows this increased variability at CA2B, as compared to the other sites. With the consistent weight over the NAEMS period, the regression analysis (Appendix F, Figures F-6 through F-10, summary in Table 4-2) showed weak correlations between hen weight and all the pollutants.

Combining inventory with hen weight, LAW (inventory * hen weight), can be predictive of emissions. With little variation in hen weight across houses in the study, the inventory drives the differences between the houses. That is, the site with the largest inventory (IN2H) has the highest LAW. Much like the inventory trend, Appendix E, Figure E-18 shows the LAW trend is relatively stable with some variation during the low weight times of hen replacement and molting. The regression analysis (Appendix F, Figures F-11 through F-15, summary in Table 4-2) showed modest correlations between LAW and each pollutant, which were consistent with the inventory correlations.

EPA derived a hen age variable based on days since placed in the house, for those flocks placed during the study. As expected, the trends for hen age in Appendix E, Figure E-19 show a steady increase over the study. The regression analysis (Appendix F, Figures F-16 through F-20, summary in Table 4-2) only shows weak correlations between hen age and each pollutant. An age was not established for flocks already in the house when the monitoring started, and therefore limited the data available for this parameter.

Table 4-2. Bird specific parameters regression analysis for high rise houses.

Pollutant	Parameter	R^2	Strength	Figure
NH_3	Inventory	0.6781	Moderately Strong	Appendix E, E-1
H_2S	Inventory	0.3377	Modest	Appendix E, E-2
PM_{10}	Inventory	0.2583	Modest	Appendix E, E-3
$PM_{2.5}$	Inventory	0.0008	Slight or weak	Appendix E, E-4
TSP	Inventory	0.2475	Modest	Appendix E, E-5
NH_3	Hen weight	0.1012	Slight or weak	Appendix E, E-6
H_2S	Hen weight	0.0489	Slight or weak	Appendix E, E-7
PM_{10}	Hen weight	0.1969	Slight or weak	Appendix E, E-8
$PM_{2.5}$	Hen weight	0.1942	Slight or weak	Appendix E, E-9
TSP	Hen weight	0.2080	Modest	Appendix E, E-10
NH_3	LAW	0.6869	Moderately strong	Appendix E, E-11
H_2S	LAW	0.3328	Modest	Appendix E, E-12
PM_{10}	LAW	0.2269	Modest	Appendix E, E-13
$PM_{2.5}$	LAW	0.0020	Slight or weak	Appendix E, E-14
TSP	LAW	0.2247	Modest	Appendix E, E-15
NH_3	Hen age	0.0253	Slight or weak	Appendix E, E-16
H_2S	Hen age	0.0008	Slight or weak	Appendix E, E-17
PM_{10}	Hen age	0.0244	Slight or weak	Appendix E, E-18
$PM_{2.5}$	Hen age	0.0279	Slight or weak	Appendix E, E-19
TSP	Hen age	0.0017	Slight or weak	Appendix E, E-20

Appendix D, Table D-11 shows all the houses maintained a similar range of relative humidities across the study, with average daily values ranging from 48.72% at IN2H H6 to 68.40% at NC2B H3. The trends in house relative humidity shown in Appendix E, Figure E-20 appear to have some seasonality, with values increasing over the winter months and then decreasing after the New Year to a low in spring. Values pick up from spring, but there is not a consistent peak in the summer across sites. Relative humidities at the houses are more variable over the summer before settling back into a decline for winter. Values do exceed 70% at CA2B and NC2B, which could limit PM emissions, as noted in Section 3.2. Regression analysis (Appendix F, Figures F-26 through F-30, summary in Table 4-3) shows a weak relationship with house relative humidity and pollutant emissions.

The mean daily house temperature (Appendix D, Table D-11) is very consistent across the sites, with less than a 2 degree variation. Appendix E, Figure E-21 shows that the temperature is fairly constant for the year, with some lower temperatures coinciding with the time when hens were removed from the house. With the controlled temperatures in the house, the regression analysis (Appendix F, Figures F-21 through F-25, summary in Table 4-3) showed only a weak relationship between house temperature and each pollutant.

Unlike house relative humidity and temperature, airflow varied between sites and houses. Table C-12 shows the average daily airflow rate was proportional with the inventory, meaning that the house with higher inventories had high average air flow rates. Appendix E, Figure E-22 shows a strong seasonal pattern at each site, with air flow rate peaking in the summer in an effort to keep the houses within the desired temperature range for the birds. The regression analysis (Appendix F, Figures F-31 through F-35, summary in Table 4-3) only indicates a weak linear relationship between airflow and any of the pollutants.

Table 4-3. House specific parameters regression analysis for high rise houses.

Pollutant	Parameter	R^2	Strength	Figure
NH_3	Exhaust temperature	0.0343	Slight or weak	Appendix E, E-21
H_2S	Exhaust temperature	0.0367	Slight or weak	Appendix E, E-22
PM_{10}	Exhaust temperature	0.0278	Slight or weak	Appendix E, E-23
$PM_{2.5}$	Exhaust temperature	0.4068	Moderate	Appendix E, E-24
TSP	Exhaust temperature	0.0143	Slight or weak	Appendix E, E-25
NH_3	House relative humidity	0.1701	Slight or weak	Appendix E, E-26
H_2S	House relative humidity	0.0514	Slight or weak	Appendix E, E-27
PM_{10}	House relative humidity	0.0852	Slight or weak	Appendix E, E-28
$PM_{2.5}$	House relative humidity	0.0410	Slight or weak	Appendix E, E-29
TSP	House relative humidity	0.0650	Slight or weak	Appendix E, E-30
NH_3	Airflow	0.0463	Slight or weak	Appendix E, E-31
H_2S	Airflow	0.3029	Modest	Appendix E, E-32
PM_{10}	Airflow	0.1737	Slight or weak	Appendix E, E-33
$PM_{2.5}$	Airflow	0.1331	Slight or weak	Appendix E, E-34
TSP	Airflow	0.0057	Slight or weak	Appendix E, E-35

The statistical summary of the ambient parameters for the high rise sites is presented in Appendix D, Table D-14. The table shows that while the sites had different average ambient relative humidities, they were subject to the same range of values across the study. Appendix E, Figure E-23 shows some seasonality to the measurements, but these patterns vary between the sites. CA2B and IN2H have peaks at the start of the year, with lows midyear. The values for NC2B are more scattered, with high values occurring all year. If we look at the minimum values (i.e., the bottom edge of the scatter), it appears as though the lowest values occur at the start of the year with low values less likely for the summer months. The regression analysis (Appendix F Figures F-41 through F-45, summarized in Table 4-4) showed ambient relative humidity correlation with each pollutant emissions were comparable to the relationship with the house relative humidity.

For ambient temperature, the average daily temperature is lowest at IN2H followed by NC2B, and CA2B. The sites did have variation in the range of temperatures covered, as CA2B was not exposed to freezing temperatures, but IN2H and NC2B were. The temporal trend in ambient temperature is as expected, with Appendix E, Figure E-24 showing peaks in the July timeframe and lows after the new year. The regression analysis (Appendix F Figures F-36 through F-40, summarized in Table 4-4) showed ambient temperature had a similar relationship to pollutant emissions as house temperature.

Table 4-4. Ambient parameters regression analysis for high rise houses.

Pollutant	Parameter	R^2	Strength	Figure
NH_3	Ambient temperature	0.1192	Slight or weak	Appendix E, E-36
H_2S	Ambient temperature	0.0341	Slight or weak	Appendix E, E-37
PM_{10}	Ambient temperature	0.0165	Slight or weak	Appendix E, E-38
$PM_{2.5}$	Ambient temperature	0.3637	Modest	Appendix E, E-39
TSP	Ambient temperature	0.0959	Slight or weak	Appendix E, E-40
NH_3	Ambient relative humidity	0.0684	Slight or weak	Appendix E, E-41
H_2S	Ambient relative humidity	0.0088	Slight or weak	Appendix E, E-42
PM_{10}	Ambient relative humidity	0.0018	Slight or weak	Appendix E, E-43
$PM_{2.5}$	Ambient relative humidity	0.2103	Modest	Appendix E, E-44
TSP	Ambient relative humidity	0.0051	Slight or weak	Appendix E, E-45

4.2.2 Manure Belt Houses

The statistical summary of the environmental parameters associated with manure belt houses are presented in Appendix D, Table D-12. Time series plots of each parameter are available in Appendix E, Figures E-25 through E-33.

The inventory was fairly consistent between the two houses, with a population of approximately 250,000 birds in each house. Appendix E, Figure E-25 shows that the number of birds present over the course of NAEMS was fairly consistent. The exception is the restocking event at IN2B H9, where the existing flock of birds were removed, the house remained empty for at least one day, and then a new flock of birds was placed in the house. The flock replacement for IN2B H8 occurred just before the start of the study. Appendix F Figures F-63 through F-67, summarized in Table 4-5, show the scatter plots of inventory versus each pollutant. In general, there is a weak positive relationship with inventory across all pollutants, which is consistent with literature. The relationship is weaker than what was seen for high rise houses as the manure is being removed from the house daily, as opposed to accumulating over an extended period of time.

Hen weight is also consistent between the two houses, with a typical weight of 1.4 kg. Appendix E, Figure E-26 shows that hen weight over the course of NAEMS was fairly consistent, except for the dip during the molting process, which occurred midway through the study. Appendix F, Figures F-68 through F-72 show the scatter plots of hen weight versus each pollutant. In general, there is a slight or weak positive relationship with hen weight across all pollutants. Similar to inventory and hen weight, LAW is consistent between the houses (Table C-13). Live animal weight follows a similar trend to hen weight, which is fairly constant except for a dip during the molting period (Appendix E, Figure E-27). Appendix F, Figures F-73 through F-67 are regression plots, summarized in Table 4-5, which suggest a weak positive relationship between LAW and each pollutant.

Hen age was also explored (Appendix E, Figure E-28) as a parameter. Appendix F Figures F-78 through F-82, summarized in Table 4-5, show the scatter plots of hen age versus each pollutant. In general, there is a weak negative relationship across all pollutants.

Table 4-5. Bird specific parameters regression analysis for manure belt houses.

Pollutant	Parameter	R^2	Strength	Figure
H_2S	Inventory	0.0870	Slight or weak	Appendix E, E-64
NH_3	Inventory	0.0524	Slight or weak	Appendix E, E-63
PM_{10}	Inventory	0.0241	Slight or weak	Appendix E, E-65
$PM_{2.5}$	Inventory	0.3679	Modest	Appendix E, E-66
TSP	Inventory	0.0012	Slight or weak	Appendix E, E-67
H_2S	Hen weight	0.0161	Slight or weak	Appendix E, E-69
NH_3	Hen weight	0.0461	Slight or weak	Appendix E, E-68
PM_{10}	Hen weight	0.0009	Slight or weak	Appendix E, E-70
$PM_{2.5}$	Hen weight	0.1552	Slight or weak	Appendix E, E-71
TSP	Hen weight	0.0087	Slight or weak	Appendix E, E-72
H_2S	LAW	0.0819	Slight or weak	Appendix E, E-74
NH_3	LAW	0.0833	Slight or weak	Appendix E, E-73
PM_{10}	LAW	0.0207	Slight or weak	Appendix E, E-75
$PM_{2.5}$	LAW	0.0357	Slight or weak	Appendix E, E-76
TSP	LAW	0.0096	Slight or weak	Appendix E, E-77
H_2S	Hen age	0.1609	Slight or weak	Appendix E, E-79
NH_3	Hen age	0.0405	Slight or weak	Appendix E, E-78
PM_{10}	Hen age	0.1006	Slight or weak	Appendix E, E-80
$PM_{2.5}$	Hen age	0.0593	Slight or weak	Appendix E, E-81
TSP	Hen age	0.0626	Slight or weak	Appendix E, E-82

House relative humidity was slightly higher in IN2B H9 for most of the study. The summary statistics for relative humidity are 3-6% higher in IN2B H9 than IN2B H8 and the time series in Appendix E, Figure E-29 is higher for IN2B H9 than IN2B H8 almost every day. The other house parameters, temperature (Appendix E, Figure E-30) and airflow (Appendix E, Figure E-31), were fairly consistent between the houses. The only exception was a drop in temperature in IN2B H9 while the flock was being replaced. The regression analysis of house relative humidity (Appendix F, Figures F-88 through F-92, summarized in Table 4-6) showed a weak positive relationship for the gaseous species and a slight or weak negative relationship for PM_{10}, which was consistent with expectations. The plots suggested $PM_{2.5}$ and house relative humidity had a neutral/no relationship and TSP had a weak positive relationship. The limited number of observations for each pollutant are the likely cause of the inconsistent relationship with PM_{10}. Both the house exhaust temperature (Appendix F, Figures F-83 through F-87, summarized in Table 4-6) and airflow (Appendix F, Figures F-93 through F-97, summarized in 6) regressions showed slight linear relationships with the pollutants.

The statistical summary of the ambient parameters for the manure belt site is presented in Appendix D, Table D-12. Both the ambient relative humidity (Appendix E, Figure E-32) and temperature (Appendix E, Figure E-33) follow the typical seasonal patterns expected in Indiana. The linear regression analysis plots of ambient parameters (Appendix F, Figure F-98 through F-107, summarized in Table 4-7) show weak relationships that are not consistent across the gaseous pollutants or PM species.

Table 4-6. House specific parameters regression analysis for manure belt houses.

Pollutant	Parameter	R^2	Strength	Figure
H_2S	Exhaust temperature	0.0716	Slight or weak	Appendix E, E-84
NH_3	Exhaust temperature	0.00004	Slight or weak	Appendix E, E-83
PM_{10}	Exhaust temperature	0.0033	Slight or weak	Appendix E, E-85
$PM_{2.5}$	Exhaust temperature	0.1947	Slight or weak	Appendix E, E-86
TSP	Exhaust temperature	0.0201	Slight or weak	Appendix E, E-87
H_2S	House relative humidity	0.0398	Slight or weak	Appendix E, E-89
NH_3	House relative humidity	0.1474	Slight or weak	Appendix E, E-88
PM_{10}	House relative humidity	0.0031	Slight or weak	Appendix E, E-90
$PM_{2.5}$	House relative humidity	0.0006	Slight or weak	Appendix E, E-91
TSP	House relative humidity	0.0302	Slight or weak	Appendix E, E-92
H_2S	Airflow	0.0450	Slight or weak	Appendix E, E-94
NH_3	Airflow	0.0078	Slight or weak	Appendix E, E-93
PM_{10}	Airflow	0.0016	Slight or weak	Appendix E, E-95
$PM_{2.5}$	Airflow	0.2047	Modest	Appendix E, E-96
TSP	Airflow	0.1518	Slight or weak	Appendix E, E-97

Table 4-7. Ambient parameter regression analysis for manure belt houses.

Pollutant	Parameter	R^2	Strength	Figure
H_2S	Ambient relative humidity	0.0010	Slight or weak	Appendix E, E-104
NH_3	Ambient relative humidity	0.0883	Slight or weak	Appendix E, E-103
PM_{10}	Ambient relative humidity	0.0008	Slight or weak	Appendix E, E-105
$PM_{2.5}$	Ambient relative humidity	0.0863	Slight or weak	Appendix E, E-106
TSP	Ambient relative humidity	0.0242	Slight or weak	Appendix E, E-107
H_2S	Ambient temperature	0.0162	Slight or weak	Appendix E, E-99
NH_3	Ambient temperature	0.0964	Slight or weak	Appendix E, E-98
PM_{10}	Ambient temperature	0.0010	Slight or weak	Appendix E, E-100
$PM_{2.5}$	Ambient temperature	0.1353	Slight or weak	Appendix E, E-101
TSP	Ambient temperature	0.0733	Slight or weak	Appendix E, E-102

4.2.3 Manure Shed

The statistical summary of the environmental parameters associated with the monitored manure shed are presented in Appendix D, Table D-12. For inventory (Appendix E, Figure E-34) and LAW (Appendix E, Figure E-37) the combined value from both houses were examined, as well as a version that represented a five-day lag from the emissions (Appendix E, Figures E-35 and E-38). Due to the scale of the plots, the five-day shift is indistinguishable. The summary statistics and plots for the inventory show it was relatively constant for the study, except when the flock was replaced at IN2B H9 in late 2008. Plots for LAW are similar, except there is a little more variation across the year. Appendix F, Figures F-120 through F-124 (summarized in Table 4-8) show the scatter plots of inventory, both lagged and not, versus each pollutant. Appendix F, Figures F-130 through F-134 show the scatter plots of LAW, both lagged and not, versus each pollutant. Table 4-8 summarizes the results for both sets of parameters. The analysis shows weak to modest linear relationship with inventory and the emissions of each pollutant.

Average hen weight saw fluctuations over the study period as new birds were added and during the molting phase (Appendix E, Figure E-36), which contributed to most of the variability in LAW. Appendix F, Figures F-125 through F-129, summarized in Table 4-8, show the scatter plots of average hen weight versus each pollutant, which showed a slight linear relationship. Average hen age (Appendix E, Figure E-39) was also examined. The value represented the average age across the two houses contributing to the manure shed. Appendix F, Figures F-135 through F-139 show the scatter plots of average hen age versus each pollutant, which showed a slight linear relationship for all pollutants except $PM_{2.5}$, which had a moderate negative linear relationship.

Table 4-8. Bird specific parameters regression analysis for manure sheds.

Pollutant	Parameter	R^2	Strength	Figure
NH_3	Inventory	0.0152	Slight or weak	Appendix E, E-120
H_2S	Inventory	0.0158	Slight or weak	Appendix E, E-121
PM_{10}	Inventory	0.3074	Modest	Appendix E, E-122
$PM_{2.5}$	Inventory	0.3074	modest	Appendix E, E-123
TSP	Inventory	0.0216	Slight or weak	Appendix E, E-124
NH_3	Inventory, 5 day lag	0.0147	Slight or weak	Appendix E, E-120
H_2S	Inventory, 5 day lag	0.0120	Slight or weak	Appendix E, E-121
PM_{10}	Inventory, 5 day lag	0.3074	Modest	Appendix E, E-122
$PM_{2.5}$	Inventory, 5 day lag	0.3074	Modest	Appendix E, E-123
TSP	Inventory, 5 day lag	0.0206	Slight or weak	Appendix E, E-124
NH_3	Hen weight	0.0003	Slight or weak	Appendix E, E-125
H_2S	Hen weight	0.0278	Slight or weak	Appendix E, E-126
PM_{10}	Hen weight	0.0214	Slight or weak	Appendix E, E-127
$PM_{2.5}$	Hen weight	0.1815	Slight or weak	Appendix E, E-128
TSP	Hen weight	0.0404	Slight or weak	Appendix E, E-129
NH_3	LAW	0.0026	Slight or weak	Appendix E, E-130
H_2S	LAW	0.0014	Slight or weak	Appendix E, E-131
PM_{10}	LAW	0.1730	Slight or weak	Appendix E, E-132
$PM_{2.5}$	LAW	0.2852	Modest	Appendix E, E-133
TSP	LAW	0.0838	Slight or weak	Appendix E, E-134
NH_3	LAW, 5 day lag	0.0000	Slight or weak	Appendix E, E-130
H_2S	LAW, 5 day lag	0.0102	Slight or weak	Appendix E, E-131
PM_{10}	LAW, 5 day lag	0.0164	Slight or weak	Appendix E, E-132
$PM_{2.5}$	LAW, 5 day lag	0.2464	Modest	Appendix E, E-133
TSP	LAW, 5 day lag	0.0954	Slight or weak	Appendix E, E-134
NH_3	Hen age	0.0206	Slight or weak	Appendix E, E-135
H_2S	Hen age	0.0530	Slight or weak	Appendix E, E-136
PM_{10}	Hen age	0.0006	Slight or weak	Appendix E, E-137
$PM_{2.5}$	Hen age	0.4424	Moderate	Appendix E, E-138
TSP	Hen age	0.0717	Slight or weak	Appendix E, E-139

Reviewing the typical house parameters, the manure shed was naturally ventilated and maintained a temperature and humidity that approximated the ambient conditions. Since the manure shed is naturally ventilated, the airflow was estimated using wind velocity measurements from five 2-D sonic anemometers and two impeller anemometers (Ni et al. 2010b). Since the airflow (Appendix E, Figure E-40) is based on ambient wind flow through the house and is not dependent on temperature, it does not follow any seasonal trends. The scatter plots (Appendix F, Figures F-140 through F-144, summarized in Table 4-9) show at least a modest positive relationship with gaseous emissions and a weak positive relationship with PM.

The statistical summary of the ambient parameters for the manure shed is presented in Appendix D, Table D-12. Both the ambient relative humidity (Appendix E, Figure E-41) and temperature (Appendix E, Figure E-42) follow the typical seasonal patterns expected in Indiana. The linear regression analysis plots (Appendix F, Figures F-145 through F-154, summarized in Table 4-9) show weak relationships that are not consistent across the gaseous pollutants or PM species.

The wind speed was examined for manure shed, as it may be related to airflow through the shed. Wind speeds (Appendix D, Table D-12) ranged from 0.04 to 8.54 ms^{-1} over the monitoring period, with an average of 0.73 ms^{-1}. Appendix E, Figure E-43 reiterates that most wind speeds are below 1 ms^{-1}, with occasional spikes likely related to synoptic events. The linear regression analysis plots (Appendix F, Figure F-155 through F-159, summarized in Table 4-9) show weak positive relationships across all pollutants.

Table 4-9. House and ambient parameter regression analysis for manure sheds.

Pollutant	Parameter	R^2	Strength	Figure
NH_3	Airflow	0.4745	Moderate	Appendix E, E-140
H_2S	Airflow	0.3917	Modest	Appendix E, E-141
PM_{10}	Airflow	0.1877	Slight or weak	Appendix E, E-142
$PM_{2.5}$	Airflow	0.6428	Moderately strong	Appendix E, E-143
TSP	Airflow	0.0689	Slight or weak	Appendix E, E-144
NH_3	Ambient temperature	0.0328	Slight or weak	Appendix E, E-145
H_2S	Ambient temperature	0.0813	Slight or weak	Appendix E, E-146
PM_{10}	Ambient temperature	0.0030	Slight or weak	Appendix E, E-147
$PM_{2.5}$	Ambient temperature	0.0040	Slight or weak	Appendix E, E-148
TSP	Ambient temperature	0.0069	Slight or weak	Appendix E, E-149
NH_3	Ambient relative humidity	0.0057	Slight or weak	Appendix E, E-150
H_2S	Ambient relative humidity	0.0200	Slight or weak	Appendix E, E-151
PM_{10}	Ambient relative humidity	0.0065	Slight or weak	Appendix E, E-152
$PM_{2.5}$	Ambient relative humidity	0.1697	Slight or weak	Appendix E, E-153
TSP	Ambient relative humidity	0.0066	Slight or weak	Appendix E, E-154
NH_3	Wind Speed	0.0017	Slight or weak	Appendix E, E-155
H_2S	Wind Speed	0.0022	Slight or weak	Appendix E, E-156
PM_{10}	Wind Speed	0.0058	Slight or weak	Appendix E, E-157
$PM_{2.5}$	Wind Speed	0.0086	Slight or weak	Appendix E, E-158
TSP	Wind Speed	0.0001	Slight or weak	Appendix E, E-159

4.3 Manure Parameters

4.3.1 High Rise Houses

Appendix D, Table D-14 summarizes manure parameters for the high rise houses. For manure age, as determined from reports of house clean outs, the time the manure was left in the house varied between sites and the houses at each site. CA2B cleaned out the stored manure more frequently than NC2B or IN2H. Appendix E, Figure E-44 shows the episodic cleaning at

CA2B (seven times), and less frequent clean outs at IN2H (one time) and NC2B (three time). Appendix F Figures F-46 through F-50 show the scatter plots of manure age versus each pollutant, which are summarized in Table 4-10. The analysis shows only a weak linear relationship with manure age and the emissions of each pollutant.

The average pH at the sites (Appendix D, Table D-15) ranged from 7.60 (CA2B H6) to 8.50 (IN2H H7). All readings fell within the range of 6.40 (CA2B H6) to 8.79 (IN2H H7). When plotted (Appendix E, Figure E-45), the sparse nature of the measurements makes it difficult to discern any trends. The regression analysis (Appendix F Figures F-51 through F-54) showed pH had a weak linear relationship to the emissions of NH_3, H_2S, and PM_{10}. For $PM_{2.5}$ and TSP emissions, there was not sufficient measurement data to conduct a linear regression analysis.

For the percent solids composition, average values were higher at CA2B, with IN2H and NC2B having slightly lower values. Again, the sparse nature of the readings makes it difficult to discern any trends or consistent temporal patterns in the measurements (Appendix E, Figure E-46). The regression analysis (Appendix F Figures F-55 through F-58) showed percent solids composition had a weak linear relationship to the emissions of NH_3, H_2S, and PM_{10}. Again, there were insufficient measurement data to conduct a regression analysis for $PM_{2.5}$ and TSP emissions.

For the percent total ammoniacal nitrogen (TAN), no sites had observations above 1%. IN2H saw the highest values followed by NC2B and CA2B. As with the other manure parameters, the sparse nature of the readings makes it difficult to discern any trends or consistent temporal patterns in the measurements (Appendix E, Figure E-47). The regression analysis (Appendix F Figures F-59 through F-62) showed TAN had a weak linear relationship to the emissions of NH_3, H_2S, and PM_{10}. Again, there were insufficient measurement data to conduct a regression analysis for $PM_{2.5}$ and TSP emissions.

Table 4-10. Manure parameter regression analysis for high rise houses.

Pollutant	Parameter	R^2	Strength	Figure
NH_3	Manure age	0.1874	Slight or weak	Appendix E, E-46
H_2S	Manure age	0.0037	Slight or weak	Appendix E, E-47
PM_{10}	Manure age	0.1625	Slight or weak	Appendix E, E-48
$PM_{2.5}$	Manure age	0.1126	Slight or weak	Appendix E, E-49
TSP	Manure age	0.0616	Slight or weak	Appendix E, E-50
NH_3	pH	0.2607	Modest	Appendix E, E-51
H_2S	pH	0.0963	Slight or weak	Appendix E, E-52
PM_{10}	pH	0.1496	Slight or weak	Appendix E, E-53
$PM_{2.5}$	pH	[a]	[a]	[a]
TSP	pH	[a]	[a]	Appendix E, E-54
NH_3	Solids	0.1597	Slight or weak	Appendix E, E-55
H_2S	Solids	0.0114	Slight or weak	Appendix E, E-56
PM_{10}	Solids	0.1154	Slight or weak	Appendix E, E-57
$PM_{2.5}$	Solids	[a]	[a]	[a]
TSP	Solids	[a]		Appendix E, E-58
NH_3	TAN	0.4703	Moderate	Appendix E, E-59
H_2S	TAN	0.0796	Slight or weak	Appendix E, E-60
PM_{10}	TAN	0.1273	Slight or weak	Appendix E, E-61
$PM_{2.5}$	TAN	[a]	[a]	[a]
TSP	TAN	[a]	[a]	Appendix E, E-62

[a] EPA did not have sufficient measurement data from NAEMS to conduct a linear regression analysis

4.3.2 Manure Belt Houses

Appendix D, Table D-15 summarizes manure parameters for the manure belt houses. For pH, the average at the site (Appendix D, Table D-16) ranged from a minimum of 7.08 (H9) to a maximum of 8.53 (H9). The average pH was slightly higher at H8 (7.98) than for H9 (7.77). When plotted (Appendix E, Figure E-48), the sparse nature of the measurements makes it difficult to discern any seasonal trends. The regression analysis (Appendix F, Figures F-108 through F-111), summarized in Table 4-11, showed pH had a weak linear relationship to the emissions of NH_3, H_2S, PM_{10}, and TSP. For $PM_{2.5}$, there was not sufficient measurement data to conduct a linear regression analysis as the manure collection events did not coincide with any $PM_{2.5}$ monitoring days.

For the percent solids composition, the values between the two houses were relatively consistent. Again, the sparse nature of the readings makes it difficult to discern any trends or consistent temporal patterns in the measurements (Appendix E, Figure E-49). The regression analysis (Appendix F, Figures F-112 through F-115, summary in Table 4-11) showed percent solids composition had a weak linear relationship to the emissions of NH_3, H_2S, and TSP. There was a modest relationship with PM_{10}. Again, there were insufficient measurement data to conduct a regression analysis for $PM_{2.5}$ emissions since the manure sampling did not coincide with days with $PM_{2.5}$ emissions measurements.

For the percent total ammoniacal nitrogen (TAN), no sites had observations above 1%. As with the other manure parameters, the sparse nature of the readings makes it difficult to discern any trends or consistent temporal patterns in the measurements (Appendix E, Figure E-50). The regression analysis (Appendix F, Figures F-116 through F-119, summary in Table 4-11) showed TAN had a weak linear relationship to the emissions of NH_3, H_2S, and PM_{10}. There was a modest relationship with TSP. Again, there were insufficient measurement data to conduct a regression analysis for $PM_{2.5}$ emissions.

Table 4-11. Manure parameter regression analysis for manure belt houses.

Pollutant	Parameter	R^2	Strength	Figure
H_2S	pH	0.0783	Slight or weak	Appendix E, E-109
NH_3	pH	0.0231	Slight or weak	Appendix E, E-108
PM_{10}	pH	0.1230	Slight or weak	Appendix E, E-110
$PM_{2.5}$	pH	[a]	[a]	[a]
TSP	pH	0.02	Slight or weak	Appendix E, E-111
H_2S	Solids	0.0122	Slight or weak	Appendix E, E-113
NH_3	Solids	0.1110	Slight or weak	Appendix E, E-112
PM_{10}	Solids	0.2291	Modest	Appendix E, E-114
$PM_{2.5}$	Solids	[a]	[a]	[a]
TSP	Solids	0.057	Slight or weak	Appendix E, E-115
H_2S	TAN	0.1739	Slight or weak	Appendix E, E-117
NH_3	TAN	0.0115	Slight or weak	Appendix E, E-116
PM_{10}	TAN	0.0119	Slight or weak	Appendix E, E-118
$PM_{2.5}$	TAN	[a]	[a]	[a]
TSP	TAN	0.219	Modest	Appendix E, E-119

[a] EPA did not have sufficient measurement data from NAEMS to conduct a linear regression analysis.

4.3.3 Manure Shed

Appendix D, Table D-15 summarizes manure parameters for the manure shed. Compared to the manure samples taken from the belt house, the manure shed samples have similar pH values. The manure shed samples have a higher solids content and a lower TAN, both of which are due to the manure drying process which reduces moisture.

For the manure shed, manure age was determined based on the clean out dates reported in the site report. This is an approximate age, as the contents of the shed may not have been completely emptied at each removal event. Appendix E, Figure E-51 shows one removal event reported on June 5, 2009. Appendix F, Figures F-160 through F-164, summarized in Table 4-12, show the scatter plots of manure age versus each pollutant. The analysis shows only a weak positive linear relationship with manure age and the gaseous pollutants, and weak negative or neutral relationship with the PM species.

The pH values for the manure shed ranged from 7.31 to 8.76 (Appendix D, Table D-15). The percent solids composition for the manure shed ranged from 49.90 to 86.05%, TAN values ranged from 0.26 % to 0.80%, and the percent TKN values ranged from 2.38 to 4.69% (Appendix D, Table D-16). The infrequent manure sample collection results in sparse scatter plots of the manure parameters (Appendix E, Figure E-52 through E-55), and makes it difficult to draw definitive conclusions about any seasonal trends in the parameters.

There was not sufficient measurement data to conduct a linear regression analysis between $PM_{2.5}$ or TSP and the manure parameters. The regression analysis with pH (Appendix F, Figures F-165 through F-167, summary in Table 4-12) showed a moderate positive linear relationship to the emissions of NH_3, and H_2S, and only a weak relationship with PM_{10}. Both solids composition (Appendix F, Figures F-168 through F-170) and TAN (Appendix F, Figures F-171 through F-173), showed a slight linear relationship to the emissions of NH_3, H_2S. For PM_{10}, solids composition had a weak relationship. However, there was a strong positive relationship between TAN and PM_{10}. The strong relationship with PM_{10} is based on only three observations and thus should not be taken as a definitive relationship. TKN (Appendix F, Figures F-174 through F-176, summary in Table 4-12) had a moderate positive linear relationship to NH_3 and a weak positive relationship with H_2S. TKN also showed a moderately strong negative relationship with PM_{10}., which was again only based on three observations and should not be considered definitive.

Table 4-12. Manure parameter regression analysis for manure belt houses.

Pollutant	Parameter	R^2	Figure	Strength
NH_3	Manure age	0.0277	Slight or weak	Appendix E, E-160
H_2S	Manure age	0.0251	Slight or weak	Appendix E, E-161
PM_{10}	Manure age	0.0010	Slight or weak	Appendix E, E-162
$PM_{2.5}$	Manure age	0.0080	Slight or weak	Appendix E, E-163
TSP	Manure age	0.0904	Slight or weak	Appendix E, E-164
NH_3	pH	0.4836	Moderate	Appendix E, E-165
H_2S	pH	0.7927	Moderately strong	Appendix E, E-166
PM_{10}	pH	0.0869	Slight or weak	Appendix E, E-167
$PM_{2.5}$	pH	[a]	[a]	[a]
TSP	pH	[a]	[a]	[a]
NH_3	Solids	0.0066	Slight or weak	Appendix E, E-168
H_2S	Solids	0.0406	Slight or weak	Appendix E, E-169
PM_{10}	Solids	0.1666	Slight or weak	Appendix E, E-170
$PM_{2.5}$	Solids	[a]	[a]	[a]
TSP	Solids	[a]	[a]	[a]
NH_3	TAN	0.1008	Slight or weak	Appendix E, E-171
H_2S	TAN	0.0067	Slight or weak	Appendix E, E-172
PM_{10}	TAN	0.9321	Strong	Appendix E, E-173
$PM_{2.5}$	TAN	[a]	[a]	[a]
TSP	TAN	[a]	[a]	[a]
NH_3	TKN	0.2271	Modest	Appendix E, E-174
H_2S	TKN	0.1150	Slight or weak	Appendix E, E-175
PM_{10}	TKN	0.7744	Moderately strong	Appendix E, E-176
$PM_{2.5}$	TKN	[a]	[a]	[a]
TSP	TKN	[a]	[a]	[a]

[a] EPA did not have sufficient measurement data from NAEMS to conduct a linear regression analysis.

5.0 DEVELOPMENT AND SELECTION OF MODELS FOR DAILY EMISSIONS

5.1 High Rise Operations

The literature review (Section 3) and exploratory data analysis (Section 4) suggested that EPA should consider ambient temperature, exhaust temperature, ambient relative humidity, exhaust relative humidity, management phase, manure age, hen age, inventory, and LAW in the development of the emissions models for the layer high rise houses. House airflow, or ventilation rate, can have a substantial influence on the emissions rate of gaseous pollutants, but was not included in the parameter list as it may not be easily obtained at all farms. Since ventilation rate is essentially driven by the temperature (i.e., the higher ambient temperature, the higher the ventilation rate), the ambient temperature provides an indication of airflow in the models evaluated.

The various combinations of these parameters were used in test models. For NH_3 and H_2S, 10 different combinations were evaluated as potential models (Table 5-1). There were 15 models (Table 5-2) evaluated for PM emissions, which had more variations using the relative humidity parameters.

Models G-6, G-10, P-13, and P-14 are slightly different due to the inclusion of the management phase categories as a parameter. These models are useful as they can investigate the potential effect of management activities on emissions, However, there is limited data for some of the management statuses (e.g., transition). EPA considers 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.

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

Model	Parameters
G-1	Intercept, LAW, Ambient temperature
G-2	Intercept, LAW, Exhaust temperature
G-3	Intercept, Inventory, Ambient temperature
G-4	Intercept, Inventory, Exhaust temperature
G-5	Intercept, Inventory, Hen age, Ambient temperature
G-6	Intercept, Inventory, Ambient temperature, Management phase (manure cleanouts (C), flock emptying and replacement (E), full flock (F), molting (M), and transition (T))
G-7	Intercept, Inventory, Manure age, Ambient temperature
G-8	Intercept, Inventory, Ambient temperature, Ambient relative humidity
G-9	Intercept, Inventory, Ambient temperature, Exhaust relative humidity
G-10	Intercept, Inventory, Ambient temperature, Ambient relative humidity, Management phase (C, E, F, M, and T)

Table 5-2. Parameter combinations evaluated as models for PM_{10}, $PM_{2.5}$, and TSP emissions.

Model	Parameters
P-1	Intercept, Inventory
P-2	Intercept, Inventory, Ambient relative humidity
P-3	Intercept, Inventory, Exhaust relative humidity
P-4	Intercept, Inventory, Ambient relative humidity, Ambient temperature
P-5	Intercept, Inventory, Ambient temperature, Exhaust relative humidity
P-6	Intercept, Inventory, Ambient relative humidity, Exhaust temperature
P-7	Intercept, Inventory, Exhaust temperature, Exhaust relative humidity
P-8	Intercept, LAW, Ambient temperature, Ambient relative humidity
P-9	Intercept, LAW, Ambient temperature, Exhaust relative humidity
P-10	Intercept, LAW, Ambient relative humidity, Exhaust temperature
P-11	Intercept, LAW, Exhaust temperature, Exhaust relative humidity
P-12	Intercept, Hen age, Inventory, Ambient relative humidity
P-13	Intercept, Inventory, Ambient relative humidity, Management phase (C, E, F, M, and T)
P-14	Intercept, Inventory, Ambient temperature, Ambient relative humidity, Management phase (C, E, F, M, and T)
P-15	Intercept, Inventory, Manure age, Ambient relative humidity

For both NH_3 (Appendix G, Table G-1) and H_2S (Appendix G, Table G-3), models G-5, G-6, and G-10 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-2) and H_2S (Appendix G, Table G-4) indicate the remaining models had comparable performance, which suggested using ambient parameters was as effective as models that included house specific parameters. As noted in the Overview report, the model selection process also looked at how easily obtainable the parameters are as not to create an undue burden on the operators. Generally, ambient parameters were preferred since ambient meteorological data is actively recorded across the country and representative site data is accessible through the NCEI website.

Therefore, considering ambient temperature is a suitable proxy for house airflow and representative ambient temperature data is accessible, the EPA concluded that a model using ambient temperature and relative humidity would be preferable to one with exhaust temperature and relative humidity. Of the remaining models that used ambient parameters (G-1, G-3, G-7, and G-8), EPA selected model G-8 (including the parameters: intercept, inventory, ambient temperature, ambient relative humidity) for further analysis for both NH_3 and H_2S as it had the best normalized mean bias of the remaining models. The final form of these models is presented in Table 5-3.

For PM_{10} (Appendix G, Table G-5), models P-12, P-13, and P-14 had terms that were not statistically significant ($p > 0.05$) and were removed from further consideration. The model fit and evaluation statistics for PM_{10} (Appendix G, Table G-6) indicate that the remaining models were comparable, which suggested using ambient parameters was as effective as house parameters. Therefore, 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. Of the remaining models that used ambient parameters (P-1, P-3, P-4, P-8, and P-15), EPA selected model P-4 (including the parameters: intercept, inventory, ambient relative humidity, ambient temperature) for further analysis as it had the lowest mean error and one of the lowest normalized mean bias of the remaining models. The full form of the model is presented in Table 5-3.

As noted in Section 6.4 of the Overview report, the PM model selection starts with the PM_{10} models, as there are more emissions data. The PM_{10} version of the models had between 1,579 and 2,712 records available depending on the completeness of the various predictive parameters. For $PM_{2.5}$ and TSP the number of records available ranged between 77 – 160 for $PM_{2.5}$ and 149 – 238 for TSP. This is substantially less data that was available for PM_{10} and does not cover the breadth of conditions that the PM_{10} data does. Therefore, the models generated with these smaller datasets were examined mainly for consistency with the PM_{10} results to build confidence in using the same model form for all the PM species. The biggest difference from PM_{10} is that more of the models have insignificant terms for both $PM_{2.5}$ and TSP. For $PM_{2.5}$ (Appendix G, Table G-7) only four models are comprised of significant parameters, and TSP (Appendix G, Table G-9) has only three significant models. Despite the insignificance of the parameters for most of the models, the relationships were consistent with the PM_{10} models and literature. The model performance statistics for $PM_{2.5}$ (Appendix G, Table G-8) and TSP (Appendix G, Table G-10) were fairly consistent, except for mean bias. Model P-4 had reasonable performance for both $PM_{2.5}$ and TSP and would be consistent with the PM_{10} formulation that was developed from a much larger dataset. Therefore, EPA selected model P-4 for both $PM_{2.5}$ and TSP to conduct further evaluation and analysis as an emissions estimation method. The full forms of the models are presented in Table 5-3.

Table 5-3. Selected daily models for high rise layer houses.

Pollutant	Formula	Equation Number
NH_3	$ln(NH_3) = 2.6598 + 0.0059 * Inventory + 0.0387 * Amb_T + 0.0018 * Amb_{RH}$	Equation 1
H_2S	$ln(H_2S) = 2.7231 + 0.0098 * Inventory + 0.0210 * Amb_T + 0.0038 * Amb_{RH}$	Equation 2
PM_{10}	$ln(PM_{10}) = 6.8702 + 0.0077 * Inventory + 0.0145 * Amb_T - 0.0030 * Amb_{RH}$	Equation 3
$PM_{2.5}$	$ln(PM_{2.5}) = 4.6219 + 0.0080 * Inventory + 0.0510 * Amb_T - 0.0181 * Amb_{RH}$	Equation 4
TSP	$ln(TSP) = 7.5995 + 0.0079 * Inventory + 0.0137 * Amb_T - 0.0058 * Amb_{RH}$	Equation 5

5.2 Manure Belt Operations

The literature review (Section 3) and exploratory data analysis (Section 4) suggested that, of the data collected during NAEM ambient temperature, exhaust temperature, ambient relative humidity, exhaust relative humidity, management phase, hen age, inventory, and LAW should be considered in the development of emissions models for the layer manure belt houses. The various combinations of these parameters were used in test models for the pollutants of interest. For NH_3 and H_2S, 12 different combinations were evaluated as potential models (Table 5-4). There were 16 models (Table 5-5) evaluated for PM emissions, which had more variations using the relative humidity parameters.

Like the high rise models, models G-6, G-10, P-13, and P-14 include the management phase categories as a parameter. As noted in Section 3, the management activities and general movement in the house can have an impact on emissions, particularly PM emissions. 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.

Table 5-4. Parameter combinations evaluated as models for manure belt house NH_3 and H_2S emissions.

Model	Parameters
G-1	Intercept, LAW, Ambient temperature
G-2	Intercept, LAW, Exhaust temperature
G-3	Intercept, Inventory, Ambient temperature
G-4	Intercept, Inventory, Exhaust temperature
G-5	Intercept, Inventory, Hen age, Ambient temperature
G-6	Intercept, Inventory, Ambient temperature, Management phase (flock emptying and replacement (E), full flock (F), molting (M), and transition (T))
G-7	Intercept, Inventory, Ambient temperature, Ambient relative humidity
G-8	Intercept, Inventory, Ambient temperature, Exhaust relative humidity
G-9	Intercept, Inventory, Ambient temperature, Ambient relative humidity, Management phase (E,F,M,T)
G-10	Intercept, Inventory
G-11	Intercept, Inventory, Exhaust temperature, Ambient relative humidity
G-12	Intercept, Inventory, Exhaust temperature, Exhaust relative humidity

Table 5-5. Parameter combinations evaluated as models for manure belt house PM_{10}, $PM_{2.5}$, and TSP emissions.

Model	Parameters
P-1	Intercept, Inventory
P-2	Intercept, Inventory, Ambient relative humidity
P-3	Intercept, Inventory, Exhaust relative humidity
P-4	Intercept, Inventory, Ambient relative humidity, Ambient temperature
P-5	Intercept, Inventory, Ambient temperature, Exhaust relative humidity
P-6	Intercept, Inventory, Ambient relative humidity, Exhaust temperature
P-7	Intercept, Inventory, Exhaust temperature, Exhaust relative humidity
P-8	Intercept, LAW, Ambient temperature, Ambient relative humidity
P-9	Intercept, LAW, Ambient temperature, Exhaust relative humidity
P-10	Intercept, LAW, Ambient relative humidity, Exhaust temperature
P-11	Intercept, LAW, Exhaust temperature, Exhaust relative humidity
P-12	Intercept, Hen age, Inventory, Ambient relative humidity
P-13	Intercept, Inventory, Ambient relative humidity, Management phase (C,E,F,M,T)
P-14	Intercept, Inventory, Ambient temperature, Ambient relative humidity, Management phase (C,E,F,M,T)
P-15	Intercept, Inventory, Ambient temperature
P-16	Intercept, Inventory, Exhaust temperature

For NH_3 (Appendix G, Table G-15), models G-2, G-4, G-5, G-11, and G-12 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-16) indicate the remaining models were comparable, which suggested using ambient parameters would incorporate regional differences due to climate. It also suggests that the ambient parameters were as effective as house parameters in estimating the effects of climate differences. Therefore, considering the potential ease of data collection, EPA concluded that ambient temperature and relative humidity would be preferable to one with exhaust temperature and relative humidity, while considering the environmental impacts on the emissions. Of the remaining models (G-1, G-3, and G-7), EPA selected model G-7 (including the parameters: intercept, inventory, ambient temperature, ambient relative humidity) for further analysis for NH_3. The final form of this model is presented in Table 5-6.

For H_2S (Appendix G, Table G-17), model G-5 had terms that were not statistically significant and was 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-18) indicate the remaining models were comparable. This suggested using ambient parameters in the models was as effective as house parameters when evaluating temperature and humidity effects on emissions. Therefore, EPA considered the potential ease of data collection and concluded that a model ambient temperature and relative humidity would be preferable to one with exhaust temperature and relative humidity. Of the remaining models that used ambient parameters, EPA selected model G-7 (including the parameters: intercept, inventory, ambient temperature, ambient relative humidity) for further analysis for H_2S as it had the one of the lowest normalized mean bias of the remaining models, and was consistent with the parameters selected for the NH_3 model, limiting the data collection burden. The selected model is presented in Table 5-6.

For PM_{10} (Appendix G, Table G-19), only models P-1 and P-16 were comprised of terms that were statistically significant ($p < 0.05$). EPA thoroughly reviewed the data to determine potential reasons for the lack of significant models. The ability of predictor variables to represent the chemical, physical and biological processes that control emissions will impact the performance of statistical models. In terms of PM emissions from manure belt houses, the two largest variables that will influence emissions is 1) the amount of source material (i.e. excreted manure, feathers, and feed) in the house, which is related to inventory; and 2) the amount of disturbance of the source materials, which is related to layer, human, and management activity. For manure belt houses, sufficient data was not collected during NAEMS to develop a variable that represents the second factor of activity inside the manure belt house. Not adequately capturing the variance of this key parameter makes it hard to determine the effect of other less influential parameters (i.e. relative humidity and temperature). The effect of not having a variable that represents house activity varies for each of the PM models, depending on how much the activity varies at a house/barn and then how much activity influences emissions. Activity level in the house does not have as strong an effect on gas emissions, which is why more of those models had significant parameters.

In addition, for a model to determine the influence of a parameters it has to vary enough for its influence to be determined above the effect of all the other predictive parameters. For the manure belt house models there is only one site, consisting of two houses, which have a fairly steady inventory apart from one flock replacement event at H9. This means the influence of inventory on emissions cannot be easily quantified. The lack of variance of the inventory will affect both gas and PM emissions. However, it will have a more pronounced effect on the PM_{10} models since there are only six daily emissions values during the flock replacement event, while NH_3 and H_2S have 20 and 21 days, respectively.

The model fit evaluation statistics for PM_{10} (Appendix G, Table G-20) indicate model P-1 and P-16 performed similarly. Therefore, EPA selected model P-1 (including the parameter: inventory) for further analysis and consideration. The full form of the model is presented in Table 5-3.

As previously noted, the PM model selection starts with the PM_{10} models, as there is more emissions data available. The PM_{10} version of the models had between 460 and 566 days' worth of data, depending on the completeness of the various predictive parameters. For $PM_{2.5}$ and TSP, the number of records available ranged between 26 – 34 for $PM_{2.5}$ and 66 – 69 for TSP. This is substantially less data that was available for PM_{10} and does not cover the same breadth of conditions that the PM_{10} data does. Therefore, the models generated with these smaller datasets were examined mainly for consistency with the PM_{10} results, to build confidence in using the same model form for all the PM species.

Model P-1 (inventory including the parameter: inventory) have insignificant terms, unlike PM_{10}. The relationship inventory is consistent across the PM size fractions. The $PM_{2.5}$ model also has a negative intercept value. The negative intercept is likely due to the fact that values for 30 out of the 56 available days are negative. The statistics for $PM_{2.5}$ (Appendix G, Table G-22) were fairly poor across all models, as the NME and NMB were greater than 100% for most of the models. The TSP model performance statistics (Appendix G, Table G-24) were nominally better than the $PM_{2.5}$ models, as NME improved to 78%. The improvement in statistics is likely due to the increased amount of daily data available for model development compared to $PM_{2.5}$. Overall, model P-1 (including the parameter: inventory) was selected for both $PM_{2.5}$ and TSP, as it would be consistent with the parameters selected for the PM_{10} model. The full forms of the models are presented in Table 5-3.

Table 5-6. Selected daily models for manure belt layer houses.

Pollutant	Formula	Equation Number
NH_3	$ln(NH_3) = 2.4392 + 0.0047 * Inventory + 0.0294 * Amb_T + 0.0019 * Amb_{RH}$	Equation 6
H_2S	$ln(H_2S) = 3.7391 + 0.0073 * Inventory + 0.0222 * Amb_T + 0.0048 * Amb_{RH}$	Equation 7
PM_{10}	$ln(PM_{10}) = 6.631005 + 0.007205 * Inventory$	Equation 8
$PM_{2.5}$	$ln(PM_{2.5}) = -127.4489 + 0.534577 * Inventory$	Equation 9
TSP	$ln(TSP) = 6.936206 + 0.00987 * Inventory$	Equation 10

5.3 Manure Sheds

The literature review (Section 3) and exploratory data analysis (Section 4) suggested that EPA should consider ambient temperature, ambient relative humidity, wind speed, airflow, management phase, manure age, average hen age, inventory, and LAW in the development of the emissions models for manure sheds associated with layer manure belt houses. As a reminder, the average hen age represented the average age from the two houses (IN2B H8 and H9) whose manure was stored in the shed. Similarly, the inventory and LAW represent the combined values for both houses that store manure in the shed.

In addition to these parameters, EPA also used additional inventory and LAW that represents a value lagged by 5 days to account for the time it takes for the manure to be transported from the house to the shed via the conveyor belts. Again, the values are the combined value from both houses supplying manure to the shed.

The various combinations of these parameters were used in test models for the pollutants of interest. For NH_3 and H_2S, 20 different combinations were evaluated as potential models (Table 5-7). Thirteen models were evaluated for PM emissions (Table 5-8).

EPA has included evaluated models that incorporated an indication of management phase into models G-9, G-18, G-19, and P-9. The management phase parameter for manure sheds incorporates the phase from both houses supplying manure to the shed, as well as any noted cleanout times in the manure shed itself. EPA considers these models experimental at this time, as validation and testing methods are still being vetted. They are included in this report to show all the options explored.

Table 5-7. Parameter combinations evaluated as models for layer manure shed NH_3 and H_2S emissions.

Model	Parameter
G-1	Intercept, Inventory, Ambient temperature
G-2	Intercept, Inventory (5 day lag), Ambient temperature
G-3	Intercept, LAW, Ambient temperature
G-4	Intercept, LAW (5 day lag), Ambient temperature

Model	Parameter
G-5	Intercept, Inventory (5 day lag), Ambient temperature, Ambient relative humidity
G-6	Intercept, Inventory (5 day lag), Ambient temperature, Wind speed
G-7	Intercept, Inventory (5 day lag), Ambient temperature, Ambient relative humidity, Wind speed
G-8	Intercept, Inventory (5 day lag), Ambient temperature, Average hen age
G-9	Intercept, Inventory (5 day lag), Ambient temperature, Management phase (Manure shed cleanout, House 8 full & House 9 molting (CFF), House 8 full & House 9 empty (FE); House 8 full & House 9 full (FF); House 8 full & House 9 molting (FM); House 8 full & House 9 transitioning (FT); and House 8 molting & House 9 full (MF))
G-10	Intercept, Inventory (5 day lag), Ambient temperature, Manure age
G-11	Intercept, Inventory (5 day lag), Wind speed
G-12	Intercept, Inventory (5 day lag), Manure age
G-13	Intercept, Inventory (5 day lag), Wind speed, Manure age
G-14	Intercept, Inventory (5 day lag), Ambient relative humidity, Manure age
G-15	Intercept, Inventory (5 day lag), Airflow
G-16	Intercept, Ambient temperature, Airflow
G-17	Intercept, Airflow, manure age
G-18	Intercept, Inventory (5 day lag), Manure age, Management phase (CFF, FE, FF, FM, FT, and MF)
G-19	Intercept, Ambient Temperature, Manure age, Management phase (CFF, FE, FF, FM, FT, and MF)
G-20	Intercept, Inventory (5 day lag)

Table 5-8. Parameter combinations evaluated as models for layer manure shed PM_{10}, $PM_{2.5}$, and TSP emissions.

Model	Parameter
P-1	Intercept, Inventory, Airflow
P-2	Intercept, Inventory (5 day lag), Airflow
P-3	Intercept, LAW, Airflow
P-4	Intercept, LAW (5 day lag), Airflow
P-5	Intercept, Inventory (5 day lag), Wind speed
P-6	Intercept, Inventory (5 day lag), Ambient temperature
P-7	Intercept, Inventory (5 day lag), Ambient relative humidity
P-8	Intercept, Inventory (5 day lag), Average hen age
P-9	Intercept, Inventory (5 day lag), Management phase (CFF, FE, FF, FM, FT, and MF)
P-10	Intercept, Inventory (5 day lag), Manure age
P-11	Intercept, Inventory (5 day lag)
P-12	Intercept, LAW (5 day lag)
P-13	Intercept, Airflow

For NH_3 (Appendix G, Table G-27), only models G-16 (includes parameters: intercept, ambient temperature, airflow) and G-17 (includes parameters: intercept, airflow, manure age) were entirely comprised of terms that were statistically significant ($p < 0.05$). The H_2S analysis (Appendix G, Table G-29) had similar results with models G-2 (which includes intercept, inventory (5 day lag), ambient temperature), G-16, and G-17 receiving 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-28) and H_2S (Appendix G, Table G-30) indicates these remaining models were comparable. Models G-16 and G-17 both contained airflow, which is not an easy parameter for a producer to calculate, as it requires hourly wind measurements in several openings of the structure (SOP A10, 2009). Depending on the structure, the number of anemometers needed may be cost prohibitive for operators.

Models G-16 and G-17 do not include a parameter that indicates the number of birds or size of the operation, which had previously been used as a proxy for the volume of manure produced. The volume of manure produced is a considerable factor in the emissions, as emissions are released from the surface of the manure. The issue in using inventory as a proxy for volume is that there is a lack of variation of inventory in this study. As mentioned earlier, for a model to determine the influence of a parameter, the parameter must have sufficient variability for its influence to be determined above the effect of other predictive parameters. For the manure shed models there is only one site for the dataset. The two houses supplying the manure shed have a fairly steady inventory apart from one flock replacement event at one house. This means the influence of inventory, as a proxy for manure volume, on emissions cannot be easily identified. The lack of variance of the inventory will affect both gas and PM emissions modeling efforts and can be seen as a limitation in the dataset.

Acknowledging the need to indicate the size of the operation, and therefore an estimate of the volume of manure produced, the EPA selected the model G-2 (includes parameters: intercept, inventory (5 day lag), ambient temperature) for both NH_3 and H_2S. The established relationship between inventory and emissions outweighs the insignificance finding in the NH_3 model tests. It should be noted that the ambient temperature coefficient is negative for the NH_3 and H_2S models. A possible explanation for this is that the higher temperatures are drying out the manure resulting in less NH_3 and H_2S generation. The final forms of the NH_3 and H_2S models are presented in Table 5-9.

For PM_{10} (Appendix F, Tables F-31, and F-32), $PM_{2.5}$ (Appendix F, Tables F-33 and F-34), and TSP (Appendix F, Tables F-35 and F-36), only model P-13 (includes parameters: intercept, airflow) was comprised of significant parameters. As with the models for NH_3 and H_2S, it does not include a parameter to indicate the number of birds or size of the operation. The primary mechanism to generate PM emissions is the disruption of the manure pile, either by agitation of the pile by manure dropping off the belt or human activity within the shed (i.e., manure removal). Surface area would be a better indicator of exposed manure that could generate emissions. However, this was not estimated during the study, aside from the square footage of the shed. In other models, inventory has served as a proxy for the volume of manure produced, which would affect the surface area. However, the modeling dataset lacks enough variability in inventory values to yield a statistically significant relationship with inventory or LAW.

Again, EPA was faced with the choice to either adhere to the established protocol of selecting from models with only significant parameters or deviate from it to select a model with relationship established by literature. Acknowledging the need to indicate the size of the operation, and therefore an estimate of the volume of manure produced, the EPA elected to select a model that included an indication of size. Of the model that included size and did not have airflow, EPA selected model P-11 (includes parameters: intercept, inventory (5 day lag)) for further consideration for PM_{10}, $PM_{2.5}$, and TSP. The final form of these models are presented in Table 5-9.

Table 5-9. Selected daily models for layer manure sheds.

Pollutant	Formula	Equation Number
NH_3	$ln(NH_3) = -0.194945 + 0.003927 * Inventory\ (5\ day\ lag) - 0.013752 * Amb_T$	Equation 11
H_2S	$ln(H_2S) = 1.295775 + 0.004976 * Inventory\ (5\ day\ lag) - 0.024164 * Amb_T$	Equation 12
PM_{10}	$ln(PM_{10}) = 4.5366 + 0.000732 * Inventory\ (5\ day\ lag)$	Equation 13
$PM_{2.5}$	$ln(PM_{2.5}) = -30.57734 + 0.067599 * Inventory\ (5\ day\ lag)$	Equation 14
TSP	$ln(TSP) = 4.041666 + 0.002286 * Inventory\ (5\ day\ lag)$	Equation 15

6.0 MODEL COEFFICIENT EVALUATION

To ensure reliable prediction of the emissions, the model coefficients were evaluated with the jackknife method (Christensen et al., 2016; Leeden et al., 2007), 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 houses at each site and the monitored sheds 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 models 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 house or shed) 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 High Rise Layer House Models

6.1.1 NH_3 Model Evaluation

Table 6-1 shows 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, except IN2H H7, which was just outside of this range for the ambient temperature and inventory. In comparison to the full model, that is where the site removed is “None”, the maximum percentage differences for parameter estimates across the six models were 11%, 12%, 5%, and 48% for intercept, ambient relative humidity, ambient temperature, and inventory, respectively. Across all models, the difference in NME and NMB (Table 6-2) in comparison to the selected model were moderate, with NME values differing by less than 6.15% and NMB by less than 4.38%.

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

Site Out	Effect	Estimate	Standard Error	p-value
None	Intercept	2.659821	0.22567	<.0001
None	Ambient Relative Humidity	0.001761	0.00031	<.0001
None	Ambient Temperature	0.038714	0.00097	<.0001
None	Inventory	0.00589	0.00126	<.0001
CA2BH5	Intercept	2.693697	0.02272	<.0001
CA2BH5	Ambient Relative Humidity	0.001914	0.00032	<.0001
CA2BH5	Ambient Temperature	0.037616	0.001	<.0001
CA2BH5	Inventory	0.005876	0.00071	<.0001
CA2BH6	Intercept	2.687925	0.10464	<.0001
CA2BH6	Ambient Relative Humidity	0.001901	0.0003	<.0001
CA2BH6	Ambient Temperature	0.037399	0.00095	<.0001
CA2BH6	Inventory	0.005869	0.00082	<.0001
IN2HH6	Intercept	2.651921	0.2604	<.0001
IN2HH6	Ambient Relative Humidity	0.001555	0.00033	<.0001
IN2HH6	Ambient Temperature	0.042286	0.0011	<.0001
IN2HH6	Inventory	0.00523	0.0016	0.0012
IN2HH7	Intercept	2.380192	0.1567	<.0001
IN2HH7	Ambient Relative Humidity	0.001594	0.00034	<.0001
IN2HH7	Ambient Temperature	0.040827	0.00112	<.0001
IN2HH7	Inventory	0.008688	0.00125	<.0001
NC2BH3	Intercept	2.656733	0.44505	<.0001
NC2BH3	Ambient Relative Humidity	0.001793	0.00038	<.0001
NC2BH3	Ambient Temperature	0.03862	0.00116	<.0001
NC2BH3	Inventory	0.005869	0.00131	<.0001
NC2BH4	Intercept	2.764139	0.3186	<.0001
NC2BH4	Ambient Relative Humidity	0.0017	0.00035	<.0001
NC2BH4	Ambient Temperature	0.03673	0.00107	<.0001
NC2BH4	Inventory	0.005059	0.00153	0.001

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

Site Out	n	LNME[a] (%)	NME[b] (%)	ME[b] (kg day^{-1})	MB[b] (kg day^{-1})	NMB[b] (%)	Corr.
None	3562	16.851	59.12	60.818	0.165	0.161	0.516
CA2BH5	3035	16.042	58.735	67.574	1.988	1.728	0.489
CA2BH6	3016	14.159	56.459	65.635	1.524	1.311	0.493
IN2HH6	3025	18.044	63.521	51.826	1.72	2.108	0.45
IN2HH7	3023	15.499	52.975	41.132	3.527	4.543	0.628
NC2BH3	2852	18.734	61.241	69.816	0.233	0.204	0.516
NC2BH4	2859	19.066	62.574	71.287	-0.254	-0.223	0.484

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

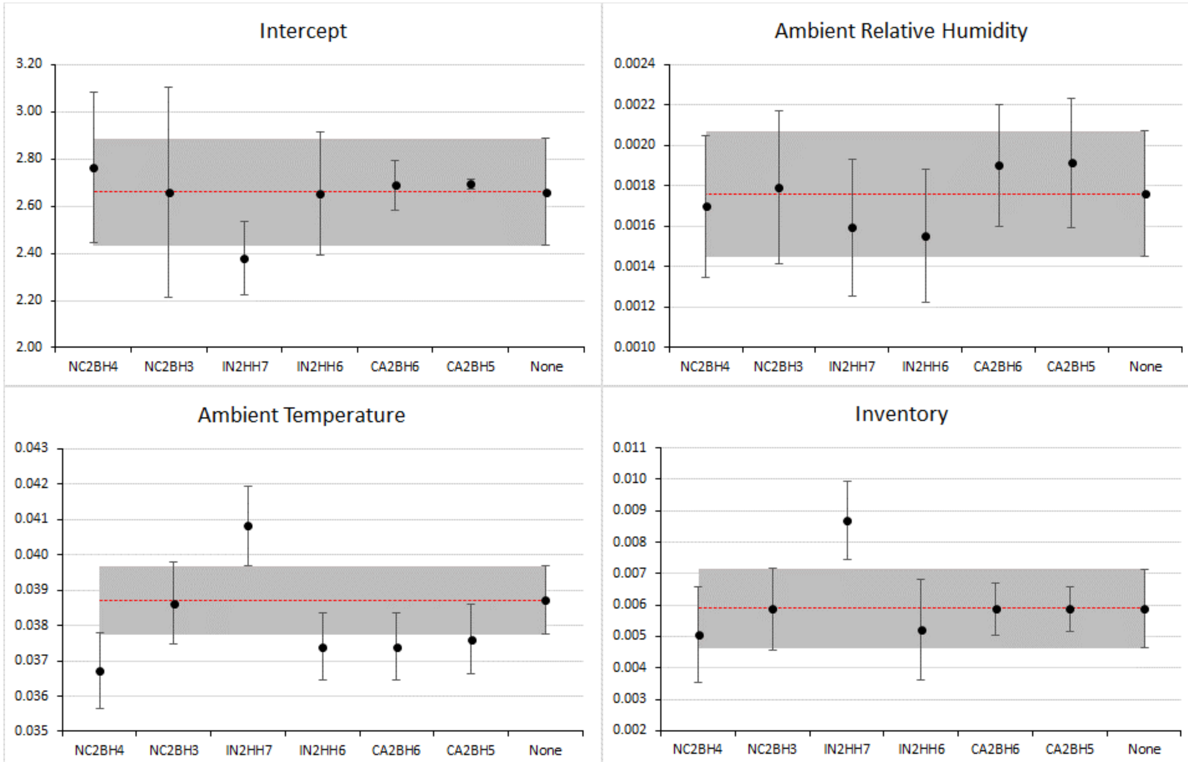

Figure 6-1. Comparison of variation in coefficients and standard errors for NH_3 high rise house model.

Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected NH_3 manure belt house model coefficient ("None", gray band for ± SE) for each model parameter.

6.1.2 H_2S Model Evaluation

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

Table 6-3 shows 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 NC2B H4 for intercept and inventory, and NC2B H3 for ambient temperature and relative humidity. In comparison to the full model, the maximum percentage differences for parameter estimates across the six models were 9%, 38%, 15%, and 43% for intercept, ambient temperature, inventory, and ambient relative humidity, respectively. Across all models, the difference in NME and NMB (Table 6-4) in comparison to the selected model were moderate, with NME values differing by less than 3.31% and NMB by less than 7.77%.

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

Site Out	Effect	Estimate	Standard Error	p-value
None	Intercept	2.723104	0.07259	<.0001
None	Ambient Temperature	0.020988	0.00163	<.0001
None	Inventory	0.009798	0.00049	<.0001
None	Ambient Relative Humidity	0.003752	0.00053	<.0001
CA2BH5	Intercept	2.610429	0.07377	<.0001
CA2BH5	Ambient Temperature	0.020363	0.0017	<.0001
CA2BH5	Inventory	0.010621	0.00049	<.0001
CA2BH5	Ambient Relative Humidity	0.003796	0.00055	<.0001
CA2BH6	Intercept	2.671677	0.07674	<.0001
CA2BH6	Ambient Temperature	0.020253	0.00178	<.0001
CA2BH6	Inventory	0.010282	0.00051	<.0001
CA2BH6	Ambient Relative Humidity	0.003665	0.00058	<.0001
IN2HH6	Intercept	2.854195	0.08094	<.0001
IN2HH6	Ambient Temperature	0.018927	0.00168	<.0001
IN2HH6	Inventory	0.009165	0.00066	<.0001
IN2HH6	Ambient Relative Humidity	0.003257	0.00054	<.0001
IN2HH7	Intercept	2.739702	0.07635	<.0001
IN2HH7	Ambient Temperature	0.019068	0.00167	<.0001
IN2HH7	Inventory	0.01021	0.00057	<.0001
IN2HH7	Ambient Relative Humidity	0.00349	0.00053	<.0001
NC2BH3	Intercept	2.573999	0.08696	<.0001
NC2BH3	Ambient Temperature	0.028865	0.00202	<.0001
NC2BH3	Inventory	0.009316	0.0005	<.0001
NC2BH3	Ambient Relative Humidity	0.005353	0.00071	<.0001
NC2BH4	Intercept	2.970026	0.09319	<.0001
NC2BH4	Ambient Temperature	0.020607	0.00196	<.0001
NC2BH4	Inventory	0.008355	0.00054	<.0001
NC2BH4	Ambient Relative Humidity	0.003926	0.00061	<.0001

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

Site Out	n	LNME[a] (%)	NME[b] (%)	ME[b] (g day^{-1})	MB[b] (g day^{-1})	NMB[b] (%)	Corr.
None	3291	9.962	52.695	58.631	-1.931	-1.735	0.721
CA2BH5	2733	9.537	52.389	65.238	-1.327	-1.066	0.715
CA2BH6	2715	9.973	52.54	66.589	-1.649	-1.301	0.71
IN2HH6	2908	9.629	52.417	44.002	-1.9	-2.263	0.71
IN2HH7	2901	9.482	49.388	43.181	0.999	1.143	0.739
NC2BH3	2595	10.335	53.332	66.998	-2.476	-1.971	0.726
NC2BH4	2603	10.334	54.317	67.339	-11.78	-9.503	0.714

[a] Based on transformed data (i.e., $\ln(H_2S)$).
[b] Based on back-transformed data.

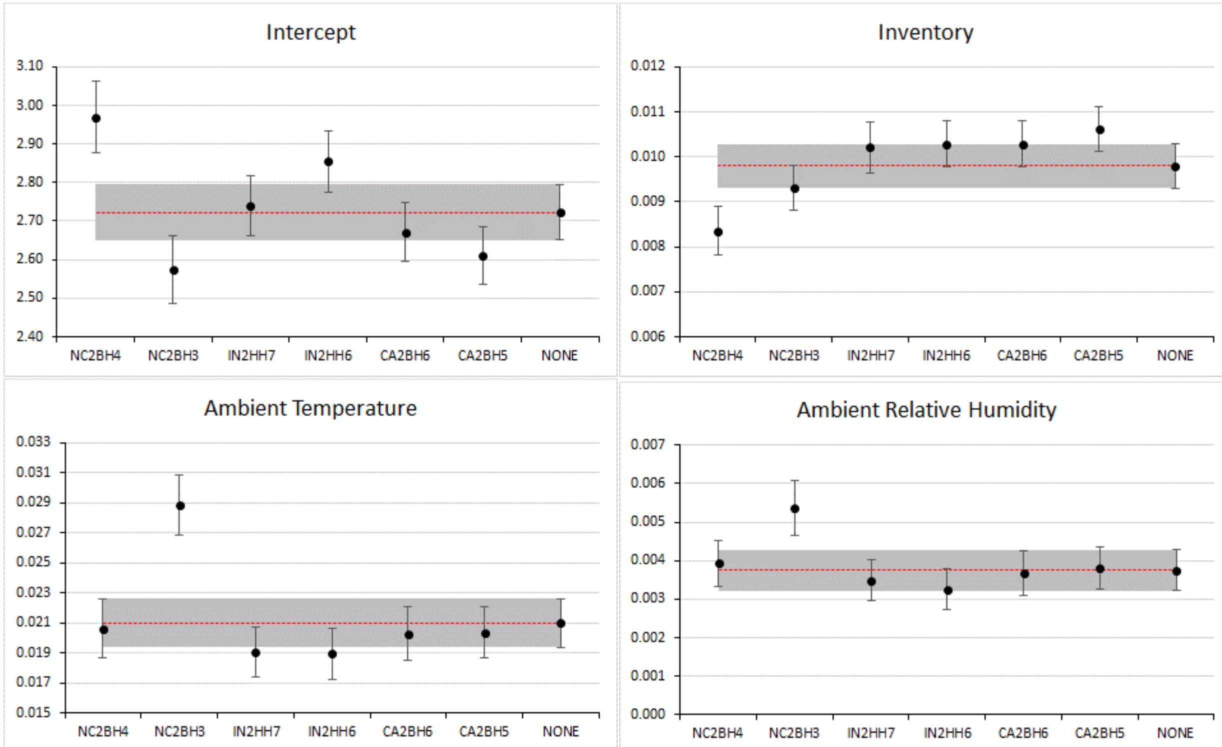

Figure 6-2. Comparison of variation in coefficients and standard errors for H_2S high rise house model.

Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected H_2S manure belt house model coefficient ("None", gray band for ± SE) for each model parameter.

6.1.3 PM_{10} Model Evaluation

Table 6-5 shows 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, except for IN2H H7 for inventory, and NC2B H3 and CA2B H6, which are just outside the range for ambient temperature. In comparison to the full model, the maximum percentage differences for parameter estimates across the six models were 2%, 27%, 19%, and 24% for intercept, inventory, ambient relative humidity, and ambient temperature, respectively. Across all models, the difference in NME and NMB (Table 6-6) in comparison to the selected model were moderate, with NME values differing by less than 7.96% and NMB by less than 15.68%.

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

Site Out	Effect	Estimate	Standard Error	p-value
None	Intercept	6.870178	0.06748	<.0001
None	Inventory	0.007684	0.00054	<.0001
None	Ambient Relative Humidity	-0.003022	0.00051	<.0001
None	Ambient Temperature	0.014477	0.00153	<.0001
CA2BH5	Intercept	6.846607	0.07861	<.0001
CA2BH5	Inventory	0.008111	0.00063	<.0001
CA2BH5	Ambient Relative Humidity	-0.003125	0.00054	<.0001
CA2BH5	Ambient Temperature	0.012766	0.00162	<.0001
CA2BH6	Intercept	6.958724	0.07918	<.0001
CA2BH6	Inventory	0.007213	0.00062	<.0001
CA2BH6	Ambient Relative Humidity	-0.002751	0.00054	<.0001
CA2BH6	Ambient Temperature	0.011153	0.00162	<.0001
IN2HH6	Intercept	6.807521	0.06686	<.0001
IN2HH6	Inventory	0.008409	0.00058	<.0001
IN2HH6	Ambient Relative Humidity	-0.003222	0.00052	<.0001
IN2HH6	Ambient Temperature	0.016333	0.00156	<.0001
IN2HH7	Intercept	6.742102	0.07799	<.0001
IN2HH7	Inventory	0.009771	0.00079	<.0001
IN2HH7	Ambient Relative Humidity	-0.003175	0.00052	<.0001
IN2HH7	Ambient Temperature	0.014566	0.0016	<.0001
NC2BH3	Intercept	6.868256	0.08028	<.0001
NC2BH3	Inventory	0.007341	0.00057	<.0001
NC2BH3	Ambient Relative Humidity	-0.002505	0.00062	<.0001
NC2BH3	Ambient Temperature	0.018019	0.00191	<.0001
NC2BH4	Intercept	6.87016	0.07509	<.0001
NC2BH4	Inventory	0.006952	0.00053	<.0001
NC2BH4	Ambient Relative Humidity	-0.003055	0.00066	<.0001
NC2BH4	Ambient Temperature	0.015921	0.00185	<.0001

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

Site Out	n	LNME[a] (%)	NME[b] (%)	ME[b] (g day^{-1})	MB[b] (g day^{-1})	NMB[b] (%)	Corr.
None	2,623	4.977	50.241	1,218.1	111.63	4.604	0.617
CA2BH5	2,184	5.099	51.3	1,360	164.59	6.208	0.594
CA2BH6	2,125	5.038	50.092	1,382.4	107.75	3.905	0.572
IN2HH6	2,258	4.671	48.397	1,037.8	99.102	4.622	0.66
IN2HH7	2,234	4.979	58.197	1,141.4	397.88	20.288	0.59
NC2BH3	2,246	5.2	50.708	1,305.7	81.332	3.159	0.617
NC2BH4	2,068	5.058	50.456	1,253.5	-12.53	-0.504	0.633

[a] Based on transformed data (i.e., ln(PM_{10})).
[b] Based on back-transformed data.

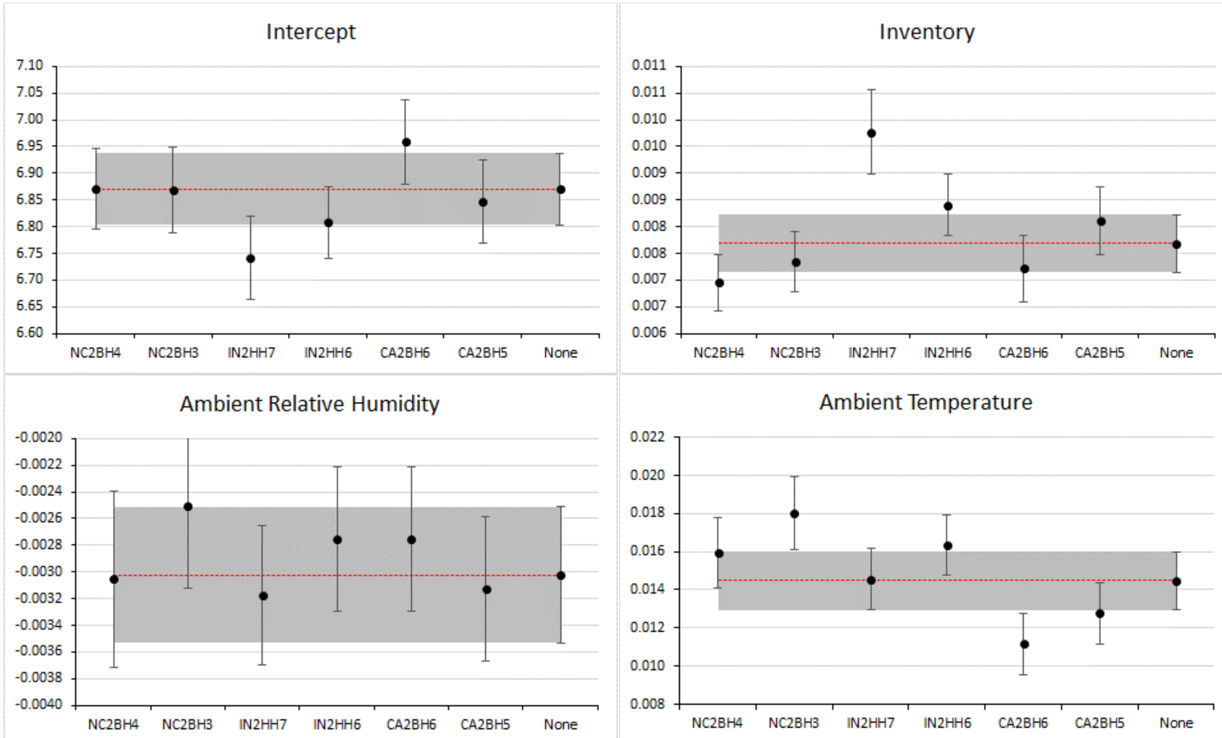

Figure 6-3. Comparison of variation in coefficients and standard errors for PM_{10} high rise house model.

Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected PM_{10} manure belt house model coefficient ("None", gray band for ± SE) for each model parameter.

6.1.4 $PM_{2.5}$ Model Evaluation

Table 6-7 shows 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, with NC2B H4 just falling into the range for ambient temperature. In comparison to the full model, the maximum percentage differences for parameter estimates across the six models were 4%, 29%, 21%, and 48% for intercept, inventory, ambient relative humidity, and ambient temperature, respectively. Across all models, the difference in NME and NMB (Table 6-8) in comparison to the selected model were moderate, with NME values differing by less than 11.14% and NMB by less than 11.36%.

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

Site Out	Effect	Estimate	Standard Error	p-value
None	Intercept	4.621874	0.46141	<.0001
None	Inventory	0.008039	0.00336	0.0295
None	Ambient Relative Humidity	-0.018133	0.00367	<.0001
None	Ambient Temperature	0.051013	0.01149	<.0001
CA2BH5	Intercept	4.653248	0.38683	0.0003
CA2BH5	Inventory	0.007859	0.00222	0.0006
CA2BH5	Ambient Relative Humidity	-0.017236	0.00354	<.0001
CA2BH5	Ambient Temperature	0.042139	0.01067	0.0001
CA2BH6	Intercept	4.592269	0.56282	<.0001
CA2BH6	Inventory	0.007681	0.00393	0.0724
CA2BH6	Ambient Relative Humidity	-0.015357	0.00418	0.0005
CA2BH6	Ambient Temperature	0.037024	0.01334	0.0067
IN2HH6	Intercept	4.663189	0.44356	<.0001
IN2HH6	Inventory	0.006925	0.00359	0.0848
IN2HH6	Ambient Relative Humidity	-0.017512	0.00376	<.0001
IN2HH6	Ambient Temperature	0.049026	0.01204	<.0001
IN2HH7	Intercept	4.442859	0.48259	<.0001
IN2HH7	Inventory	0.010404	0.00387	0.0177
IN2HH7	Ambient Relative Humidity	-0.018169	0.00384	<.0001
IN2HH7	Ambient Temperature	0.054367	0.01256	<.0001
NC2BH3	Intercept	4.677209	0.43766	<.0001
NC2BH3	Inventory	0.00805	0.00258	0.0081
NC2BH3	Ambient Relative Humidity	-0.019376	0.00398	<.0001
NC2BH3	Ambient Temperature	0.054242	0.01191	<.0001
NC2BH4	Intercept	4.557335	0.50869	<.0001
NC2BH4	Inventory	0.007702	0.00267	0.0298
NC2BH4	Ambient Relative Humidity	-0.021994	0.00561	0.0002
NC2BH4	Ambient Temperature	0.075354	0.0143	<.0001

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

Site Out	n	LNME[a] (%)	NME[b] (%)	ME[b] (g day-1)	MB[b] (g day-1)	NMB[b] (%)	Corr.
None	142	16.51	78.095	164.4	-44.37	-21.08	0.636
CA2BH5	117	13.6	76.908	132.53	-16.74	-9.716	0.504
CA2BH6	110	16.688	89.236	179.76	-22.82	-11.33	0.377
IN2HH6	126	17.276	74.491	157.15	-58.24	-27.61	0.785
IN2HH7	133	16.636	78.008	169.95	-42.58	-19.55	0.542
NC2BH3	124	17.206	74.787	174.13	-50.59	-21.73	0.677
NC2BH4	100	16.083	68.557	155.69	-63.25	-27.85	0.853

[a] Based on transformed data (i.e., $\ln(PM_{2.5})$).
[b] Based on back-transformed data.

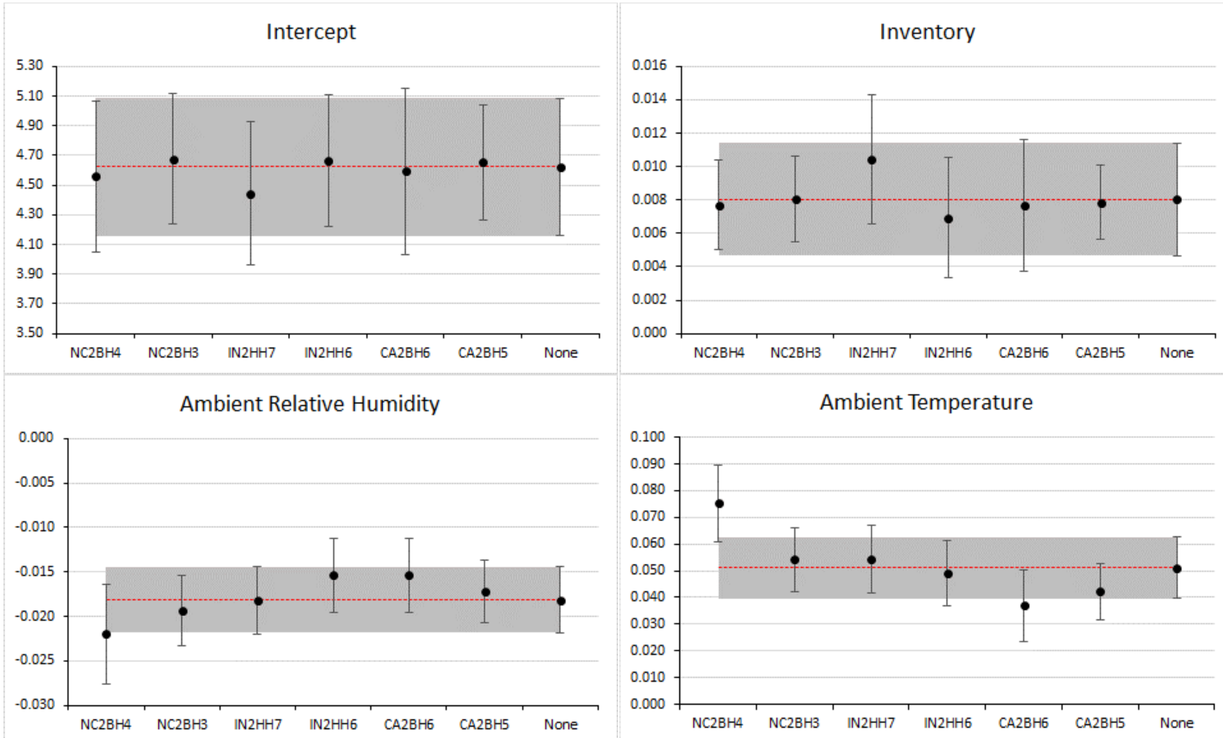

Figure 6-4. Comparison of variation in coefficients and standard errors for $PM_{2.5}$ high rise house model.

Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected $PM_{2.5}$ manure belt house model coefficient ("None", gray band for ± SE) for each model parameter.

6.1.5 TSP Model Evaluation

Table 6-9 shows 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. In comparison to the full model, the maximum percentage differences for parameter estimates across the six models were 3%, 32%, 30%, and 121% for intercept, inventory, ambient relative humidity, and ambient temperature, respectively. However, the plots in Figure 6-5 show that the results for all jackknife models overlap the full model estimate ± 1 standard error. Across all models, the difference in NME and NMB (Table 6-10) in comparison to the selected model were moderate, with NME values differing by less than 3.65% and NMB by less than 2.71%.

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

Site Out	Effect	Estimate	Standard Error	p-value
None	Intercept	7.599452	0.30204	<.0001
None	Inventory	0.007927	0.0012	<.0001
None	Ambient Relative Humidity	-0.005795	0.00282	0.0423
None	Ambient Temperature	0.01367	0.00924	0.1417
CA2BH5	Intercept	7.582551	0.29409	<.0001
CA2BH5	Inventory	0.00778	0.00144	<.0001
CA2BH5	Ambient Relative Humidity	-0.005215	0.00254	0.0412
CA2BH5	Ambient Temperature	0.012892	0.00808	0.1125
CA2BH6	Intercept	7.421154	0.35744	<.0001
CA2BH6	Inventory	0.009214	0.00159	<.0001
CA2BH6	Ambient Relative Humidity	-0.006977	0.00315	0.0296
CA2BH6	Ambient Temperature	0.018426	0.01036	0.0784
IN2HH6	Intercept	7.843589	0.32542	<.0001
IN2HH6	Inventory	0.005379	0.00196	0.0181
IN2HH6	Ambient Relative Humidity	-0.00759	0.00293	0.011
IN2HH6	Ambient Temperature	0.012946	0.00972	0.1855
IN2HH7	Intercept	7.594248	0.30187	<.0001
IN2HH7	Inventory	0.007871	0.00119	<.0001
IN2HH7	Ambient Relative Humidity	-0.004642	0.00285	0.1067
IN2HH7	Ambient Temperature	0.009979	0.00956	0.2991
NC2BH3	Intercept	7.38713	0.40201	<.0001
NC2BH3	Inventory	0.009109	0.00143	<.0001
NC2BH3	Ambient Relative Humidity	-0.006726	0.00388	0.0859
NC2BH3	Ambient Temperature	0.030217	0.01211	0.0145
NC2BH4	Intercept	7.747179	0.31464	<.0001
NC2BH4	Inventory	0.006533	0.00109	<.0001
NC2BH4	Ambient Relative Humidity	-0.004076	0.00305	0.1845
NC2BH4	Ambient Temperature	0.004942	0.00998	0.6215

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

Site Out	n	LNME[a] (%)	NME[b] (%)	ME[b] (g day^{-1})	MB[b] (g day^{-1})	NMB[b] (%)	Corr.
None	221	7.467	40.869	1641.5	64.602	1.608	0.524
CA2BH5	194	7.198	39.65	1675.2	74.729	1.769	0.508
CA2BH6	189	8.084	42.694	1805.2	163.03	3.856	0.505
IN2HH6	206	8.128	41.585	1545.1	-32.51	-0.875	0.409
IN2HH7	204	7.317	37.223	1449	-42.89	-1.102	0.605
NC2BH3	176	8.241	43.467	1810.6	166.63	4	0.519
NC2BH4	136	5.894	40.763	1578.9	43.373	1.12	0.602

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

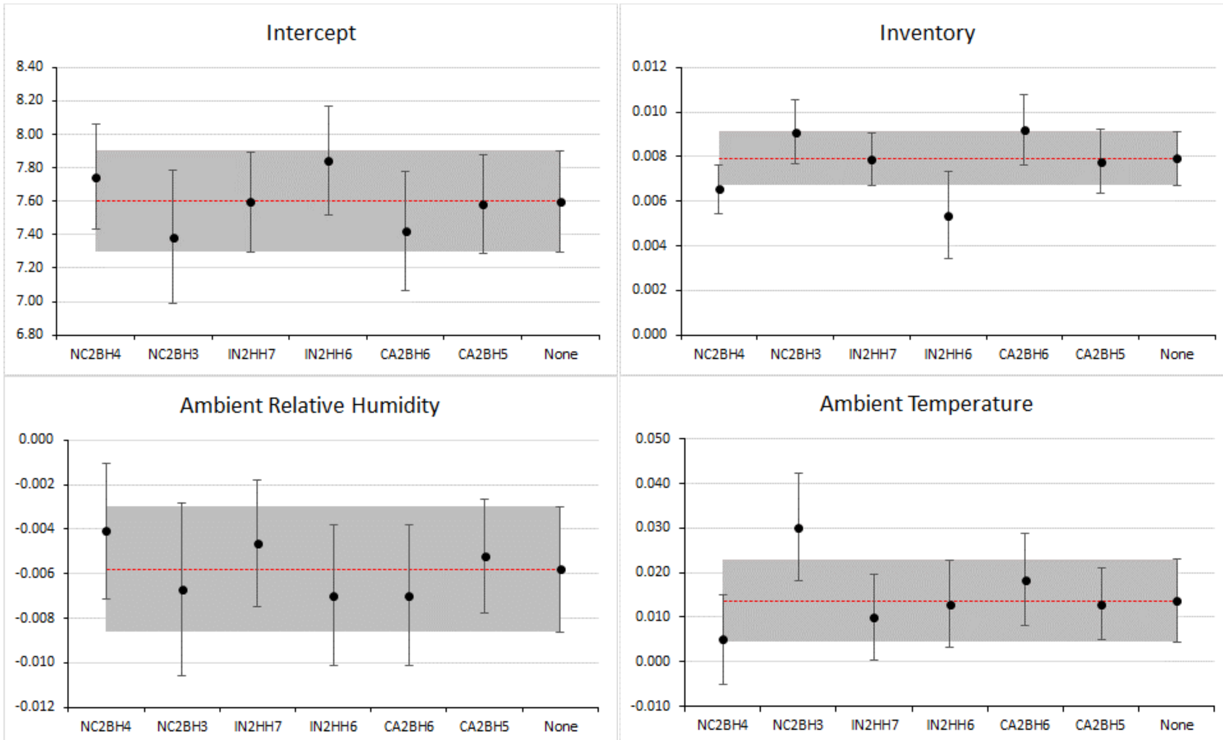

Figure 6-5. Comparison of variation in coefficients and standard errors for TSP high rise house model.

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

6.2 Manure Belt Layer House Models

6.2.1 NH_3 Model Evaluation

The model coefficients from the jackknife approach were comparable across the withheld sets (Table 6-11), though a few parameters were insignificant in the withheld models. However, the plots in Figure 6-6 show that the results for all jackknife models overlap the full model estimate ± 1 standard error, often with the average value falling within ± 1 standard error. Comparing the full model to the withheld models, the maximum percentage differences for parameter estimates across the two models were 17%, 28%, 5%, and 5% for intercept, inventory, ambient temperature, and ambient relative humidity, respectively. Across all models, the difference in NME and NMB (Table 6-12) in comparison to the selected model were minor, with NME values differing by less than 4.39% and NMB by less than 1.50%.

Table 6-11. Model coefficients developed using the jackknife approach for NH_3 emissions from manure belt houses.

Site Out	Effect	Estimate	Standard Error	p-value
None	Intercept	2.439187	0.38084	<.0001
None	Inventory	0.004716	0.00148	0.0015
None	Ambient temperature	0.029431	0.0021	<.0001
None	Ambient relative humidity	0.001858	0.0008	*0.0211*
IN2BH8	Intercept	2.370221	0.42525	<.0001
IN2BH8	Inventory	0.004633	0.0016	0.004
IN2BH8	Ambient temperature	0.030883	0.00319	<.0001
IN2BH8	Ambient relative humidity	0.001972	0.0012	0.1001
IN2BH9	Intercept	2.851005	2.69364	0.3089
IN2BH9	Inventory	0.003414	0.01076	0.756
IN2BH9	Ambient temperature	0.027856	0.00275	<.0001
IN2BH9	Ambient relative humidity	0.00176	0.00107	0.1006

Table 6-12. Model fit statistics for the manure belt house NH_3 jackknife.

Site Out	n	LNME[a] (%)	NME[b] (%)	ME[b] (kg day^{-1})	MB[b] (kg day^{-1})	NMB[b] (%)	Corr.
None	1,159	12.551	58.798	40.195	9.866	14.432	-0.199
IN2BH8	583	13.255	63.191	41.67	10.508	15.934	-0.185
IN2BH9	576	11.646	54.568	38.639	9.286	13.114	-0.242

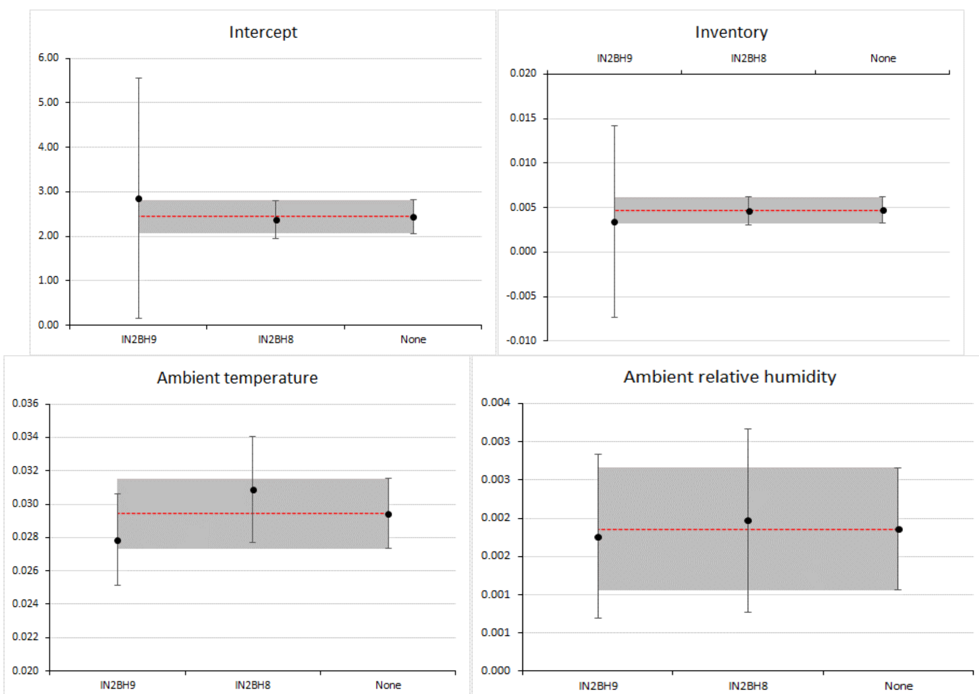

Figure 6-6. Comparison of variation in coefficients and standard errors for NH_3 manure belt house model.

Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected NH_3 manure belt house model coefficient (“None”, gray band for ± SE) for each model parameter.

6.2.2 H_2S Model Evaluation

The model coefficients from the jackknife approach were comparable across the withheld sets (Table 6-13) and were significant, except for IN2B H9. As with NH_3, the plots in Figure 6-7 show that the results for all jackknife models overlap the full model estimate ± 1 standard error. The maximum percentage differences for parameter estimates compared to the full model were 32%, 69%, 18%, and 12% for intercept, inventory, ambient temperature, and ambient relative humidity, respectively. Across all models, the difference in NME and NMB (Table 6-14) in comparison to the selected model were moderate, with NME values differing by less than 8.45% and NMB by less than 2.65%.

Table 6-13. Model coefficients developed using the jackknife approach for H_2S emissions from manure belt houses.

Site Out	Effect	Estimate	Standard Error	p-value
None	Intercept	3.739104	0.34302	<.0001
None	Ambient temperature	0.022216	0.00179	<.0001
None	Inventory	0.007345	0.00135	<.0001
None	Ambient relative humidity	0.004788	0.00068	<.0001
IN2BH8	Intercept	3.678677	0.3546	<.0001
IN2BH8	Ambient temperature	0.026288	0.00279	<.0001
IN2BH8	Inventory	0.007002	0.00136	<.0001
IN2BH8	Ambient relative humidity	0.005352	0.00102	<.0001
IN2BH9	Intercept	2.545273	1.34145	0.0689
IN2BH9	Ambient temperature	0.019604	0.00225	<.0001
IN2BH9	Inventory	0.012431	0.00535	*0.0283*
IN2BH9	Ambient relative humidity	0.00436	0.00091	<.0001

Table 6-14. Model fit statistics for the manure belt house H_2S jackknife.

Site Out	n	LNME[a] (%)	NME[b] (%)	ME[b] (g day^{-1})	MB[b] (g day^{-1})	NMB[b] (%)	Corr.
None	1,185	6.18	38.385	185.96	7.55	1.559	0.338
IN2BH8	598	7.42	46.835	221.81	19.952	4.213	0.199
IN2BH9	587	4.894	31.064	153.93	1.635	0.33	0.503

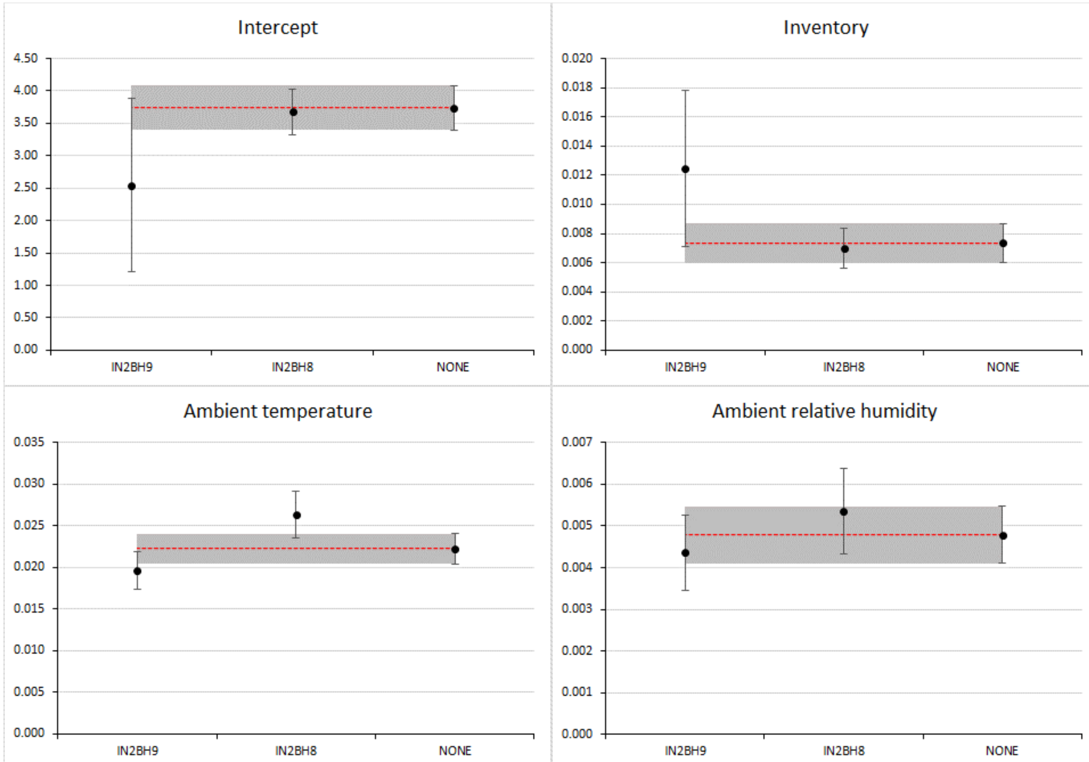

Figure 6-7. Comparison of variation in coefficients and standard errors for H_2S manure belt house model.

Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected H_2S manure belt house model coefficient ("None", gray band for ± SE) for each model parameter.

6.2.3 PM_{10} Model Evaluation

The model coefficients from the jackknife approach were comparable across the withheld sets (Table 6-15), except for IN2BH9. The intercept and inventory parameters for the IN2BH9 withheld model fall outside the full model estimate ± 1 standard error band shown in Figure 6-8. The maximum percentage differences for parameter estimates compared to the full model 122% and 435% for intercept and inventory, respectively. Across all models, the difference in NME and NMB (Table 6-16) in comparison to the selected model were moderate, with NME values differing by less than 8.30% and NMB by less than 0.77%.

Table 6-15. Model coefficients developed using the jackknife approach for PM_{10} emissions from manure belt houses.

Site Out	Effect	Estimate	Standard Error	p-value
None	Intercept	6.631005	0.74268	<.0001
None	Inventory	0.007205	0.00304	0.0186
IN2BH8	Intercept	7.038744	0.75413	<.0001
IN2BH8	Inventory	0.006027	0.00309	**0.0525**
IN2BH9	Intercept	-1.475494	2.38503	**0.5391**
IN2BH9	Inventory	0.038528	0.00973	0.0002

Table 6-16. Model fit statistics for the manure belt house PM_{10} jackknife.

Site Out	n	LNME[a] (%)	NME[b] (%)	ME[b] (g day^{-1})	MB[b] (g day^{-1})	NMB[b] (%)	Corr.
None	566	9.608	85.204	4,619.6	-61.72	-1.138	0.187
IN2BH8	334	9.188	79.429	5,386.5	-42.89	-0.632	0.135
IN2BH9	232	8.088	76.906	2,664.2	-66.03	-1.906	0.323

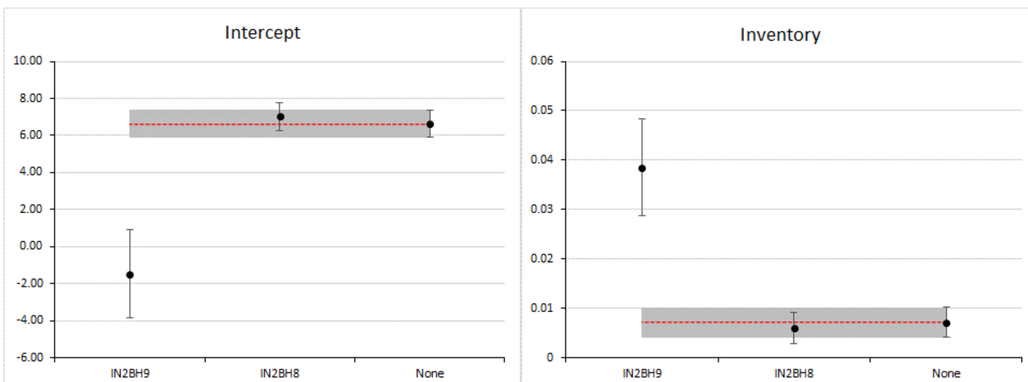

Figure 6-8. Comparison of variation in coefficients and standard errors for PM_{10} manure belt house model.

Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected PM_{10} manure belt house model coefficient ("None", gray band for ± SE) for each model parameter.

6.2.4 $PM_{2.5}$ Model Evaluation

Table 6-17 shows the variation in coefficients and standard errors for the selected model ("None") and each of the jackknife models. The intercept and inventory parameters for the IN2BH8 withheld model fall outside the full model estimate ± 1 standard error band shown in Figure 6-9. When compared to the full model, the coefficients vary up to 123% and 119% for intercept and inventory, respectively. This may be due to the model selection being based off of PM_{10} data, and not $PM_{2.5}$ data. However, this was necessary as there is a total of 34 days of $PM_{2.5}$ data from both houses. The plots in Figure 6-9 show that the results for all jackknife models overlap the full model estimate ± 1 standard error. Across all models, the difference in NME and NMB (Table 6-18) in comparison to the selected model were substantial, with NME values differing up to 94.40% and NMB by up to 110.07% from the full model.

Table 6-17. Model coefficients developed using the jackknife approach for $PM_{2.5}$ emissions from manure belt houses.

Site Out	Effect	Estimate	Standard Error	p-value
None	Intercept	-127.4489	61.0184	0.0681
None	Inventory	0.534577	0.24656	0.0604
IN2BH8	Intercept	29.681669	68.2977	0.6864
IN2BH8	Inventory	-0.099217	0.27555	0.737
IN2BH9	Intercept	-152.4	41.9311	0.0073
IN2BH9	Inventory	0.635083	0.16867	0.0062

Table 6-18. Model fit statistics for the manure belt house $PM_{2.5}$ jackknife.

Site Out	n	LNME[a] (%)	NME[b] (%)	ME[b] (g day^{-1})	MB[b] (g day^{-1})	NMB[b] (%)	Corr.
None	34	24.719	158.33	485.85	322.42	105.07	0.337
IN2BH8	23	18.389	94.887	197.28	18.756	9.021	-0.138
IN2BH9	11	16.2	63.933	328.47	-25.7	-5.002	0.433

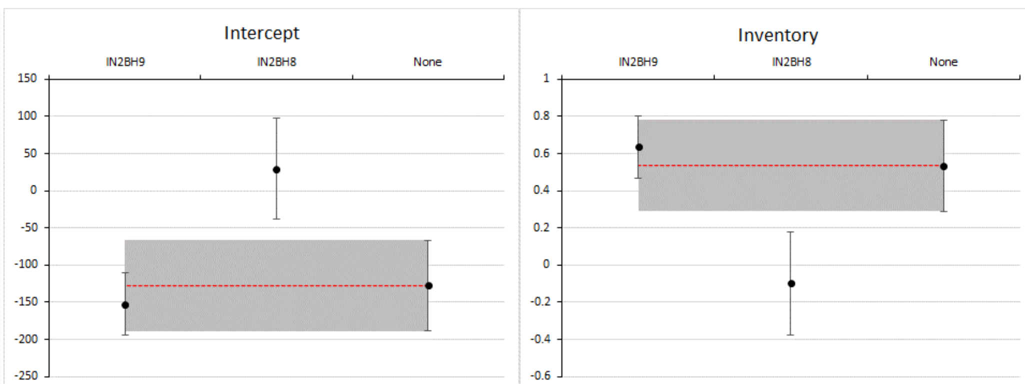

Figure 6-9. Comparison of variation in coefficients and standard errors for $PM_{2.5}$ manure belt house model.

Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected $PM_{2.5}$ manure belt house model coefficient ("None", gray band for ± SE) for each model parameter.

6.2.5 TSP Model Evaluation

The model coefficients from the jackknife approach were comparable across the withheld sets (Table 6-19), though the parameters were insignificant. When compared to the full model, the coefficients vary up to 45% and 123% for intercept and inventory, respectively. Again, this is largely due to the reduced number of days available for the TSP models. However, the plots in Figure 6-10 show that the results for all jackknife models overlap the full model estimate ± 1 standard error. Across all models, the difference in NME and NMB (Table 6-20) in comparison to the selected model were moderate, with NME values differing by less than 24.70% and NMB by less than 0.69% from the full model.

Table 6-19. Model coefficients developed using the jackknife approach for TSP emissions from manure belt houses.

Site Out	Effect	Estimate	Standard Error	p-value
None	Intercept	6.936206	8.87165	0.4404
None	Inventory	0.00987	0.03594	0.7855
IN2BH8	Intercept	10.081357	11.6563	0.3995
IN2BH8	Inventory	-0.002242	0.04719	0.9627
IN2BH9	Intercept	7.026336	10.2175	0.5012
IN2BH9	Inventory	0.006512	0.04163	0.8776

Table 6-20. Model fit statistics for the manure belt house TSP jackknife.

Site Out	n	LNME[a] (%)	NME[b] (%)	ME[b] (kg day^{-1})	MB[b] (kg day^{-1})	NMB[b] (%)	Corr.
None	69	9.95	78.285	11668	82.753	0.555	-0.044
IN2BH8	34	9.001	76.513	16,734	-28.81	-0.132	0.166
IN2BH9	35	10.914	53.585	4,359.8	65.823	0.809	-0.157

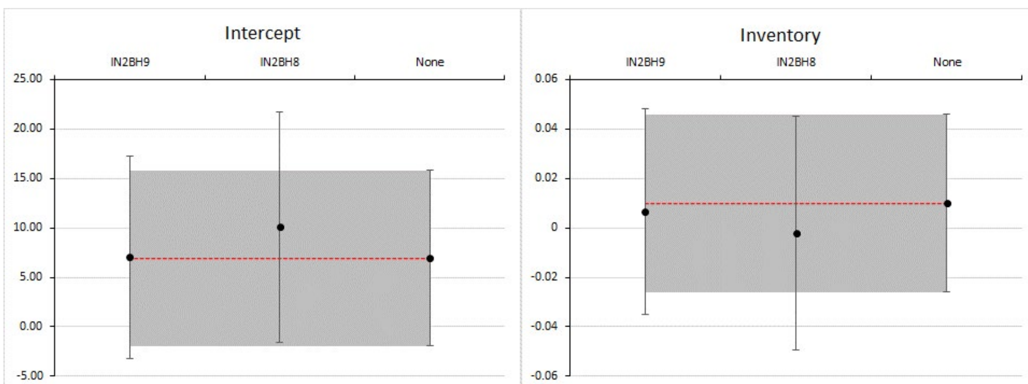

Figure 6-10. Comparison of variation in coefficients and standard errors for TSP manure belt house model.

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

6.3 Manure Shed Models

For the manure shed model, we did not complete jackknife analysis because there was only one site in the dataset. We also did not pursue a model evaluation using a k-fold cross validation technique based on previous SAB comments (SAB, 2013) recommending against using this method to select data for temporally correlated data.

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, house, and manure shed parameters. For an actual emissions estimate, the daily estimates are based on meteorology from nearby monitors and house occupancy 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 sources (e.g., houses, manure sheds), annual emissions are determined for individual sources and then 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 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. Section 8 contains examples of this calculation.

Table 7-1. Back transformation parameters.

Animal Type	Pollutant	$\overline{E_i}$	C	Resulting Units
High Rise House	NH_3	1.58238	0	kg
High Rise House	H_2S	1.24359	15	g
High Rise House	PM_{10}	1.11745	494	g
High Rise House	$PM_{2.5}$	1.51089	37	g
High Rise House	TSP	1.11429	0	g
Manure Belt House	H_2S	1.09812	39	g
Manure Belt House	NH_3	1.27315	0	kg
Manure Belt House	PM_{10}	1.45218	1045	g
Manure Belt House	$PM_{2.5}$	2.97703	108	g
Manure Belt House	TSP	1.34146	696	g
Manure Shed	H_2S	1.36619	6.0	g
Manure Shed	NH_3	1.28615	1.3	kg
Manure Shed	PM_{10}	1.68902	54.0	g
Manure Shed	$PM_{2.5}$	1.68697	0.0	g
Manure Shed	TSP	2.01361	30.0	g

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:

$$S_{an} = \sqrt{(S_{r1})^2 + (S_{r2})^2 + \ldots (S_{rn})^2} \qquad \text{Equation 16}$$

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 16 simplifies to:

$$S_{an} = S_r n^{0.5} \qquad \text{Equation 17}$$

Table 7-2 lists the S_r values for layer houses and manure sheds by pollutant. 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:

$$U_{an} \approx 1.96\, S_{an} \qquad \text{Equation 18}$$

Combining Equations 17 and 18 with an n value of 365 (representing the number of days in the annual uncertainty calculation) yields:

$$U_{an} \approx 1.96\, S_{an} \approx 1.96\, S_r n^{0.5} \approx 1.96\, S_r*(365)^{0.5} \approx 37.45\, S_r \qquad \text{Equation 19}$$

EPA has not calculated PM annual uncertainty models for the manure belt house and manure shed models in order to allow more time to optimize the models.

Table 7-2. Daily Residual Standard Deviation Values for Layer Houses and Manure Sheds.

Process	Pollutant	S_r	Emissions Units
High Rise	NH_3	87.746	kg/d
High Rise	H_2S	121.035	g/d
High Rise	PM_{10}	2041.8	g/d
High Rise	$PM_{2.5}$	286.63	g/d
High Rise	TSP	2,235.6	g/d
Manure Belt House	NH_3	49.882	kg/d
Manure Belt House	H_2S	246.84	g/d
Manure Belt House	PM_{10}	7,074.6	g/d
Manure Belt House	$PM_{2.5}$	532.71	g/d
Manure belt House	TSP	17,593	g/d
Manure Shed	NH_3	6.375	kg/d
Manure Shed	H_2S	48.086	g/d
Manure Shed	PM_{10}	294.28	g/d
Manure Shed	$PM_{2.5}$	63.568	g/d
Manure Shed	TSP	408.58	g/d

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

$$Total\ farm\ uncertainty = \sqrt{(U_{B1})^2 + \cdots + (U_{Bi})^2 + (U_{L1})^2 + \cdots + \left(U_{Lj}\right)^2} \qquad \text{Equation 20}$$

Where:

Total farm uncertainty = total uncertainty for the total emissions from all farm sources.
UBi = the resulting uncertainty for houses, with i representing the total number of houses on the farm,
ULj = the resulting uncertainty for manure sheds, with j representing the total number of open sources 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 of how the daily, annual, 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 (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). Finally, this section wraps up with a discussion of data limitations that could be driving sensitivity or performance issues.

8.1 Model Application Example

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

Section 6.4 of the Overview report noted that, since the data were log transformed prior to developing the models, the result would need to be back transformed to represent emissions in units of grams or kilograms. To complete the back transformation, users need two parameters that are specific to each model 1) $\overline{E_\iota}$, the average 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. The values for $\overline{E_\iota}$ and C for each layer model are provided in Table 7-1.

For transparency and to help stakeholders better understand the process of calculating emissions, this section presents example calculations to estimate NH_3 emissions from a high rise layer house, a manure belt house, and a manure shed.

The examples in this section use a fictional farm located in Hancock County, Iowa on January 1, 2020. Iowa was chosen as it is a top five egg producing state according to the USDA Economic Research Service (https://www.ers.usda.gov/topics/animal-products/poultry-eggs/sector-at-a-glance/). 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 Forest City Municipal Airport, IA site (WBAN: 54940), a Local Climatological Data (LCD) Station located in Hancock County and its data file provides the daily average vales of the key meteorological parameters needed for calculations.

Additionally, the high rise and manure belt models require the number of birds in the house. For this fictious farm, 100,000 birds are placed in each house. 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 used for the example calculations is provided in Table 8-1.

Table 8-1. Daily calculation parameter values.

Parameter	Value
Daily Average Ambient Temperature (°C)	-0.9
Daily Average Relative Humidity (%)	89
Inventory (birds)	100,000

8.1.1 High Rise Example

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

$$\ln(NH_3) = 2.6598 + 0.0059 * Inventory + 0.0387 * Amb_T + 0.0018 * Amb_{RH}$$

$$\ln(NH_3) = 2.6598 + 0.0059 * \left(\frac{100{,}000}{1{,}000}\right) + 0.0387 * -0.9 + 0.0018 * 89$$

$$\ln(NH_3) = 2.6598 + 0.5890 - 0.0348 + 0.1567$$

$$\ln(NH_3) = 3.3707$$

To back transform the results to NH_3 in kg, use Equation 7 from the Overview report. For a high rise house, $\overline{E_i}$ is 1.58238 and C is 0.

$$NH_3 = e^{3.3707} \times 1.58238 - 0$$

This comes to 46.09 kg NH_3 for the day. This 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 house was calculated at 25,997.17 kg. To calculate the uncertainty associated with this estimate, use Equation 19 with the S_r value from Table 7-2. This results in an annual uncertainty of ± 3,286.09 kg. Thus, the final annual estimate for this house is 25,997.17 kg ± 3,286.09 kg. This calculation would be repeated for any other high rise houses on the site.

8.1.2 Manure Belt House Example

Referring back to Equation 6 in Section 5, the log transformed NH_3 emissions values for manure belt houses are calculated as follows:

$$ln(NH_3) = 2.4392 + 0.0047 * Inventory + 0.0294 * Amb_T + 0.0019 * Amb_{RH}$$

$$ln(NH_3) = 2.4392 + 0.0047 * \left(\frac{100{,}000}{100}\right) + 0.0294 * -0.9 + 0.0019 * 89$$

$$ln(NH_3) = 2.4392 + 0.4700 - 0.0265 + 0.1691$$

$$ln(NH_3) = 3.05184$$

To back transform the results to NH_3 in kg, use Equation 7 from the Overview report. For a manure belt house, $\overline{E_\iota}$ is 1.27315 and C is 0.

$$NH_3 = e^{3.05184} \times 1.27315 - 0$$

This comes to 26.95 kg NH_3 for the day. This 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 manure belt house was calculated at 13,402.68 kg. To calculate the uncertainty associated with this estimate, use Equation 19 with the S_r value from Table 7-2. This results in an annual uncertainty of ± 1,868.08 kg. Thus, the final annual estimate for this house is 13,402.68 kg ± 1,868.08 kg. This calculation would be repeated for any other manure belt houses on the site.

8.1.3 Manure Shed Example

Similar to the set up in NAEMS, the hypothetical farm will have two houses, with constant inventories of 200,000 birds, that move manure into a shed. Referring back to Equation 11, in Section 5, the log transformed NH_3 emissions values for the manure shed are calculated as follows:

$$ln(NH_3) = -0.194945 - 0.01375 * Amb_T + 0.00393 * Inventory\ (5\ day\ lag)$$

$$ln(NH_3) = -0.194945 - 0.01375 * -0.9 + 0.003927 * \left(\frac{200{,}000}{1{,}000}\right)$$

$$ln(NH_3) = -0.19494 + 0.0124 + 0.7854$$

$$ln(NH_3) = 0.60283$$

To back transform the results to NH_3 in kg, use Equation 7. For a manure shed, $\overline{E_\iota}$ is 1.2862 and C is 1.3.

$$NH_3 = e^{0.60283} \times 1.2862 - 1.3$$

This comes to 1.05 kg NH_3 for the day. This 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 house was calculated at 288.71 kg. To calculate the uncertainty associated with this estimate, use Equation 19 with the Sr value from

Table 7-2. This results in an annual uncertainty of ± 238.74 kg. Thus, the final annual estimate for this house is 288.71 kg ± 238.74 kg. This calculation would be repeated for any other manure sheds on the site.

8.1.4 Combining Structures

To calculate farm total emissions, the emissions from each unit are added. As an example, consider a farm with two high rise houses with a capacity of 100,000 birds. These houses will have the same emissions estimate for the year, 25,997.17 kg ± 3,286.09 kg. The annual farm emissions estimate is:

$$Farm\ Total\ Emissions = 25{,}997.17 + 25{,}997.17 = 51{,}994.34\ kg\ NH_3$$

To estimate the total farm uncertainty, use Equation 20:

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

$$Total\ Farm\ Uncertainty = \sqrt{(3{,}282.72)^2 + (3{,}282.72)^2}$$

$$Total\ Farm\ Uncertainty = 4{,}642.47\ \text{kg}$$

The final annual NH_3 estimate for the farm is 51,994.34 ± 4,642.47 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 150,000 birds. Using the same meteorology from Section 8.1, the emissions for a high rise house on January 1, 2020, is as follows:

$$\ln(NH_3) = 2.6598 + 0.0059 * \left(\frac{150{,}000}{1{,}000}\right) + 0.0387 * -0.9 + 0.0018 * 89$$

$$\ln(NH_3) = 2.6598 + 0.8835 - 0.0348 + 0.1567$$

$$\ln(NH_3) = 3.6652$$

$$NH_3 = e^{3.6652} \times 1.58238 - 0$$

This comes to 61.81 kg NH_3 for the day. This is 15.7 kg (34%) more than a house with a bird population of 100,000 layers for the same day. This demonstrates the model has sensitivity to the number of animals in the house. When the annual emissions for this house are calculated, the annual difference is 8,902.86 kg, which is a 34% increase.

Looking at the manure belt house, increasing the bird population to 150,000 birds for January 1, 2020, results in the following:

$$ln(NH_3) = 2.4392 + 0.0047 * \left(\frac{150{,}000}{100}\right) + 0.0222 * -0.9 + 0.0048 * 89$$

$$ln(NH_3) = 2.4392 + 0.7050 - 0.0265 + 0.1691$$

$$ln(NH_3) = 3.2868$$

$$NH_3 = e^{3.2868} \times 1.27315 - 0$$

This comes to 34.09 kg NH_3 for the day. This is 7.17 kg more NH_3 than a house with a bird population of 100,000 layers for the same day. When the annual emissions for this house are calculated, the annual difference is 3,550.49 kg, a 26% change with a 50% change in inventory. This demonstrates the model has a sensitivity to the number of animals in the house.

Looking at the manure shed, increasing the number of birds contributing to the house to 300,000 birds for January 1, 2020, results in the following:

$$ln(NH_3) = -0.194945 - 0.01375 * -0.9 + 0.003927 * \left(\frac{300{,}000}{1{,}000}\right)$$

$$ln(NH_3) = -0.194945 + 0.0127 + 1.1781$$

$$ln(NH_3) = 0.99553$$

$$NH_3 = e^{0.99553} \times 1.2862 - 1.3$$

This comes to 2.18 kg NH_3 for the day. This is 1.13 kg more NH_3 than a shed supplied by a bird population of 200,000 layers for the same day. When the annual emissions for this shed are calculated, the annual difference is 367.71 kg, a 127% change with a 50% change in inventory. This demonstrates the model's sensitivity, perhaps overly, to the number of animals in the house.

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 from the previous example (Section 12.1) that is in northern Iowa. The NH_3 emissions for this same farm setup (i.e., one high rise house and one manure belt house that empties into a manure shed) were calculated using meteorology from Dalton, Georgia. These locations were chosen based on 2017 Census of agriculture data indicating areas of poultry and egg sales (Figure 8-1).

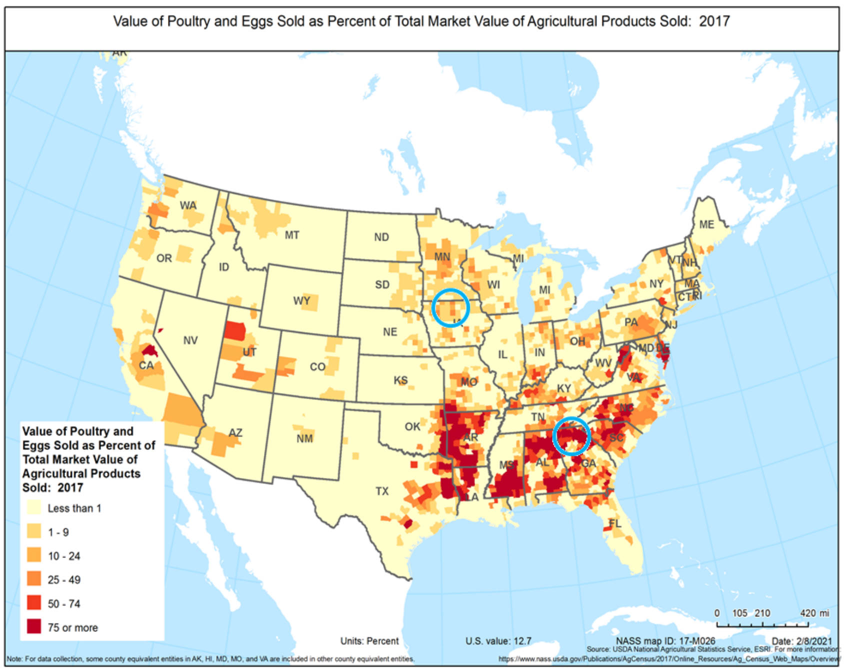

Figure 8-1. 2017 Census of Agriculture plot indicating areas of broiler sales.
Blue circles indicate approximate locations of test meteorology from Iowa (IA) and Georgia (GA).

For our test sites, the temperatures from the Iowa (IA) site were typically lower than the Georgia (GA) site (Figure 8-1). Average daily temperatures differences between Iowa and Georgia by as little as 4 °C to as much as 35 °C across the year. On average, the temperatures in Iowa were 8.4 °C less than those in Georgia (Table 8-2). With respect to relative humidity, the IA and GA sites were fairly similar during the warmer months (Apr-Oct; Figure 8-2 and Figure 8-3), however, during the cooler months (Nov-Mar), average humidity was 16.2% higher in IA in comparison to GA. Both locations have humidities that vary between 35% to 100% across the year.

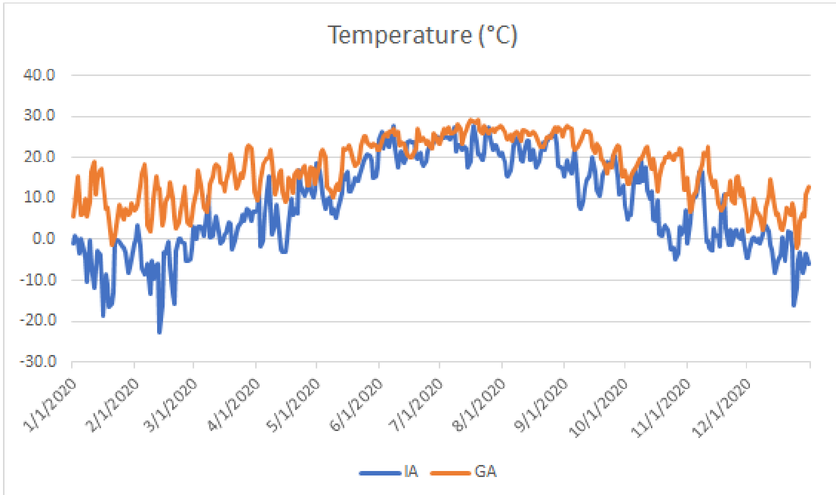

Figure 8-2. Comparison on temperatures at test locations in Iowa (IA) and Georgia (GA).

Table 8-2. Summary of temperature at the two meteorological sites.

Site	Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Overall
IA	Min	-18.9	-22.7	-2.2	-3.2	5.3	17.7	17.6	15.4	7.5	-4.8	-4.5	-16.1	-22.7
IA	Max	0.8	3.6	10.8	16.9	20.7	27.9	27.7	25.7	22.2	19.4	16.5	3.3	27.9
IA	Average	-5.7	-5.9	3.3	7.0	13.8	22.4	23.2	21.1	15.4	6.5	3.7	-2.9	8.5
GA	Min	-1.2	2.0	6.7	9.1	10.4	20.0	23.5	22.7	15.4	11.7	6.0	-2.1	-2.1
GA	Max	18.9	18.2	23.2	21.9	25.4	27.0	29.2	27.5	27.7	22.7	22.6	14.6	29.2
GA	Average	8.6	8.7	15.0	15.2	19.3	24.0	26.9	25.5	22.4	18.2	12.7	6.3	16.9

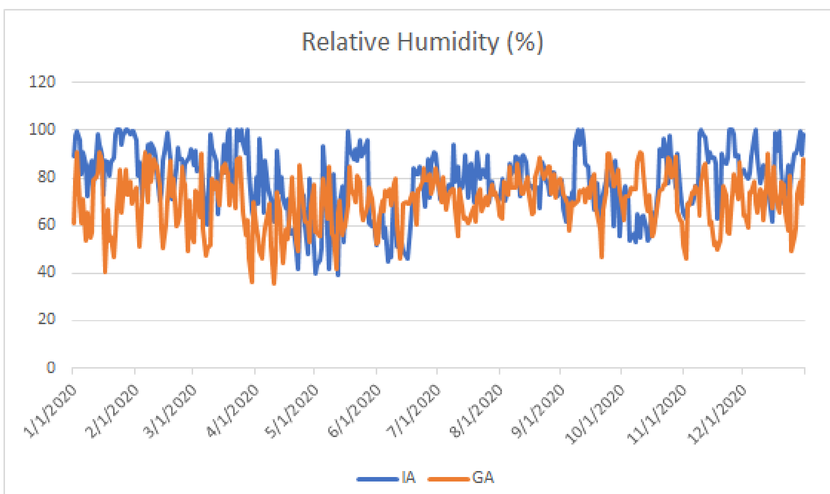

Figure 8-3. Comparison of relative humidities at test locations IA and GA.

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

Site	Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Overall
IA	Min	72.3	70.3	60.4	41.6	39.3	44.6	69.6	67.4	55.6	52.9	63.2	61.7	39.3
IA	Max	100.0	98.7	100.0	96.4	99.6	90.8	94.2	89.6	100.0	97.7	100.0	100.0	100.0
IA	Average	91.2	85.1	84.9	68.6	70.9	66.0	79.2	79.0	76.8	71.5	83.8	84.9	78.5
GA	Min	40.4	49.4	36.3	35.5	41.9	46.2	55.2	63.1	46.7	55.3	46.1	49.2	35.5
GA	Max	91.0	90.7	90.5	85.2	84.7	84.1	80.8	88.2	90.5	91.1	86.8	90.0	91.1
GA	Average	68.6	72.1	69.3	60.0	66.3	71.1	69.7	77.1	72.7	74.2	68.2	70.8	70.1

8.2.2.1 High rise house

When the daily calculations are performed for the entire year for a high rise house with 100,000 birds, the Georgia site typically has a higher daily emissions values for the gaseous pollutants than the Iowa site (Figure 8-3). Table 8-4 has the estimated annual emissions of all the pollutants studied. The total annual NH_3 emissions estimate for the farm using meteorology from Georgia was 25,997 kg, a 7,911 kg increase from the same high rise house with meteorology from Iowa. A similar trend is seen across the other pollutants. This is consistent with the trends of lower temperatures yielding lower gas emissions and higher humidity yielding lower PM emissions seen during the data exploration in Section 4. Overall, this suggests that the emissions models are robust enough to account for the climatic differences of the different growing regions in the results for high rise houses.

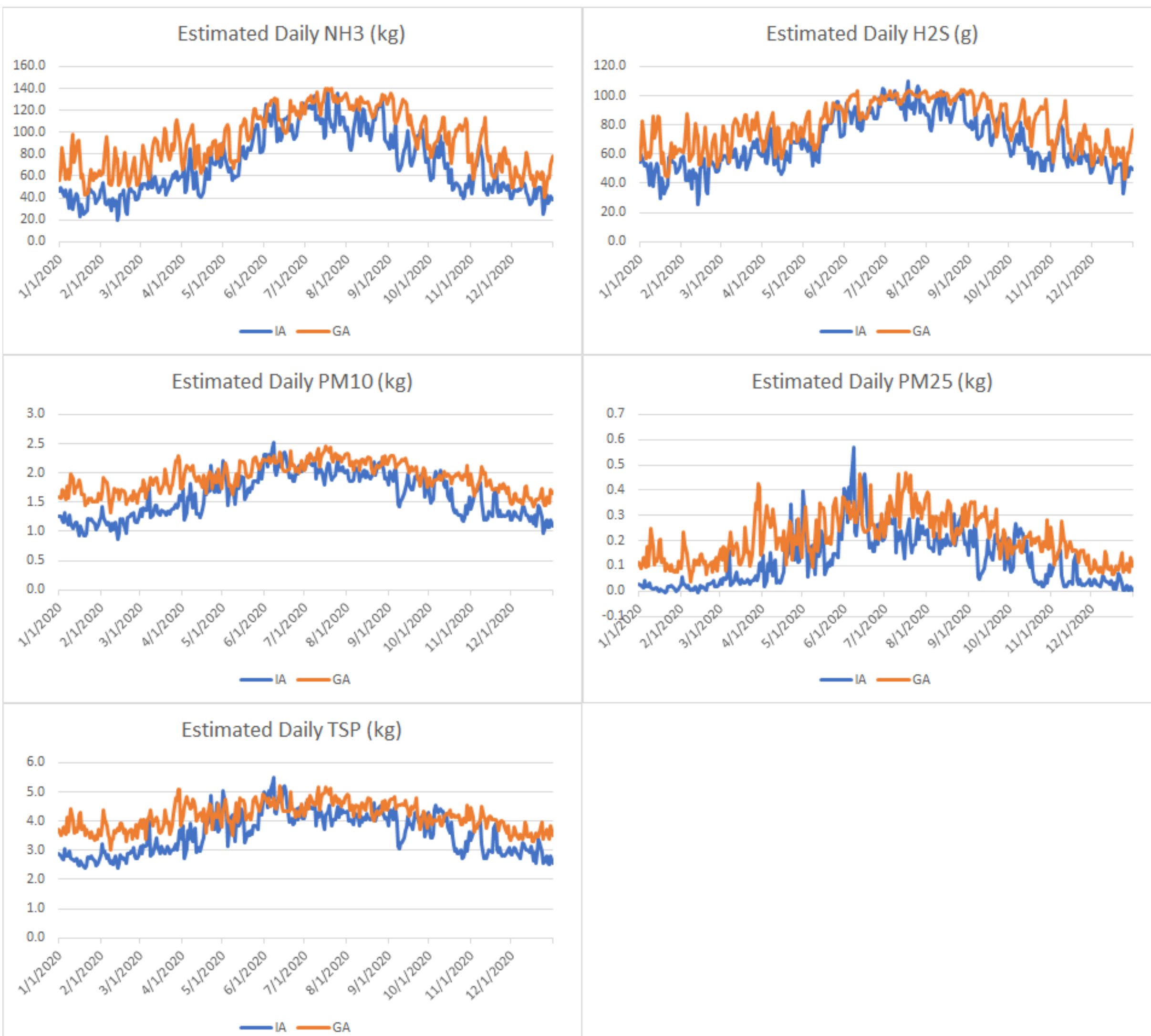

Figure 8-4. Comparison of daily emissions at test high rise locations IA and GA.

Table 8-4. Total annual emissions from the theoretical high rise houses in IA and GA.

Pollutant	IA Emissions (kg per year)	GA Emissions (kg per year)
NH_3	25,997	33,909
H_2S	25	29
PM_{10}	590	702
$PM_{2.5}$	45	77
TSP	1,308	1,520

8.2.2.2 Manure belt house

For a manure belt house, when the daily calculations are performed for the entire year for a high rise house with 100,000 birds, the Georgia site typically has greater daily emissions value for the gaseous pollutants than the Iowa site (Figure 8-4). Particulate matter estimates are the same between the locations as there were no ambient parameters included in the selected models. Table 8-5 has the annual emissions estimates of all the pollutants studied. The total annual NH_3 emissions estimate for the farm using meteorology from Georgia was 16,466 kg, a 3,063 kg increase from the same manure belt house with meteorology from Iowa. A similar trend is seen with H_2S. This is consistent with the trend of lower temperatures yielding lower gas emissions seen during the data exploration in Section 4. Overall, this suggests that the emissions models are robust enough to account for the climatic differences of the different growing regions in the results for manure belt houses for the gaseous pollutant.

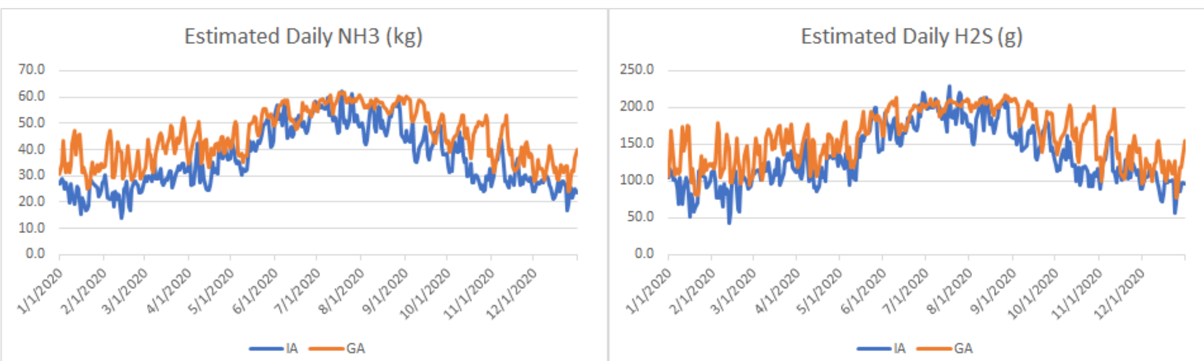

Figure 8-5. Comparison of daily emissions at a theoretical manure belt house in IA and GA.

Table 8-5. Total annual emissions from a theoretical manure belt house in IA and GA.

Pollutant	IA Emissions (kg per year)	GA Emissions (kg per year)
NH_3	13,403	16,466
H_2S	49	58
PM_{10}	446	446
$PM_{2.5}$	-40	-40

Pollutant	IA Emissions (kg per year)	GA Emissions (kg per year)
TSP	1,101	1,101

8.2.2.3 Manure Shed

For a manure shed, when the daily calculations are performed for the entire year the Georgia site has lower daily emissions values for the gaseous pollutants than the Iowa site (Figure 8-5). Particulate matter estimates are the same between the locations as there were no ambient parameters included in the selected models. Table 8-6 has the estimate annual emissions of all the pollutants studied. The total annual NH_3 emissions estimate for the farm using meteorology from Iowa was 289 kg, an 88 kg difference from the same high rise house with meteorology from Georgia. A similar trend is seen with H_2S. Emissions of NH_3 and H_2S are higher when ambient temperatures are lower due to the negative ambient temperature coefficients in the models. As mentioned, a possible explanation for this is that the higher temperatures are leading to a drying of the manure and thus less NH_3 and H_2S generation. Overall, this suggests that the emissions models are robust enough to account for the climatic differences of the different growing regions in the results for high rise houses.

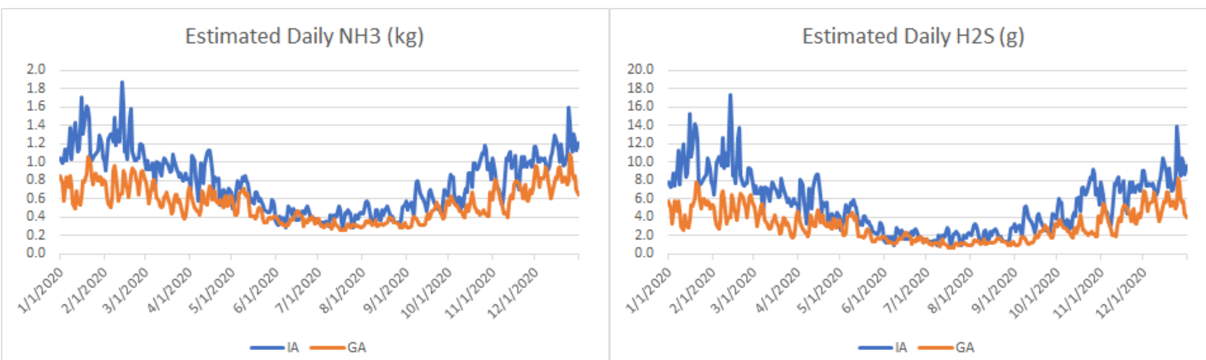

Figure 8-6. Comparison of daily emissions at a theoretical manure shed in IA and GA.

Table 8-6. Total annual emissions from a theoretical manure shed in IA and GA.

Pollutant	IA Emissions (kg per year)	GA Emissions (kg per year)
NH_3	289	201
H_2S	2	1
PM_{10}	47	47
$PM_{2.5}$	0	0
TSP	55	55

8.2.3 Model Limitations

As noted in the 2013 SAB review, extrapolating beyond conditions represented in the model development dataset could produce unreasonable 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 evaluated one parameter at a time, with the selected parameter varied by a constant value through the range. For example, the 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 determined in the model development dataset. The emissions values for each individual test were plotted on graphs for further examination.

If the sensitivity analysis produces unreasonable emissions or emissions trends under certain conditions, this may indicate the need to limit the range of conditions that the model should be applied. Examples of unreasonable emissions or emissions trends include unreasonably high (or low) emissions in certain conditions, and/or large changes in relative sensitivity (i.e., changes in sensitivity analysis slope). The following sections outlines the analysis for each of the selected models and provides a rudimentary examination of the sensitivity analysis for conditions where there may be unreasonable emissions or emissions trends. It should be noted that this analysis does not account for interaction between multiple terms within an equation, which could further affect the results. For example, a manure belt 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.

8.2.3.1 High rise

All of the high rise house models included inventory, ambient temperature, and ambient relative humidity. The ranges evaluated for each parameter are in Table 8-7, with the plotted results plotted in Figure 8-7 and Figure 8-8. For all the variables, the emissions increase with increasing values, which is consistent with established relationships for all three parameters. For inventory and ambient temperature, there are some changes in relative sensitivity, but the changes are not extreme. Neither the NH_3 nor H_2S models produce negative emissions under average conditions, which is an indicator of unreasonable emissions. For PM_{10}, $PM_{2.5}$, and TSP (Figure 8-8), only the $PM_{2.5}$ model produces negative values when ambient temperatures are very low under average conditions.

Table 8-7. Parameter ranges evaluated for the high rise house models.

Parameter	Upper limit	Lower limit	Average Value	Increment
Ambient temperature (°C)	32	-25	15.4	0.9
Ambient relative humidity (%)	100	27	66.2	1
Inventory (birds)	338,800	0	90,522	4,600

To further explore any limitations in the models, emissions were calculated for 416,250 combinations of the range of values specified in Table 8-7. Across this range of conditions, neither the NH_3, PM_{10}, nor TSP models produce negative emissions. The models for H_2S and $PM_{2.5}$ will produce negative values in instances of negative ambient temperature. Specifically, for H_2S, when the ambient temperature falls below -15 °C and house inventory is less than 20,000 birds the models can produce negative emissions values. For $PM_{2.5}$, the range of values that can produce negative values increases to temperatures less than 7 °C and inventory is less than 200,000. The plots in Figure 8-9 show 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.

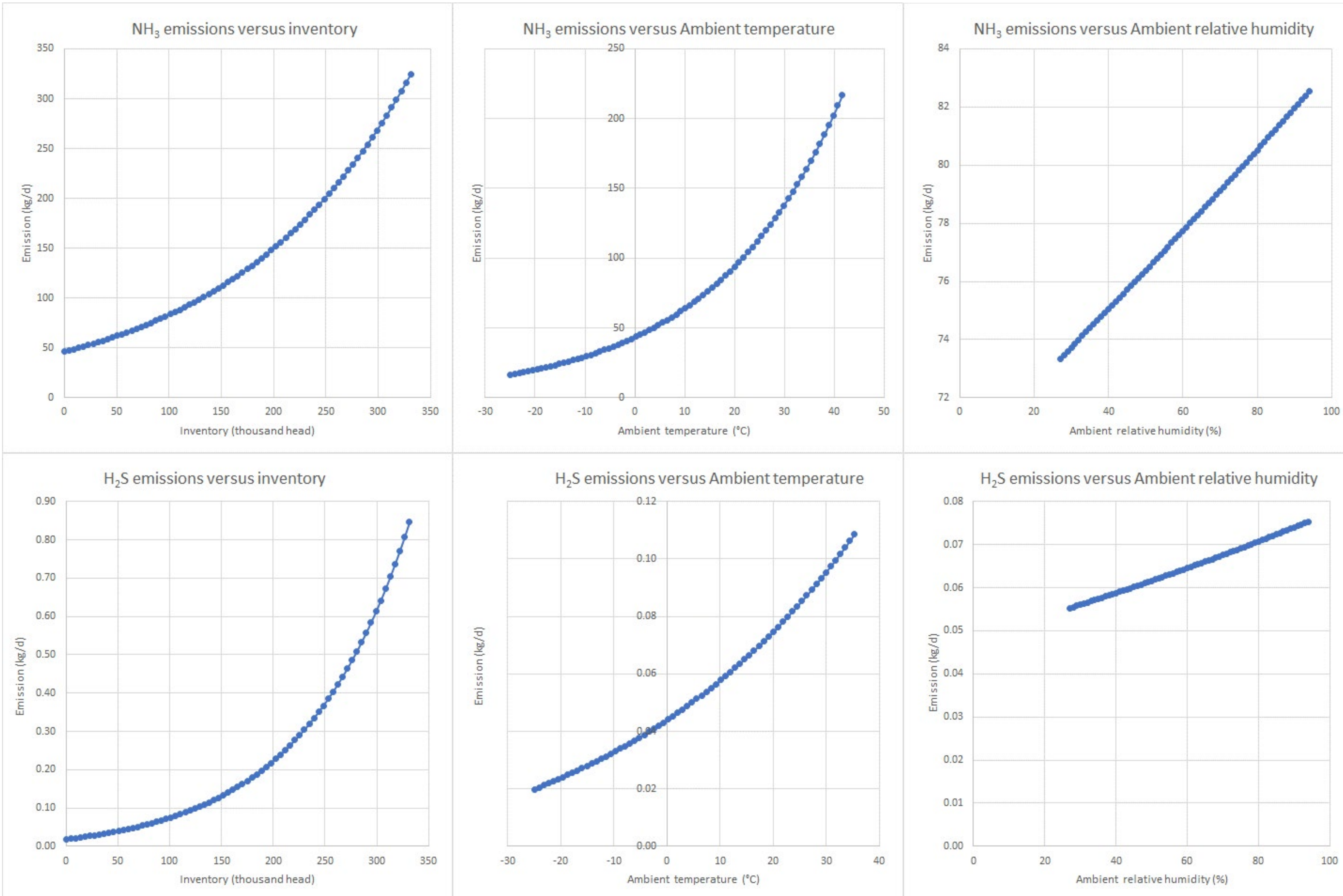

Figure 8-7. High rise house limitation tests for gaseous pollutants.

Visualization of the results for NH_3 (top row) and H_2S (bottom row) with tests for inventory (left), ambient temperature (center) and relative humidity (right).

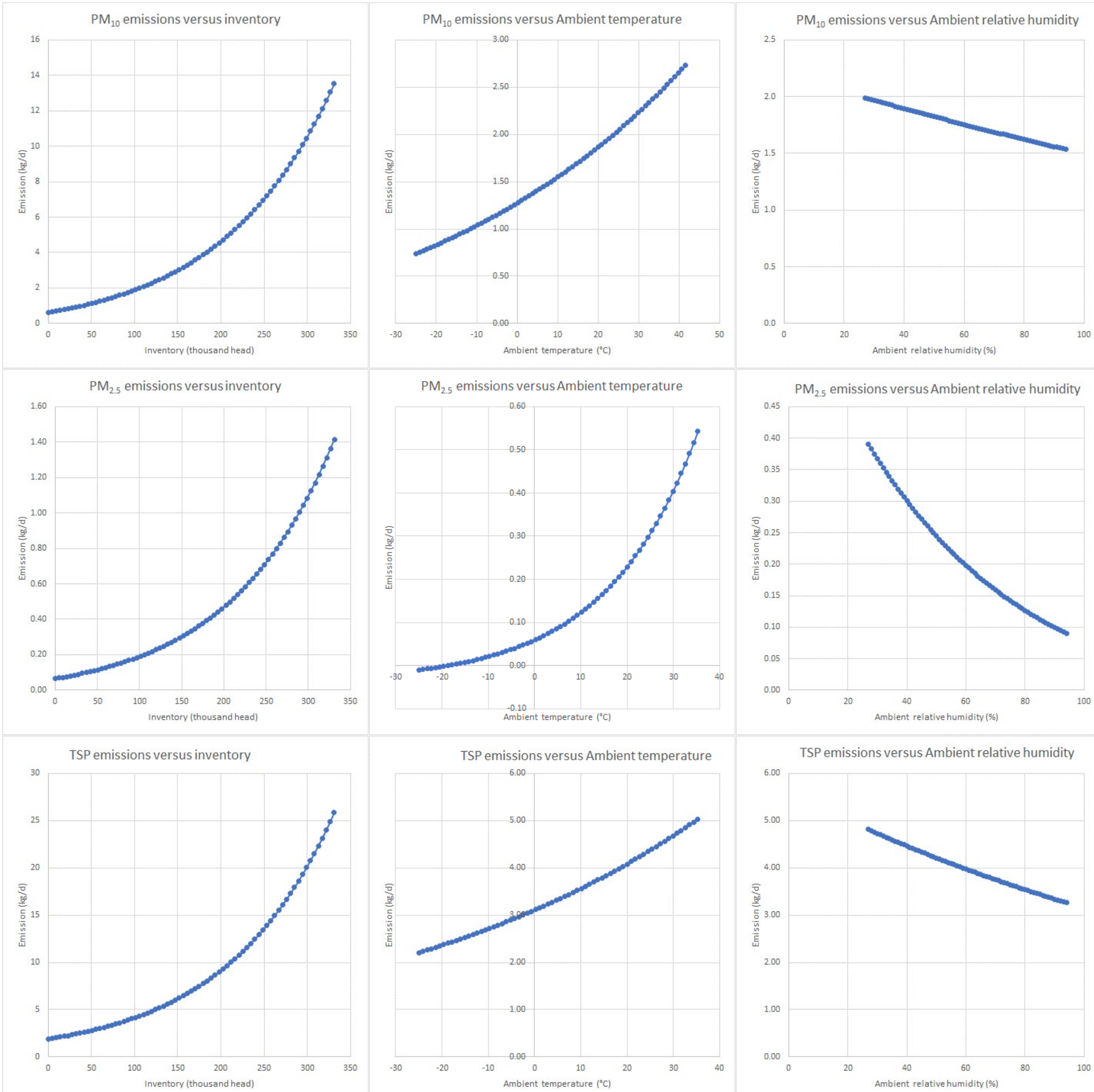

Figure 8-8. High rise house limitation tests for PM.

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

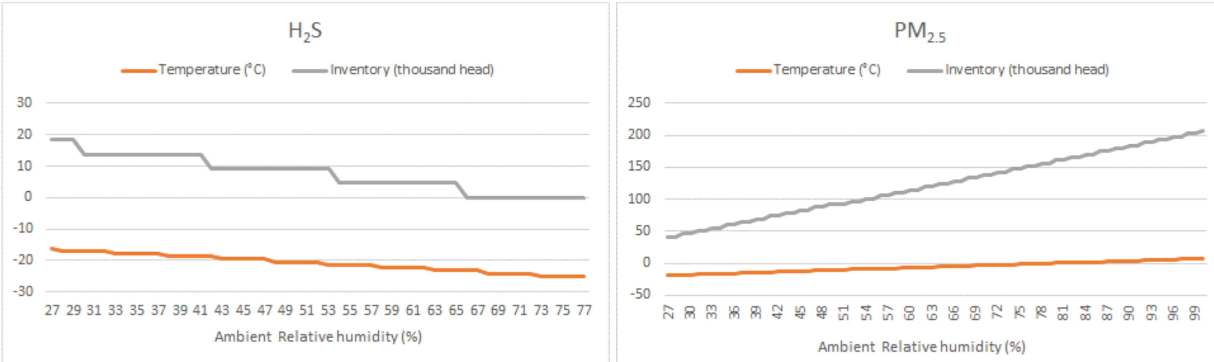

Figure 8-9. Maximum values at which the high rise house models yield negative emissions. Visualization of the results for PM_{10} (top left), $PM_{2.5}$ (top right), and TSP (bottom).

8.2.3.2 Manure Belt Houses

For the manure belt house, the NH_3 and H_2S equations included inventory, ambient temperature, and ambient relative humidity. The ranges evaluated for each parameter are in Table 8-8 with the plotted results in Figure 8-10. For all the variables, the emissions increase with increasing values, which is consistent with established relationships for all three parameters. Neither the NH_3 nor H_2S models produce negative emissions under average conditions, which is an indicator of unreasonable emissions.

PM_{10}, $PM_{2.5}$, and TSP models use only inventory. The range and average values used for testing are listed in Table 8-8 and the results are plotted in Figure 8-11. Neither PM_{10} nor TSP models produce negative emissions under average conditions, which is an indicator of unreasonable emissions. For $PM_{2.5}$, the model produces negative emissions for inventory levels less than 248,000 birds for average exhaust temperatures, which is unreasonable. The figure for $PM_{2.5}$ also shows a rapid change in relative sensitivity with the model producing very high emissions values for inventories greater than 260,000 birds. Overall, this analysis suggests that for $PM_{2.5}$, the conditions applied in the sensitivity analysis have exceeded the range of conditions that the model should be applied. The testing suggests the model will likely be suitable only for house inventories similar to those at IN2B.

Table 8-8. Parameter ranges evaluated for the manure belt model.

Parameter	Upper Limit	Lower Limit	Average Value	Increment
Ambient temperature (°C)	32	-25	15.4	0.9
Ambient relative humidity (%)	100	27	66.2	1
Inventory (birds)	338,800	0	90,522	4,600

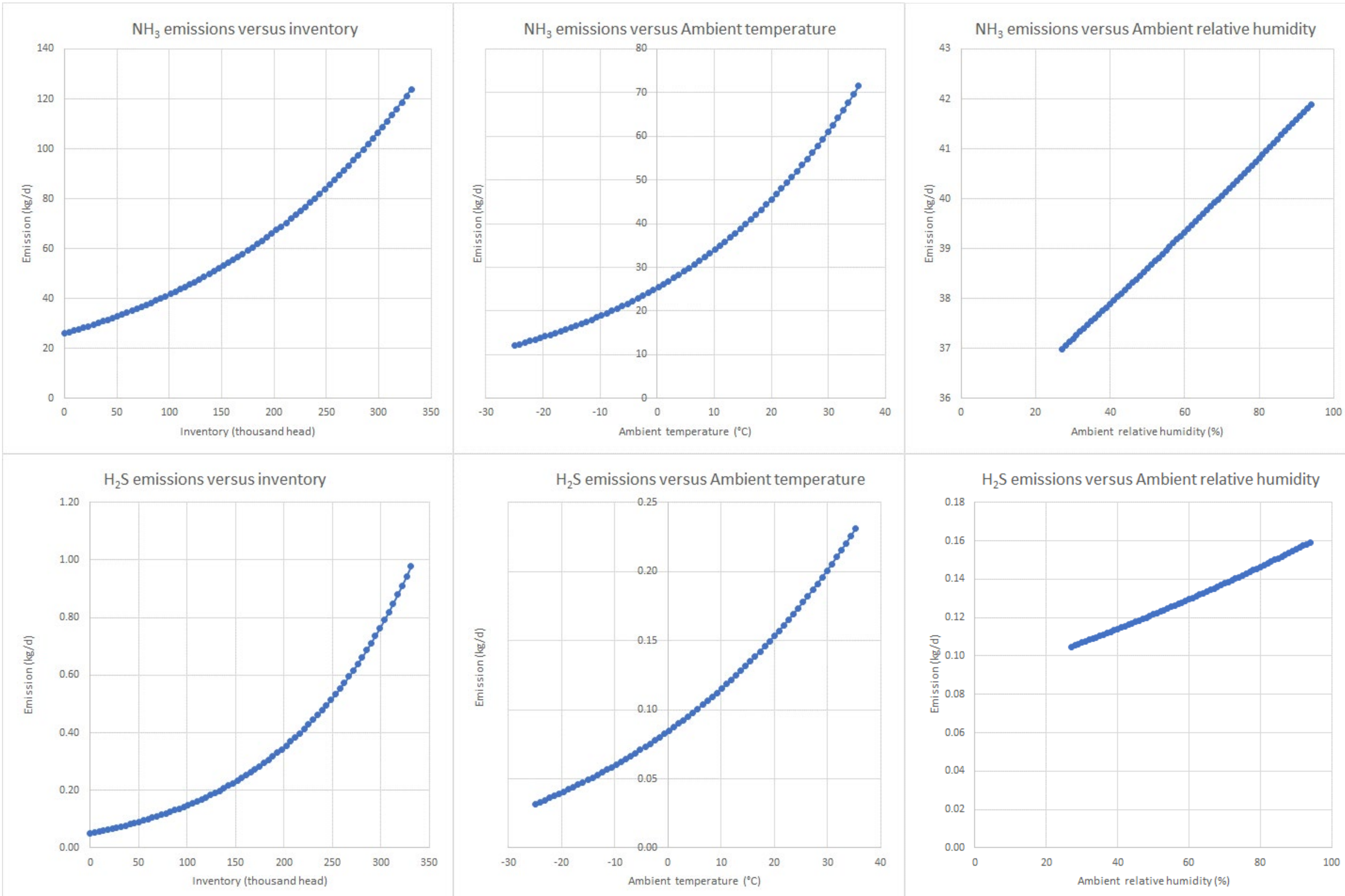

Figure 8-10. Manure belt limitation tests for gaseous pollutants.

Visualization of the results for NH_3 (top row) and H_2S (bottom row) with tests for inventory (left), ambient temperature (center) and relative humidity (right).

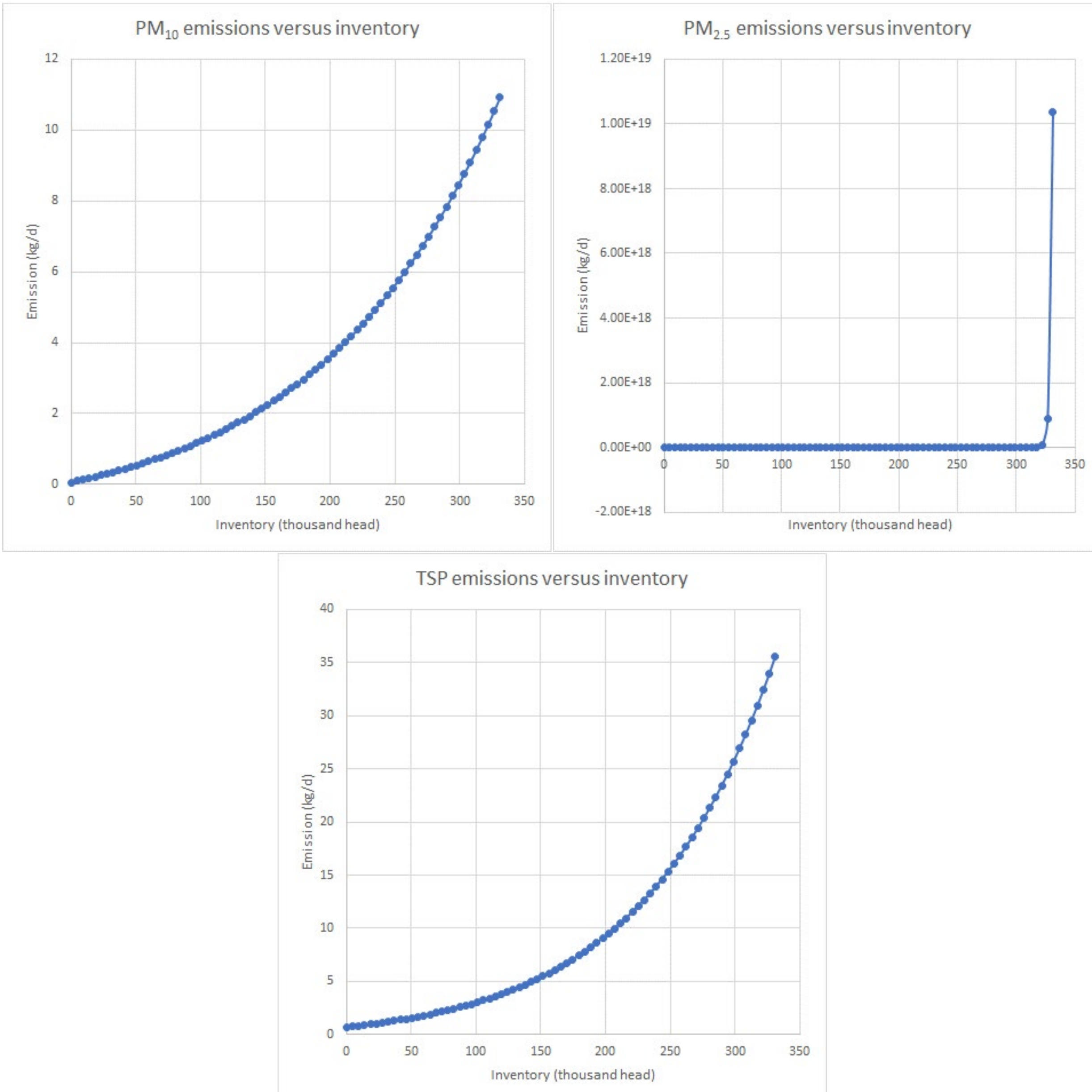

Figure 8-11. Manure belt limitation tests for PM.

Visualization of the results of inventory tests for PM_{10} (top left), $PM_{2.5}$ (top right), and TSP (bottom row).

To further explore any limitations in the models, emissions were calculated for 416,250 combination of the range of values specified in Table 8-8. Across this range of conditions, neither the NH_3, PM_{10}, nor TSP models produce negative emissions. For H_2S the model will produce negative values in instances when the ambient temperature falls below -14.2 °C and house inventory is less than 33,000 birds the models can produce negative emissions values. The plots in Figure 8-12 show 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.

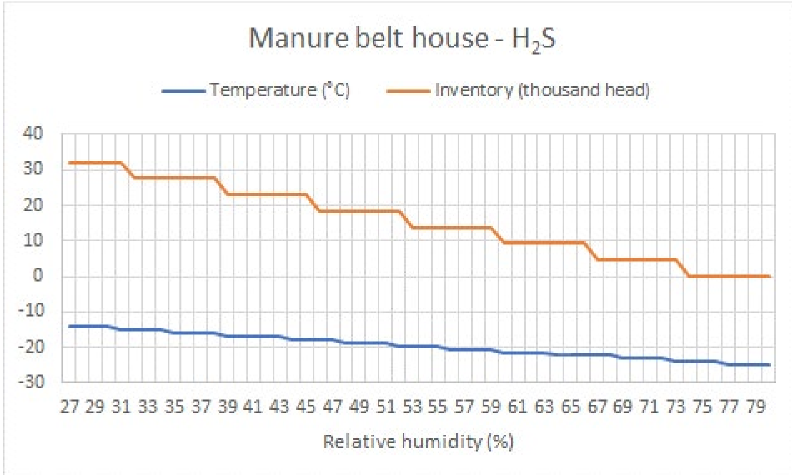

Figure 8-12. Maximum values at which the manure belt house models yield negative emissions. Visualization of the results for H_2S.

8.2.3.3 Manure Shed

For the manure shed, the NH_3 and H_2S equations included ambient temperature and inventory (lagged by 5 days). The ranges evaluated for each parameter are in Table 8-9, with the plotted results in Figure 8-13. The plots show emissions increase with increased inventory and emissions decrease with increasing temperature. The decrease in emissions with increasing temperature could be due to increased drying of the manure. Both the NH_3 and H_2S models produce negative emissions as temperatures increase over 10 °C.

PM_{10}, $PM_{2.5}$, and TSP models only use inventory (lagged by 5 days) to predict emissions. The range and average values used for testing are listed in Table 8-9 and the results are plotted in Figure 8-14. For all pollutants, emissions increase as airflow increases. There is a substantial change in relative sensitivity when the inventory of the supplying houses is over 620,000 birds. None of the PM models produced negative emissions across the range evaluated.

Table 8-9. Parameter ranges evaluated for the manure shed model.

Parameter	Upper Limit	Lower Limit	Average Value	Increment
Ambient temperature (°C)	32	-25	15.4	0.9
Inventory	677,600	0	90,522	10,000

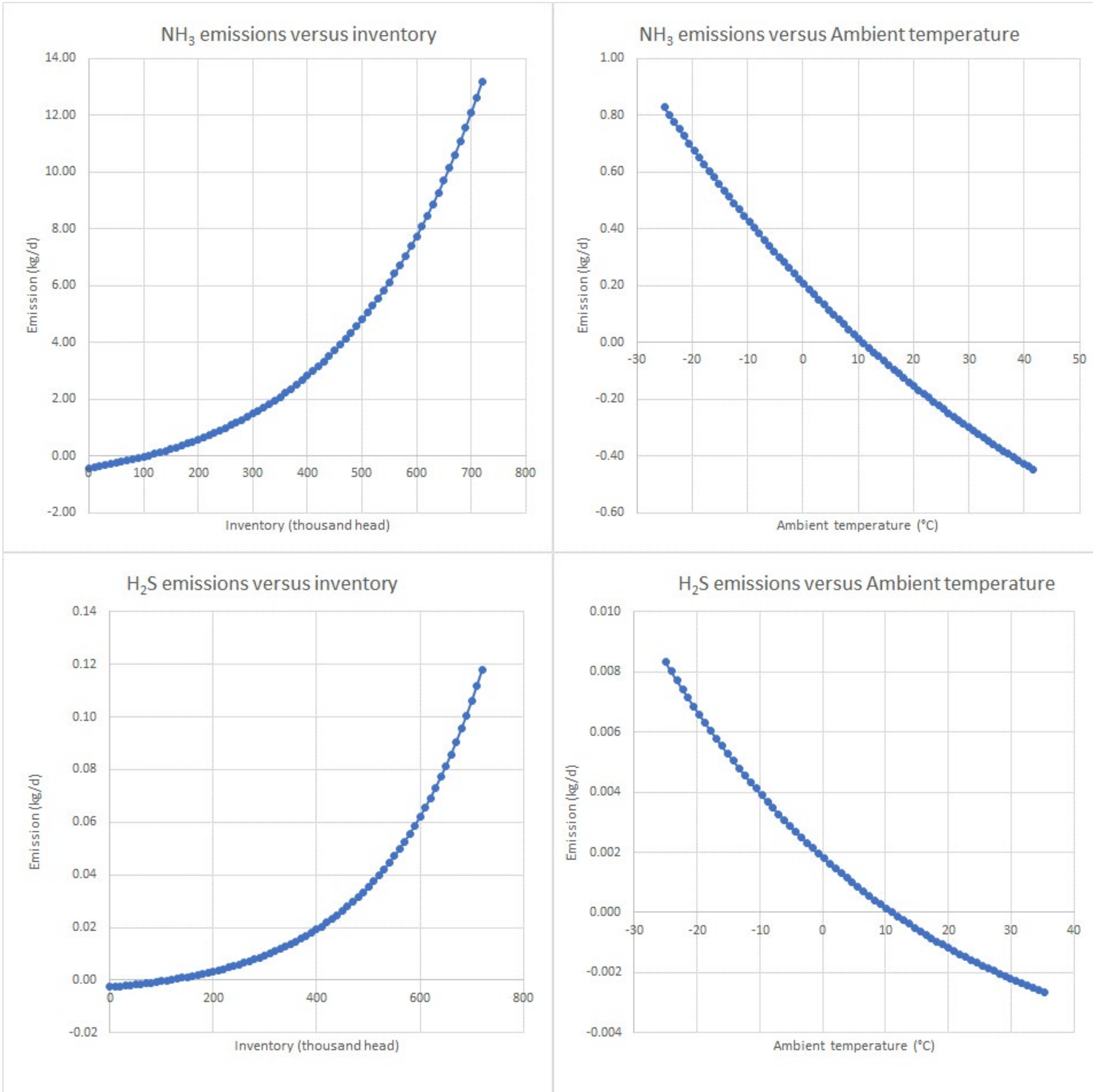

Figure 8-13. Manure shed limitation tests for gaseous pollutants.

Visualization of the results for NH_3 (top row) and H_2S (bottom row) with tests for inventory (left) and airflow (right).

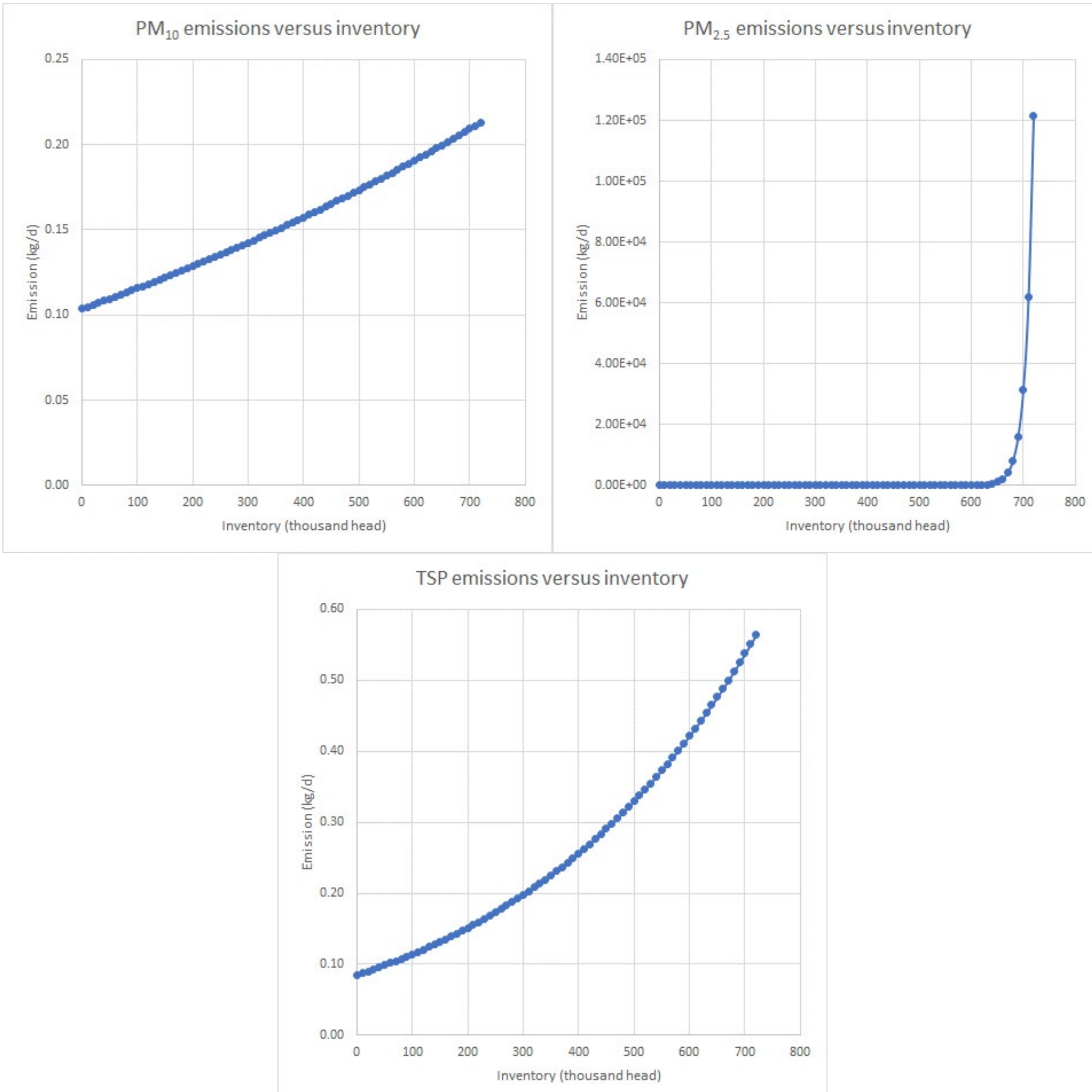

Figure 8-14. Manure shed limitation tests for PM.

Visualization of the results for PM_{10} (top left), $PM_{2.5}$ (top right), and TSP (bottom) for tests of airflow.

To further explore any limitations in the models, emissions were calculated for 5,625 combination of the range of ambient temperature and inventory values specified in Table 8-9. For NH_3 and H_2S, the models have an inverse relationship with emissions and inventory. As a result, as temperatures increase, there is an increased level of inventory that will produce negative values. The plots in Figure 8-15 show the maximum values of inventory that produce negative emissions at the ambient temperature specified on the x-axis.

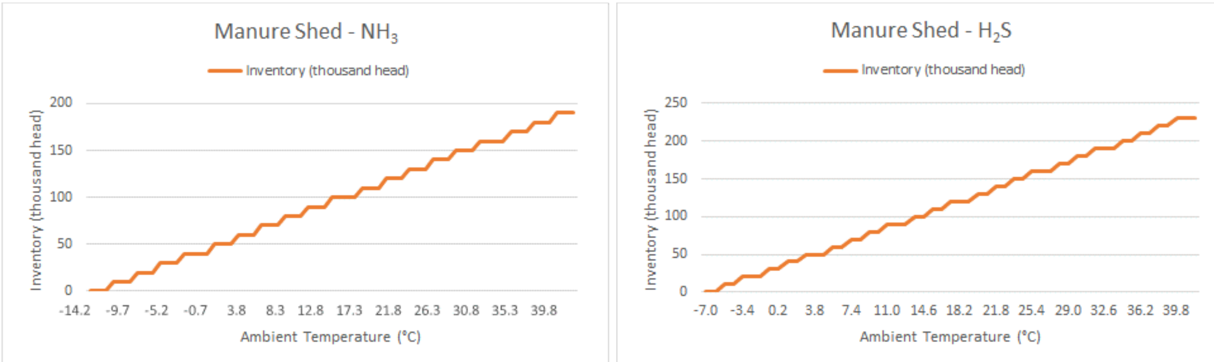

Figure 8-15. Maximum values at which the manure belt house models yield negative emissions. Visualization of the results for NH_3 (right) and H_2S (left).

8.3 Comparison to literature

To further validate the emissions models 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. Wood et al. (2015) contained a review of emissions factors for both layer house types for NH_3. Liang et al. (2005) provided additional factors for manure belt houses. EPA selected the two most recent factors not derived from NAEMS for comparison, which are summarized separately for each house type in their respective sections.

8.3.1 High Rise House

The factors selected for comparison are listed in Table 8-10. The original units provided in Wood et al. (2015) were g yr^{-1} AU^{-1}, based on an animal unit (AU) of 500kg. Consistent with Liang (2005), an average bird weight of 1.5 kg was used to convert AU the head (hd). For further comparison, the emissions factor included in EPA's 2001 draft AP-42 chapter is included. The emissions factor was converted from the original units of the document, which were lb yr^{-1} AU^{-1}, where AU was equivalent to 1000 birds, to kg hd^{-1} yr^{-1}.

Table 8-10. NH_3 Emissions factors for high rise houses from literature.

Source	lb yr^{-1} AU^{-1}	g yr^{-1} AU^{-1}	kg hd^{-1} yr^{-1}
EPA (2001)	28.5 [a]	-	0.285
Heber et al. (2005)	-	278 [a]	0.304
Liang et al. (2005)	-	298 [a]	0.326

[a] As reported in source.

These emissions factors were then applied to the theoretical high rise houses from the previous example calculations. Comparisons were made for an inventory of 100,000 birds and 150,000 birds for both a cold weather location (Iowa) and a warm weather location (Georgia). The results are presented in Table 8-11. For both inventory levels, the emissions factors from literature fall between the estimate produced by the emissions models for the two climate extremes.

Table 8-11. Comparison of resulting high rise house NH_3 emissions from various estimation methods.

Meteorology Site	Inventory (hd)	2021 Emissions Models (kg yr^{-1})	EPA, 2001 (kg yr^{-1})	Heber et al., 2005 (kg yr^{-1})	Liang et al., 2005(kg yr^{-1})
Iowa	100,000	25,997	28,500	30,441	32,631
Georgia	100,000	33,909	28,500	30,441	32,631
Iowa	150,000	34,900	42,750	45,661	48,946
Georgia	150,000	45,521	42,750	45,661	48,946

8.3.2 Manure Belt House

The emissions factors selected for manure belt house model comparison are listed in Table 8-12. The original units provided in Wood et al. (2015) and Liang et al. (2005) were g yr^{-1} AU^{-1}, based on an animal unit (AU) of 500kg. An average bird weight of 1.58 kg was used to convert AU to head (hd). Since the manure belt house was not included in EPA's 2001 draft AP-42 chapter, a third refence was included to show the range of values provided in literature. To a degree, the emissions factors vary based on the removal frequency and whether the manure drying was enhanced beyond what was offered by house ventilation.

Table 8-12. NH_3 Emissions factors for manure belt houses from literature.

Source	Manure Management Details	g d^{-1} AU^{-1} [a]	kg hd^{-1} yr^{-1}
Liang et al., 2005	Removed twice a week	30.8	0.036
Morgan et al., 2014	Removed twice a week	19.5	0.022
Nicholson et al., 2004	Removed weekly	96	0.111

[a] As reported in source.

These emissions factors were then applied to the theoretical high rise houses from the previous example calculations. Comparisons were made for an inventory of 100,000 birds and 150,000 birds for both a cold weather location (Iowa) and a warm weather location (Georgia). The results are presented in Table 8-13. Overall, the emissions models presented here produce greater emissions than what has previously been reported in literature. The emissions model results for the cold weather site were fairly consistent with the Nicholson et al. (2014), which was also based in a cooler climate (United Kingdom).

Table 8-13. Comparison of resulting manure belt house NH_3 emissions from various estimation methods.

Meteorology Site	Inventory (hd)	2021 Emissions Models (kg NH_3 yr^{-1})	Liang et al., 2005 (kg NH_3 yr^{-1})	Morgan et al., 2014 (kg NH_3 yr^{-1})	Nicholson et al., 2014 (kg NH_3 yr^{-1})
Iowa	100,000	13,403	3,552	2,249	11,073
Georgia	100,000	16,466	3,552	2,249	11,073
Iowa	150,000	16,953	5,329	3,374	16,609
Georgia	150,000	20,873	5,329	3,374	16,609

8.3.3 Manure Shed

EPA searches did not find sources with emissions factors for manure sheds.

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 Air Pollutant Emissions from Confined Animal Buildings (APECAB) Project. The APECAB project was conducted from the fall of 2002 through 2004 (Jacobson et. al 2011; Heber et. al 2006). Similar to NAEMS, the goal was to collect long-term (i.e., at least a year) air pollutant information from animal feeding operations buildings. The project collected emissions data, ambient meteorological, and building parameters. Since APECAB collect many of the same parameters as NAEMS, the emissions models can be applied and then compared to the observed emissions.

The APECAB project included two caged hen layer houses in Indiana. EPA was able to obtain data for this site, which included the inventory and meteorological parameters needed to estimate emissions from the houses using the developed emissions models. 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 Figure 8-14. These statistics suggest the current model underpredicts all three pollutants to some degree. The model performance statistics were also calculated for each season (Figure 8-15). The season statistics show better performance during the summer and autumn for NH_3, and during the autumn for H_2S. PM_{10} performed similarly across all seasons.

Table 8-14. Model performance evaluation statistics for high rise houses.

Pollutant	n	MB (kg)	ME (kg)	NMB (%)	NME (%)	r
NH_3	544	-164.32	204.96	-51%	64%	-0.379
H_2S	578	-0.049	0.244	-13%	64%	0.628

Pollutant	n	MB (kg)	ME (kg)	NMB (%)	NME (%)	r
PM_{10}	560	-7542.73	7938.27	-53%	56%	0.366

Table 8-15. Model performance evaluation statistics by season.

Pollutant	Season	n	MB	ME	NMB	NME	r
NH3	Spring (MAM)	166	-137.85	220.95	-46%	74%	-0.49
NH3	Summer (JJA)	68	6.36	99.02	3%	40%	0.55
NH3	Autumn (SON)	156	-73.79	81.15	-30%	34%	0.40
NH3	Winter (DJF)	154	-359.93	359.93	-79%	79%	-0.25
H2S	Spring (MAM)	166	-0.11	0.29	-25%	65%	0.59
H2S	Summer (JJA)	94	-0.35	0.48	-45%	61%	0.31
H2S	Autumn (SON)	154	0.04	0.12	12%	39%	0.65
H2S	Winter (DJF)	164	0.10	0.19	65%	116%	0.26
PM10	Spring (MAM)	162	-6503.98	6734.67	-49%	50%	0.12
PM10	Summer (JJA)	97	-12010.28	12010.28	-59%	59%	-0.11
PM10	Autumn (SON)	135	-8742.36	9012.29	-57%	59%	0.38
PM10	Winter (DJF)	166	-4970.31	5859.97	-47%	55%	-0.19

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 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 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 observations has been used as a model performance metric in air quality modeling 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 coded to show the performance for each house. The NH_3 scatter plots (Figure 8-16) show that a vast majority of the predicted values fall within a factor of two of the observations during summer and autumn. The scatter plot for winter (lower right) shows the model underpredicts in all instances, particularly at house B13. The H_2S scatter plots (Figure 8-17) show that a vast majority of the predicted values fall within a factor of two of the observations during all seasons. The scatter is more pronounced in spring and summer, but overall, it is reasonable model performance for these sites. The PM_{10} scatter plots (Figure 8-18) show reasonable model performance, with most of the predicted values falling within a factor of two of the observation for all seasons, except summer. The scatter plots also show that most of the severe underprediction occurs at house B13. Additional plots and statistics are available in Appendix H.

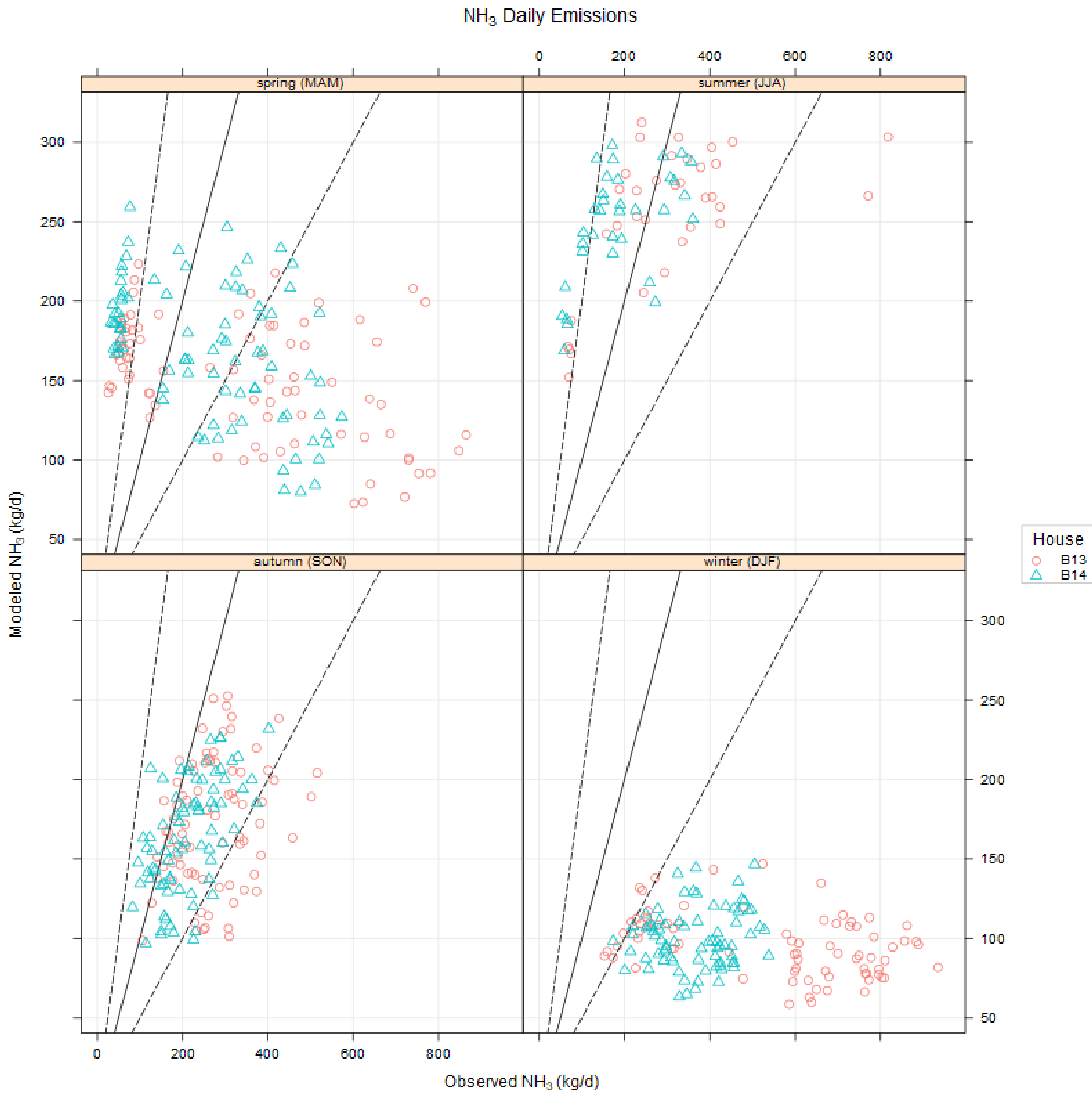

Figure 8-16. Scatter plot of the observed NH_3 emissions at the APECAB IN high rise site versus the emissions model estimates.

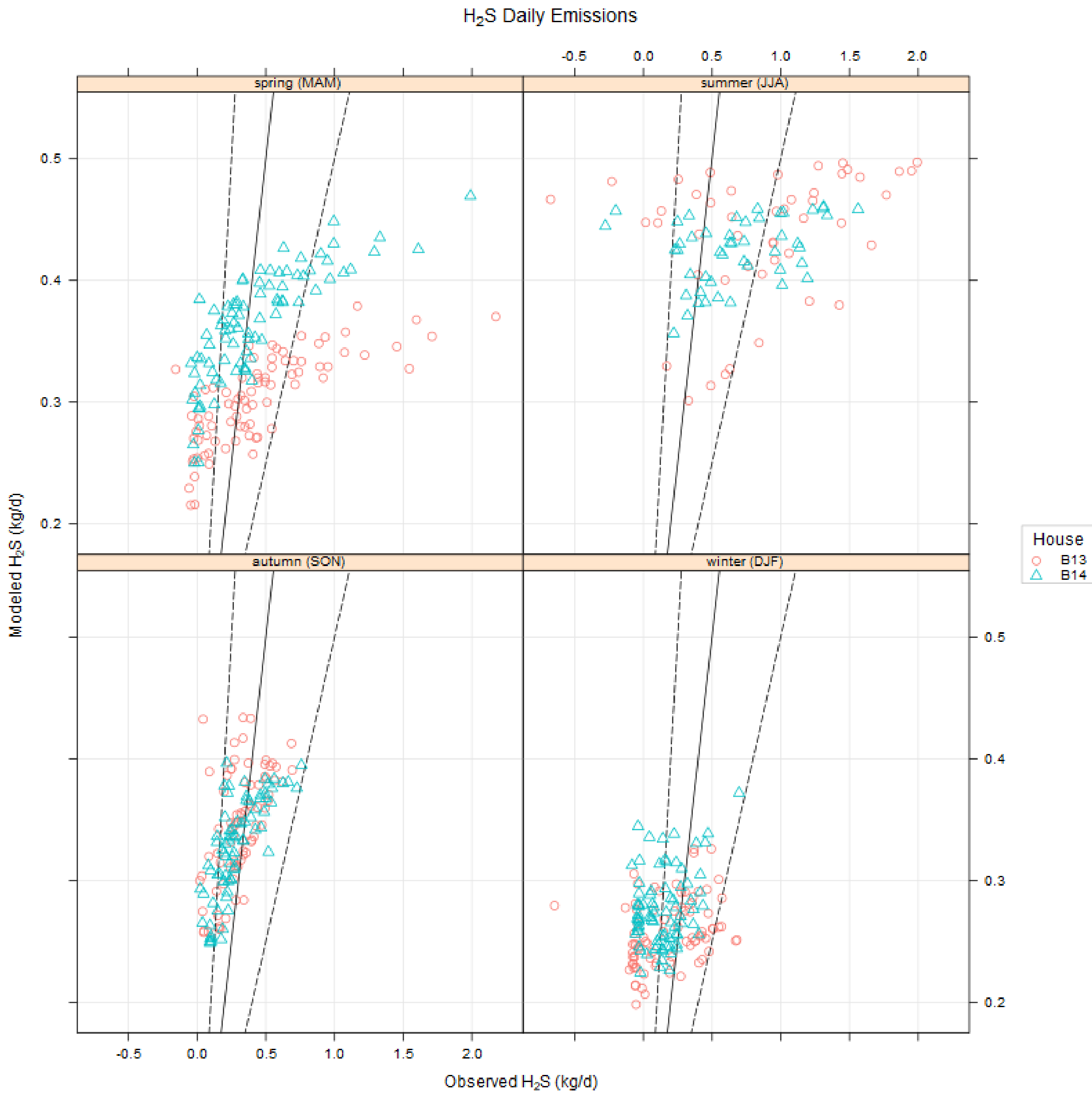

Figure 8-17. Scatter plot of the observed H_2S emissions at the APECAB IN high rise site versus the emissions model estimates.

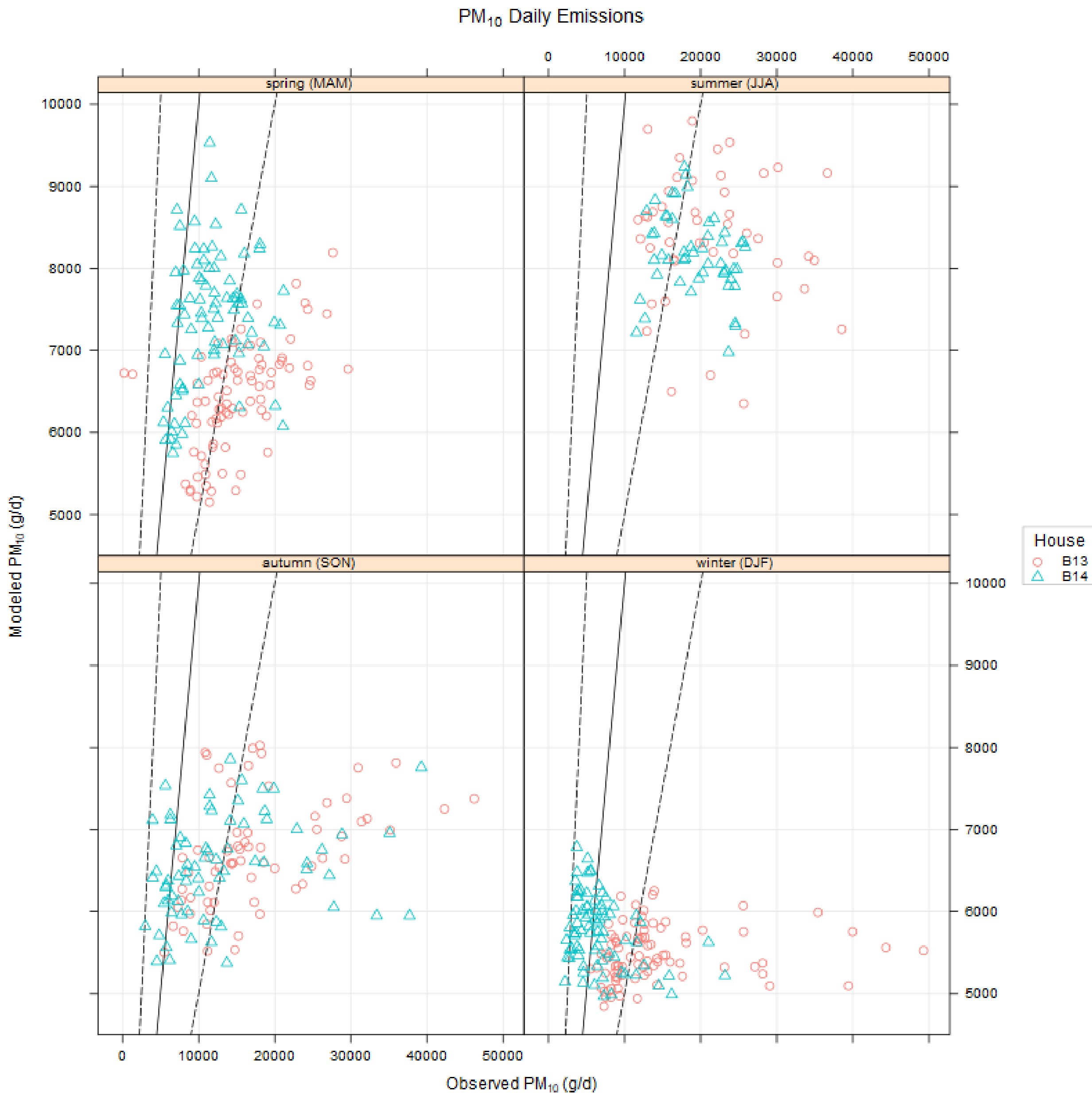

Figure 8-18. Scatter plot of the observed PM_{10} emissions at the APECAB IN high rise site versus the emissions model estimates.

8.5 Data Concerns

In an effort to better characterize the model performance, EPA examined the data and data collection methods to identify areas that may have contributed to poorer model performance. The following section summarizes these areas for each egg-layer source.

8.5.1 High Rise

At NC2B, there are ventilation fans at both the manure pit level and the layer room level of the houses. During NAEMS, PM concentration measurements were made at the manure pit level. However, Li et al. (2013), which is a peer-reviewed paper that summarizes and discusses PM emissions from NC2B, describes that PM measurements at the layer room level of house 4 were also made for a period of several months. Li et al. (2013) compared PM emissions using manure pit only measurements and combined manure pit and layer room measurements and found PM emissions using the combined measurements to be 23%, 28% and 39% higher for $PM_{2.5}$, PM_{10} and TSP, respectively. Differences in emissions were related to ambient temperature as ambient temperatures greater than 20°C caused the layer room fans to turn on (Li et al. 2013). Accordingly, the NAEMS NC2B PM dataset may underestimate PM emissions, particularly during warmer periods.

8.5.2 Manure Belt

The PM models for manure belt were difficult to develop. As noted in the Section 5.2 discussion, there are two primary influences on PM emissions: 1) the amount of source material (i.e., excreted manure, feathers, and feed) and 2) disturbance of the source materials. With respect to the first mechanism, inventory or LAW has been used in the models to account for the amount of source material. For an indication of when and to what extent the source material is disturbed, there is not a good indicator available in the dataset. The lack of an estimate for the effect of this component of the on emissions makes it harder to detect if other parameters have a significant influence on emissions and thus can potentially result in models with a limited number of significant parameters.

Another factor adding to the challenge of the PM models was the lack of variability in the data available to develop the models. NAEMS only included one manure belt site, with two houses. These two houses have a steady inventory for the two years, except for a flock replacement event at H9. This is a problem for model development because it is hard to tease out the influence of inventory on emissions if it is roughly constant. This was not as much of an issue for the gaseous pollutants because they had approximately 20 daily observations during the flock replacement, while PM_{10} only had 6 daily observations.

A third factor adding to the challenge was concern about the quality of the PM_{10} measurements. The PM inlet measurement is from instrumentation that resides on top of the on-farm instrument shelter (OFIS). The manure belt site (IN2B) was part of a large farm that also provided high-rise monitoring data for NAEMS (IN2H). For the manure belt house emissions calculations, the inlet concentration data from the companion site (IN2H) was used, which was located on top of the IN2H OFIS between H6 and H7 (Figure 8-19). The use of this inlet concentration assumes that the high-rise house inlet concentration is representative of the manure belt house inlet concentration. The inlet PM_{10} measurements might be unrepresentative due to the influence of nearby exhaust fan locations and local (farm scale) meteorological conditions.

The diagram from the site report (Figure 8-20), shows the inlet monitor in raceway between the two houses. The figure also shows there are exhaust fans that point outward into that same raceway. If the inlet PM concentrations are more influenced by these exhaust fans than the air entering the manure belt houses, this would result in an overestimation of inlet concentrations for the manure belt houses, particularly during periods of higher exhaust temperature and ventilation rate. This would then result in a higher frequency of negative emissions during these periods of high exhaust temperature and ventilation rates. Not only is this an issue because negative emissions values are generated, but it could lead to a negative relationship between PM_{10} emissions and exhaust temperature. The exploratory data analysis plots for IN2B H8 (See Appendix F, Figures F-85), does indicate a negative relationship with exhaust temperature.

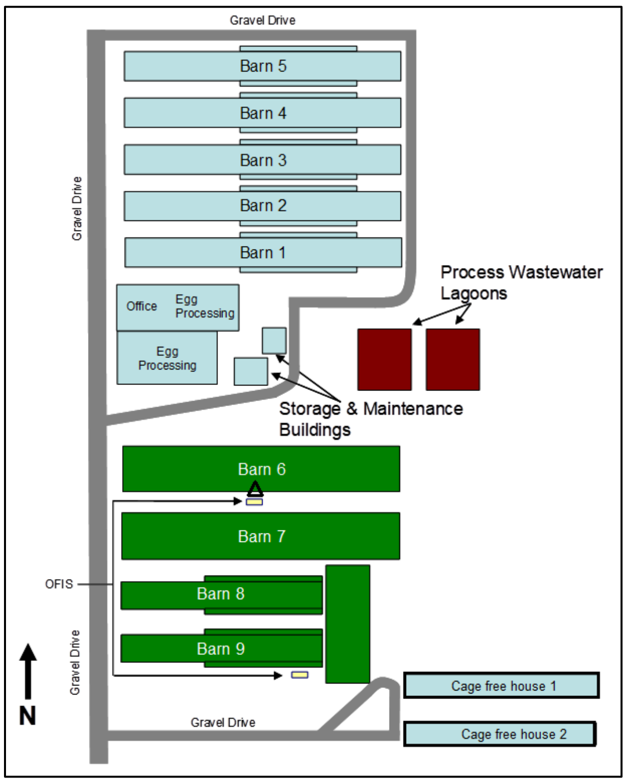

Figure 8-19. Overhead view of IN2H/IN2B, with the PM inlet measurement location indicated by a triangle. (Ni et al. 2010a).

Triangle indicates PM inlet concentration measurement location for both IN2H and IN2B.

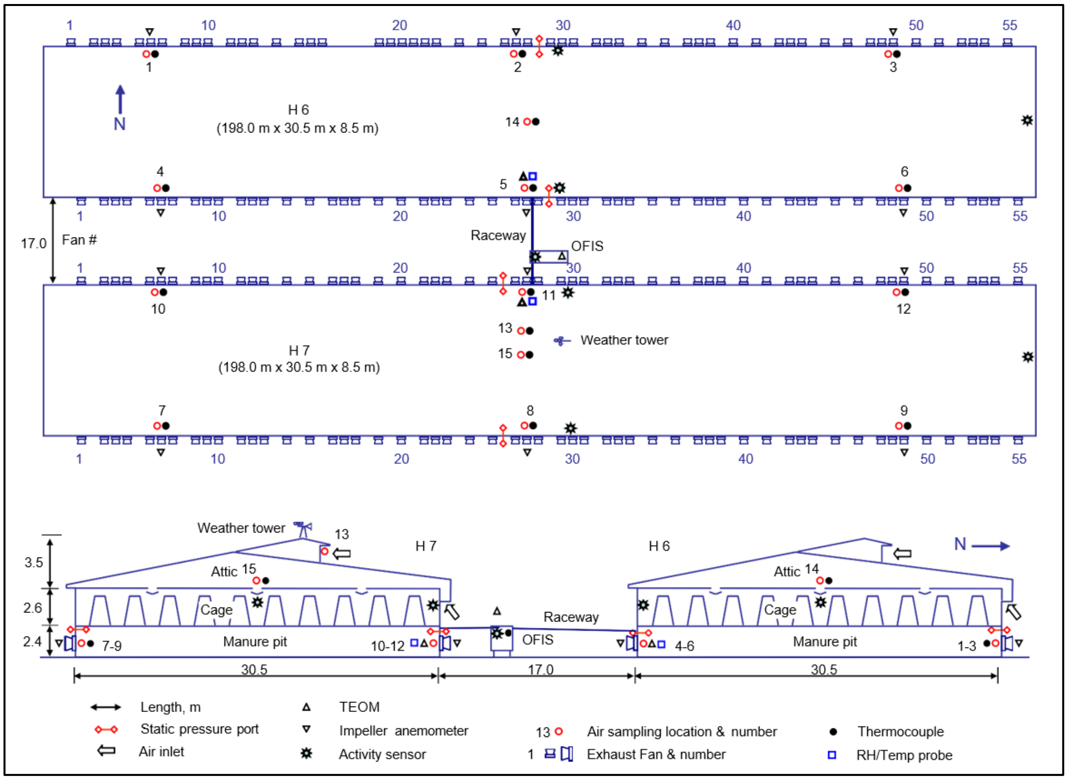

Figure 8-20. Overhead (top) and side (bottom) view of sensor measurements at IN2H (Ni et al. 2010a).

8.5.3 Manure Shed

There are concerns with the quality of the manure shed data due to the methodology used to determine building inlet concentrations, exhaust concentrations, airflow and thus emissions. Each wall or ridge of the manure shed can act as an inlet or exhaust depending on the direction of the wind, therefore it is important to accurately determine average concentrations and airflow. Accordingly, the NAEMS QAPP (Heber et al. 2008) provides a reasonable methodology for determining average concentrations, airflow and thus emissions from naturally ventilated buildings. This monitoring plan was applied at the dairy barns with multiple concentration and airflow measurements made on each wall and ridge (Figure 8-21).

For the naturally ventilated manure shed at IN2B, an alternative methodology was used which involved five 2-D sonic anemometers, two impeller anemometers and one concentration measurement (Figure 8-22), which was used as the exhaust concentration when winds were generally and steadily from the west.

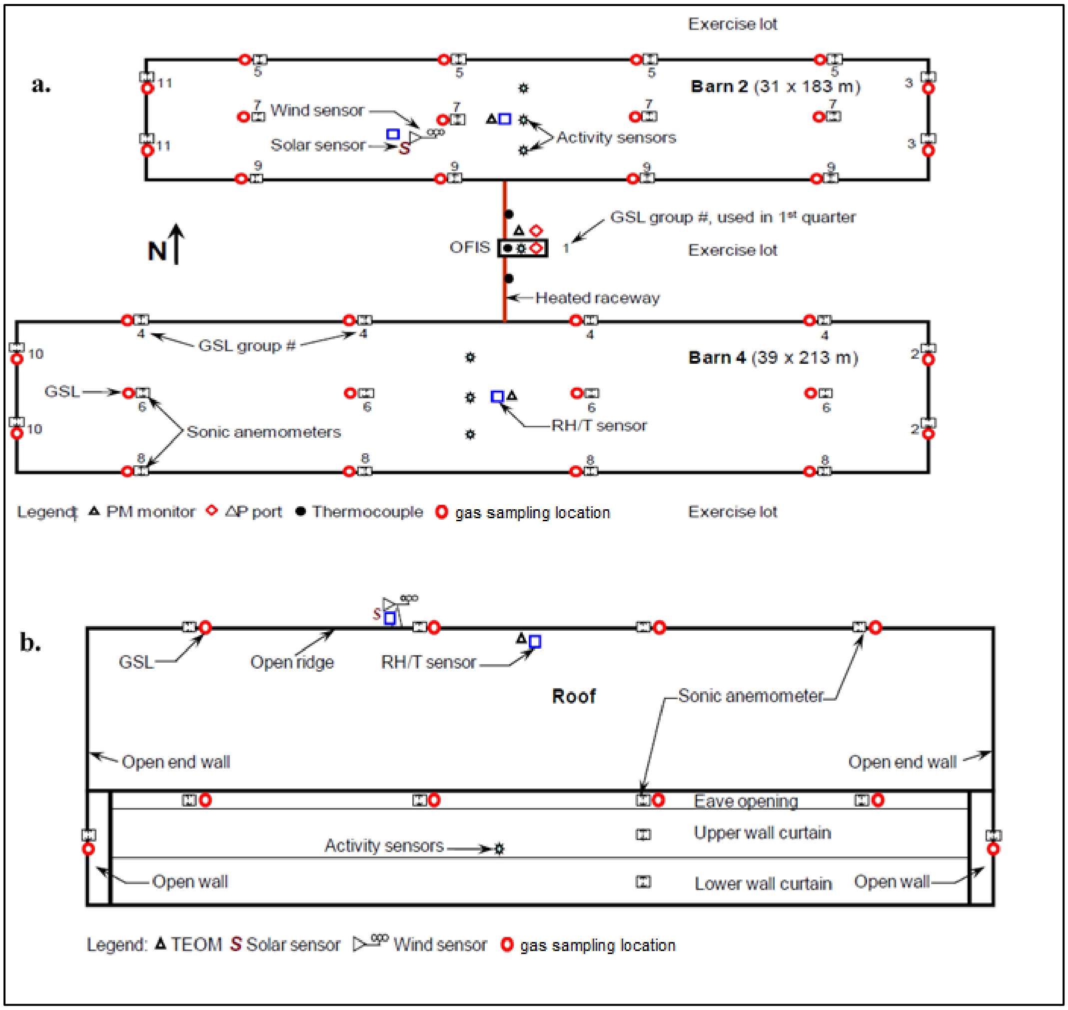

Figure 8-21. Overhead (a.) and side (b.) view of sensor measurements at WA5A barn (Ramirez-Dorronsoro et al. 2010).

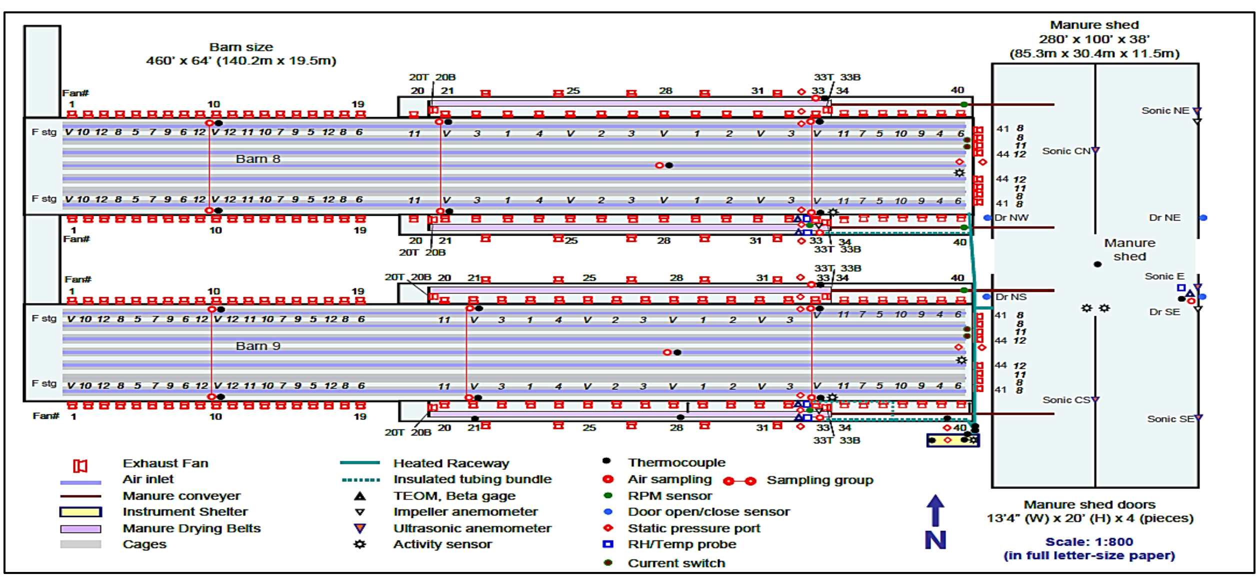

Figure 8-22. Overhead view of sensor measurements at IN2B (Ni et al. 2010b).

Inlet concentrations for the manure shed were not measured at the manure shed. Instead, the gas inlets from the manure belt houses were used for NH_3 and H_2S, and for. For PM, the PM inlet from the high-rise inlet at IN2H was used. The accuracy and thus error associated with this alternative methodology is not known, however, there are a number of concerns associated with this alternative methodology that are likely to increase the error associated with the emissions measurements. One concern is related to the representativeness of using inlet concentrations that were not measured at the manure shed. It is unknown how representative the high-rise house inlet and manure-belt house inlet concentrations are of the manure shed; however, it is possible that these inlet measurements are unrepresentative due to the influence of nearby exhaust fan locations and local (farm scale) meteorological conditions.

A further concern is related to the small number of airflow measurements at the various walls and ridges of the manure shed, which may not account for the spatial variability of airflow, which can be highly variable in livestock buildings (Ogink et al. 2013). There is a similar concern regarding how well the concentration measurements used represent the spatial variability of concentrations in animal buildings, which can also be highly variable. For example, a study by Lefcourt, (2002) identified that incorrect selection of sampling locations could results in errors in gas concentrations ranging from -50% to over 200%.

Another concern with the emissions measurements is due to problems with the sensors used to determine when the manure shed doors were open (Heber, personal communication), which could result in errors associated with airflow measurements and thus emissions. Furthermore, at the manure shed, airflow measurements were determined using 2-D sonic anemometers. However, Ogink et al. (2013) recommends that 3-D sonic anemometers be used to measure airflows, since the direction of airflow in an opening is varied and related to ambient wind conditions. The effect of using 2-D sonic anemometers on emissions measurements is not known and is likely site dependent.

9.0 SUMMARY AND 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 and manure storage sources at layer 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.

For high rise houses, inventory was identified as a key parameter and is used in all the models as a proxy for the volume of manure generated. Temperature parameters were also identified as important variables for NH_3 and H_2S emissions rates across many of the confinement house emissions models. Relative humidity parameters proved to be key for PM prediction, as the higher moisture levels keep house materials from entraining into the air with mechanical disruptions. Confinement parameters specific to the house, like ventilation rate and 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 high rise emissions models put forward for potential use in this document apply 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/).

For manure belt houses, inventory was identified as a key parameter and is used in all the models as a proxy for the volume of manure generated. Temperature parameters were also identified as important variables for NH_3 and H_2S emissions rates across many of the confinement house emissions models. For PM, most evaluated models contained parameters that, while found in literature to have a relationship with emissions, were statistically insignificant when evaluated. The established development process produced only two combinations of models that were composed entirely of statistically significant parameters. One of the two models included exhaust temperature, which is not necessarily retained by producers. The manure shed models had limited statistically significant models for all pollutants. Airflow was the key parameter in predicting emissions for both gaseous pollutants and PM. However, airflow is not routinely measured for manure sheds, and can be particularly difficult to estimate for naturally ventilated structures. For the manure belt house and manure shed models, EPA considered overlooking the significance calculations and selecting models purely based on the relationships established in literature. All candidate models evaluated appear in Appendix F for review and consideration during this comment period.

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 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 or manure shed 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 various categories of layer operations across the U.S., process-based models would allow producers to estimate the impacts of different best management practices to reduce air emissions, helping to incentivize change.

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