Development of Emissions Estimating Methodologies for Animal Feeding Operations
Volume 2: Swine

Draft

Prepared by:

U.S. Environmental Protection Agency
Office of Air and Radiation
Office of Air Quality Planning and Standards
109 T.W. Alexander Drive
Research Triangle Park, N.C. 27709

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This document is a preliminary draft. It has not been formally released by the U.S. Environmental Protection Agency (EPA) and should not at this stage be construed to represent Agency policy. It is being circulated for comments on its technical merit.

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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 INTRODUCTION

1.1 Confinement site descriptions

Although there are still many operations where pigs are raised outdoors, the trend in the swine industry is toward larger operations where pigs are raised in totally or partially enclosed confinement facilities. Typically, the gestation and farrowing, nursery, and grow-finish phases of the production cycle occur in separate, specially designed facilities. Farrowing operations require intense management to reduce piglet mortality. Houses have farrowing pens and provide the piglets a protected area of about 8 square feet. Nursery systems are typically designed to provide a clean, warm, dry, and draft-free environment in which animal stress is minimized to promote rapid growth and reduce injury and mortality. Nursery buildings are cleaned and disinfected thoroughly between groups of pigs to prevent transmission of disease from one herd to another. Finishing pigs require less intensive management and can tolerate greater variations in environmental conditions without incurring health problems.

Five swine facilities had barns that were monitored continuously for approximately two years during NAEMS. The locations were selected based on site-specific factors including facility age, size, design and management, swine diet, and genetics. Table 1-1 summarizes the sites and their characteristics. The following sections describe each site in more detail.

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

Site	Monitoring Period	Production Phase	Ventilation Type	Number of Units Measured	Manure Collection	Manure Storage[2]
IA4B	7/19/07 - 9/4/09	Breeding/gestation	MV (tunnel)	2	Deep pit[3]	Deep pit[3]
IA4B	7/19/07 - 9/4/09	Farrowing	MV	1	PPR[4]	Gestation pits
IN3B	7/14/07 - 7/24/09	Finisher	MV (tunnel)	4	Deep pit[3]	Deep pit[3]
NC3B	12/4/07 - 1/13/10	Finisher	MV (tunnel)	3	PPR[4]	Lagoon
NC4B[1]	12/15/07 - 12/14/09	Breeding/gestation	MV (tunnel)	2	PPR[4]	Lagoon
NC4B[1]	12/15/07 - 12/14/09	Farrowing	MV	1	PPR[4]	Lagoon
OK4B[1]	7/19/07 - 7/19/09	Breeding/gestation	MV (tunnel)	2	PPR[4]	Lagoon
OK4B[1]	/19/07 - 7/19/09	Farrowing	MV	1	PPR[4]	Lagoon

[1] Barn sites that also have measured lagoons/basins.
[2] Characterizes type of farm, not necessarily a measurement location.
[3] Storage is inside the barn so separate measurement not needed for storage.
[4] PPR = pull plug with recharge.

1.1.1 IA4B

This gestation and farrowing farm facility located in Iowa was built in 1998 and consisted of 4 barns: 2 gestation barns, a 16-room farrowing barn, and an isolation barn. Figure 1-1 shows the farm layout at site IA4B. For the study, both gestation barns and one farrowing room (room 9) were monitored. The gestation barns had a capacity of 1,100 head each, while each room in the farrowing barn could hold 24 sows. (Cortus et al., 2010a).

The gestation barns had slatted concrete floors with deep pits for manure storage. The farrowing barn had a combination iron/plastic/concrete floor with a shallow pit for short-term manure storage. Stored manure in the farrowing barn was transferred once every 21to 24 days into the deep pit of the nearest gestation barn, where the manure was stored for about 6 months. This site was selected for monitoring because its use of deep pits and other manure and animal management practices are representative of farrowing and gestation farms in the Midwestern U.S.

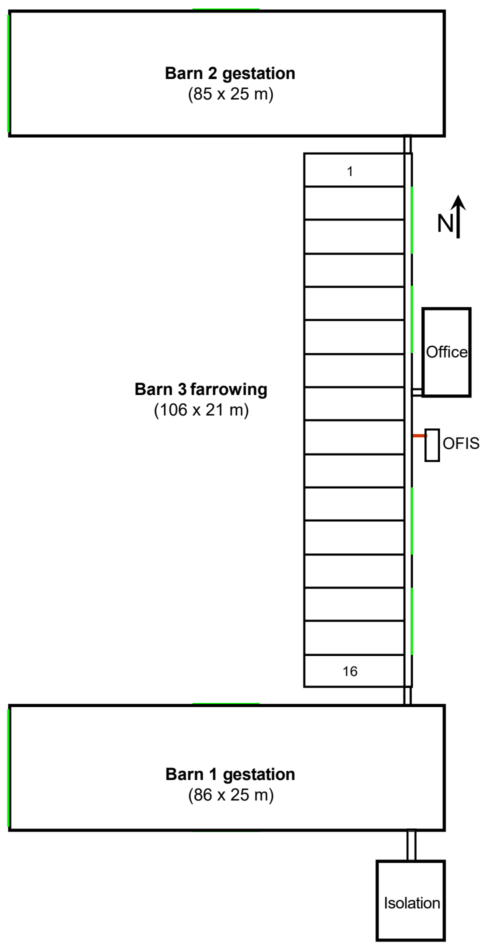

Figure 1-1. IA4B Farm layout.

1.1.2 IN3B

The finishing farm monitored in Indiana consisted of two "quad" barns with deep pits (see Figure 1-2). A quad barn is a barn with four separate rooms, each with its own ventilation. Each room was treated as a separate barn for NAEMS. The individual rooms of the quad barns had a 1,000-head capacity and were constructed in 2003. For NAEMS, all four rooms of one barn were monitored (Lim et al., 2010).

The producer at IN3B practiced double-stocking, which is when twice as many piglets are placed per pen at the beginning of the cycle than there will be at the end of the cycle. The piglets are eventually redistributed to other pens later in the cycle. Using the monitored barn as an example, room 5 is stocked 75 pigs per pen for the first 2 months, during which time the animals in rooms 7 and 8 finish out. After rooms 7 and 8 were emptied and cleaned, the pigs in room 5 would be moved to rooms 7 and 8 and redistributed to about 30 pigs per pen. For IN3B Rooms 5 and 6 always had younger pigs, and rooms 7 and 8 had older pigs.

This site was selected for monitoring because its use of deep pits and other manure management practices were representative of finishing farms in the Midwestern U.S. Additionally, the "quad" barn design had become increasingly popular in recent years, and the site did not use any additives in their manure pit that would potentially affect emissions.

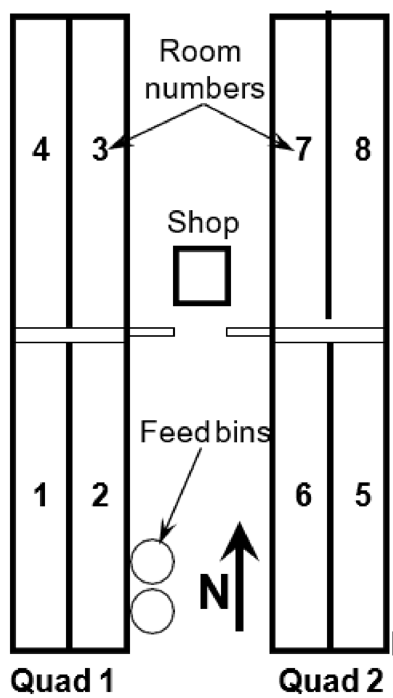

Figure 1-2. IN3B Facility layout. Rooms 5 through 8 in Quad 2 were monitored.

1.1.3 NC3B

The farm site consisted of nine finishing barns constructed in 1996, and a lagoon (see Figure 1-3). The farm had a capacity of 7,200 head, which was divided among the nine barns. The finishing barns had slatted concrete floors with metal panels. The manure was stored in a shallow pit located underneath each barn. The barn pits were emptied weekly, transferring the manure into an anaerobic lagoon. The pit was recharged (0.1 to 0.5 m deep) with lagoon water.

The finishing barns were all tunnel-ventilated, with each barn controlled individually. Each finishing barn had curtain sidewalls that were raised during normal operation, meaning that the bulk of the air entering the barn did so through an opening at one end of the building that was opposite the tunnel fans. The sidewalls also contain eave baffles (16 per side; 32 per building) that were adjusted according to season.

Three of the finishing barns were monitored as a part of NAEMS. This site was selected for monitoring because its ventilation scheme and use of pull plug pits with recharge from the lagoon is typical of finishing farms in the Southeastern U.S. Additionally, the site did not apply any additives to the manure (Bogan et al., 2010).

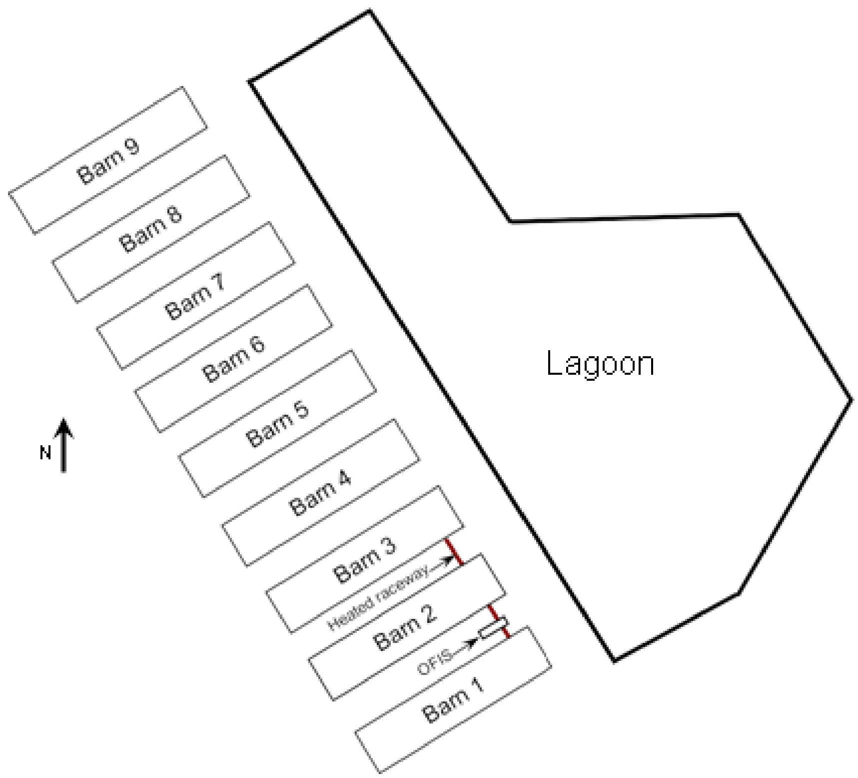

Figure 1-3. NC3B facility layout. Barns 1, 2, and 3 were monitored.

1.1.4 NC4B

This sow farm consisted of three barns, an office, and an anaerobic waste treatment lagoon (see Figure 1-4). For the study, emissions were monitored at both gestation barns and one room (room 15) in the farrowing barn. The farm's lagoon was also monitored as part of NAEMS, as described in Section 1.2.4. Construction of the barns was completed in 1995. The farm had a capacity of 300 farrowing, 776 breeding, and 924 gestating sows in the farrowing, breeding, and gestation barns, respectively. The gestation and breeding barns had concrete slatted floors, which were cleaned as needed. Manure from the barns was transferred weekly from all barns to the lagoon. The gestation barns were mechanically ventilated throughout the year and tunnel ventilated in warm weather. There were no sidewall fans in these barns; therefore, all the air exhausted through the end walls. This site was selected because its animal management practices, ventilation scheme, and use of pull plug pits with recharge from the lagoon is representative of farrowing and gestation farms in the Southeastern U.S. (Robarge et al., 2010).

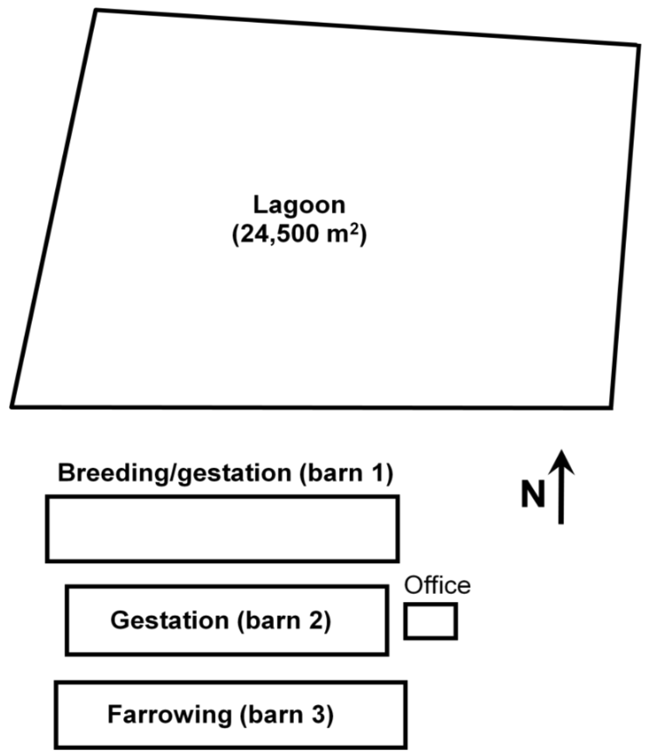

Figure 1-4. NC4B farm layout showing the barns and lagoon.

1.1.5 OK4B

This sow farm consisted of three barns, an office, and a waste lagoon (see Figure 1-5). For the study, both gestation barns and one of the 16 farrowing rooms were monitored. The farm's lagoon was also monitored, as described in Section 1.2.5. Construction of the barns was completed in 1994. The farm had a capacity of 1,200 breeding and gestation sows in each of two gestation units, and 384 farrowing sows in one farrowing unit. The gestation barns had concrete slatted floors, and the farrowing barn had a woven wire floor. Manure on the floor was cleaned daily, while manure from the barns was transferred to a lagoon once a week from the 2 gestation barns and every 2.5 weeks from the farrowing barn by pull-plug pits. The gestation barns were also mechanically ventilated throughout the year and tunnel ventilated in warm weather. This site was selected for monitoring as its ventilation scheme, animal management practices, and use of use of pull plug pit with recharge from the lagoon is representative of farrowing and gestation farms in the Western U.S. (Cortus et al., 2010b).

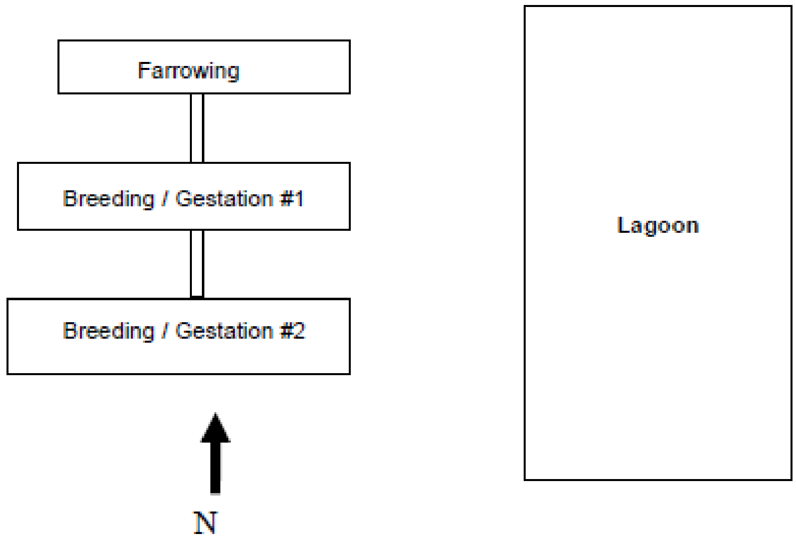

Figure 1-5. OK4B farm layout showing the barns and lagoon.

1.2 Open Source Sites

Six swine farms had lagoons or basins monitored as part of NAEMS, as listed in Table 1-2. The swine manure basin or lagoon emissions were measured at one farm (IN4A) continuously for one year. Emissions were measured up to 21 days per season over 2 years at the remaining farms (IA3A, NC3A, NC4A, OK3A, and OK4A). Table 1-3 lists the sampling periods for each site. Sites for monitoring were selected to capture different stages and manure practices typical of the industry. The sites also represent the broad geographical extent of swine production, different climatological settings for farms, and any regional differences in farm practices.

Table 1-2. NAEMS data for swine and dairy lagoon confinement operations.

Site	Animal Sector	Confinement Description	Unit Measured	Manure Management System
IA3A	Swine	Grow/finish	Storage basin	Deep pit (emptied ~ every 10 weeks)
NC3A	Swine	Grow/finish	Anaerobic lagoon	Pull plug pit w/pit recharge (emptied daily)
OK3A	Swine	Grow/finish	Anaerobic lagoon	Pull plug pit w/pit recharge (emptied 3 times a week)
IN4A	Swine	Sow	Anaerobic lagoon	Deep pit (emptied once every two weeks)
OK4A	Swine	Sow	Anaerobic lagoon	Pull plug pit w/pit recharge (emptied weekly from the two gestation units and every 2.5 weeks from the farrowing unit)
NC4A	Swine	Gestation, farrowing, and breeding	Anaerobic lagoon	Pull plug pit w/pit recharge (emptied once every week)

Table 1-3. Summary of NAEMS swine open source monitoring sites and monitoring period dates.

Site	Phase[1]	Source Type	Manure Collection	1	2	3	4	5	6	7	8	9	10
IA3A	Finisher	Basin	PP[4]		8/30/07 – 9/26/07	12/19/07 – 1/15/08	5/16/08 - 5/31/08	6/1/08 - 6/24/08	11/14/08 - 11/30/08	12/1/08 - 12/16/08	4/8/09 - 4/23/09	7/28/09 - 8/18/09	
IN4A	Sow	Lagoon	PPR[3]	6/19/07 – 8/31/07	9/1/07 – 11/30/07	12/1/07 – 3/5/08	3/6/08 - 6/6/08	6/7/08 - 7/16/08					
NC3A	Finisher	Lagoon	Flush		10/24/07 - 11/7/07	2/13/08 – 3/5/08	3/6/08 - 3/26/08		9/25/08 - 10/14/08	2/4/09 - 2/23/09	5/12/09 - 6/2/09	6/2/09 - 6/22/09	9/24/09 - 12/1/09
NC4A[5]	Sow	Lagoon[2]	Flush		10/4/07 – 10/22/07	1/29/08 – 2/11/08	3/31/08 - 4/16/08	8/13/08 - 9/2/08	9/4/08 - 9/23/08	1/14/09 - 2/2/09	4/28/09 - 5/11/09	7/1/09 - 7/21/09	
OK3A	Finisher	Lagoon	PPR		8/30/07 – 9/18/07	1/24/08 – 2/19/08	5/7/08 - 5/29/08	5/29/08 - 6/10/08	11/5/08 - 12/2/08	12/2/08 - 12/16/08	4/23/09 - 5/14/09	7/15/09 - 8/4/09	
OK4A[5]	Sow	Lagoon	PPR	6/27/07 – 8/29/07	11/7/07 – 11/27/07	11/28/07 – 12/18/07	4/23/08 - 5/6/08		10/1/08 - 10/15/08	1/8/09 - 1/27/09	4/1/09 - 4/21/09	6/25/09 - 7/14/09	

[1] Characterizes the type of farm.
[2] Lagoon can be single or double stage.
[3] PPR = pull plug with recharge.
[4] PP= pull plug.
[5] Area site that also had barns sites.

1.2.1 IA3A

The grow-finish farm in Iowa consisted of four barns and a manure basin (Figure 1-6). The facility had a capacity of 3,840 finishers in the four units. The construction of the facility was completed in 1998.

Manure from the 2-foot deep pits in each of the 4 barns was transferred to the basin, which was west of the barns, approximately once every 10 weeks through 2 inlets. The concrete, circular basin had a diameter of 55 m (180 ft) with its sides approximately 0.5 m (1.5 ft) above and 2 m (6.5 ft) below ground level. At maximum capacity the basin had a liquid depth of 2 m (7 ft), surface area of 2,364 m^2 and a volume of 5,764 m^3. Sludge had never been removed from the lagoon (Grant and Boehm, 2010a).

Figure 1-6. Aerial view of IA3A.

1.2.2 IN4A

The Indiana farm consisted of nine barns and a lagoon (Figure 1-7) and had a capacity of 1,400 sows. The facility had been added to for many years, starting operations in 1968, while the last building addition was completed in 1992. In 1998, the facility was changed from a finisher operation to a farrow-to-wean operation.

Liquid waste from the deep pits of the barns was transferred once every two weeks to the lagoon by a single inlet on the east side of the lagoon. The lagoon was south of the barns. The clay-lined waste lagoon was 112 m (367 ft) by 115 m (377 ft). At maximum capacity, the liquid depth was 4 m (13 ft) with a surface area of 13,580 m^2 and a volume of 34,000 m^3. Sludge had never been removed from the lagoon. During the growing season, corn completely surrounded the lagoon (Grant and Boehm, 2010b).

Figure 1-7. Aerial view of IN4A.

1.2.3 NC3A

The North Carolina grow-finish farm consisted of five barns (Figure 1-8) and an office, in addition to the lagoon itself. The facility had a capacity of 8,000 finishing pigs in 5 units. Construction of the farm was completed in 1996.

Manure from the barns was transferred daily to the lagoon from pull plug pits with lagoon water recharge. Wastewater from all barns was channeled into a single pipe that fed into the lagoon. The rectangular waste lagoon was located to the east and was separated by a drainage swale from the barns. The clay-lined lagoon was 113 m (371 ft) wide and 173 m (568 ft) long and was oriented east to west. The lagoon had a maximum liquid depth of 3.3 m (11 ft), a surface area of 18,987 m^2 and a volume of 45,973 m^3. Wastewater was removed for irrigation as weather permitted. Sludge from the lagoon had not been removed since construction (15-year sludge removal cycle) (Grant and Boehm, 2010c).

Figure 1-8. Aerial view of NC3A.

1.2.4 NC4A

The breeding/gestation farm in North Carolina consisted of three barns, one each of gestation, breeding, and farrowing, and an office (Figure 1-9). The facility had a capacity of 2,000 sows in three units. Construction of the farm was completed in 1994.

Manure from the barns was transferred once a week from the gestation, farrowing, and breeding barns to the lagoon from pull plug pits with lagoon water recharge. Wastewater from all three buildings combined into one inlet (SW corner of lagoon in Figure 1-9). The waste lagoon was located to the north of the barns. The clay-lined, trapezoidal-shaped lagoon was oriented east to west and measured 123 m (404 ft) wide and 187 m (614 ft) long. The lagoon had a surface area of 23,195 m^2 and a volume of 56,851 m^3. At the beginning of NAEMS, the sludge depth was approximately 0.7 m (2 ft). Liquid was removed as the weather permitted. Sludge from the lagoon had not been removed since construction (15-yr sludge removal cycle). Barns on this farm were also monitored as a part of NAEMS (Grant and Boehm, 2010d).

Figure 1-9. Aerial view of NC4A.

1.2.5 OK3A

The Oklahoma grow-finish farm consisted of three barns (Figure 1-10). The facility had a maximum capacity of 3,024 finishing pigs. Construction was completed in 1997. Manure from the barns was transferred three times a week to the lagoon from pull plug pits with lagoon water recharge. Wastewater from all three units was combined into one inlet. The waste lagoon was rectangular and was located to the west of the barns (separated by a drainage swale). The clay-lined lagoon was 59 m (194 ft) wide and 210 m (689 ft) long and was oriented north to south. At maximum capacity, the liquid depth was 6 m (20 ft) with a surface area of 22,500 m^2 and a volume of 28,700 m^3. Liquid was removed approximately every six months. Sludge from the lagoon had not been removed since construction (20-yr sludge removal cycle) (Grant and Boehm, 2010e).

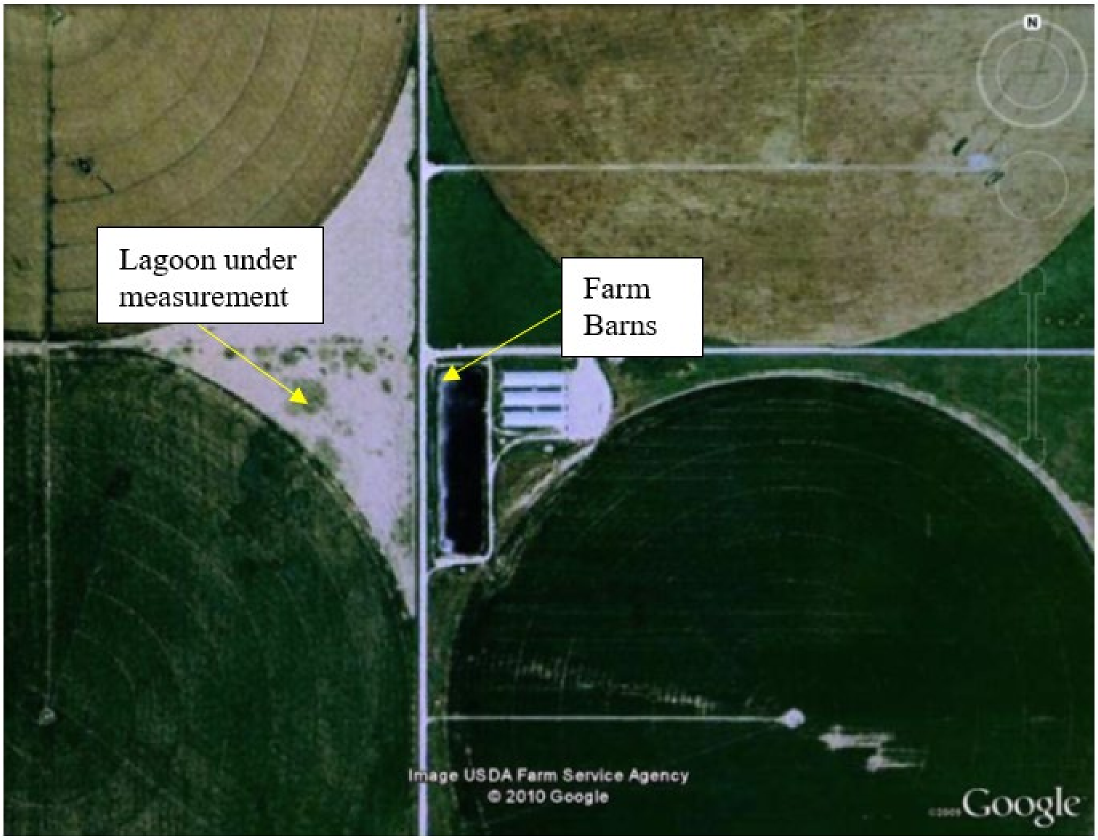

Figure 1-10. Aerial view of OK3A.

1.2.6 OK4A

The Oklahoma breeding/gestation farm consisted of three barns and one office (Figure 1-11). The facility had a capacity of 1,225 breeding and gestation sows in each of 2 breeding and gestation units, and 384 farrowing sows in 1 farrowing unit. Construction of the sow farm was completed in 1994.

Manure from the barns was transferred weekly from the 2 gestation units and every 2.5 weeks from the farrowing unit to the lagoon from pull plug pits with lagoon water recharge. Wastewater from the two gestation units was combined into one inlet while wastewater from the farrowing unit entered the lagoon from the northerly inlet. The rectangular waste lagoon was located to the east and was separated by a drainage swale from the barns. The clay-lined lagoon was 119 m (390 ft) wide and 193 m (633 ft) long and was oriented north to south. Liquid depth was approximately 5.5 m (18 ft). The lagoon had a surface area of 22,488 m^2 and volume was approximately 72,800 m^3. Sludge from the lagoon has not been removed since construction (20-yr sludge removal cycle). Field applications occurred up to two times per year, based on rainfall (Grant and Boehm, 2010f).

Figure 1-11. Aerial view of OK4A.

1.3 Data Sampled

NAEMS collected a host of data from the sites. Data collected included gaseous pollutant samples, particulate matter (PM) samples, meteorological data, confinement parameters, and biomaterial samples. All procedures for barn sites were outlined in the project Quality Assurance Project Plan (QAPP) (Heber et al., 2008) and open sources were summarized in open source project QAPP (Grant, 2008), and are summarized in Section 4 of the Overview Report. The following section outlines any collection specific to the dairy sites.

1.3.1 Particulate Matter

At any one time, the sampled filterable PM size class was either equal to or less than a nominal aerodynamic diameter of 10 micrometers (PM_{10}), and 2.5 micrometers ($PM_{2.5}$) or total suspended particulate (TSP). Appendix A contains summary tables, which note the PM sampling schedules for the confinement sites. Particulate matter emissions data were not collected from the open sources.

1.3.2 Animal Husbandry

For both IA4B and NC4B, the producer provided monthly farm records of the inventory in each gestation barn and the monitored farrowing room, average animal mass, mortalities, and special events like generator tests.

For OK4B, the producer provided monthly farm records of the number of piglets born and weaned, the gilts brought on site, culled sows, and sow mortalities. From the average number of piglets born and weaned between July 2007 and July 2009, the average piglet mortality rate was calculated and applied to all batches. The sow inventory in each gestation barn was calculated from the total number of sows on site, minus the farrowing barn sow capacity, divided in two.

For the finishing barns, IN3B and NC3B, data on animal inventory and mortalities were recorded manually and on a daily basis by the producer and provided to site personnel. Animal inventory was determined by comparing on-farm inventory records and sales reports. The sales reports usually contained information such as the date, packing plant name, number of pigs delivered to the plant, and total weight of each truck load. Average incoming nursery pig weights were also provided by the farm. Each barn was divided into sub-groups of pigs according to truck loads, because each had a specific date and average weight. A growth curve was applied to estimate the weight gain per week, for each pig subgroup, following the "standard" growth rate given in MWPS-8, Swine Housing and Equipment Handbook (MWPS, 1983). For each sub-group, the curve was fitted to the beginning and final weights to estimate the weight gain (in percentage with respect to the final weight and age). The average pig weights were estimated based on daily gains of each subgroup, while the total inventory and total weight were the summation of each subgroup within the room. Weekly mortality records were also included in this calculation. The calculated average pig weight within the room was used to estimate unknown weights, because mortalities were not weighed when removed from the rooms.

1.3.3 Biomaterials Sampling Methods and Schedule

All analyses of biomaterials were performed by the same independent laboratory Midwest Laboratories, Omaha, NE, except NC3B, which was analyzed by North Carolina State University's lab. Samples were collected based on procedures outlined in the QAPP (Heber, 2008). Specific sampling details for each site are summarized below. There were no lagoon samples collected for content analysis.

Manure in the barns was sampled multiple times during the study to determine pH, solids content, ammoniacal N, and total N. All analyses of biomaterials were performed by an independent laboratory (Midwest Laboratories, Omaha, NE). Sampling included full-depth manure profiles (loadout sampling) and surface manure samples. For the sites with pull plug pit recharge (i.e., IA4B, NC3B, NC4B, and OK4B), measurement of recharge water depth did not occur routinely due to the amount of time taken to refill the pits with recharge water (e.g., timer controlled pit recharge was not always completed while site engineer was able to be on site).

1.3.3.1 IA4B

Feed and water characteristics were evaluated based on analyses of two water samples taken in each year of the study. The feed samples were analyzed for total nitrogen and dry matter content, and the second sample also analyzed for sulfur content.

Manure samples from the liquid surface were taken every 3 to 4 months over the course of the two year monitoring period. The liquid was analyzed for pH, solids and ammonia (NH_3) content. Additionally, samples were taken during manure loadout twice form each barn and analyzed for solids and nitrogen content.

1.3.3.2 IN3B

Water was evaluated based on analyses of three samples of water provided to the pigs. The water samples were analyzed for sulfur content, nitrate/nitrite nitrogen and total Kjeldahl nitrogen (TKN) concentration. Feed samples were collected from each finishing room 10 time over the two year study period (6 samples in 2008 and 4 in 2009). The feed samples were analyzed for nitrogen and solids content.

Manure in the barns was sampled 15 times from 4/4/08 to 8/21/09. Sampling in 2008 was approximately every 3 months and then shifted to approximately every month in 2009. Manure was also sampled eight time during loadout, starting in mid-2008. Both sets of manure samples were analyzed for pH, solids content, and ammoniacal N. Ash content was determined starting in November 2008 for the surface manure samples. All loadout samples were analyzed for ash content.

1.3.3.3 NC3B

Water was evaluated based on analyses of three samples of the well water provided to the pigs, which was sampled on 6/2/09, 9/17/09, and 12/2/09 . Water usage for the whole farm was monitored with a single gauge.

A total of 49 feed samples were collected, with approximately 10 feed samples representing each of five feed formulations used at the farm. The samples were analyzed by NCSU, with results provided in Appendix D.

Manure in the barns was sampled multiple times from 2/15/09 to 6/10/09 to determine pH, solids content, ammoniacal N, and total N.

1.3.3.4 NC4B

All analyses of biomaterials were conducted by an independent laboratory (Midwest Laboratories, Omaha, NE).

Water characteristics were evaluated based on analyses of two samples of the water provided to the animals.

For six consecutive weeks, feed samples were collected from feed bins in the farrowing room (1 sample/week) and one of the gestation barns (1 sample/week). The feed samples were analyzed for total nitrogen and dry matter content by Midwest Labs. Full-depth manure profiles (loadout sampling) were collected six times in the gestation barns, five times in the farrowing room. Surface manure samples were collected once from each building. The full-depth profile samples were analyzed for total nitrogen and total solids, and the surface layer samples were analyzed for total solids, NH_3, and pH by Midwest Labs.

1.3.3.5 OK4B

All analyses of biomaterials were performed by an independent laboratory (Midwest Laboratories, Omaha, NE).

Water characteristics were evaluated based on analyses of two samples of the water provided to the animals.

For six consecutive weeks, feed samples were collected from feed bins in the farrowing room (1 sample/week) and one of the gestation barns (1 sample/week). The feed samples were analyzed for total nitrogen and dry matter content by MidWest Labs.

In B3, six full depth profile and four surface layer samples were collected once per cycle (approximately 21 days) between 8/25/08 and 7/13/09. At the time of manure sampling, manure depth was measured and recorded. Due to the amount of time taken to refill the pits with recharge water, measurement of recharge water depth did not occur routinely (timer controlled pit recharge was not always completed while site engineer was able to be on-site).

In the gestation barns, samples were collected during the scheduled site visit on a Monday or Tuesday, prior to routine emptying of the pits on Wednesday and Thursday, every three weeks between 8/25/08 and 7/13/09. At the time of manure sampling, manure depth was measured and recorded. Twelve full depth profile and 12 surface layer samples were taken from each gestation barn every sampling period.

The full depth profile samples were analyzed for total nitrogen and total solids, and the surface layer samples were analyzed for total solids, NH_3, and pH by MidWest Labs.

2 REVISIONS TO DATASET AND EMISSIONS DATA SUMMARY

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

2.1 Revisions to the 2010 Dataset

2.1.1 Barn data

As described in Section 4.2 of Volume 1: Overview Report, the NAEMS monitoring data were submitted to EPA in 2010, with revisions submitted in 2015. Section 6.1.1 of the Overview Report (Volume 1) describes the process used to remove negative emissions values that resulted from elevated background concentrations. For swine, the negative emissions were only removed from the farrowing NH_3 dataset, grow-finish PM_{10}, and the $PM_{2.5}$ dataset for both gestation and grow-finish barns. This represents less than 1% of the farrowing NH_3 and grow-finish PM_{10} datasets, and 3% and 7% of the gestation and grow-finish $PM_{2.5}$ datasets, respectively. Appendix B provides a summary of both the cutoffs and the number of values removed due to this process by barn for each pollutant.

Additional revisions to the dataset included the invalidation of additional air flow rates for periods when the ventilation was shut off. The invalidated air flow rates resulted in the invalidation of NH_3, H_2S, and PM measurements. NC3B and NC4B had periods where the ventilation was shut off for fan duty cycling (a period where fan(s) regularly switch on and off). For these instances, a running average of pressure differential was used with a running average value to determine invalid emissions. Other revisions included the removal of erroneous PM concentrations at NC3B and OK4B and using a nearby weather station to revise meteorological data collected at NC3B. In addition, three days of invalid ambient air temperature was removed from IN3B (July 17, 2007, through July 18, 2007). Comparison to a nearby weather station confirmed that the values in the 2010 dataset for these days were incorrect.

2.1.2 Open source data

Further studies comparing the VRPM and bLS methods found the bLS method to be closer to the true emissions value for lagoon sources and advanced an approach to adjust VRPM measurements based on bLS measurements (Grant et al. 2016). Grant et al. (2016) then averaged the adjusted bLS and VRPM estimates to calculate a final NH_3 emissions estimate. As noted in the Volume 1: Overview Report, the NH_3 30-minute values for use in calculating daily averages were adjusted according to Table 2-1. After the adjustment, the bLS and VRPM data were used together to determine which day had more than 24 half hour values to meet the revised 52% completeness criteria days.

Table 2-1. Open source data adjustment factor.

Site	Adjustment
IA3A	bLS/0.63
IN4A	RPM*1.12
NC3A	RPM*1.02
NC4A	RPM*1.57
OK3A	RPM*0.95
OK4A	RPM*1.08

In addition, EPA invalidated 14 days of pH data from June 26 through July 9, 2009, at OK4A. On June 26, 2009, a trend in decreasing pH values started that resulted in pH being between 6.5 and 7.0 from June 28, 2009, until July 9, 2009. These data were considered invalid because the pH probe failed accuracy calibration tests on July 14, 2009, and July 15, 2009 (Grant and Boehm, 2010f).

2.2 Comparison Between the 2010 and Revised Barn Data Sets

The influence of the corrections on the revised data sets can be observed by comparing the summary statistics of all the valid emissions values (at 75% data completeness) between the 2010 dataset, as summarized in the final site reports, and the revised data set used for model development. The following sections summarize the differences between the 2010 data set and revised data set for each of the barn types for a set of standard summary statics (e.g., mean, standard deviation, minimum, maximum, count (N), and number less than 0 (N<0)) of the average daily emissions. For summary tables presented, the percentage difference was calculated as the revised data set minus the 2010 version of the data set, divided by the 2010 version of the data set (e.g., % Diff = (Revised - $Data_{2010}$)/$Data_{2010}$ * 100). This calculation yields negative values when values decreased in the revised version of the dataset. This section presents the differences. Appendix B includes the summary statistics used in the comparison.

2.2.1 Farrowing Rooms

For farrowing rooms, the largest differences occur for the minimum and the number of daily averages less than 0 (N<0). In most cases, the data set changed by less than 1% or minimum values and N<0 counts saw an increase (negative percentage) as extreme negative value were removed in the modeling data set. The H_2S (Table 2-3) and PM_{10} (Table 2-4) emissions from NC4B also had an increase in minimum value. However, the minimum value from the 2010 data set increased from 0 to a larger positive number.

The exception to this were OK4B for all pollutants other than NH_3 (Table 2-2), and all pollutants for TSP (Table 2-6). For the H_2S at OK4B, a negative reading was restored to the dataset that was initially determined to be an outlier. For the TSP emissions at all sites and PM_{10} and $PM_{2.5}$ (Table 2-5) at OK4B, the change is related to recalculations, as N<0 does not change between the datasets, but the minimum value decreases.

Table 2-2. Percentage difference in NH_3 summary statistics between the 2010 and revised farrowing rooms dataset.

Parameter	IA4B F9	NC4B F15	OK4B F9
Mean	5.7%	-5.2%	10.6%
Standard Deviation	3.6%	-3.1%	2.0%
Minimum	-106.3%	-94.7%	-22.3%
Maximum	1.7%	0.9%	0.8%
N	-3.2%	25.4%	-14.7%
N<0	-100.0%	-66.7%	0.0%

Table 2-3. Percentage difference in H_2S summary statistics between the 2010 and revised farrowing rooms dataset.

Parameter	IA4B F9	NC4B F15	OK4B F9
Mean	1.5%	-7.6%	13.7%
Standard Deviation	0.8%	-1.8%	8.9%
Minimum	-25.7%	-100%*	195.1%
Maximum	0.3%	19.9%	19.7%
N	-2.8%	25.7%	-14.7%
N<0	0.0%	0.0%	100.0%

*Values increased from 0.

Table 2-4. Percentage difference in PM_{10} summary statistics between the 2010 and revised farrowing rooms dataset.

Parameter	IA4B F9	NC4B F15	OK4B F9
Mean	1.1%	-8.6%	14.2%
Standard Deviation	-0.1%	-3.7%	6.2%
Minimum	0.0%	-100%*	0.1%
Maximum	0.0%	0.8%	5.3%
N	-1.0%	27.1%	-14.4%
N<0	0.0%	0.0%	0.0%

*Values increased from 0.

Table 2-5. Percentage difference in $PM_{2.5}$ summary statistics between the 2010 and revised farrowing rooms dataset.

Parameter	IA4B F9	NC4B F15	OK4B F9
Mean	0.0%	-9.2%	29.8%
Standard Deviation	0.0%	-5.5%	17.1%
Minimum	0.0%	-35.0%	14.2%
Maximum	0.2%	-9.9%	14.6%

Parameter	IA4B F9	NC4B F15	OK4B F9
N	0.0%	14.3%	-18.2%
N<0	0.0%	0.0%	0.0%

Table 2-6. Percentage difference in TSP summary statistics between the 2010 and revised farrowing rooms dataset.

Parameter	IA4B F9	NC4B F15	OK4B F9
Mean	4.2%	-5.8%	7.2%
Standard Deviation	-1.1%	0.6%	15.3%
Minimum	0.3%	1.0%	0.1%
Maximum	-0.2%	1.0%	7.1%
N	-6.3%	10.0%	-10.8%
N<0	0.0%	0.0%	0.0%

2.2.2 Breeding and Gestation Barns

For most of the breeding and gestation sites, the reprocessing of the data led to minimal changes (i.e., less than 1%) for all tracked metrics for NH_3 (Table 2-7), H_2S (Table 2-8), PM_{10} (Table 2-9), $PM_{2.5}$ (Table 2-10), and TSP (Table 2-11). The largest changes were seen at NC4B and in the $PM_{2.5}$ data for OK4B. The reprocessing of the emissions data led to an overall increase in valid daily averages for NC4B. Despite a 10% to 100% change in the number of valid days across all the pollutants, the average daily emissions changed by less than 15% for any pollutant. Three negative values were introduced into the H_2S dataset that still fell within valid ranges, that led to less than a 10% change in average emissions for both houses. Unlike NC4B, the reprocessing led to a decrease in the number of valid $PM_{2.5}$ emissions days at both OK4B barns. These values were removed during the excessive negative removal process and resulted in a slight increase in the average $PM_{2.5}$ emissions rate for both barns (Table 2-10).

Table 2-7. Percentage difference in NH_3 summary statistics between the 2010 and revised gestation barn dataset.

Parameter	IA4BB1	IA4BB2	NC4BB1	NC4BB2	OK4BB1	OK4BB2
Mean	0.5%	1.5%	-4.9%	-6.2%	-0.3%	-0.2%
Standard Deviation	0.8%	1.8%	-15.1%	-16.5%	-1.1%	-3.1%
Minimum	0.7%	48.9%	-9.9%	-65.4%	0.4%	-0.2%
Maximum	1.1%	1.7%	-6.4%	-17.5%	-1.0%	4.5%
N	-0.3%	-0.2%	32.2%	30.2%	-0.3%	-0.3%
N<0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 2-8. Percentage difference in H_2S summary statistics between the 2010 and revised gestation barn dataset.

Parameter	IA4BB1	IA4BB2	NC4BB1	NC4BB2	OK4BB1	OK4BB2
Mean	0.1%	0.2%	-5.0%	-8.3%	-0.2%	-0.2%
Standard Deviation	0.1%	0.1%	-9.8%	-10.2%	-0.5%	-1.0%
Minimum	0.0%	0.0%	*	-125.6%	-3.0%	15.2%

Parameter	IA4BB1	IA4BB2	NC4BB1	NC4BB2	OK4BB1	OK4BB2
Maximum	-0.1%	0.1%	0.5%	-0.6%	-0.8%	1.0%
N	0.0%	-0.2%	31.0%	30.2%	-0.3%	-0.3%
N<0	0.0%	0.0%	*	*	0.0%	0.0%

*Values increased from 0.

Table 2-9. Percentage difference in PM_{10} summary statistics between the 2010 and revised gestation barn dataset.

Parameter	IA4BB1	IA4BB2	NC4BB1	NC4BB2	OK4BB1	OK4BB2
Mean	0.0%	0.2%	-3.2%	-5.0%	0.0%	0.0%
Standard Deviation	0.0%	-0.1%	-13.1%	-10.1%	0.1%	0.1%
Minimum	0.1%	0.0%	*	0.9%	0.0%	0.0%
Maximum	0.4%	0.1%	0.8%	1.2%	0.0%	-0.3%
N	0.0%	-0.3%	20.3%	19.1%	-0.2%	-0.2%
N<0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

*Values increased from 0.

Table 2-10. Percentage difference in $PM_{2.5}$ summary statistics between the 2010 and revised gestation barn dataset.

Parameter	IA4BB1	IA4BB2	NC4BB1	NC4BB2	OK4BB1	OK4BB2
Mean	0.0%	0.0%	-11.9%	-15.2%	12.9%	15.6%
Standard Deviation	0.1%	0.0%	4.4%	-25.9%	-22.6%	-38.0%
Minimum	0.0%	0.0%	7.5%	-21.5%	-116.3%	-105.6%
Maximum	0.1%	0.1%	0.1%	-0.5%	0.0%	-0.2%
N	0.0%	0.0%	40.0%	108.3%	-7.0%	-7.1%
N<0	0.0%	0.0%	0.0%	0.0%	-100.0%	-100.0%

Table 2-11. Percentage difference in TSP summary statistics between the 2010 and revised gestation barn dataset.

Parameter	IA4BB1	IA4BB2	NC4BB1	NC4BB2	OK4BB1	OK4BB2
Mean	0.0%	0.0%	0.9%	1.5%	0.0%	0.0%
Standard Deviation	0.0%	-0.1%	-16.7%	-10.5%	0.0%	0.1%
Minimum	0.3%	-0.1%	43.4%	0.7%	0.0%	0.1%
Maximum	0.2%	-0.1%	-19.6%	-14.0%	0.1%	-0.3%
N	0.0%	0.0%	11.4%	9.4%	0.0%	0.0%
N<0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

2.2.3 Grow-Finish Barns

The reprocessing led to a slight increase in average daily emissions at IN3B for NH_3 (Table 2-12) and H_2S (Table 2-13), with Room 5 (IN3BR5) seeing a slight decrease in average H2S emissions. The PM_{10} (Table 2-14) and TSP (Table 2-16) reprocessing generally yielded slightly lower average emissions, except at IN3BB8 for PM_{10}. The change between the original dataset and revised dataset were less than 12% for these pollutants. The largest changes were seen in the $PM_{2.5}$ (Table 2-15) values, where average emissions dropped for IN3BB5 and IN3BB7 due to recalculations, as seen in the reduction of the maximum value. For Rooms 6 and

8, the average increased for $PM_{2.5}$. The reprocessing led to a 12.5% increase in the number of days in Room 8 contributed to the increased average. While the increase in average emissions in Room 6 was due in part to the removal of excessive negative values.

NC3B saw an increase in the number of valid days and slight decrease in average daily emissions for NH_3 (Table 2-12), H_2S (Table 2-13), PM_{10} (Table 2-14), and $PM_{2.5}$ (Table 2-15). Changes in the average daily emissions were less than 15% for these pollutants. The revised dataset for TSP (Table 2-16) showed an increase in the average of the daily emissions, with a decrease in the total count (i.e., N). The recalculations increased the emissions rate for the site, as seen by the increase in the minimum daily emissions and slight increase in the maximum daily emissions in Barns 1 and 3.

Table 2-12. Percentage difference in NH_3 summary statistics between the 2010 and revised grow-finish barn dataset.

Parameter	IN3BR5	IN3BR6	IN3BR7	IN3BR8	NC3BB1	NC3BB2	NC3BB3
Mean	2.0%	2.8%	1.8%	11.3%	-5.4%	-5.2%	-11.4%
Standard Deviation	-1.1%	-6.4%	-0.3%	-13.1%	-0.4%	0.5%	4.5%
Minimum	*	*	*	*	-7.8%	-28.5%	-27.8%
Maximum	8.1%	-0.6%	-0.3%	-0.8%	-0.7%	-8.9%	-8.9%
N	-0.5%	-1.2%	-0.9%	-8.9%	8.1%	10.0%	23.3%
N<0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

*Values increased from 0.

Table 2-13. Percentage difference in H_2S summary statistics between the 2010 and revised grow-finish barn dataset.

Parameter	IN3BR5	IN3BR6	IN3BR7	IN3BR8	NC3BB1	NC3BB2	NC3BB3
Mean	-0.2%	1.1%	1.4%	8.3%	-7.7%	-5.7%	-14.6%
Standard Deviation	-2.0%	-1.3%	-0.2%	-2.0%	-6.4%	-3.0%	-4.6%
Minimum	-110.8%	*	606.2%	*	20.6%	-78.1%	235.8%
Maximum	-5.8%	-2.1%	-1.8%	-3.7%	-9.1%	-2.0%	-0.6%
N	-0.4%	-0.4%	-0.5%	-7.9%	9.0%	9.9%	20.8%
N<0	-100.0%	0.0%	50.0%	0.0%	150.0%	0.0%	0.0%

*Values increased from 0.

Table 2-14. Percentage difference in PM_{10} summary statistics between the 2010 and revised grow-finish barn dataset.

Parameter	IN3BR5	IN3BR6	IN3BR7	IN3BR8	NC3BB1	NC3BB2	NC3BB3
Mean	-0.4%	-1.1%	-0.7%	7.6%	0.7%	-7.1%	-12.9%
Standard Deviation	-2.4%	-1.4%	-2.2%	-2.4%	0.4%	-2.0%	-8.3%
Minimum	1.1%	0.1%	-66.4%	0.5%	0.9%	25.3%	0.0%
Maximum	-1.5%	-0.2%	-1.7%	-2.4%	0.5%	-2.2%	0.5%
N	-0.7%	0.0%	0.0%	-8.7%	0.0%	10.8%	38.5%
N<0	0.0%	0.0%	7.1%	-7.7%	0.0%	0.0%	0.0%

*Values increased from 0.

Table 2-15. Percentage difference in $PM_{2.5}$ summary statistics between the 2010 and revised grow-finish barn dataset.

Parameter	IN3BR5	IN3BR6	IN3BR7	IN3BR8	NC3BB1	NC3BB2	NC3BB3
Mean	-8.4%	110.7%	-149.0%	44.1%	-11.1%	-3.1%	-10.1%
Standard Deviation	-32.5%	-43.1%	-85.9%	-6.7%	16.0%	3.6%	12.6%
Minimum	-82.4%	-95.8%	-98.9%	-53.8%	-30.3%	-23.6%	-16.4%
Maximum	-21.1%	-0.1%	-2.0%	-8.9%	0.6%	0.4%	1.6%
N	7.4%	-7.4%	-18.5%	12.5%	22.9%	7.3%	37.5%
N<0	-40.0%	-75.0%	-75.0%	10.0%	0.0%	0.0%	0.0%

Table 2-16. Percentage difference in TSP summary statistics between the 2010 and revised grow-finish barn dataset.

Parameter	IN3BR5	IN3BR6	IN3BR7	IN3BR8	NC3BB1	NC3BB2	NC3BB3
Mean	-0.8%	-1.2%	-1.0%	-1.4%	3.6%	15.3%	15.1%
Standard Deviation	-1.7%	-4.3%	-2.1%	-1.7%	-10.0%	-16.9%	-31.9%
Minimum	-0.2%	-0.4%	0.0%	0.1%	1613.2%	3278.9%	3848.5%
Maximum	-1.4%	-2.3%	-0.7%	-2.0%	0.3%	-2.7%	0.6%
N	0.0%	0.0%	0.0%	0.0%	-1.9%	-14.8%	-14.8%
N<0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

2.3 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. (2013c), in which NH_3 emissions were modeled from swine lagoons based on NAEMS data, investigated data completeness and associated accuracy. The swine lagoon NH_3 emissions dataset had limited data availability at a data completeness of 75%. Grant et al. (2013c) 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. (2013c) 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.

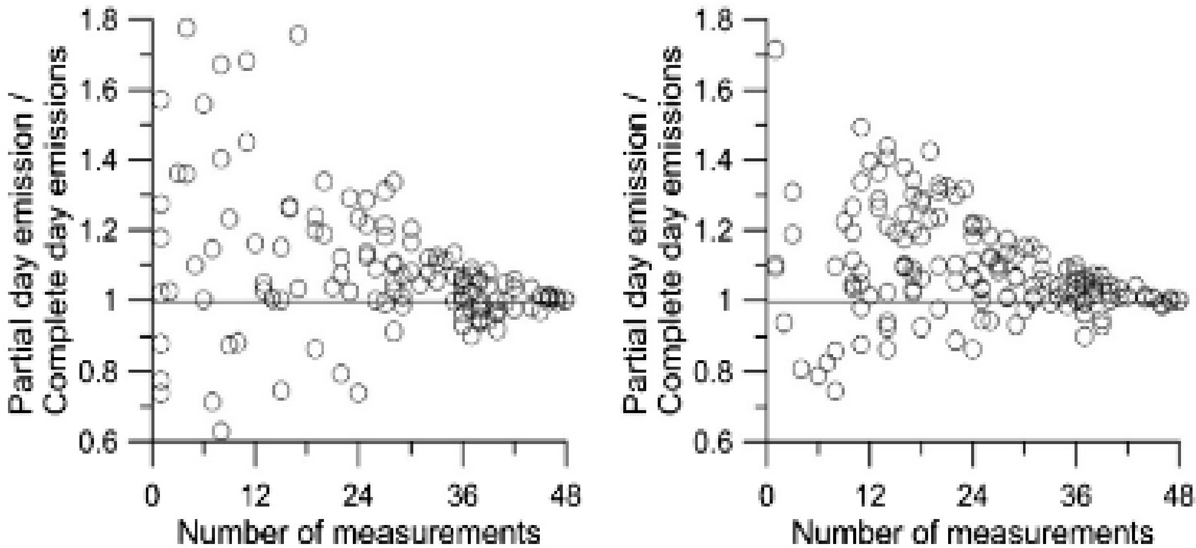

Figure 2-1. Ratio of mean predicted emissions for portion of day with valid emissions measurements to mean predicted emissions for the complete day at the finishing (A) and sow (B) farm. Error plotted against number of valid 30-minute measurements (from Grant et al., 2013c).

The following sections examine the effect of a reduced data completeness criterion on the number of valid average daily means (ADM) for both swine barn and swine opens sources observed during NAEMS. For swine barns, the examination is based on additional analysis completed by Heber that examined the effect of different completeness criteria by comparing the number of valid ADM. For swine open sources, the analysis is based on the Grant et al. studies that assessed the effect of daily data completeness by comparing the number of valid ADM at 52% and 75%. Where Grant et al. only considered one of the emissions models, EPA expanded the definition of completeness to include either a valid bLS measurement, a valid VRPM measurement or a combination of both. For example, if the bLS model had valid measurements for every half hour between 6:00 AM and 5:30 PM (inclusive), this would be 24 half-hour measurements and would not meet the completeness criteria (25 of 48 half-hour measurements) for a complete day under the Grant et al. analysis. For the final revised method, if VRPM had valid half-hour measurements for 9:00 PM through 11:30 PM, these 5 measurements would be included with the bLS measurements to make a complete day. As Section 2.3.3 shows, this revised method further improved the number of ADM available for EEM development.

2.3.1 Data Completeness Criteria for the Revised Dataset

Table 2-17 and Table 2-18 show the number of ADM for NH_3 and H_2S emissions, respectively, at varying percentages of data completeness for the revised dataset. For the swine sow site dataset, decreasing the daily completeness criteria from 75% to 50% would increase the number of valid days by 774 (17%) for NH_3 and 786 (16%) for H_2S, but based on the Grant et al.

(2013c) study, there would be an approximate 15% increase in error. Since the small increase in the number of ADM values does not justify a 15% increase in error, a daily completeness criterion of 75% was chosen for the revised NH_3 and H_2S sow site dataset. This value also matches the data completeness criteria used in the 2010 NAEMS datasets (Grant et al., 2008; Heber et al., 2008).

Table 2-17. Number of ADM for sow NH_3 emissions at varying percentages of data completeness.

% Valid Data	0	10	20	30	40	50	60	70	75	80	90	100
IA4B B1	549	535	530	517	495	495	440	396	378	353	307	139
IA4B B2	640	631	618	602	574	574	503	449	432	414	353	159
IA4B F	645	640	636	620	607	607	571	533	512	490	467	304
NC4B B1	661	651	648	645	625	610	595	566	554	542	517	341
NC4B B2	673	660	652	643	634	619	605	590	578	572	560	404
NC4B F	633	620	611	606	586	566	544	518	516	510	491	349
OK4B B1	711	711	710	704	691	676	659	630	610	580	530	203
OK4B B2	710	709	707	697	682	664	647	607	579	547	460	151
OK4B F	670	669	664	653	630	609	570	522	487	454	331	136
Total	5,892	5,826	5,776	5,687	5,524	5,420	5,134	4,811	4,646	4,462	4,016	2,186

Table 2-18. Number of ADM for sow H_2S emissions at varying percentages of data completeness.

% Valid Data	0	10	20	30	40	50	60	70	75	80	90	100
IA4B B1	561	551	547	536	514	514	455	412	391	369	323	149
IA4B B2	678	669	655	637	611	611	539	484	463	442	374	162
IA4B F	679	677	672	658	646	646	607	572	550	529	507	334
NC4B B1	688	681	677	677	663	650	633	604	592	579	553	364
NC4B B2	695	692	688	687	682	673	661	646	633	627	615	444
NC4B F	661	657	653	657	633	614	593	565	562	556	533	381
OK4B B1	717	717	716	710	697	685	667	638	619	589	538	204
OK4B B2	716	715	713	703	688	673	655	618	589	557	468	154
OK4B F	676	675	671	659	638	617	581	534	498	466	339	137
Total	6,071	6,034	5,992	5,924	5,772	5,683	5,391	5,073	4,897	4,714	4,250	2,329

For PM, the number of ADM at varying percentages of data completeness for the revised dataset are shown in Table 2-19, Table 2-20, and Table 2-21 for PM_{10}, $PM_{2.5}$ and TSP, respectively. For the swine sow site dataset, decreasing the daily completeness criteria from 75% to 50% would increase the number of valid days by 456 (14 %) for PM_{10}, 63 (21%) for $PM_{2.5}$, and 92 (20%) for TSP, respectively. Again, since the small increase in the number of ADM values does not justify a 15% increase in error, a daily completeness criterion of 75% was chosen for the all the PM species for the breeding and gestation dataset. This value also matches the initial data completeness criteria used in the 2010 NAEMS datasets (Grant et al., 2008; Heber et al., 2008).

Table 2-19. Number of ADM for sow PM_{10} emissions at varying percentages of data completeness.

% Valid Data	0	10	20	30	40	50	60	70	75	80	90	100
IA4B B1	478	469	465	454	437	437	391	369	359	337	279	102
IA4B B2	478	469	460	444	421	421	373	349	341	321	257	97
IA4B F	498	492	488	476	464	464	430	410	395	391	359	186
NC4B B1	423	422	421	426	416	404	391	381	379	378	367	220
NC4B B2	332	331	330	334	327	321	309	308	305	304	302	198
NC4B F	287	283	281	286	271	251	249	232	230	233	202	59
OK4B B1	570	569	569	564	548	531	519	500	494	478	425	134
OK4B B2	533	532	530	520	502	483	473	449	434	411	335	104
OK4B F	494	493	493	483	465	450	423	393	369	336	227	66
Total	4,093	4,060	4,037	3,987	3,851	3,762	3,558	3,391	3,306	3,189	2,753	1,166

Table 2-20. Number ADM for sow $PM_{2.5}$ emissions at varying percentages of data completeness.

% Valid Data	0	10	20	30	40	50	60	70	75	80	90	100
IA4B B1	51	51	51	51	49	49	40	38	36	34	31	6
IA4B B2	59	58	57	53	52	52	44	42	39	35	28	9
IA4B F	66	66	66	66	63	63	54	52	51	51	49	25
NC4B B1	39	37	37	37	36	34	31	30	28	28	26	10
NC4B B2	31	29	29	29	28	26	25	25	25	24	24	12
NC4B F	28	28	28	27	26	24	24	24	24	24	23	4
OK4B B1	55	55	55	55	51	50	48	45	43	41	40	22
OK4B B2	55	54	54	54	52	50	48	43	42	40	37	18
OK4B F	17	17	17	16	13	12	12	10	9	8	1	0
Total	401	395	394	388	370	360	326	309	297	285	259	106

Table 2-21. Number of ADM for sow TSP emissions at varying percentages of data completeness.

% Valid Data	0	10	20	30	40	50	60	70	75	80	90	100
IA4B B1	59	58	56	52	50	50	40	39	39	36	35	16
IA4B B2	68	67	67	66	62	62	46	46	45	45	40	18
IA4B F	70	70	68	67	60	60	48	47	45	45	45	30
NC4B B1	60	58	58	56	54	50	42	41	39	38	35	17
NC4B B2	47	45	45	45	43	40	36	36	35	35	32	18
NC4B F	43	43	43	42	40	37	33	33	33	33	32	11
OK4B B1	120	120	120	119	109	100	95	91	88	87	75	40

% Valid Data	0	10	20	30	40	50	60	70	75	80	90	100
OK4B B2	109	109	109	107	101	90	87	84	81	77	67	24
OK4B F	86	86	86	80	72	66	66	61	58	56	36	19
Total	662	656	652	634	591	555	493	478	463	452	397	193

2.3.2 Data Completeness Review and Conclusions for Grow-Finish Datasets

Table 2-22 and Table 2-23 show the number of ADM for NH_3 and H_2S emissions respectively at varying percentages of data completeness for the revised dataset. For the swine grow-finish dataset in this study, decreasing the daily completeness criteria from 75% to 50% would increase the number of valid days by 311 (10%) for NH_3 and 395 (12%) for H_2S, but based on the Grant et al. (2013) study, there would be an approximate 15% increase in error. Since the small increase in the number of ADM values does not justify the 15% increase in error, a daily completeness criterion of 75% was chosen for the revised NH_3 and H_2S swine dataset. This value also matches the data completeness criteria used in the 2010 NAEMS datasets (Grant et al., 2008; Heber et al., 2008).

Table 2-22. Number of grow-finish ADM for grow-finish NH_3 at varying percentages of data completeness.

% Valid Data	0	10	20	30	40	50	60	70	75	80	90	100
IN3B R5	459	455	451	444	435	419	399	379	373	343	339	265
IN3B R6	427	415	412	404	386	372	359	342	336	301	297	236
IN3B R7	422	416	413	406	387	374	360	342	331	307	298	213
IN3B R8	390	380	376	372	366	351	335	315	307	286	285	228
NC3B B1	637	635	630	627	624	618	600	586	571	558	545	386
NC3B B2	632	629	624	622	619	608	590	573	561	543	527	374
NC3B B3	628	624	621	620	618	604	592	569	556	534	521	376
Total	3595	3554	3527	3495	3435	3346	3235	3106	3035	2872	2812	2078

Table 2-23. Number of grow-finish ADM for grow-finish H_2S at varying percentages of data completeness.

% Valid Data	0	10	20	30	40	50	60	70	75	80	90	100
IN3B R5	602	602	600	592	577	560	535	508	497	466	457	339
IN3B R6	564	553	549	544	529	507	487	457	446	408	398	302
IN3B R7	565	558	555	546	530	509	479	455	437	399	389	274
IN3B R8	503	491	484	477	464	448	421	395	385	354	349	279
NC3B B1	619	616	612	608	605	600	585	568	555	542	536	399
NC3B B2	614	610	606	603	602	589	574	555	543	524	518	382
NC3B B3	610	606	603	601	600	586	577	555	541	527	522	389
Total	4077	4036	4009	3971	3907	3799	3658	3493	3404	3220	3169	2364

For PM, the number of ADM for PM_{10}, $PM_{2.5}$, and TSP emissions at varying percentages of data completeness for the revised dataset are shown in Table 2-24, Table 2-25, and Table

2-26, respectively. Decreasing the daily completeness criteria from 75% to 50% would increase the number of valid PM_{10} days by 238 (10%), valid $PM_{2.5}$ days by 27 (9.9%), and valid TSP days by 29 (13%). Again, based on the Grant et al. (2013a) study, there would be an approximate 15% increase in error for these increases in the number of ADM values available. Since the small increase in the number of ADM values does not justify a 15% increase in error, a daily completeness criterion of 75% was chosen for the revised swine PM dataset. This value also matches the data completeness criteria used in the 2010 NAEMS datasets (Grant et al., 2008; Heber et al., 2008).

Table 2-24. Number of ADM for grow-finish PM_{10} at varying percentages of data completeness.

% Valid Data	0	10	20	30	40	50	60	70	75	80	90	100
IN3B R5	392	382	379	370	351	339	320	311	301	293	280	179
IN3B R6	376	369	365	351	333	317	291	282	271	264	245	162
IN3B R7	382	377	377	370	351	335	321	308	297	289	270	178
IN3B R8	303	290	286	276	257	245	227	218	210	199	185	125
NC3B B1	534	532	529	527	519	503	489	473	466	454	394	125
NC3B B2	517	514	512	510	503	494	484	476	473	471	455	298
NC3B B3	383	380	378	376	370	365	357	347	342	334	325	211
Total	2887	2844	2826	2780	2684	2598	2489	2415	2360	2304	2154	1278

Table 2-25. Number of ADM for grow-finish $PM_{2.5}$ at varying percentages of data completeness.

% Valid Data	0	10	20	30	40	50	60	70	75	80	90	100
IN3B R5	44	43	43	42	40	36	34	33	32	32	26	16
IN3B R6	42	41	41	40	37	35	34	32	31	31	29	22
IN3B R7	41	40	40	39	37	35	34	32	31	30	29	21
IN3B R8	39	39	38	37	35	32	31	30	28	28	27	18
NC3B B1	69	69	69	69	68	63	59	59	59	59	58	35
NC3B B2	69	69	69	68	67	63	59	59	59	59	59	37
NC3B B3	39	39	39	39	38	36	33	33	33	33	33	24
Total	343	340	339	334	322	300	284	278	273	272	261	173

Table 2-26. Number of ADM for grow-finish TSP at varying percentages of data completeness.

% Valid Data	0	10	20	30	40	50	60	70	75	80	90	100
IN3B R5	39	38	37	37	33	29	25	24	24	24	22	16
IN3B R6	36	35	35	34	34	31	27	24	24	23	21	14
IN3B R7	44	43	43	43	42	39	34	34	34	34	33	22
IN3B R8	29	29	29	28	27	25	22	22	22	22	21	15
NC3B B1	65	65	64	64	60	55	53	52	52	52	52	41
NC3B B2	65	65	64	64	61	56	53	53	52	52	52	40

% Valid Data	0	10	20	30	40	50	60	70	75	80	90	100
NC3B B3	29	29	29	29	26	25	23	23	23	23	23	20
Total	307	304	301	299	283	260	237	232	231	230	224	168

2.3.3 Data Completeness Review and Conclusions for Open Source Datasets

For NH_3 emissions, reducing the completeness criteria to 52% results in at least a 70% increase in the ADM values available at each site (see Table 2-27). In most instances, the number of ADM values at least doubles with the relaxed completeness criteria. This substantial increase in the number of ADM values justifies a 15% increase in error. As such, the daily completeness criterion of 52% was chosen for the revised NH_3 emissions from swine open source dataset.

Similarly, reducing the completion criteria for H_2S to 52% results in at least a 100% increase in ADM values available at each site (see Table 2-28). Overall, for both pollutants, the number of ADM available is more than double when the completeness criteria are relaxed to 52%. This substantial increase in the number of ADM values available justifies an estimated 15% increase in error.

Table 2-27. Number of ADM for open source NH_3 at different percentages of data completeness.

Completeness Criteria	NC3A bLS	NC3A VRPM	NC3A Sum	OK3A bLS	OK3A VRPM	OK3A Sum	NC4A bLS	NC4A VRPM	NC4A Sum	OK4A bLS	OK4A VRPM	OK4A Sum	IA3A bLS	IA3A VRPM	IA3A Sum
52%	10	8	21	22	24	45	28	13	35	48	42	80	31	12	38
75%	5	3	7	8	8	23	14	4	20	24	30	47	17	4	20
% Change	100%	167%	200%	177%	200%	196%	100%	225%	75%	100%	40%	70%	82%	200%	90%

Table 2-28. Number of ADM for open source H_2S at different percentages of data completeness.

Completeness Criteria	NC3A bLS	OK3A bLS	IN4A bLS	NC4A bLS	OK4A bLS	IA3A bLS
52%	15	53	34	30	36	27
75%	7	19	15	14	18	8
% Change	114%	179%	127%	114%	100%	238%

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

Where possible, EPA compared the revised dataset developed for this report to values presented in peer reviewed journals and reports to quantify any differences due to the application of the revised calculation methods and other adjustments discussed in Section 2.1. Summaries of the gaseous emissions from naturally ventilated barns can be found in Joo et al. (2015). Lagoon and basin summaries have been presented in Grant and Boehm (2015), and corrals in Grant et al. (2020). Summaries of the mechanically ventilated barn data and PM data could not be found at the time of writing.

A simple comparison of the summary statistics presented in these papers and the summary statistics of the revised dataset is presented in the following sections. Overall, the dataset used for model development and presented in the papers are different due to difference in data screening methods. For NH_3 and H_2S at naturally ventilated barns, the model development dataset contains at least twice the number of observations than used in the article due to different choices in processing the data. Similarly, the revisions to the acceptance criteria for open sources noted in Section 2.3 also resulted in differences between the published data set and the modeling data set. For the open sources, the acceptance criteria used by EPA are the culmination of several published papers aiming to improve the data quality and go beyond what was discussed in the compared work. Overall, the comparison highlights that EPA has done extensive analysis and review of the dairy data sets to obtain a robust data set for model development.

2.4.1 Barn Sources

The NAEMS data for swine confinement sites has not been explicitly published in peer reviewed journal articles at this time. With the NH_3 data, averages of H_2S across all swine barns were included in Lui (2014). The NAEMS averages presented in this paper a consistent with averages generated by this effort. Additionally, Lui (2014) compared the NAEMS swine data to several other studies and found the NAEMS swine house H_2S emissions range data fell within the range of other studies. Additional recent sources of H_2S data that could readily be compared to NAEMS data were not identified during this effort.

The NAEMS data for swine confinement sites has not been explicitly published in peer reviewed journal articles at this time. EPA also identified peer reviewed journal articles that provided daily emissions estimates for swine confinement sites to directly compare NAEMS data to verify repressiveness to national conditions. However, the journal articles did not present the emissions in a format that made conversion to a common unit readily possible.

2.4.2 Open Sources

NH_3 emissions from all swine open sources have been reported in Grant et al. (2016) and Grant and Boehm (2018). Overall, the counts of valid days and the ADM between the revised datasets for EEM development and the Grant et al. (2016) study match well. The major difference in the datasets is related to the removal of data affected by moisture interference for the EPA revised dataset; thus, the largest difference is that the EPA revised dataset does not include any data from IN4A, whereas Grant et al. (2016) had 18 valid days from the site.

In terms of the overall site ADM, NC3A, and OK4A had lower averages in the revised EPA dataset compared to Grant et al. (2016), with emissions 11.79% (NC3A) and 1.68% (OK4A) less. At OK3A and NC4A, the revised EPA dataset had higher overall site ADM in comparison to Grant et al. (2016) with emissions 23.79% (OK3A) and 12.29% (NC4A) higher. Grant and Boehm (2018) analyzed NH_3 emissions from a swine basin using a similar NAEMS dataset and found that the number of valid days was similar, with the site ADM 26.4% higher in the revised EPA dataset.

H_2S emissions from the swine sow sites were reported in Grant et al. (2013b). Grant et al. (2013b) published bLS emissions at a data completeness level of 75%. For comparison, EPA also used a data completeness of 75%. While the count of valid days matched for IN4A, the daily average H_2S emissions are different, as the revised dataset has an average emissions that is 92.6% lower. For the other two sites, there are discrepancies between both the number of valid days and the ADM, however the difference in the ADM is significantly smaller than at IN4A with values 38.6% higher for OK4A and 57.2% lower for NC4A.

3 RELATIONSHIPS ESTABLISHED IN LITERATURE

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

3.1 NH_3 and H_2S from Confinement Sources

The amount of manure produced at a swine barn is a key factor in 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 (i.e., movement of gas from manure into the air) into the air. Proxies for the amount of manure produced at a swine barn are LAW and inventory. For model development, LAW and inventory were selected as (production) predictor variables, which allows the influence of these variables to be quantified. Furthermore, this allows the production predictor variable to potentially represent the pig rotation characteristics. For example, LAW at a swine grow-finish AFO could represent the effects of pig age, feed consumption and retention efficiency as well as the effects of the number and weight of pigs. LAW and inventory were determined daily during the NAEMS and thus were selected for further analysis.

The concentration of NH_3 and H_2S in the manure is also an important factor in influencing NH_3 and H_2S emissions. Total Kjeldahl Nitrogen (TKN; NH_3-N + organic N), Total Ammoniacal Nitrogen (TAN; NH_3-N) and sulfide are measurements that relate to these and thus can also have a major influence on NH_3 and H_2S emissions from swine manure (Ni 1999; Aneja et al. 2001; Montes et al. 2009; Rumsey and Aneja, 2014). In NAEMS, measurements of TKN and TAN were made from collected manure samples, however the frequency of the measurements at each site varied greatly, ranging from none to a sample every two-three months. TKN and TAN were selected for further analysis, however sulfide could not be selected since no measurements of sulfide or sulfur in swine barn surface manure were made.

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 has a major influence on NH_3 and H_2S emissions from swine manure (Aneja et al. 2000; Rumsey et al. 2014). The temperature of manure influences the microbial degradation of animal waste, with increasing temperatures resulting in increasing degradation rates (Zhang, 1992; Ni 1999). Increasing manure temperature will also increase the Henry's law constant and dissociation constant for NH_3 and H_2S (Montes et al. 2009; Rumsey and Aneja, 2014). For NH_3, this increases the potential amount of NH_3 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 of H_2S 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; Rumsey and Aneja, 2014). It should be noted 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 barn. During the NAEMS, measurements of exhaust temperature (temperature at barn fan exhaust) and ambient temperature were made continuously and thus both were selected for further analysis.

Manure pH can influence the amount of NH_3 and H_2S released to the air as it influences the chemical equilibrium of NH_3 and NH_4^+ (Montes et al. 2009; Sommer and Husted, 1995), and H_2S and HS^- (Blunden and Aneja, 2008). The pH of swine manure typically ranges from 7 to 8.5, which can result in the percentage of NH_3 and H_2S at 25ºC varying from ~0.6 to 15% and ~44 to 2%, respectively. In the NAEMS, Barn manure pH was measured in collected manure samples, which were taken at frequency of every 2-3 months at most sites. This variable was selected for further analysis.

Barn 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 (Arogo et al. 1999; Rumsey and Aneja, 2014). An increase in air velocity reduces the boundary layer thickness above the manure surface, therefore lowering the resistance to volatilization, resulting in an increase in the transfer of NH_3 and H_2S across the air-manure interface (Arogo et al. 1999; Rumsey and Aneja, 2014). Barn ventilation rate was measured continuously during the NAEMS and were therefore selected for further analysis.

As previously mentioned, 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 barn. However, barn activity measurements were not provided to the EPA, therefore the influence of this variable could not be explored further. In farrowing rooms at sow operations, there is likely to be an increase in piglet activity as piglets become older, thus meaning increased disturbance of manure on the floor of the farrowing room. Additionally, there will be more manure on the floor of the farrowing room to disturb as the cycle goes on (note: floors of farrowing rooms are typically clean at the beginning of cycle due to power-washing of room between cycle). These factors could result in increasing H_2S emissions throughout the approximate 21-day farrowing cycle. These hypotheses are supported by the observation of a regular cycle occurring in the NC4A and OK4A H_2S emissions trends (see Section 3.3). Accordingly, the variable ‘cycle day’ was selected for further analysis for H_2S emissions from farrowing rooms. Although NH_3 emissions are not governed by ebullition mechanisms (Ni et al., 2009) and do not appear to have an emissions trend related to the farrow cycle, the variable ‘cycle’ day was also selected for NH_3 so that a consistent approach could be applied to the farrowing room methodology.

The production cycle for hogs has three phases: farrowing, nursing, and finishing. The first phase begins with breeding and gestation over a 114 day period followed by farrowing (i.e., the birth of the piglet). After farrowing, the newly born pigs are nursed for a period of three to four weeks until they reach a weight of 10 to 15 pounds. After weaning, pigs are relocated to a nursery, for the second phase of the cycle. Nursery operations receive weaned pigs and grow them to a weight of 40 to 60 pounds (feeder pigs) or to an age of eight to ten weeks of age. The third phase of swine production is the growing-finishing phase where the feeder pigs are fed until they reach a market weight, typically between 240 and 280 pounds. Growing-finishing usually takes between 15 and 18 weeks, with the hogs slaughtered at about 26 weeks of age.

Some farms specialize in a single phase of the growth cycle, while other farms may contain two or all three phases. It is common for farms to operate as a farrow-to-finish operation, which encompasses all three phases of swine production. Another common production mode is the combination of the farrowing and nursing phases, which provide feeder pigs for stand-alone grow-finish operations. Operations can also specialize in either feeder pig production, nursery, or grow-finish phases of the production cycle. These operations may be linked by common ownership or separately owned, but all under contract with a single integrator. Thus, pigs may begin their life-cycle in a sow herd on one site, move to a nursery on another, and then move again to a finishing facility. Specialized operations can take advantage of skilled labor, expertise, advanced technology, streamlined management, and disease control. The farms that participated in the NAEMS encompassed the farrowing-nursing phases (also referred to as breeding and gestation farms) or finishing farms.

Barns for the farrowing and finishing have difference concerns and management practices. Farrowing operations require intense management to reduce piglet mortality. Nursery systems are typically designed to provide a clean, warm, dry, and draft-free environment in which animal stress is minimized to promote rapid growth and reduce injury and mortality. Nursery buildings are cleaned and disinfected thoroughly between groups of pigs to prevent transmission of disease from one herd to another. Finishing pigs require less intensive management and can tolerate greater variations in environmental conditions without incurring health problems. Because of the differences in management practices for each phase, separate EEMs were developed for each phase.

The way manure is managed at the farm can also influence emissions. There are four principal types of waste management systems used with total and partially enclosed confinement housing in the swine industry: deep pit, pull-plug pit, pit recharge, and flush systems. These practices do not represent all of the practices in use today; however, they are the predominant practices currently used by swine operations. The deep pit, pull-plug pit, and pit recharge systems are used with slatted floors whereas flush systems can be used with either solid or slatted floors. For flush systems, either fresh water or, more commonly, supernatant from an anaerobic lagoon transports accumulated waste to an anaerobic lagoon. The flush frequency can be daily or as often as every two hours. The frequency that the pit is flushed depends on the design characteristics such as channel length and slope and volume of water used per flush.

In pit recharge systems, relatively shallow pits are drained periodically by gravity to an anaerobic lagoon. The frequency of draining varies but between four and seven days is standard. Following draining, the empty pit is partially refilled with water, typically with supernatant from the anaerobic lagoon.

Pull-plug pits are similar to pit recharge in that pit contents are drained by gravity to a storage or stabilization system. Pits are drained frequently, often each week or every two weeks. However, water is not added back into the pit. The system relies on the natural moisture in the manure. Deep pits are similar to pull-plug pits in that they store the manure directly under a slatted flooring system, and no water is added into the pit. They differ in that deep pits are typically sized to collect and store six months of waste. The accumulated manure has a higher solids content than pull-plug systems and is emptied by pumping. To reduce odor, NH_3, and hydrogen sulfide (H_2S) concentrations in confinement facilities with deep pits, ventilation air may flow through the animal confinement area, down through the slatted floor, and over the accumulated manure before discharge from the building. Alternatively, deep pits may be ventilated separately.

Each of these storage methods affect emissions of NH_3, and H_2S differently. Emissions of NH_3 and H_2S may be higher in flush systems than from pit recharge and pull-plug pit systems due to turbulence during flushing. Even with ventilation, emissions of NH_3 and H_2S from confinement facilities with deep pits will likely be higher than from facilities with other types of manure collection and storage systems due to the sheer volume of manure stored. Because the different in house manure management systems can impact emissions, separate EEMs will be developed for each.

3.2 Particulate Matter from Barns

The release of PM_{10}, TSP, and $PM_{2.5}$ into swine barn air is caused by the physical suspension of a range of different materials in swine barns including feed, manure and skin

(Cambra-Lopez et al. 2011). Accordingly, LAW and inventory were selected as predictor variables as they will be related to the amount of source material. Physical suspension of PM from barn surfaces can be caused by air flow, animal activity and human activity (Aarnink and Ellen, 2007); however, as mentioned, barn activity measurements were not provided to the EPA, therefore the influence of this variable could not be explored further. Physical suspension may also be influenced by moisture conditions and relative humidity (Cambra-Lopez et al. 2010). 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 (Takai et al. 1998).

There are limited observational studies that have examined the influence of environmental variables on swine PM emissions, however, Hauessermann et al. (2008) developed statistical models to predict PM_{10} emissions from swine operations in Germany and Italy and found ventilation rate and barn relative humidity to have a significant influence on PM_{10} emissions. Winkel et al. (2015) analyzed PM_{10} and $PM_{2.5}$ emissions rates from animal houses including swine in Netherlands using a statistical model. In the Winkel et al. (2015) paper, they do not include environmental variables in their models, but do suggest based on preliminary analysis that ambient temperature is a promising predictor variable. It should be noted that determining the influence of temperature, relative humidity and ventilation rate on emissions is complicated by the intrinsic relationship between these variables as barn ventilation rate and relative humidity is typically a function of temperature changes. In the NAEMS, ventilation rate was measured continuously. Relative humidity and temperature were also measured continuously outside the barn (ambient RH and ambient temperature) and at the barn exhaust (exhaust RH and exhaust temperature). Accordingly, the variables, barn RH, ambient RH, barn temp, ambient temp and ventilation rate were selected for exploratory data analysis for PM_{10}, $PM_{2.5}$, and TSP emissions from swine barns.

As previously mentioned, when discussing H_2S farrowing room emissions, there is likely to be an increase in activity and increase in manure accumulation on the floor of farrowing room as the piglets become older. Similarly, there is likely to be an increase in dust accumulation from pig skin and feed throughout the cycle. Furthermore, the dust associated with feed may increase throughout the cycle as feed consumption increases. These factors could result in increasing PM emissions throughout the ~21-day farrowing cycle. Similar to H_2S, these hypotheses are supported by the observation of a regular cycle occurring in the NC4B and OK4B PM_{10} farrowing room emissions trends, although the cycle pattern (see Section 3.3) does not appear to be as strong as it is for H_2S. Accordingly, the variable 'cycle day' was selected for further analysis for PM_{10} emissions from farrowing rooms. The influence of 'cycle day' is supported by the aforementioned Haeusserman et al. (2008) study, which reported that cycle day had an influence on PM concentrations in swine barns. There is not enough data to observe whether there is a regular cycle in TSP and $PM_{2.5}$ trends; however, because the emissions processes are similar, TSP and $PM_{2.5}$ are likely to be also affected by increased activity, manure accumulation, dust accumulation and feed consumption in piglets throughout the farrowing cycle.

3.3 NH_3 and H_2S for Open Sources

Lagoon surface area, inventory and LAW are potential proxies for the amount of manure produced at an AFO and are generally related to each other. For open source model development, lagoon surface area was used to normalize emissions as it influences the physical amount of a pollutant that is emitted into the air. LAW was also considered as a predictor variable, but was not selected because the LAW at a swine AFO for an individual day does not necessarily represent the amount of manure in a lagoon on that day (i.e., the amount of manure in a lagoon is also related to manure loading from different stages of rotation and from previous rotations).

Similarly, to barn sources, TAN, TKN, sulfide, temperature, pH, and air flow above the manure surface can have a major influence on swine open source NH_3 and H_2S emissions. For further information on how they influence emissions, the reader is referred to the previous section. For NAEMS open source sites, there were limited measurements of TAN at three of the five sites (5, 3, and 1 daily measurements at IA3A, OK3A, and OK4A, respectively), therefore the influence of this variable was not selected for further analysis. TKN was measured more frequently, particularly at NC3A and NC4A, where it was measured approximately every two months, therefore this variable was selected for further investigation. There were no measurements of sulfide in open source manure samples, therefore this parameter could not be investigated further. At lagoon open source sites, there were continuous measurements of lagoon temperature, lagoon pH, air temperature and wind speed, which represents the air flow across the manure surface. These four variables were accordingly selected for further analysis for lagoon sources. At the basin site, there were also continuous measurements of air temperature and wind speed, but no measurements of lagoon temperature. For the basin, lagoon pH was only measured in collected manure samples (i.e., not continuously measured like it was for lagoons) of which there were five manure sampling events over the NAEMS sampling period. Accordingly, the continuously measured air temperature and wind speed were selected for further analysis at basins.

In literature, studies have suggested that there may be additional factors that could have a major influence on H_2S emissions from open sources. Ebullition of H_2S from open area sources has been linked to decreases in atmospheric pressure or lagoon depth (Grant et al. 2013; Varadharajan and Hemond, 2012). Grant et al. (2013), who conducted analysis on a similar swine sow NAEMS data set to that in this study commented that "Bursts or episodes of high H_2S emissions at the IN and NC lagoons were often associated with the passage of cold fronts", however further analysis by Grant et al. (2013) concluded that changes in atmospheric pressure and lagoon depth did not correlate with periods of high H_2S emissions. Due to this analysis from the Grant et al. (2013) study and also that the influence of barometric pressure on H_2S emissions is unlikely to be determined in a data set of average daily values, barometric pressure change was not selected for further analysis. The presence of purple sulfur bacteria (PSB) in lagoons has also been identified to decrease H_2S emissions from anaerobic lagoons (Holm and Vennes, 1970; Grant et al. 2013). Grant et al. (2013) analyzed a similar swine sow NAEMS lagoon data set to that in this study and hypothesized that H_2S emissions at the NC and IN sow lagoons were an order of magnitude lower than at OK due to the presence of PSB at NC and IN, which have favorable conditions for growth at these sites due to the warmer temperatures. No measurements of PSB in lagoons was made during the NAEMS, therefore this variable was not explored further.

4 SITE COMPARISON, TRENDS, AND ANALYSIS

Before developing the EEMs, EPA evaluated NAEMS data for each pollutant to identify patterns and trends in the emissions, environmental, and ambient 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. Sections 4.1, 4.2, 4.3, 4.4, and 4.5 summarize the emissions trends from breeding and gestation barns, farrowing rooms, grow-finish barns, lagoons, and basins, respectively. Appendix D contains the tables of summary statistics for all sources. Appendix E presents the time series plots of the site-specific emissions, environmental and production parameters, and manure data collected under NAEMS, and Appendix F contains the least squares regression analyses between the emissions and the identified environmental and ambient parameters.

Based on the analysis described in Section 3.0, EPA identified the key environmental and manure parameters that potentially affect emissions from swine barns and associated open sources. Parameters of particular interest for confinement sources included inventory, LAW, exhaust temperature, ambient temperature, ventilation rate, manure moisture, manure total ammoniacal nitrogen (TAN), manure pH, and manure accumulation time, which can be represented by cycle day. For PM emissions, exhaust and ambient relative humidity are of interest, in addition to the previously mentioned parameters. For open sources, wind speed, lagoon temperature, pH, and ORP will be explored in addition to the ambient parameters previously listed confinement sources.

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

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

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 Breeding and Gestation Barns

4.1.1 Emissions Data

Tables D-1 and D-2 of Appendix D present the summary statistics for daily average emissions of NH_3 for the swine gestation barn sites in kilograms per day and grams per day per head (kg d^{-1} and g d^{-1} hd^{-1}), respectively. Based on Table D-1, the emissions do vary across sites, even when presented on a per head basis, as in Appendix D, Table D-2. The emissions for NC4B and OK4b are fairly consistent, with average daily emissions ranging from 6.199 g d^{-1} hd^{-1} at NC4B-B1 to 9.597 g d^{-1} hd^{-1} at OK4B-B2. IA4B emissions are 2 to 3 times higher than the NC4B or OK4B, with Appendix E, Figure E-1 showed that the emissions follow a seasonal cycle, with average daily emissions values 17.549 and 29.635 g d^{-1} hd^{-1} for IA4B-B2 and B1, respectively. Looking further at the statistics, both IA4B barns have the largest standard deviations, which can be seen in as enhanced variability in the time series plots (Appendix E, Figures E-1 and E-2). The time series plots also show a weak season pattern, with greater emissions typically occurring in the summer and decreasing to lows in winter months. NC4B deviates frow this pattern, with emissions in a similar range for most of the study period.

The summary statistics for daily average H_2S emissions are presented in Appendix D, Tables D-3 and D-4 for g d^{-1} and mg d^{-1} hd^{-1}, respectively. IA4B average daily emissions are again higher than the other two sites by an order of magnitude. Appendix E, Figures E-3 and E-4 show the time series plot for H_2S emissions. The plots show IA4B has similar emissions to NC4B and OK4B, particularly during the winter months. However, IA4B sees high spikes and increased variability over the summer months, and in particular over the middle half of 2008. NC4B and OK4B have a less pronounced seasonal trend. The higher H_2S emissions at IA4B could possibly be due to differences in the manure handling at the site. IA4B uses a deep pit system, which transfer manure every 21-24 days, while the other sites are a pull plug recharge system that are flushed weekly. The longer residence time of the manure may allow for more emissions. IA4B has slightly higher LAWs than the other sites, which would lead to more manure produced and higher H_2S emissions during these longer residence times.

Tables D-5 and D-6 of Appendix D present the summary statistics in units of g d^{-1} and mg d^{-1} hd^{-1}, respectively, for the daily average emissions of PM_{10} for the breeding and gestation sites. The emissions between sites and between barns varied both in the total for the day and when normalized on a per head basis. The average daily emissions ranged from 251.912 g d^{-1} (279.409 mg d^{-1} hd^{-1}) at NC4B-B1 to 526.882 g d^{-1} (485.683 mg d^{-1} hd^{-1}) at IA4B-B2. The time series plots (Appendix E, Figures E-5 and E-6) show similar scattered patterns to emissions, with no discernable seasonal patterns. NC4B-B2 has a noticeable spike in the summer of 2008, which likely contributed to the difference in average emissions in the two barns at the site.

For $PM_{2.5}$ average daily emissions have some variability but are comparable across sites. The average daily emissions summarized in Table D-7 of Appendix D show sites ranged from 31.292 g d^{-1} at OK4B-B1 up to 56.636 g d^{-1} at OK4B-B2. When accounting for inventory difference (Appendix D, Table D-8), the average value ranged from 26.959 mg d^{-1} hd^{-1} at OK4B-B1 compared to 49.868 mg d^{-1} hd^{-1} at IA4B-B2. Appendix E, Figures E-7 and E-8 show the temporal variability of $PM_{2.5}$ emissions. The sparse temporal nature of the daily $PM_{2.5}$ values, due to a rotating monitoring schedule for the PM size fractions at the NAEMS sites, makes determination of seasonal trends in the data difficult. Site IA4B-B2 was the only site with a negative value after the processing in Section 2.1.

The daily average TSP emissions followed a similar trend to PM_{10}, where the average emissions vary between sites and between barns, both in the total for the day and when normalized on a per head basis (Appendix D, Tables D-9 and D-10). Again, IA4B is on the high end, with IA4B-B2 approximately twice the average emissions at the NC4B-B1 site. Like $PM_{2.5}$, the sparse temporal nature of the daily TSP values makes determination of seasonal trends difficult.

4.1.2 Environmental Data

The statistical summary of the environmental parameters associated with breeding and gestation barns are presented in Table D-11 of Appendix D. Table 4-2 provides a summary of the regression analysis for environmental parameters for breeding and gestation barns. The average inventory for the barn ranged from 885 head at NC4B-B2 to 1,171 head at OK4B-B2. The time series shown in Figure E-11 of Appendix E shows inventory levels at barn at the same site are generally synchronized, with similar trends in animal additions and removals. NC4B proved to be the exception as Barn 1 shows little variability over the study period, while Barn 2 has a frequent cyclical pattern similar to the farrowing rooms. Appendix F, Figures F.2-1, F.2-2, F.2-13, F.2-14, F.2-25, F.2-26, F.2-37, F.2-38, F.2-49, and F.2-50 show the scatter plots of inventory versus each pollutant. The scatter plots generally showed only slight or weak linear relationship with emissions.

Table 4-2. Breeding and gestation barn environmental parameter regression analysis summary.

Pollutant	Parameter	R	R^2	Strength	Figure
NH_3 (kgd^{-1})	Inventory (hd)	0.20	0.04	Slight or weak	F.2-1
NH_3 ($gd^{-1}hd^{-1}$)	Inventory (hd)	0.11	0.01	Slight or weak	F.2-2
H_2S (gd^{-1})	Inventory (hd)	0.12	0.01	Slight or weak	F.2-13
H_2S ($mgd^{-1}hd^{-1}$)	Inventory (hd)	0.09	0.01	Slight or weak	F.2-14
PM_{10} (gd^{-1})	Inventory (hd)	0.20	0.04	Slight or weak	F.2-25
PM_{10} ($mgd^{-1}hd^{-1}$)	Inventory (hd)	-0.03	0.00	Slight or weak	F.2-26
$PM_{2.5}$ (gd^{-1})	Inventory (hd)	0.11	0.01	Slight or weak	F.2-37
$PM_{2.5}$ ($mgd^{-1}hd^{-1}$)	Inventory (hd)	-0.09	0.01	Slight or weak	F.2-38
TSP (gd^{-1})	Inventory (hd)	0.22	0.05	Slight or weak	F.2-49
TSP ($mgd^{-1}hd^{-1}$)	Inventory (hd)	0.04	0.00	Slight or weak	F.2-50
NH_3 (kgd^{-1})	Average weight (kg)	0.60	0.37	Modest	F.2-3
NH_3 ($gd^{-1}hd^{-1}$)	Average weight (kg)	0.58	0.33	Modest	F.2-4
H_2S (gd^{-1})	Average weight (kg)	0.74	0.54	Moderate	F.2-15
H_2S ($mgd^{-1}hd^{-1}$)	Average weight (kg)	0.73	0.53	Moderate	F.2-16
PM_{10} (gd^{-1})	Average weight (kg)	0.35	0.12	Slight or weak	F.2-27
PM_{10} ($mgd^{-1}hd^{-1}$)	Average weight (kg)	0.29	0.08	Slight or weak	F.2-28
$PM_{2.5}$ (gd^{-1})	Average weight (kg)	0.24	0.06	Slight or weak	F.2-39
$PM_{2.5}$ ($mgd^{-1}hd^{-1}$)	Average weight (kg)	0.18	0.03	Slight or weak	F.2-40
TSP (gd^{-1})	Average weight (kg)	0.36	0.13	Slight or weak	F.2-51
TSP ($mgd^{-1}hd^{-1}$)	Average weight (kg)	0.33	0.11	Slight or weak	F.2-52
NH_3 (kgd^{-1})	Live animal weight, LAW (kg)	0.49	0.24	Modest	F.2-5
NH_3 ($gd^{-1}hd^{-1}$)	LAW (kg)	0.42	0.18	Slight or weak	F.2-6
H_2S (gd^{-1})	LAW (kg)	0.53	0.28	Modest	F.2-17
H_2S ($mgd^{-1}hd^{-1}$)	LAW (kg)	0.51	0.26	Modest	F.2-18
PM_{10} (gd^{-1})	LAW (kg)	0.35	0.12	Slight or weak	F.2-29
PM_{10} ($mgd^{-1}hd^{-1}$)	LAW (kg)	0.18	0.03	Slight or weak	F.2-30
$PM_{2.5}$ (gd^{-1})	LAW (kg)	0.23	0.05	Slight or weak	F.2-41
$PM_{2.5}$ ($mgd^{-1}hd^{-1}$)	LAW (kg)	0.08	0.01	Slight or weak	F.2-42
TSP (gd^{-1})	LAW (kg)	0.38	0.14	Slight or weak	F.2-53
TSP ($mgd^{-1}hd^{-1}$)	LAW (kg)	0.25	0.06	Slight or weak	F.2-54
NH_3 (kgd^{-1})	Exhaust temperature (°C)	-0.06	0.00	Slight or weak	F.2-7
NH_3 ($gd^{-1}hd^{-1}$)	Exhaust temperature (°C)	-0.07	0.00	Slight or weak	F.2-8
H_2S (gd^{-1})	Exhaust temperature (°C)	-0.26	0.07	Slight or weak	F.2-19
H_2S ($mgd^{-1}hd^{-1}$)	Exhaust temperature (°C)	-0.26	0.07	Slight or weak	F.2-20
PM_{10} (gd^{-1})	Exhaust temperature (°C)	-0.21	0.04	Slight or weak	F.2-31
PM_{10} ($mgd^{-1}hd^{-1}$)	Exhaust temperature (°C)	-0.17	0.03	Slight or weak	F.2-32
$PM_{2.5}$ (gd^{-1})	Exhaust temperature (°C)	-0.23	0.05	Slight or weak	F.2-43
$PM_{2.5}$ ($mgd^{-1}hd^{-1}$)	Exhaust temperature (°C)	-0.22	0.05	Slight or weak	F.2-44
TSP (gd^{-1})	Exhaust temperature (°C)	-0.41	0.17	Slight or weak	F.2-55

Pollutant	Parameter	R	R^2	Strength	Figure
TSP ($mgd^{-1}hd^{-1}$)	Exhaust temperature (°C)	-0.38	0.14	Slight or weak	F.2-56
NH_3 (kgd^{-1})	Exhaust relative humidity (%)	0.13	0.02	Slight or weak	F.2-9
NH_3 ($gd^{-1}hd^{-1}$)	Exhaust relative humidity (%)	0.12	0.01	Slight or weak	F.2-10
H_2S (gd^{-1})	Exhaust relative humidity (%)	0.09	0.01	Slight or weak	F.2-21
H_2S ($mgd^{-1}hd^{-1}$)	Exhaust relative humidity (%)	0.08	0.01	Slight or weak	F.2-22
PM_{10} (gd^{-1})	Exhaust relative humidity (%)	-0.29	0.08	Slight or weak	F.2-33
PM_{10} ($mgd^{-1}hd^{-1}$)	Exhaust relative humidity (%)	-0.20	0.04	Slight or weak	F.2-34
$PM_{2.5}$ (gd^{-1})	Exhaust relative humidity (%)	0.10	0.01	Slight or weak	F.2-45
$PM_{2.5}$ ($mgd^{-1}hd^{-1}$)	Exhaust relative humidity (%)	0.11	0.01	Slight or weak	F.2-46
TSP (gd^{-1})	Exhaust relative humidity (%)	-0.52	0.27	Modest	F.2-57
TSP ($mgd^{-1}hd^{-1}$)	Exhaust relative humidity (%)	-0.48	0.23	Modest	F.2-58
NH_3 (kgd^{-1})	Airflow (dsm^3s^{-1})	0.30	0.09	Slight or weak	F.2-11
NH_3 ($gd^{-1}hd^{-1}$)	Airflow (dsm^3s^{-1})	0.25	0.06	Slight or weak	F.2-12
H_2S (gd^{-1})	Airflow (dsm^3s^{-1})	0.17	0.03	Slight or weak	F.2-23
H_2S ($mgd^{-1}hd^{-1}$)	Airflow (dsm^3s^{-1})	0.14	0.02	Slight or weak	F.2-24
PM_{10} (gd^{-1})	Airflow (dsm^3s^{-1})	-0.02	0.00	Slight or weak	F.2-35
PM_{10} ($mgd^{-1}hd^{-1}$)	Airflow (dsm^3s^{-1})	-0.05	0.00	Slight or weak	F.2-36
$PM_{2.5}$ (gd^{-1})	Airflow (dsm^3s^{-1})	-0.04	0.00	Slight or weak	F.2-47
$PM_{2.5}$ ($mgd^{-1}hd^{-1}$)	Airflow (dsm^3s^{-1})	-0.11	0.01	Slight or weak	F.2-48
TSP (gd^{-1})	Airflow (dsm^3s^{-1})	-0.42	0.17	Slight or weak	F.2-59
TSP ($mgd^{-1}hd^{-1}$)	Airflow (dsm^3s^{-1})	-0.41	0.17	Slight or weak	F.2-60

Average sow weight (average animal weight) was comparable across the houses and ranged from 181 kg at NC4B to 249 kg at IA4B. The summary statistics (Appendix D, Table D-11) and time series (Appendix E, Figure E-12) show the value was steady over the study and likely represent an overall average for the site and not actual daily averages. The time series also shows gaps in weight data for time the house was empty while emissions measurements were taken. The scatter plots (Appendix F, Figures F.2-3, F.2-4, F.2-15, F.2-16, F.2-27, F.2-28, F.2-39, F.2-40, F.2-51, and F.2-52) show a modest positive relationship between weight and NH_3 emissions, a moderate positive relationship with H_2S, and only a slight relationship for all the PM size fractions.

Combining the inventory with weight to obtain a total live animal weight (LAW = (inventory * average animal weight)) provides a better proxy for manure volume, as the animal weight and inventory determines the volume of manure generated. The summary statistics (Appendix D, Table D-11) show LAW ranges from 160,168.622 Mg at NC4BB2 to 275,306.238 Mg at IA4BB2. The trends in LAW (Appendix E, Figure E-13) mirror those of the inventory, as weight is constant through the study. The scatter plots (Appendix F, Figures F.2-5, F.2-6, F.2-17, F.2-18, F.2-29, F.2-30, F.2-41, F.2-42, F.2-53, and F.2-54) show a modest positive relationship between LAW and NH_3 and H_2S, and only a slight relationship for all the PM size fractions. The positive relationship with NH_3 and H_2S emissions was anticipated because LAW is proportional to the volume of manure produced and, therefore, the amount of NH_3 emissions produced.

Average exhaust temperatures were comparable across all the sites, ranging from an average of 17.168 °C at IA4B-B2 to 24.638 °C at NC4B-B2. The time series (Appendix E, Figure E-14) show the expected seasonal trend of peak exhaust temperatures in the summer decreasing to a minimum in the new year, and increasing again in the spring. The linear regression analysis (Appendix F, Figures F.2-7, F.2-8, F.2-19, F.2-20, F.2-31, F.2-32, F.2-43, F.2-44, F.2-55, and F.2-56) show weak negative relationships with emissions. On its surface, the weak relationship with exhaust temperature and emissions seems to go against the published literature noted in Section 3.0 that asserts emissions should increase with increases in temperature. However, the temperature is confined to a relatively small range with limited variability in temperature compared to the emissions rates. Figure F.2-7 shows separate linear regressions of exhaust temperature and NH_3 emissions for each site. NC4B appears to be masking a positive linear relationship with exhaust temperature, as IA4B and OK4B show positive relationships and NC4B displays no linear relationship.

A review of the summary statistics for exhaust relative humidity show comparable values, with average values ranging from 52.170% at OK4B-B1 to 63.172% at NC4B-B1. The time series (Appendix E, Figure E-15) show the exhaust relative humidity values are fairly variable, as there is a spread in the data for any time of the year. The plots also suggest some seasonality to the data, with lower values occurring in the winter that increase to peaks in the summer. IA4B barns do not show this seasonality as strongly as NC4B and OK4B. When regressed with the emissions (Appendix F, Figures F.2-9, F.2-10, F.2-21, F.2-22, F.2-33, F.2-34, F.2-45, F.2-46, F.2-57, and F.2-58), there are only slight or weak relationships for gaseous pollutants, PM_{10}, and $PM_{2.5}$. TSP daily emissions have a modest negative relationship with exhaust relative humidity.

The measured airflow through the barn was comparable across sites and ranged from 25.265 dry standard cubic meter per second (dsm^3s^{-1}) at NC4B-B2 to 35.669 dsm^3s^{-1} at IA4B-B2. The time series (Appendix E, Figure E-16) showed a seasonal pattern, as ventilation rates would increase to maintain barn temperatures during warm months. The regression analyses (Appendix F, Figures F.2-11, F.2-12, F.2-23, F.2-24, F.2-35, F.2-36, F.2-47, F.2-48, F.2-59, and F.2-60) showed weak positive relationships with gaseous emissions, and weak negative relationships with all three PM size fractions. The plots for PM_{10} and TSP suggest that the relationship might be better represented by a quadratic form.

4.1.3 Ambient Data

The statistical summary of the ambient parameters associated with breeding and gestation barns are presented in Table D-12 of Appendix D. Table 4-3 provides a summary of the regression analysis for ambient parameters for breeding and gestation barns. The range of ambient temperature and the variation shown in Figure E-17 of Appendix E is indicative of their varying geographic locations. The average daily temperatures were coolest at IA4B where the average was 8.949 °C, compared to 19.523 °C at NC4B. The coastal North Carolina farm is not subject to as many snowstorms or freezing weather as compared to the OK4B and IA4B farms, lending to the higher average temperature. In fact, NC4B did not drop below 0 °C for the entire study period, unlike the IA4B and OK4B. The time series plot in Figure E-17 of Appendix E shows the typical seasonal pattern to temperatures (i.e., maximum in summer and minimum in winter). The scatter plots of ambient temperature (Appendix F, Figures F.2-61, F.2-62, F.2-67, F.2-68, F.2-73, F.2-74, F.2-79, F.2-80, F.2-85, and F.2-86), and summarized in Table 4-3, show slight or weak relationships with emissions. As with the exhaust parameters, the weak relationships between temperature and emissions in the breeding and gestation barns seem to be the result of a non-linear relationship between NH_3 emissions and ambient temperature, particularly at NC4B. PM_{10} and TSP show similar relationships with temperature. As stated in the Overview Report, based on SAB comments, the EPA was not looking at fitting nonlinear forms at this time. This analysis sufficiently indicates a relationship between temperature and NH_3 emissions.

Ambient relative humidity is similar between sites, ranging from an average value of 52.437% at OK4B to 71.577% at IA4B. The time series (Appendix E, Figure E-18) show the values vary by at least 20% for any given time of the year, with no particular seasonal pattern. The regression analyses (Appendix F, Figures F.2-63, F.2-64, F.2-69, F.2-70, F.2-75, F.2-76, F.2-81, F.2-82, F.2-87, and F.2-88) indicate slight or weak relationships between ambient relative humidity and emissions.

Table 4-3. Breeding and gestation barn ambient parameter regression analysis summary.

Pollutant	Parameter	R	R^2	Strength	Figure
NH_3 (kgd^{-1})	Ambient temperature (°C)	0.09	0.01	Slight or weak	F.2-61
NH_3 ($gd^{-1}hd^{-1}$)	Ambient temperature (°C)	0.08	0.01	Slight or weak	F.2-62
H_2S (gd^{-1})	Ambient temperature (°C)	-0.06	0.00	Slight or weak	F.2-67
H_2S ($mgd^{-1}hd^{-1}$)	Ambient temperature (°C)	-0.07	0.01	Slight or weak	F.2-68
PM_{10} (gd^{-1})	Ambient temperature (°C)	-0.06	0.00	Slight or weak	F.2-73
PM_{10} ($mgd^{-1}hd^{-1}$)	Ambient temperature (°C)	-0.05	0.00	Slight or weak	F.2-74
$PM_{2.5}$ (gd^{-1})	Ambient temperature (°C)	-0.11	0.01	Slight or weak	F.2-79
$PM_{2.5}$ ($mgd^{-1}hd^{-1}$)	Ambient temperature (°C)	-0.13	0.02	Slight or weak	F.2-80
TSP (gd^{-1})	Ambient temperature (°C)	-0.35	0.12	Slight or weak	F.2-85

Pollutant	Parameter	R	R^2	Strength	Figure
TSP ($mgd^{-1}hd^{-1}$)	Ambient temperature (°C)	-0.33	0.11	Slight or weak	F.2-86
NH_3 (kgd^{-1})	Ambient relative humidity (%)	0.13	0.02	Slight or weak	F.2-63
NH_3 ($gd^{-1}hd^{-1}$)	Ambient relative humidity (%)	0.14	0.02	Slight or weak	F.2-64
H_2S (gd^{-1})	Ambient relative humidity (%)	0.17	0.03	Slight or weak	F.2-69
H_2S ($mgd^{-1}hd^{-1}$)	Ambient relative humidity (%)	0.16	0.03	Slight or weak	F.2-70
PM_{10} (gd^{-1})	Ambient relative humidity (%)	-0.17	0.03	Slight or weak	F.2-75
PM_{10} ($mgd^{-1}hd^{-1}$)	Ambient relative humidity (%)	-0.06	0.00	Slight or weak	F.2-76
$PM_{2.5}$ (gd^{-1})	Ambient relative humidity (%)	0.06	0.00	Slight or weak	F.2-81
$PM_{2.5}$ ($mgd^{-1}hd^{-1}$)	Ambient relative humidity (%)	0.14	0.02	Slight or weak	F.2-82
TSP (gd^{-1})	Ambient relative humidity (%)	-0.14	0.02	Slight or weak	F.2-87
TSP ($mgd^{-1}hd^{-1}$)	Ambient relative humidity (%)	-0.06	0.00	Slight or weak	F.2-88
NH_3 (kgd^{-1})	Barometric pressure (kPa)	-0.02	0.00	Slight or weak	F.2-65
NH_3 ($gd^{-1}hd^{-1}$)	Barometric pressure (kPa)	0.03	0.00	Slight or weak	F.2-66
H_2S (gd^{-1})	Barometric pressure (kPa)	0.12	0.01	Slight or weak	F.2-71
H_2S ($mgd^{-1}hd^{-1}$)	Barometric pressure (kPa)	0.12	0.01	Slight or weak	F.2-72
PM_{10} (gd^{-1})	Barometric pressure (kPa)	-0.12	0.02	Slight or weak	F.2-77
PM_{10} ($mgd^{-1}hd^{-1}$)	Barometric pressure (kPa)	0.07	0.00	Slight or weak	F.2-78
$PM_{2.5}$ (gd^{-1})	Barometric pressure (kPa)	-0.02	0.00	Slight or weak	F.2-83
$PM_{2.5}$ ($mgd^{-1}hd^{-1}$)	Barometric pressure (kPa)	0.15	0.02	Slight or weak	F.2-84
TSP (gd^{-1})	Barometric pressure (kPa)	-0.08	0.01	Slight or weak	F.2-89
TSP ($mgd^{-1}hd^{-1}$)	Barometric pressure (kPa)	0.08	0.01	Slight or weak	F.2-90

4.2 Farrowing rooms

4.2.1 Emissions Data

Appendix D, Tables D-13 and D-14 present the summary statistics for daily average emissions of NH_3 for the farrowing rooms in kg d^{-1} and g d^{-1} hd^{-1}, respectively. Across the sites, NC4B has the lowest farrowing room emissions, followed by IA4B and OK4B which is consistent with site NC4B having the lowest inventory of the sites. When emissions are on a per head basis, the daily emissions are comparable. The time series plot shown in Figure E-20 of Appendix E suggests more variation at IA4B, which is supported by IA4B having the largest standard deviation. The cyclical nature of the emissions for both the farrowing rooms and the gestation barns can be seen in the time series plot (Figures E-20 and E-21). The cycle for the farrow room is shorter than the gestation barns, suggesting that the duration is linked to the placement cycle, while gestation barns are linked to season.

The summary statistics for daily average H_2S emissions are presented in Appendix D, Tables D-15 and D-16 for g d^{-1} and mg d^{-1} hd^{-1}, respectively. Emissions ranged from 91.041 gd^{-1} at IA4B to 131.807 gd^{-1} at NC4B. This is a reversal from the NH_3 emissions rankings. Despite the lower emissions at IA4B, the time series plot (Appendix E, Figures E-21 and E-22) shows a lot of variability in the emissions at IA4B. The emissions are relatively low for most of the year with a substantial spike in emissions during the summer months. The other sites show the same emissions patter as NH_3, initially low emissions that ramp up and then drop back to a minimum value after a short period of time. As with NH_3, this short cycle is likely synchronized with animal placement and removal.

Summaries of the PM_{10} emissions are available in Tables D-17 and D-18 of Appendix D presents the summary statistics in g d^{-1} and mg d^{-1} hd^{-1}, respectively, for the daily average emissions of PM_{10} for the farrowing rooms. The emissions ranged from 27.82 gd^{-1} at NC4B to 46.214 gd^{-1} at OK4B. The time series plots (Appendix E, Figures E-21 and E-22) continue to show a cyclical pattern to emissions that corresponds to the growing cycle. Summary statistics for $PM_{2.5}$ and TSP emissions are provided in Appendix D, Tables D-19 through D-22. The time series plots of $PM_{2.5}$ emissions are in Appendix E, Figures E-26 and E-27, while Appendix E, Figures E-28 and E-29 show the time series plots for TSP. The sparse nature of $PM_{2.5}$ and TSP data makes determination of seasonal trends in the data difficult.

4.2.2 Environmental Data

Table D-23 presents the summary statistics for environmental and production parameters for the farrowing rooms. Table 4-4 provides a summary of the regression analysis for environmental parameters for farrowing rooms. The average inventory counts for the farrowing rooms were relatively similar, with all rooms ranging from 200 to 286 head. There is a lot of variability between the sites, as IA4B and NC4B have periods where the head count drops to zero. However, the inventory at site OK4B remains fairly constant (between 263 and 310), There are only 3 instances of inventory levels falling to 118, which was the minimum for the house. This difference in inventory variation is apparent from Figure E-30. This figure shows the cyclical nature of the inventory levels in the farrowing rooms, where inventory numbers quickly recede from peak values followed by an abrupt jump back to maximums. Appendix F, Figures F.3-1, F.3-2, F.3-13, F.3-14, F.3-25, F.3-26, F.3-37, F.3-38, F.3-49, and F.3-50 show the scatter plots of inventory versus each pollutant and are summarized in Table 4-4. The scatter plots generally showed only slight or weak linear relationship with emissions.

Table 4-4. Farrowing room environmental parameter regression analysis summary.

Pollutant	Parameter	R	R^2	Strength	Figure
NH_3 (kgd^{-1})	Inventory (hd)	0.36	0.13	Slight or weak	F.3-1
NH_3 ($gd^{-1}hd^{-1}$)	Inventory (hd)	-0.34	0.11	Slight or weak	F.3-2
NH_3 (kgd^{-1})	Average weight (kg)	-0.06	0.00	Slight or weak	F.3-3
NH_3 ($gd^{-1}hd^{-1}$)	Average weight (kg)	0.61	0.37	Modest	F.3-4
NH_3 (kgd^{-1})	Live animal weight (kg)	0.46	0.21	Modest	F.3-5
NH_3 ($gd^{-1}hd^{-1}$)	Live animal weight (kg)	-0.02	0.00	Slight or weak	F.3-6
NH_3 (kgd^{-1})	Exhaust temperature (°C)	-0.03	0.00	Slight or weak	F.3-7
NH_3 (kgd^{-1})	Exhaust relative humidity (%)	-0.09	0.01	Slight or weak	F.3-8

Pollutant	Parameter	R	R^2	Strength	Figure
NH_3 ($gd^{-1}hd^{-1}$)	Exhaust temperature (°C)	0.08	0.01	Slight or weak	F.3-9
NH_3 ($gd^{-1}hd^{-1}$)	Exhaust relative humidity (%)	0.00	0.00	Slight or weak	F.3-10
NH_3 (kgd^{-1})	Airflow (dsm^3s^{-1})	0.41	0.17	Slight or weak	F.3-11
NH_3 ($gd^{-1}hd^{-1}$)	Airflow (dsm^3s^{-1})	0.23	0.06	Slight or weak	F.3-12
H_2S (gd^{-1})	Inventory (hd)	-0.15	0.02	Slight or weak	F.3-13
H_2S ($mgd^{-1}hd^{-1}$)	Inventory (hd)	-0.52	0.27	Modest	F.3-14
H_2S (gd^{-1})	Average weight (kg)	0.05	0.00	Slight or weak	F.3-15
H_2S ($mgd^{-1}hd^{-1}$)	Average weight (kg)	0.62	0.38	Modest	F.3-16
H_2S (gd^{-1})	Live animal weight (kg)	-0.01	0.00	Slight or weak	F.3-17
H_2S ($mgd^{-1}hd^{-1}$)	Live animal weight (kg)	-0.28	0.08	Slight or weak	F.3-18
H_2S (gd^{-1})	Exhaust temperature (°C)	0.18	0.03	Slight or weak	F.3-19
H_2S ($mgd^{-1}hd^{-1}$)	Exhaust temperature (°C)	0.13	0.02	Slight or weak	F.3-20
H_2S (gd^{-1})	Exhaust relative humidity (%)	0.17	0.03	Slight or weak	F.3-21
H_2S ($mgd^{-1}hd^{-1}$)	Exhaust relative humidity (%)	0.10	0.01	Slight or weak	F.3-22
H_2S (gd^{-1})	Airflow (dsm^3s^{-1})	0.15	0.02	Slight or weak	F.3-23
H_2S ($mgd^{-1}hd^{-1}$)	Airflow (dsm^3s^{-1})	0.04	0.00	Slight or weak	F.3-24
PM_{10} (gd^{-1})	Inventory (hd)	0.23	0.05	Slight or weak	F.3-25
PM_{10} ($mgd^{-1}hd^{-1}$)	Inventory (hd)	-0.23	0.05	Slight or weak	F.3-26
PM_{10} (gd^{-1})	Average weight (kg)	-0.06	0.00	Slight or weak	F.3-27
PM_{10} ($mgd^{-1}hd^{-1}$)	Average weight (kg)	0.34	0.12	Slight or weak	F.3-28
PM_{10} (gd^{-1})	Live animal weight (kg)	0.31	0.10	Slight or weak	F.3-29
PM_{10} ($mgd^{-1}hd^{-1}$)	Live animal weight (kg)	0.02	0.00	Slight or weak	F.3-30
PM_{10} (gd^{-1})	Exhaust temperature (°C)	-0.11	0.01	Slight or weak	F.3-31
PM_{10} ($mgd^{-1}hd^{-1}$)	Exhaust temperature (°C)	0.04	0.00	Slight or weak	F.3-32
PM_{10} (gd^{-1})	Exhaust relative humidity (%)	-0.19	0.04	Slight or weak	F.3-33
PM_{10} ($mgd^{-1}hd^{-1}$)	Exhaust relative humidity (%)	-0.03	0.00	Slight or weak	F.3-34
PM_{10} (gd^{-1})	Airflow (dsm^3s^{-1})	0.19	0.03	Slight or weak	F.3-35
PM_{10} ($mgd^{-1}hd^{-1}$)	Airflow (dsm^3s^{-1})	0.18	0.03	Slight or weak	F.3-36
$PM_{2.5}$ (gd^{-1})	Inventory (hd)	0.22	0.05	Slight or weak	F.3-37
$PM_{2.5}$ ($mgd^{-1}hd^{-1}$)	Inventory (hd)	-0.69	0.47	Moderate	F.3-38
$PM_{2.5}$ (gd^{-1})	Average weight (kg)	-0.01	0.00	Slight or weak	F.3-39
$PM_{2.5}$ ($mgd^{-1}hd^{-1}$)	Average weight (kg)	0.91	0.83	Strong	F.3-40
$PM_{2.5}$ (gd^{-1})	Live animal weight (kg)	0.33	0.11	Slight or weak	F.3-41
$PM_{2.5}$ ($mgd^{-1}hd^{-1}$)	Live animal weight (kg)	-0.38	0.14	Slight or weak	F.3-42
$PM_{2.5}$ (gd^{-1})	Exhaust temperature (°C)	0.28	0.08	Slight or weak	F.3-43
$PM_{2.5}$ ($mgd^{-1}hd^{-1}$)	Exhaust temperature (°C)	0.17	0.03	Slight or weak	F.3-44
$PM_{2.5}$ (gd^{-1})	Exhaust relative humidity (%)	-0.19	0.03	Slight or weak	F.3-45
$PM_{2.5}$ ($mgd^{-1}hd^{-1}$)	Exhaust relative humidity (%)	0.03	0.00	Slight or weak	F.3-46
$PM_{2.5}$ (gd^{-1})	Airflow (dsm^3s^{-1})	0.51	0.26	Modest	F.3-47
$PM_{2.5}$ ($mgd^{-1}hd^{-1}$)	Airflow (dsm^3s^{-1})	0.10	0.01	Slight or weak	F.3-48
TSP (gd^{-1})	Inventory (hd)	0.13	0.02	Slight or weak	F.3-49
TSP ($mgd^{-1}hd^{-1}$)	Inventory (hd)	-0.63	0.39	Modest	F.3-50
TSP (gd^{-1})	Average weight (kg)	-0.14	0.02	Slight or weak	F.3-51
TSP ($mgd^{-1}hd^{-1}$)	Average weight (kg)	0.74	0.55	Moderate	F.3-52
TSP (gd^{-1})	Live animal weight (kg)	0.26	0.07	Slight or weak	F.3-53

Pollutant	Parameter	R	R^2	Strength	Figure
TSP ($mgd^{-1}hd^{-1}$)	Live animal weight (kg)	-0.33	0.11	Slight or weak	F.3-54
TSP (gd^{-1})	Exhaust temperature (°C)	-0.27	0.07	Slight or weak	F.3-55
TSP ($mgd^{-1}hd^{-1}$)	Exhaust temperature (°C)	0.04	0.00	Slight or weak	F.3-56
TSP (gd^{-1})	Exhaust relative humidity (%)	-0.44	0.20	Slight or weak	F.3-57
TSP ($mgd^{-1}hd^{-1}$)	Exhaust relative humidity (%)	-0.13	0.02	Slight or weak	F.3-58
TSP (gd^{-1})	Airflow (dsm^3s^{-1})	0.00	0.00	Slight or weak	F.3-59
TSP ($mgd^{-1}hd^{-1}$)	Airflow (dsm^3s^{-1})	0.13	0.02	Slight or weak	F.3-60

Animal weight between the farrowing rooms does not vary much between sites, with each farm growing pigs to approximately 25 kg. Site IA4B reported weights of 0 kg; however, these values correspond to times when the room was empty. Both IA4B and NC4B have instances of average weights above 150 kg, which likely correspond to periods where sows were housed on the farrowing rooms. Figure E-31 shows that, like the inventory levels, shows a cyclical pattern. Unlike the inventory levels, weight steadily increases as the animal age until they are removed. After which the cycle repeats, starting at the minimum weight with the younger animals. The scatter plots (Appendix F, Figures F.3-3, F.3-4, F.3-15, F.3-16, F.3-27, F.3-28, F.3-39, F.3-40, F.3-51, and F.3-52) show a modest positive relationship between weight and NH_3 and H_2S emissions and a slight to moderate relationship for all the PM size fractions.

Combining the inventory with weight to obtain a total LAW provides a better proxy for manure volume, as the animal weight and inventory determines the volume of manure generated. For the farrowing rooms, Figure E-32 shows a cyclical pattern similar to the weight trends, with LAW increasing until the room is emptied. For the gestation barns, the higher weight at IA4B leads to a higher LAW than OK4B, despite similar inventory values. The scatter plots (Appendix F, Figures F.3-5, F.3-6, F.3-17, F.3-18, F.3-29, F.3-30, F.3-41, F.3-42, F.3-53, and F.3-54) show a slight relationship between LAW and pollutant emissions.

The exhaust temperature from the site was similar to the farrowing rooms with the average temperature ranging from 24.0 °C at OK4B and 25.5 °C at NC4B. The variability in exhaust temperature is small, 1.42 °C to 2.21 °C, which is consistent with the fact that warm temperature is best for piglets, as they are more susceptible to temperature changes, with severe swings in temperature contributing to higher mortality rates. Despite this, Figure E-33 does show a seasonal trend in exhaust temperatures, with peaks in summer and lows in winter. IA4B does have a slightly larger range than the other two sites, due to less temperature regulation during times when the room was empty. Average exhaust temperatures in the gestation barns was more variable across sites, with a minimum of 17.2 °C at IA4B (Barn 1) up to a maximum of 24.6 °C at NC4B (Barn 2). The exhaust temperature variation within barns is also more variable, with standard deviations ranging from 2.10 °C at NC4B (Barn 2) to 5.24 °C at IA4B (Barn 2). This results in a broader temperature range for sows, which is consistent with the fact that they are not as susceptible to cold as the piglets.

A review of the summary statistics for exhaust relative humidity show comparable values, with average values ranging from 53.117% at OK4BF to 59.892% at NC4BF. The time series (Appendix E, Figure E-34) suggests some seasonality to the data, with lower values occurring in the winter that increase to peaks in the summer. When regressed with the emissions (Appendix F, Figures F.3-9, F.3-10, F.3-21, F.3-22, F.3-33, F.3-34, F.3-45, F.3-46, F.3-57, and F.3-58), there are only slight or weak relationships for gaseous and particulate pollutants.

The farrowing rooms had a lower airflow rates than the gestation barns, but had similar seasonal pattern of peaks in summer and lows in winter (Figure E-35). The seasonal pattern reiterates the efforts to maintain a consistent temperature within the barns with the ventilation schemes. The regression analyses (Appendix F, Figures F.3-11, F.3-12, F.3-23, F.3-24, F.3-35, F.3-36, F.3-47, F.3-48, F.3-59, and F.3-60) showed slight to weak relationships with gaseous and particulate emissions.

4.2.3 Ambient Data

The statistical summary of the ambient parameters associated with farrowing rooms barns are presented in Table D-24 of Appendix D. Table 4-5 provides a summary of the regression analysis for environmental parameters for farrowing rooms. The range of ambient temperature and the variation shown in Figure E-36 of Appendix E is indicative of their varying geographic locations. The average daily temperatures were coolest at IA4B where the average was 8.391 °C, compared to 19.469 °C at NC4B. The coastal North Carolina farm was not subject to temperatures lower than 0 °C for the entire study period, unlike the IA4B and OK4B. The time series plot in Figure E-36 of Appendix E shows the typical seasonal pattern to temperatures (i.e., maximum in summer and minimum in winter).

Table 4-5. Farrowing room ambient parameter regression analysis summary.

Pollutant	Parameter	R	R^2	Strength	Figure
NH_3 (kgd^{-1})	Ambient temperature (°C)	0.18	0.03	slight or weak	F.3-61
NH_3 ($gd^{-1}hd^{-1}$)	Ambient temperature (°C)	0.17	0.03	slight or weak	F.3-62
NH_3 (kgd^{-1})	Ambient relative humidity (%)	-0.42	0.18	slight or weak	F.3-63
NH_3 ($gd^{-1}hd^{-1}$)	Ambient relative humidity (%)	-0.18	0.03	slight or weak	F.3-64
NH_3 (kgd^{-1})	Barometric pressure (kPa)	-0.69	0.48	moderate	F.3-65
NH_3 ($gd^{-1}hd^{-1}$)	Barometric pressure (kPa)	-0.25	0.06	slight or weak	F.3-66
H_2S (gd^{-1})	Ambient temperature (°C)	0.23	0.05	slight or weak	F.3-67
H_2S ($mgd^{-1}hd^{-1}$)	Ambient temperature (°C)	0.13	0.02	Slight or weak	F.3-68
H_2S (gd^{-1})	Ambient relative humidity (%)	0.02	0	Slight or weak	F.3-69
H_2S ($mgd^{-1}hd^{-1}$)	Ambient relative humidity (%)	0.04	0	Slight or weak	F.3-70
H_2S (gd^{-1})	Barometric pressure (kPa)	0.08	0.01	Slight or weak	F.3-71

Pollutant	Parameter	R	R^2	Strength	Figure
H_2S ($mgd^{-1}hd^{-1}$)	Barometric pressure (kPa)	0.16	0.02	Slight or weak	F.3-72
PM_{10} (gd^{-1})	Ambient temperature (°C)	0.04	0	Slight or weak	F.3-73
PM_{10} ($mgd^{-1}hd^{-1}$)	Ambient temperature (°C)	0.15	0.02	Slight or weak	F.3-74
PM_{10} (gd^{-1})	Ambient relative humidity (%)	-0.24	0.06	Slight or weak	F.3-75
PM_{10} ($mgd^{-1}hd^{-1}$)	Ambient relative humidity (%)	-0.12	0.01	Slight or weak	F.3-76
PM_{10} (gd^{-1})	Barometric pressure (kPa)	-0.37	0.13	Slight or weak	F.3-77
PM_{10} ($mgd^{-1}hd^{-1}$)	Barometric pressure (kPa)	-0.13	0.02	Slight or weak	F.3-78
$PM_{2.5}$ (gd^{-1})	Ambient temperature (°C)	0.02	0	Slight or weak	F.3-79
$PM_{2.5}$ ($mgd^{-1}hd^{-1}$)	Ambient temperature (°C)	0.19	0.04	Slight or weak	F.3-80
$PM_{2.5}$ (gd^{-1})	Ambient relative humidity (%)	-0.11	0.01	Slight or weak	F.3-81
$PM_{2.5}$ ($mgd^{-1}hd^{-1}$)	Ambient relative humidity (%)	-0.04	0	Slight or weak	F.3-82
$PM_{2.5}$ (gd^{-1})	Barometric pressure (kPa)	-0.41	0.17	Slight or weak	F.3-83
$PM_{2.5}$ ($mgd^{-1}hd^{-1}$)	Barometric pressure (kPa)	0.12	0.02	Slight or weak	F.3-84
TSP (gd^{-1})	Ambient temperature (°C)	-0.12	0.02	Slight or weak	F.3-85
TSP ($mgd^{-1}hd^{-1}$)	Ambient temperature (°C)	0.1	0.01	Slight or weak	F.3-86
TSP (gd^{-1})	Ambient relative humidity (%)	-0.44	0.19	Slight or weak	F.3-87
TSP ($mgd^{-1}hd^{-1}$)	Ambient relative humidity (%)	-0.19	0.04	Slight or weak	F.3-88
TSP (gd^{-1})	Barometric pressure (kPa)	-0.33	0.11	Slight or weak	F.3-89
TSP ($mgd^{-1}hd^{-1}$)	Barometric pressure (kPa)	0.09	0.01	Slight or weak	F.3-90
NH_3 (kgd^{-1})	Ambient temperature (°C)	0.18	0.03	Slight or weak	F.3-61

The scatter plots of ambient temperature (Appendix F, Figures F.3-61, F.3-62, F.3-67, F.3-68, F.3-73, F.3-74, F.3-79, F.3-80, F.3-85, and F.3-86) show slight or weak relationships with emissions. As with the exhaust parameters, the weak relationships between temperature and emissions in the farrowing rooms seem to be the result of a non-linear relationship between NH_3 emissions and ambient temperature, particularly at OK4B. IA4B and NC4B both have positive linear relationships, but upon closer inspection, could be better fit with a curvilinear function. PM_{10} and TSP show similar relationships with temperature. As stated in the Overview Report, based on SAB comments, the EPA was not looking at fitting nonlinear forms at this time. This analysis sufficiently indicates a relationship between temperature and NH_3 emissions.

Ambient relative humidity is similar between sites, ranging from an average value of 50.852% at OK4B to 71.662% at IA4B. The time series (Appendix E, Figure E-37) shows the values vary by at least 20% for any given time of the year, with no particular seasonal pattern. The regression analyses (Appendix F, Figures F.3-63, F.3-64, F.3-69, F.3-70, F.3-75, F.3-76, F.3-81, F.3-82, F.3-87, and F.3-88) indicate slight or weak relationships between ambient relative humidity and emissions.

4.3 Grow-Finish Barns

4.3.1 Emissions Data

Appendix D, Tables D-25 and D-26 present the summary statistics for daily average emissions of NH_3 for the grow-finish barns in kg d^{-1} and g d^{-1} hd^{-1}, respectively. As shown in the tables, site IN3B had slightly higher NH_3 values than the NC3B site, which is likely due to the larger capacity of the Indiana barns. Both of the sites had a cyclical pattern to the emissions that is apparent in the time series plots (Figures E-39 and 40). This pattern of increasing emissions is likely related to the growing cycle within the barns. The figures also show a steady decrease in peak emissions from NC3B, as each iteration of the cycle produces lower emissions. IN3B had a more consistent cycle of NH_3 emissions over the course of the monitoring period.

The summary statistics for daily average H_2S emissions are presented in Tables D-27 and D-28 in Appendix D for g d^{-1} and mg d^{-1} hd^{-1}, respectively. Site IN3B had higher H_2S emissions than site NC3B. While the difference is more extreme than with NH_3, this difference is likely due to the difference in animal inventory between the sites. Additionally, the barns at NC3B each had several negative H_2S emissions values, which drove down the overall average. There is also more variation in emissions between the barns at each site. This is particularly noticeable at IN3B, where Rooms 5 and 7 have an average daily emissions value that is nearly half of Rooms 6 or 8. Figures E-41 and E-42 show an extreme value in the H_2S emissions at IN3B room 6.

Tables D-29 and D-30 of Appendix D present the summary statistics in g d^{-1} and mg d^{-1} hd^{-1}, respectively, for the daily average emissions of PM_{10} for the farrowing rooms. As shown in the tables, the daily average PM emissions values for the growing finishing sites and their houses were variable. Rooms 5 and 6 at site IN3B have higher emissions values than the other two houses for PM_{10} and $PM_{2.5}$. This trend does not hold for TSP, where Rooms 6 and 8 have the highest emissions. Site IN3B also had a substantial number of negative average daily emissions values for both PM_{10} and $PM_{2.5}$. The dataset for Room 7 at site IN3B contained 12 negative $PM_{2.5}$ values, with the most negative value being -166 g d^{-1}, which contributed to an overall negative $PM_{2.5}$ emissions value for the site. The time series plots of PM_{10} (Figures E-43 and E-44) show the same cyclical nature of the emissions that were observed with NH_3 and H_2S. The plots for $PM_{2.5}$ (Figures E-45 and E-46) and TSP (Figures E-47 and E-48) do not clearly show the same trends, largely because of the shorter sampling periods.

4.3.2 Environmental Data

The length of the grow-finish cycle depends on the finished weight specified by the processor. Extremely hot or cold weather can reduce the rate of weight gain of the pigs and lengthen the grow-finish period. The duration of the clean-out period between groups of feeder pigs may be only a few days or several weeks depending on market conditions. A typical range for a grow-finish operation is 2.4 to 3.4 turnovers per year. Turnovers affect the amount of manure generation. A grow-finish operation with a confinement capacity of 1,000 pigs and 2.4 turnovers per year will produce approximately 2,400 pigs for slaughter per year whereas the same operation with 3.4 turnovers per year will produce 3,400 pigs per year. Assuming the same initial and final weights and the same rate of weight gain, this difference translates into one third more manure production per year.

Table D-35 of Appendix D presents the summary statistics for environmental parameters for the finishing farms. Table 4-6 provides a summary of the regression analysis for environmental parameters for grow-finish barns. The houses at IN3B had a highest inventory and LAW than the houses at NC3B. The animal weights at the NC3B houses were slightly higher than the IN3B houses, with mean house values ranging from 63.02 kg at IN3B (Room 7) to 75.15 kg at NC3B (Barn 2). The time series shown in Figure E-49 of Appendix E shows inventory levels at barn at the same site are generally synchronized, with similar trends in animal additions and removals. Appendix F, Figures F.4-1, F.4-2, F.4-13, F.4-14, F.4-25, F.4-26, F.4-37, F.4-38, F.4-49, and F.4-50 show the scatter plots of inventory versus each pollutant. The scatter plots generally showed only slight or weak linear relationship with emissions.

Table 4-6. Grow-finish barns R^2 values for environmental parameters.

Pollutant	Parameter	R	R^2	Strength	Figure
NH_3 (kgd^{-1})	Inventory (hd)	0.23	0.05	Slight or weak	F.4-1
NH_3 ($gd^{-1}hd^{-1}$)	Inventory (hd)	-0.42	0.17	Slight or weak	F.4-2
NH_3 (kgd^{-1})	Average weight (kg)	0.52	0.27	Modest	F.4-3
NH_3 ($gd^{-1}hd^{-1}$)	Average weight (kg)	0.56	0.31	Modest	F.4-4
NH_3 (kgd^{-1})	Live animal weight (kg)	0.70	0.48	Moderate	F.4-5
NH_3 ($gd^{-1}hd^{-1}$)	Live animal weight (kg)	0.22	0.05	Slight or weak	F.4-6
NH_3 (kgd^{-1})	Exhaust temperature (°C)	0.18	0.03	Slight or weak	F.4-7
NH_3 (kgd^{-1})	Exhaust relative humidity (%)	-0.09	0.01	Slight or weak	F.4-8
NH_3 ($gd^{-1}hd^{-1}$)	Exhaust temperature (°C)	-0.03	0.00	Slight or weak	F.4-9
NH_3 ($gd^{-1}hd^{-1}$)	Exhaust relative humidity (%)	0.07	0.00	Slight or weak	F.4-10
NH_3 (kgd^{-1})	Airflow (dsm^3s^{-1})	0.42	0.17	Slight or weak	F.4-11
NH_3 ($gd^{-1}hd^{-1}$)	Airflow (dsm^3s^{-1})	0.20	0.04	Slight or weak	F.4-12
H_2S (gd^{-1})	Inventory (hd)	0.11	0.01	Slight or weak	F.4-13
H_2S ($mgd^{-1}hd^{-1}$)	Inventory (hd)	-0.21	0.04	Slight or weak	F.4-14
H_2S (gd^{-1})	Average weight (kg)	0.29	0.09	Slight or weak	F.4-15
H_2S ($mgd^{-1}hd^{-1}$)	Average weight (kg)	0.33	0.11	Slight or weak	F.4-16
H_2S (gd^{-1})	Live animal weight (kg)	0.37	0.13	Slight or weak	F.4-17
H_2S ($mgd^{-1}hd^{-1}$)	Live animal weight (kg)	0.12	0.01	Slight or weak	F.4-18
H_2S (gd^{-1})	Exhaust temperature (°C)	0.02	0.00	Slight or weak	F.4-19
H_2S ($mgd^{-1}hd^{-1}$)	Exhaust temperature (°C)	-0.09	0.01	Slight or weak	F.4-20
H_2S (gd^{-1})	Exhaust relative humidity (%)	-0.12	0.01	Slight or weak	F.4-21
H_2S ($mgd^{-1}hd^{-1}$)	Exhaust relative humidity (%)	-0.01	0.00	Slight or weak	F.4-22

Pollutant	Parameter	R	R^2	Strength	Figure
H_2S (gd^{-1})	Airflow (dsm^3s^{-1})	0.19	0.03	Slight or weak	F.4-23
H_2S ($mgd^{-1}hd^{-1}$)	Airflow (dsm^3s^{-1})	0.12	0.02	Slight or weak	F.4-24
PM_{10} (gd^{-1})	Inventory (hd)	0.17	0.03	Slight or weak	F.4-25
PM_{10} ($mgd^{-1}hd^{-1}$)	Inventory (hd)	-0.34	0.12	Slight or weak	F.4-26
PM_{10} (gd^{-1})	Average weight (kg)	0.44	0.20	Slight or weak	F.4-27
PM_{10} ($mgd^{-1}hd^{-1}$)	Average weight (kg)	0.49	0.24	Modest	F.4-28
PM_{10} (gd^{-1})	Live animal weight (kg)	0.55	0.30	Modest	F.4-29
PM_{10} ($mgd^{-1}hd^{-1}$)	Live animal weight (kg)	0.22	0.05	Slight or weak	F.4-30
PM_{10} (gd^{-1})	Exhaust temperature (°C)	0.11	0.01	Slight or weak	F.4-31
PM_{10} ($mgd^{-1}hd^{-1}$)	Exhaust temperature (°C)	0.02	0.00	Slight or weak	F.4-32
PM_{10} (gd^{-1})	Exhaust relative humidity (%)	-0.30	0.09	Slight or weak	F.4-33
PM_{10} ($mgd^{-1}hd^{-1}$)	Exhaust relative humidity (%)	-0.09	0.01	Slight or weak	F.4-34
PM_{10} (gd^{-1})	Airflow (dsm^3s^{-1})	0.34	0.12	Slight or weak	F.4-35
PM_{10} ($mgd^{-1}hd^{-1}$)	Airflow (dsm^3s^{-1})	0.23	0.05	Slight or weak	F.4-36
$PM_{2.5}$ (gd^{-1})	Inventory (hd)	-0.15	0.02	Slight or weak	F.4-37
$PM_{2.5}$ ($mgd^{-1}hd^{-1}$)	Inventory (hd)	-0.39	0.15	Slight or weak	F.4-38
$PM_{2.5}$ (gd^{-1})	Average weight (kg)	0.57	0.32	Modest	F.4-39
$PM_{2.5}$ ($mgd^{-1}hd^{-1}$)	Average weight (kg)	0.60	0.37	Modest	F.4-40
$PM_{2.5}$ (gd^{-1})	Live animal weight (kg)	0.55	0.30	Modest	F.4-41
$PM_{2.5}$ ($mgd^{-1}hd^{-1}$)	Live animal weight (kg)	0.40	0.16	Slight or weak	F.4-42
$PM_{2.5}$ (gd^{-1})	Exhaust temperature (°C)	0.03	0.00	Slight or weak	F.4-43
$PM_{2.5}$ ($mgd^{-1}hd^{-1}$)	Exhaust temperature (°C)	-0.04	0.00	Slight or weak	F.4-44
$PM_{2.5}$ (gd^{-1})	Exhaust relative humidity (%)	0.12	0.01	Slight or weak	F.4-45
$PM_{2.5}$ ($mgd^{-1}hd^{-1}$)	Exhaust relative humidity (%)	0.13	0.02	Slight or weak	F.4-46
$PM_{2.5}$ (gd^{-1})	Airflow (dsm^3s^{-1})	0.45	0.20	Modest	F.4-47
$PM_{2.5}$ ($mgd^{-1}hd^{-1}$)	Airflow (dsm^3s^{-1})	0.44	0.20	Slight or weak	F.4-48
TSP (gd^{-1})	Inventory (hd)	0.68	0.46	Moderate	F.4-49
TSP ($mgd^{-1}hd^{-1}$)	Inventory (hd)	0.25	0.06	Slight or weak	F.4-50
TSP (gd^{-1})	Average weight (kg)	0.00	0.00	Slight or weak	F.4-51
TSP ($mgd^{-1}hd^{-1}$)	Average weight (kg)	0.27	0.07	Slight or weak	F.4-52
TSP (gd^{-1})	Live animal weight (kg)	0.43	0.18	Slight or weak	F.4-53
TSP ($mgd^{-1}hd^{-1}$)	Live animal weight (kg)	0.37	0.14	Slight or weak	F.4-54
TSP (gd^{-1})	Exhaust temperature (°C)	-0.12	0.01	Slight or weak	F.4-55
TSP ($mgd^{-1}hd^{-1}$)	Exhaust temperature (°C)	-0.03	0.00	Slight or weak	F.4-56
TSP (gd^{-1})	Exhaust relative humidity (%)	-0.62	0.39	Modest	F.4-57
TSP ($mgd^{-1}hd^{-1}$)	Exhaust relative humidity (%)	-0.52	0.27	Modest	F.4-58
TSP (gd^{-1})	Airflow (dsm^3s^{-1})	0.22	0.05	Slight or weak	F.4-59
TSP ($mgd^{-1}hd^{-1}$)	Airflow (dsm^3s^{-1})	0.26	0.07	Slight or weak	F.4-60

The inventory trends differed between the two sites, which is likely due to differences in the barn design and management practices. Site IN3B was a quad barn, where the building was split into four rooms. The standard practice was to initially load two rooms (i.e., Rooms 5 and 6) with all the weaner pigs, keeping Rooms 7 and 8 empty. After 3 or 4 weeks, the pigs were then redistributed evenly across the rooms. The creates the stepped pattern to the IN3B inventory plots (Figure E-49), where the inventory falls to approximately half in Rooms 5 and 6 after a short period of time. After the initial 3 to 4 weeks, the trends between the farms are similar: slight decrease in animal number for the bulk of the cycle as there is irregular loss of pigs, followed by a more rapid decrease in inventory as the pigs complete the growth cycle and are shipped for processing. Site NC3B displayed a more “typical” pattern, where inventory level decrease slightly with pig mortalities from an initial maximum placement. Near the end of the growth cycle, the inventory decreases more rapidly as the finished pigs are shipped, as seen in Figure E-49, in the halving of the population near the end of the cycle. Both houses are run in sync for efficiency.

The trends in weight gain between the farms shown in Figure E-50 are similar with a steady increase in weight from the initial placement (values of 0 kg in Figure E-50 note when the house or room was empty). Site NC3B begins with a slightly larger piglet and raises the pigs to a slightly higher finishing weight. The time series also shows gaps in weight data for time the house was empty while emissions measurements were taken. Appendix F, Figures F.4-3, F.4-4, F.4-15, F.4-16, F.4-27, F.4-28, F.4-39, F.4-40, F.4-51, and F.4-52 show the scatter plots of animal weight versus each pollutant. The scatter plots generally showed slight or weak linear relationship with emissions.

The trends in LAW (Figure E-51) reiterate the difference in loading practice at site IN3B, as there is more of a stair step to the curve for each cycle. Again, IN3B had a slightly higher inventory at IN3B, resulting in a higher LAW than NC3B. As expected, NC4B had the lowest weight, inventory, and LAW. Appendix F, Figures F.4-5, F.4-6, F.4-17, F.4-18, F.4-29, F.4-30, F.4-41, F.4-42, F.4-53, and F.4-54 show the plots of LAW versus each pollutant. The scatter plots generally showed slight or weak linear relationship with emissions.

Average exhaust temperatures were comparable across all the sites, ranging from an average of 20.505 °C at IN3B-R7 to 24.273 °C at NC3B-B3. The time series (Appendix E, Figure E-52) show the expected seasonal trend of peak exhaust temperatures in the summer decreasing to a minimum in the winter, and increasing again in the spring. The linear regression analysis (Appendix F, Figures F.4-7, F.4-8, F.4-19, F.4-20, F.4-31, F.4-32, F.4-43, F.4-44, F.4-55, and F.4-56) show slight-to-weak relationships with emissions.

A review of the summary statistics for exhaust relative humidity show comparable values, with average values ranging from 56.070% at IN3B-R8 to 63.275% at NC3B-B3. The time series (Appendix E, Figure E-53) show the exhaust relative humidity values are fairly variable, as there is a spread in the data for any time of the year. The plots also suggest some seasonality to the data, with lower values occurring in the winter that increase to peaks in the summer. When regressed with the emissions (Appendix F, Figures F.4-9, F.4-10, F.4-21, F.4-22, F.4-33, F.4-34, F.4-45, F.4-46, F.4-57, and F.4-58), there are only slight or weak relationships for gaseous pollutants, PM_{10}, and $PM_{2.5}$. TSP daily emissions have a modest negative relationship with exhaust relative humidity.

Average ventilation rates ranged from 10.076 dsm^3/s at NC3B-B3 to 15.282 m^3/s at IN3B-R7 and the daily ventilation rates displayed seasonal patterns with peaks in summer and lows in winter (Figure E-54). The regression analyses (Appendix F, Figures F.4-11, F.4-12, F.4-23, F.4-24, F.4-35, F.4-36, F.4-47, F.4-48, F.4-59, and F.4-60) showed mostly slight to weak relationships with gaseous and particulate emissions.

4.3.3 Ambient Data

Appendix D, Table D-36 present the summary statistics for daily average ambient parameters for the grow-finish barns. Table 4-7 provides a summary of the regression analysis for ambient parameters for grow-finish barns. The range of ambient temperatures and the variation shown in Figure E-55 of Appendix E is indicative of their varying geographic locations. The warmest ambient temperatures were at NC3B, with IN3B having the largest variance in ambient temperatures. The ambient temperatures at IN3B fell below 0 °C for extended periods of time for both winters of the monitoring period, while the ambient temperature at site NC3B was below 0 °C for only a few days. The exhaust temperatures followed a similar trend as ambient temperatures, with the peaks during the summer and lower values in the winter. The scatter plots of ambient temperature (Appendix F, Figures F.4-61, F.4-62, F.4-67, F.4-68, F.4-73, F.4-74, F.4-79, F.4-80, F.4-85, and F.4-86) show mostly slight or weak relationships with emissions.

Table 4-7. Summary of swine grow-finish barns R^2 values for ambient parameters.

Pollutant	Parameter	R	R^2	Strength	Figure
NH_3 (kgd^{-1})	Ambient temperature (°C)	-0.03	0.00	Slight or weak	F.4-61
NH_3 ($gd^{-1}hd^{-1}$)	Ambient temperature (°C)	0.00	0.00	Slight or weak	F.4-62
NH_3 (kgd^{-1})	Ambient relative humidity (%)	0.05	0.00	Slight or weak	F.4-63
NH_3 ($gd^{-1}hd^{-1}$)	Ambient relative humidity (%)	0.14	0.02	Slight or weak	F.4-64
NH_3 (kgd^{-1})	Barometric pressure (kPa)	-0.38	0.14	Slight or weak	F.4-65
NH_3 ($gd^{-1}hd^{-1}$)	Barometric pressure (kPa)	-0.08	0.01	Slight or weak	F.4-66
H_2S (gd^{-1})	Ambient temperature (°C)	-0.13	0.02	Slight or weak	F.4-67
H_2S ($mgd^{-1}hd^{-1}$)	Ambient temperature (°C)	-0.09	0.01	Slight or weak	F.4-68
H_2S (gd^{-1})	Ambient relative humidity (%)	0.09	0.01	Slight or weak	F.4-69
H_2S ($mgd^{-1}hd^{-1}$)	Ambient relative humidity (%)	0.11	0.01	Slight or weak	F.4-70
H_2S (gd^{-1})	Barometric pressure (kPa)	-0.35	0.12	Slight or weak	F.4-71
H_2S ($mgd^{-1}hd^{-1}$)	Barometric pressure (kPa)	-0.23	0.06	Slight or weak	F.4-72
PM_{10} (gd^{-1})	Ambient temperature (°C)	0.07	0.01	Slight or weak	F.4-73
PM_{10} ($mgd^{-1}hd^{-1}$)	Ambient temperature (°C)	0.14	0.02	Slight or weak	F.4-74

Pollutant	Parameter	R	R^2	Strength	Figure
PM_{10} (gd^{-1})	Ambient relative humidity (%)	-0.26	0.07	Slight or weak	F.4-75
PM_{10} ($mgd^{-1}hd^{-1}$)	Ambient relative humidity (%)	-0.11	0.01	Slight or weak	F.4-76
PM_{10} (gd^{-1})	Barometric pressure (kPa)	-0.12	0.01	Slight or weak	F.4-77
PM_{10} ($mgd^{-1}hd^{-1}$)	Barometric pressure (kPa)	0.05	0.00	Slight or weak	F.4-78
$PM_{2.5}$ (gd^{-1})	Ambient temperature (°C)	0.11	0.01	Slight or weak	F.4-79
$PM_{2.5}$ ($mgd^{-1}hd^{-1}$)	Ambient temperature (°C)	0.15	0.02	Slight or weak	F.4-80
$PM_{2.5}$ (gd^{-1})	Ambient relative humidity (%)	-0.09	0.01	Slight or weak	F.4-81
$PM_{2.5}$ ($mgd^{-1}hd^{-1}$)	Ambient relative humidity (%)	-0.02	0.00	Slight or weak	F.4-82
$PM_{2.5}$ (gd^{-1})	Barometric pressure (kPa)	0.34	0.12	Slight or weak	F.4-83
$PM_{2.5}$ ($mgd^{-1}hd^{-1}$)	Barometric pressure (kPa)	0.33	0.11	Slight or weak	F.4-84
TSP (gd^{-1})	Ambient temperature (°C)	-0.15	0.02	Slight or weak	F.4-85
TSP ($mgd^{-1}hd^{-1}$)	Ambient temperature (°C)	0.02	0.00	Slight or weak	F.4-86
TSP (gd^{-1})	Ambient relative humidity (%)	-0.34	0.12	Slight or weak	F.4-87
TSP ($mgd^{-1}hd^{-1}$)	Ambient relative humidity (%)	-0.31	0.10	Slight or weak	F.4-88
TSP (gd^{-1})	Barometric pressure (kPa)	-0.60	0.36	Modest	F.4-89
TSP ($mgd^{-1}hd^{-1}$)	Barometric pressure (kPa)	-0.23	0.05	Slight or weak	F.4-90

Ambient relative humidity is similar between sites, ranging from an average value of 67.741% at IN3B to 70.053 at NC3B. The time series plot (Appendix E, Figure E-56) shows the values vary by at least 20% for any given time of the year, with no particular seasonal pattern. The regression analyses (Appendix F, Figures F.4-63, F.4-64, F.4-69, F.4-70, F.4-75, F.4-76, F.4-81, F.4-82, F.4-87, and F.4-88) indicate mostly slight or weak relationships between ambient relative humidity and emissions.

4.4 Lagoons

4.4.1 Emissions Data

Lagoons at swine AFOs are not sources of PM emissions. Tables D-37 and D-38 in Appendix D present the summary statistics for daily average emissions of NH_3 for the lagoons in kg d^{-1} and in kilograms per day per square meter of surface area (kg d^{-1} m^{-2}), respectively.

For the lagoon sites, the NH_3 emissions varied greatly across the sites. Site OK4A stands out with an ADM that is approximately two times higher than the next highest site, NC4A. Figures E-58 and E-59 reiterate that OK4A is consistently higher than all the other sites. Given that there is another open source monitoring site in Oklahoma, it is unlikely that the emissions difference is due to a meteorological factor such as temperature or winds speed. Reviewing the other differences between sites, differences in the LAW stand out as the likely driver in the emissions differences. Emissions are tied directly to the amount of manure generated, and OK4A, having the largest LAW of all the sites, had the highest emissions. This trend generally holds for all the sites, with the exception being OK3A. This site has the lowest LAW, but the third highest emissions. There is a lot of variability in emissions, as indicated by the high standard deviations at each site. The emissions from the IN4A site were invalidated due to moisture interference with the data collection method.

Tables D-39 and D-40 in Appendix D present the summary statistics for daily average emissions of H_2S for the lagoons in g d^{-1} and g d^{-1} m^{-2}, respectively. Similar to the trends seen in NH_3, there is a lot of variation in H_2S emissions across the sites, likely due to the varying number of animals contributing to lagoon loading (Figures E-60 and E-61). Again, the largest emissions are typically with the farms with more animals.

4.4.2 Environmental Data

Table D-41 in Appendix D presents the summary statistics of the environmental parameters measured for swine lagoons. Table 4-8 provides a summary of the regression analysis for environmental parameters for lagoons. Data for the lagoon liquid pH, temperature, and oxidation-reduction potential (ORP) were collected continuously via probes set at a 0.3 meter depth in the lagoon. For the continuous samples, the average lagoon temperature was highest at IN4A (20.573 °C) and NC4A (20.883 °C), with the average lagoon temperatures below 20 °C for the remaining sites. The time series shown in Figure E-62 of Appendix E indicate a seasonal pattern to lagoon liquid temperatures, with higher temperatures occurring during the warmer months of the year. The scatter plots of lagoon liquid temperature (Appendix F, Figures F.5-1, F.5-2, F.5-7, and F.5-8) show modest relationships to NH_3 emissions and slight or weak relationships to H_2S emissions.

Table 4-8. Summary of swine lagoons R^2 values for environmental parameters.

Pollutant	Parameter	R	R^2	Strength	Figure
NH_3 (kgd^{-1})	Lagoon temperature (°C)	0.57	0.32	Modest	F.5-1
NH_3 ($kgd^{-1}m^{-2}$)	Lagoon temperature (°C)	0.64	0.41	Moderate	F.5-2
NH_3 (kgd^{-1})	Oxidation reduction potential (mV)	-0.33	0.11	Slight or weak	F.5-3
NH_3 ($kgd^{-1}m^{-2}$)	Oxidation reduction potential (mV)	-0.29	0.08	Slight or weak	F.5-4
NH_3 (kgd^{-1})	pH	-0.14	0.02	Slight or weak	F.5-5
NH_3 ($kgd^{-1}m^{-2}$)	pH	-0.15	0.02	Slight or weak	F.5-6
H_2S (gd^{-1})	Lagoon temperature (°C)	-0.03	0.00	Slight or weak	F.5-7
H_2S ($gd^{-1}m^{-2}$)	Lagoon temperature (°C)	-0.02	0.00	Slight or weak	F.5-8
H_2S (gd^{-1})	Oxidation reduction potential (mV)	0.08	0.01	Slight or weak	F.5-9
H_2S ($gd^{-1}m^{-2}$)	Oxidation reduction potential (mV)	0.02	0.00	Slight or weak	F.5-10
H_2S (gd^{-1})	pH	-0.17	0.03	Slight or weak	F.5-11
H_2S ($gd^{-1}m^{-2}$)	pH	-0.20	0.04	Slight or weak	F.5-12

The ORP provides an indication of how much oxygen is available in the water. Higher ORP values can indicate the potential for the lagoon to emit less H_2S and NH_3 emissions, as the available oxygen can convert nitrogen and sulfur containing compounds into more soluble compounds by oxidation. Of the NAEMS sites, IN4A has the highest ORP (-204.810) with all other sites falling between -468.808 and -490.490. IN4A is the only deep pit system, which might be the cause of the difference in ORP. The time series plots shown in Figure E-63 of Appendix E do not indicate a seasonal pattern to lagoon liquid ORP. The scatter plots of lagoon liquid ORP (Appendix F, Figures F.5-3, F.5-4, F.5-9, and F.5-10) show slight or weak relationships to NH_3 and H_2S emissions.

The pH readings were comparable across the sites with the highest reading at IN4A (7.898), followed by OK4A (7.892), OK3A (7.845), NC3A (7.75), NC4A (7.769), and NC4A (7.737). The time series plots shown in Figure E-64 of Appendix E do not indicate a seasonal pattern to lagoon liquid pH. The scatter plots of lagoon liquid pH (Appendix F, Figures F.5-5, F.5-6, F.5-11, and F.5-12) show slight or weak relationships to NH_3 and H_2S emissions.

4.4.3 Ambient Data

Table D-42 in Appendix D presents the summary statistics for daily average ambient data for lagoons. Table 4-9 provides a summary of the regression analysis for ambient parameters for lagoons. Average ambient temperatures were similar across the lagoon sites with site NC4A having the warmest ambient temperatures and sites OK3A and OK4A having the largest variance in ambient temperature. All sites, except NC3A, recorded temperatures below 0 °C during the study period. Site OK4A had the lowest reading at -9.9 °C, as well as the highest reading at 31.15 °C. While Figure E-65 demonstrates the intermittent nature of the measurements at the open source sites, the figure still shows a seasonal trend in the temperatures. The scatter plots of ambient temperature (Appendix F, Figures F.5-12, F.5-13, F.5-20, and F.5-21) show moderate relationships to NH_3 and slight or weak relationships to H_2S emissions.

Table 4-9. Summary of swine lagoons R^2 values for ambient parameters.

Pollutant	Parameter	R	R^2	Strength	Figure
NH_3 (kgd^{-1})	Air temperature (°C)	0.64	0.41	Moderate	F.5-13
NH_3 ($kgd^{-1}m^{-2}$)	Air temperature (°C)	0.71	0.51	Moderate	F.5-14
NH_3 (kgd^{-1})	Relative humidity (%)	-0.16	0.03	Slight or weak	F.5-15
NH_3 ($kgd^{-1}m^{-2}$)	Relative humidity (%)	-0.19	0.04	Slight or weak	F.5-16
NH_3 (kgd^{-1})	Barometric pressure (kPa)	-0.33	0.11	Slight or weak	F.5-17
NH_3 ($kgd^{-1}m^{-2}$)	Barometric pressure (kPa)	-0.42	0.17	Slight or weak	F.5-18
NH_3 (kgd^{-1})	Wind speed (ms^{-1})	0.26	0.07	Slight or weak	F.5-19
NH_3 ($kgd^{-1}m^{-2}$)	Wind speed (ms^{-1})	0.27	0.07	Slight or weak	F.5-20
H_2S (gd^{-1})	Air temperature (°C)	0.00	0.00	Slight or weak	F.5-21
H_2S ($gd^{-1}m^{-2}$)	Air temperature (°C)	0.02	0.00	Slight or weak	F.5-22

Pollutant	Parameter	R	R^2	Strength	Figure
H_2S (gd^{-1})	Relative humidity (%)	-0.17	0.03	Slight or weak	F.5-23
H_2S ($gd^{-1}m^{-2}$)	Relative humidity (%)	-0.21	0.05	Slight or weak	F.5-24
H_2S (gd^{-1})	Barometric pressure (kPa)	-0.19	0.04	Slight or weak	F.5-25
H_2S ($gd^{-1}m^{-2}$)	Barometric pressure (kPa)	-0.28	0.08	Slight or weak	F.5-26
H_2S (gd^{-1})	Wind speed (ms^{-1})	0.24	0.06	Slight or weak	F.5-27
H_2S ($gd^{-1}m^{-2}$)	Wind speed (ms^{-1})	0.32	0.10	Slight or weak	F.5-28

Comparing the relative humidity (Figure E-66) across sites, the Oklahoma sites stand out as lower than the Indiana and North Carolina sites. Relative humidity values were quite variable across the year. The scatter plots of relative humidity (Appendix F, Figures F.5-14, F.5-15, F.5-22, and F.5-23) show slight or weak relationships to NH_3 and H_2S emissions. The barometric pressure was lowest at the Oklahoma sites, with comparable readings at the Indiana and North Carolina sites. The variability of readings was comparable across sites, with Figure E-67 showing no distinct consistent temporal pattern. The scatter plots of barometric pressure (Appendix F, Figures F.5-16, F.5-17, F.5-24, and F.5-25) show slight or weak relationships to NH_3 and H_2S emissions.

The wind speed (Figure E-68) statistics are similar for the NC and IN sites, with the OK3A and OK4A sites standing out with higher average speeds or 4.787 and 5.499 ms^{-1}, respectively. The IN4A average of 3.957 ms^{-1} approaches the average values seen at the Oklahoma sites, however the North Carolina average wind speed is at least half of the speeds seen at OK and with less variability. With this variation, it is worth exploring what relationship the wind speed might have to emissions. The scatter plots of wind speed (Appendix F, Figures F.5-18, F.5-19, F.5-26, and F.5-27) show slight or weak relationships to NH_3 and H_2S emissions.

4.5 Basins

4.5.1 Emissions Data

Appendix D, Tables D-43 and D-44 present the summary statistics for daily average emissions of NH_3 and H_2S for the basin site, respectively. Figures E-69 and E-70 show the time series plots of NH_3 emissions in kg d^{-1} and g d^{-1} m^{-2}, respectively. For the basin site (IA3A), the NH_3 emissions are roughly twice as high as the sites with lagoons. This could be the result of some interference from the barn, as the exhaust fans are on the wall that face the basin. Figures E-71 and E-72 show the time series plots of H_2S emissions in in g d^{-1} and mg d^{-1} m^{-2}, respectively. The basin has much lower H_2S emissions than the lagoon sites. This is likely due to the smaller surface are of the basin compared to the lagoons.

4.5.2 Ambient Data

Table D-45 in Appendix D presents the summary statistics for daily average ambient data for basins. Table 4-10 provides a summary of the regression analysis for ambient parameters for basins. The scatter plots of ambient temperature (Appendix F, Figures F.6-1, F.6-2, F.6-9, and F.6-10) show moderately strong relationships to NH_3 and slight or weak relationships to H_2S emissions. The scatter plots of relative humidity (Appendix F, Figures F.6-3, F.6-4, F.6-10, and F.6-11), barometric pressure (Appendix F, Figures F.6-5, F.6-6, F.6-13, and F.6-14), and wind speed (Appendix F, Figures F.6-7, F.5-8, F.5-15, and F.5-16) show slight or weak relationships with NH_3 and H_2S emissions

Table 4-4-40. Summary of swine basin R^2 values for ambient parameters.

Pollutant	Parameter	R	R^2	Strength	Figure
NH_3 (kgd^{-1})	Air temperature (°C)	0.78	0.61	Moderately strong	F.6-1
NH_3 ($kgd^{-1}m^{-2}$)	Air temperature (°C)	0.78	0.61	Moderately strong	F.6-2
NH_3 (kgd^{-1})	Relative humidity (%)	0.06	0.00	Slight or weak	F.6-3
NH_3 ($kgd^{-1}m^{-2}$)	Relative humidity (%)	0.06	0.00	Slight or weak	F.6-4
NH_3 (kgd^{-1})	Barometric pressure (kPa)	-0.28	0.08	Slight or weak	F.6-5
NH_3 ($kgd^{-1}m^{-2}$)	Barometric pressure (kPa)	-0.28	0.08	Slight or weak	F.6-6
NH_3 (kgd^{-1})	Wind speed (ms^{-1})	-0.43	0.19	Slight or weak	F.6-7
NH_3 ($kgd^{-1}m^{-2}$)	Wind speed (ms^{-1})	-0.43	0.19	Slight or weak	F.6-8
H_2S (gd^{-1})	Air temperature (°C)	0.42	0.18	Slight or weak	F.6-9
H_2S ($gd^{-1}m^{-2}$)	Air temperature (°C)	0.42	0.18	Slight or weak	F.6-10
H_2S (gd^{-1})	Relative humidity (%)	-0.13	0.02	Slight or weak	F.6-11
H_2S ($gd^{-1}m^{-2}$)	Relative humidity (%)	-0.13	0.02	Slight or weak	F.6-12
H_2S (gd^{-1})	Barometric pressure (kPa)	-0.33	0.11	Slight or weak	F.6-13
H_2S ($gd^{-1}m^{-2}$)	Barometric pressure (kPa)	-0.33	0.11	Slight or weak	F.6-14
H_2S (gd^{-1})	Wind speed (ms^{-1})	0.07	0.01	Slight or weak	F.6-15
H_2S ($gd^{-1}m^{-2}$)	Wind speed (ms^{-1})	0.07	0.01	Slight or weak	F.6-16

5 DEVELOPMENT AND SELECTION OF MODELS FOR DAILY EMISSIONS

5.1 Breeding and Gestation Barns

The exploratory data analysis suggested that EPA should consider ambient temperature, exhaust temperature, inventory, and LAW in the development of the EEMs for the breeding and gestation barns. As noted in the emissions trends and the exploratory data analysis (Section 4.0), the farrowing rooms emissions were very different from the gestation rooms emissions. This, coupled with the understanding that different management processes (e.g., cleaning frequency), feeding characteristics (e.g., feeding frequency and nitrogen content), and other characteristics unique to each of these barn types can contribute to emissions differences (see Section 4), led EPA to develop separate models for the farrowing rooms and gestation barns. Additionally, EPA identified differences in NH_3 and H_2S emissions levels and trends (see Section 4) between gestation barns with different manure handling practices (i.e., shallow pit or deep pit). Therefore, EPA applied a slightly different model development approach, developing NH_3 and H_2S models using the same model coefficients, but with different intercepts for shallow and deep pit, which was achieved by using shallow pit and deep pit as class variables. As expected, based on theoretical considerations, the pit type employed at the farm did not appear to have an impact on PM emissions. Appendix G contains the summary tables and figures for the model evaluations.

As discussed in the following sections, adding "cycle days" to the farrowing models improved model predictions for H_2S and PM_{10} emissions. However, the addition of a cycle day did not change model predictions for NH_3 emissions. EPA posits that for H_2S and PM_{10}, the cycle day likely correlates with management activities that occur at specific times in the growth cycle. For example, the later cycle days may correlate with more activity in the barn, which could increase the physical agitation of surface manure on the slats, thereby increasing H_2S and PM_{10} emissions. Also, manure accumulates over the course of the farrowing process, providing more fresh emissions source material until the stalls are cleared out. After adding a cycle day, ambient temperature became a less significant factor for the estimation of H_2S. However, EPA retained this parameter in the final model to maintain consistency with the other model and to reflect the link reported in the literature between emissions and temperature.

5.1.1 NH_3 Model Results and Evaluation

Table 5-1 and Table 5-2 present the parameters, estimates, and fit and evaluation statistics for the farrowing barn NH_3 models. EPA developed six different models with different combinations of the four predictor variables—ambient temperature, exhaust temperature, inventory, and LAW. Models 1, 2, 5, and 6 had coefficients that were not significant ($p > 0.05$); those coefficients are in boldface in Table 5-1. For models 3 and 4, EPA found a significant positive correlation between NH_3 emissions and LAW, meaning that as inventory or LAW increase, so do NH_3 emissions (see Table 5-2). EPA expected this positive relationship because

LAW is a proxy for the volume of manure produced. Similarly, the temperature variables also correlate positively with emissions. As previously mentioned, higher temperatures increase NH_3 release rates.

Table 5-2 provides the model fit statistics (-2 log likelihood, AIC, AICc, and BIC) and the model evaluation statistics (ME, NME, MB, NMB) for the six models. Out of the two models with significant coefficients, model 4, which contained ambient temperature and LAW, had the lowest model fit statistics, and therefore the best fit. Both models produced comparable model fit statistics, especially with respect to mean error (ME), mean bias (MB) and normalized mean bias (NMB). Therefore, when EPA selected a model for further analysis, it considered the potential ease of data collection and ease of use. EPA concluded that ambient temperature would be easier to obtain than exhaust temperature, and so selected model 4 for further analysis. Model 4 is as follows:

$$Farrowing, ln(NH_3) = 0.6888 + 0.0020 * cycleday + 0.0006 * Amb_T + 0.0084 * LAW$$ Equation 1

Where:

ln(NH₃) = the natural log transformed predicted NH_3 emissions in kilograms per day (kg day^{-1}).
cycleday = the day of the animal placement cycle (e.g., the day the sow is moved to the barn is cycle day 1).
Amb_T = ambient temperature (°C).
LAW = live animal weight in thousands of kilograms (Mg).

Table 5-1. Parameters and estimates for the farrowing barn NH3 models evaluated.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	0.619374	0.04527	<0.0001
1	Cycleday	0.002028	0.00084	0.017
1	AmbT	0.00017	0.00035	**0.6266**
1	ExhT	0.003027	0.00175	**0.084**
1	LAW	0.00805	0.00187	<0.0001
2	Intercept	0.634065	0.04378	<0.0001
2	Cycleday	0.002188	0.00069	0.0018
2	AmbT	0.00006	0.00035	**0.8659**
2	ExhT	0.003527	0.00173	0.0422
2	Inv	0.03089	0.04146	**0.4566**
3	Intercept	0.607334	0.02146	<0.0001
3	Cycleday	0.001882	0.00056	0.0011
3	ExhT	0.003658	0.00073	<0.0001
3	LAW	0.007369	0.00169	<0.0001
4	Intercept	0.68875	0.01775	<0.0001
4	Cycleday	0.001961	0.0008	0.0157
4	AmbT	0.000581	0.00029	0.0449
4	LAW	0.008405	0.00154	<0.0001
5	Intercept	0.627724	0.02043	<0.0001
5	Cycleday	0.002053	0.0005	<0.0001
5	ExhT	0.003771	0.00069	<0.0001
5	Inv	0.028189	0.03115	**0.3658**
6	Intercept	0.713155	0.01572	<0.0001
6	Cycleday	0.002087	0.0007	0.0035
6	AmbT	0.00054	0.00029	**0.0596**
6	Inv	0.049431	0.03829	**0.1972**

Table 5-2. Fit and evaluation statistics for the farrowing barn NH_3 models evaluated.

Model	2LogL	AIC	AICc	BIC	Corr.	LNME[a] (%)	NME[b] (%)	ME[b] (kg day^{-1})	MB[b] (kg day^{-1})	NMB[b] (%)
1	-5,975	-5,953	-5,953	-5,926	0.429	9.305	57.162	0.174	-0.0009	-0.303
2	-5,948	-5,926	-5,926	-5,899	0.227	10.195	59.898	0.182	-0.0002	-0.078
3	-6,698	-6,678	-6,678	-6,653	0.412	9.215	60.058	0.175	-0.0009	-0.291
4	-6,010	-5,990	-5,990	-5,965	0.503	9.086	55.927	0.169	-0.0012	-0.392
5	-6,673	-6,653	-6,653	-6,628	0.215	9.971	62.692	0.182	-0.0002	-0.073
6	-5,973	-5,953	-5,953	-5,928	0.347	9.903	58.310	0.177	-0.0006	-0.200

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

To estimate NH_3 emissions from gestation barns, EPA started with six models based on different combinations of the four predictor variables: ambient temperature, exhaust temperature, inventory and LAW. EPA also evaluated two versions of these models, one that did not distinguish between the type of manure pit used in the barn ("no pit model"; Table 5-3 and Table 5-4) and one that did ("pit model"; Table 5-5 and Table 5-6).

For the no pit model, all environmental parameter coefficients were significant ($p < 0.05$). Although the intercept was insignificant for models 1, 4, and 6, EPA still considered intercept for the final model. As with the farrowing model, all six models showed that the animal size variables (LAW and inventory) correlated positively with NH_3 emissions, as well as with the temperature variables (Table 5-3).

Table 5-4 provides the model fit statistics and the model evaluation statistics for the six models. Models 2, 4, and 6 had the lowest model fit statistics, while models 3 and 4 had the two lowest mean MEs, followed by models 1 and 6. Across the six models, MEs ranged from 4.653 kg day^{-1} for model 3 to 7.096 kg day^{-1} for model 2, which produced NME values of 36.748% and 54.764%, respectively, a difference of 18%. Across the six models, MB ranged from -0.655 kg day^{-1} (model 3) to 0.386 kg day^{-1} (model 5). Correspondingly, NMB ranged from -5.169% to 3.052% for models 3 and 5, respectively. The positive (negative) values indicate that the model is over (under) predicting in comparison to measured (observed) values.

Overall, EPA concluded that models 1, 3, and 4 produced fairly similar model fit and evaluation statistics. Therefore, when selecting the model for further analysis, EPA considered the potential ease of use and concluded that ambient temperature would be potentially easier to obtain than exhaust temperature. Therefore, EPA selected model 4 for further analysis. Model 4 is as follows:

$$Gestation\ Barn, No\ Pit: ln(y_p) = 0.7844 + 0.0056 * Amb_T + 0.0073 * LAW \qquad \text{Equation 2}$$

Where:

$ln\ y_p$ = the natural log transformed predicted NH_3 emissions in kilograms per day (kg day^{-1}).

Amb_T = ambient temperature (°C).

LAW = live animal weight in thousands of kilograms (Mg).

Table 5-3. Parameters and estimates for the no pit gestation barn NH_3 models evaluated.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	-0.124019	0.14725	**0.4013**
1	AmbT	0.003627	0.00112	0.0012
1	ExhT	0.012324	0.00365	0.0007
1	LAW	0.009382	0.00052	<0.0001
2	Intercept	-0.571962	0.21034	0.0078
2	AmbT	0.003585	0.00108	0.0009
2	ExhT	0.012258	0.00346	0.0004
2	Inv	2.256826	0.1715	<0.0001
3	Intercept	-0.380329	0.1093	0.0007
3	ExhT	0.024796	0.00174	<0.0001
3	LAW	0.009566	0.00042	<0.0001
4	Intercept	0.154785	0.11861	**0.1972**
4	AmbT	0.006855	0.00055	<0.0001
4	LAW	0.009122	0.00051	<0.0001
5	Intercept	-0.887715	0.15215	<0.0001
5	ExhT	0.02473	0.00165	<0.0001
5	Inv	2.343046	0.1268	<0.0001
6	Intercept	-0.266956	0.19692	**0.1811**
6	AmbT	0.00678	0.00052	<0.0001
6	Inv	2.18221	0.16987	<0.0001

Table 5-4. Fit and evaluation statistics for the no pit gestation barn NH_3 models evaluated.

Model	-2LogL	AIC	AICc	BIC	Corr.	LNME[a] (%)	NME[b] (%)	ME[b] (kg day^{-1})	MB[b] (kg day^{-1})	NMB[b] (%)
1	-2,851	-2,819	-2,819	-2,823	0.738	12.528	36.917	4.783	-0.655	-5.056
2	-2,825	-2,793	-2,793	-2,796	0.383	16.686	54.764	7.096	0.369	2.846
3	-3,006	-2,976	-2,976	-2,979	0.747	12.755	36.748	4.653	-0.655	-5.169
4	-2,841	-2,811	-2,811	-2,815	0.739	12.461	36.699	4.755	-0.652	-5.033
5	-2,980	-2,950	-2,950	-2,953	0.395	17.12	55.258	6.996	0.386	3.052
6	-2,816	-2,786	-2,785	-2,789	0.421	16.246	53.086	6.878	0.229	1.764

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

For the "pit" model set, the intercept was varied for each pit type, while the same coefficients were used for the predictive parameters. For each of the models, one of the intercept coefficients was insignificant ($p > 0.05$). Model 2 was the only model with an insignificant coefficient for an environmental parameter (see Table 5-5). As with the other NH_3 models, the parameters have a significant positive relationship with NH_3 emissions, which is consistent with literature.

Table 5-6 provides the model fit statistics and the model evaluation statistics for the six models. Models 1, 4, and 6 had the lowest model fit statistic values, while models 3 and 5 had the two lowest mean MEs, followed by models 1 and 4. Across the six models, ME ranged from 3.862 g day^{-1} for model 3 to 4.053 g day^{-1} for model 6, which produced NME values of 30.499 and 31.28%, respectively, a difference of 0.781%. Overall, EPA concluded that all the models produced comparable model fit statistics and evaluation statistics. Therefore, when selecting a model for further analysis, EPA considered the potential ease of use. Consistent with the "no pit" version of the model, EPA selected model 4 for further analysis. Model 4 for the different pit types is as follows:

$$Gestation\ Barn, Shallow\ Pit\colon ln(y_p) = 0.3075 + 0.0118 * Amb_T + 0.0079 * LAW \qquad \text{Equation 3}$$

$$Gestation\ Barn, Deep\ Pit\colon ln(y_p) = 0.8348 + 0.0118 * Amb_T + 0.0079 * LAW \qquad \text{Equation 4}$$

Where:

$ln(y_p)$ = the natural log transformed predicted NH_3 emissions in kilograms per day (kg day^{-1}).

Amb_T = ambient temperature (°C).

LAW = live animal weight in thousands of kilograms (Mg).

Table 5-5. Parameters and estimates for the pit gestation barn NH_3 models evaluated.

Model	Parameter	Estimate	Standard Error	p-value
1	Deep	0.820119	0.2827	0.0045
1	Shallow	0.290714	0.23005	**0.2084**
1	AmbT	0.011567	0.00157	<0.0001
1	ExhT	0.000783	0.00489	**0.8726**
1	LAW	0.007912	0.001	<0.0001
2	Deep	0.837378	0.28892	0.0045
2	Shallow	-0.156823	0.29033	**0.59**
2	AmbT	0.011558	0.00157	<0.0001
2	ExhT	0.000673	0.00489	**0.8905**
2	Inv	1.95569	0.25514	<0.0001
3	Deep	0.160772	0.24154	**0.507**
3	Shallow	-0.447705	0.18902	0.0193
3	ExhT	0.037453	0.00257	<0.0001
3	LAW	0.008436	0.00087	<0.0001
4	Deep	0.834777	0.26817	0.0025
4	Shallow	0.30747	0.20558	**0.1382**
4	AmbT	0.011778	0.00085	<0.0001
4	LAW	0.007899	0.001	<0.0001
5	Deep	0.145302	0.24822	**0.5594**
5	Shallow	-0.95979	0.24429	0.0001
5	ExhT	0.03733	0.00258	<0.0001
5	Inv	2.117453	0.22432	<0.0001
6	Deep	0.850101	0.27458	0.0026
6	Shallow	-0.141677	0.26961	**0.6004**
6	AmbT	0.011739	0.00085	<0.0001
6	Inv	1.952928	0.25467	<0.0001

Table 5-6. Fit and evaluation statistics for the pit gestation barn NH_3 models evaluated.

Model	2LogL	AIC	AICc	BIC	Corr.	LNME[a] (%)	NME[b] (%)	ME[b] (kg day^{-1})	MB[b] (kg day^{-1})	NMB[b] (%)
1	-2,009	-1,995	-1,995	-1,996	0.779	11.615	31.179	4.040	-0.361	-2.787
2	-2,007	-1,993	-1,992	-1,994	0.776	11.713	31.257	4.050	-0.373	-2.877
3	-2,046	-2,034	-2,034	-2,035	0.796	11.458	30.499	3.862	-0.306	-2.415
4	-2,009	-1,997	-1,997	-1,998	0.779	11.622	31.205	4.043	-0.361	-2.786
5	-2,044	-2,032	-20,32	-2,033	0.794	11.521	30.563	3.870	-0.314	-2.482
6	-2,007	-1,995	-1,994	-1,996	0.775	11.719	31.28	4.053	-0.373	-2.876

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

5.1.2 H_2S Model Results and Evaluation

For the farrowing rooms, EPA developed seven different models with different combinations of the four predictor variables, ambient temperature, exhaust temperature, inventory, and LAW. All models, except model 7, had at least one coefficient that was insignificant ($p > 0.05$); these are in boldface in Table 5-7. Model 7 included only LAW and cycle day as parameters, both of which correlated positively with NH_3 emissions.

Table 5-8 provides the model fit statistics and the model evaluation statistics for the seven models. Models 1 and 2, which had both temperature parameters, had the best model fit statistics. The model evaluation statistics were similar for all the models, with the ME ranging from 72.316 g day^{-1} for model 3 to 73.785 g day^{-1} for model 7, which produced NME values of 68.944% and 70.892%, respectively. The models had an MB that ranged from 18.9 g day^{-1} to 20.322 g day^{-1}, and NMBs of 18.019% and 19.455% for models 3 and 6, respectively.

EPA ultimately selected model 7 for further analysis because this was the only model with significant coefficients and parameters that were readily available to producers. Model 7 is expressed as follows:

$$Farrowing\ room,\ ln(H_2S) = 2.1423 + 0.1298 * cycleday + 0.0614 * LAW \qquad \text{Equation 5}$$

Where:

ln(H₂S) = the natural log transformed predicted H_2S emissions in grams per day (g day^{-1}).
cycleday = the day of the animal placement cycle (e.g., the day the sow is moved to the barn is cycle day 1).
LAW = live animal weight in thousands of kilograms (Mg).

Table 5-7. Parameters and estimates for the farrowing barn H_2S models developed.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	1.696616	0.4	<0.0001
1	cycleday	0.128162	0.00595	<0.0001
1	AmbT	0.002557	0.0033	0.4392
1	ExhT	0.009579	0.01667	0.5657
1	LAW	0.091992	0.01932	<0.0001
2	Intercept	1.998359	0.40565	<0.0001
2	cycleday	0.12883	0.00574	<0.0001
2	AmbT	0.001747	0.0033	0.5971
2	ExhT	0.016646	0.01666	0.3179
2	Inv	0.181305	0.39501	0.6463
3	Intercept	1.599675	0.33031	<0.0001
3	cycleday	0.128651	0.00561	<0.0001
3	ExhT	0.018381	0.01242	0.1393
3	LAW	0.080834	0.0186	<0.0001
4	Intercept	2.030664	0.13947	<0.0001
4	cycleday	0.128944	0.0059	<0.0001
4	AmbT	0.003998	0.00256	0.1184
4	LAW	0.0684	0.01688	<0.0001
5	Intercept	1.923371	0.33545	<0.0001
5	cycleday	0.129496	0.00554	<0.0001
5	ExhT	0.021562	0.01243	0.0831
5	Inv	0.123177	0.38741	0.7506
6	Intercept	2.393581	0.13808	<0.0001
6	cycleday	0.128682	0.00575	<0.0001
6	AmbT	0.003897	0.00255	0.1264
6	Inv	0.089971	0.3678	0.8068
7	Intercept	2.142329	0.12728	<0.0001
7	cycleday	0.129797	0.00562	<0.0001
7	LAW	0.061406	0.01641	0.0002

Table 5-8. Fit and evaluation statistics for the farrowing barn H_2S models developed.

Model	2LogL	AIC	AICc	BIC	Corr.	LNME[a] (%)	NME[b] (%)	ME[b] (kg day-1)	MB[b] (kg day-1)	NMB[b] (%)
1	1,346	1,368	1,369	1,396	0.592	20.071	70.091	72.624	19.724	19.036
2	1,372	1,394	1,394	1,421	0.613	19.663	69.993	72.644	19.193	18.492
3	1,473	1,493	1,494	1,519	0.602	19.626	68.944	72.316	18.900	18.019
4	1,386	1,406	1,406	1,430	0.600	19.946	69.932	72.382	19.485	18.826
5	1,496	1,516	1,516	1,541	0.622	19.264	69.283	72.779	18.945	18.035
6	1,406	1,426	1,426	1,451	0.612	19.712	70.892	73.497	20.170	19.455
7	1,516	1,534	1,534	1,556	0.598	19.730	70.283	73.785	20.322	19.357

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

[b] Based on back-transformed data.

For the gestation barns, EPA developed six different models based on different combinations of the four predictor variables, ambient temperature, exhaust temperature, inventory, and LAW. Again, EPA evaluated two sets of models, one that did not distinguish between the type of pit ("no pit model"; Table 5-9) and one that did ("pit model"; Table 5-11).

For the "no pit" model set, EPA found exhaust temperature to be insignificant when used in combination with the ambient temperatures, as in models 1 and 2. For all other models, all the parameter coefficients were significant. For these four models, the activity variables again showed a significant positive correlation with emissions (Table 5-9). Table 5-10 provides the model fit statistics and the model evaluation statistics for the six models. Out of the four models with significant coefficients, models 4 and 6 had the lowest and best model fit statistic values. The model evaluation statistics were a mixed bag, with the models with the lowest ME, model 3 and 4, also had the largest NMB, in absolute terms.

Overall, EPA concluded that the models produced relatively similar model fit statistics and evaluation statistics, when looking across all statistics. Therefore, when selecting a model for further analysis, EPA considered producers' potential ease of data collection and ease of use and concluded that ambient temperature would be potentially easier to obtain than exhaust temperature. Therefore, EPA selected model 4 for further analysis. Model 4 is as follows:

$$Gestation\ Barns, No\ Pit: ln(H_2S) = 2.0773 + 0.0035 * Amb_T + 0.0199 * LAW \qquad \text{Equation 6}$$

Where:

$ln(H_2S)$ = the natural log transformed predicted H_2S emissions in grams per day (g day^{-1}).
Amb_T = ambient temperature (^oC).
LAW = live animal weight in thousands of kilograms (Mg).

Table 5-9. Parameters and estimates for the gestation barn H_2S models developed for the no pit model.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	2.340339	0.20448	<0.0001
1	AmbT	0.006591	0.00213	0.002
1	ExhT	-0.01153	0.00705	0.1021
1	LAW	0.01961	0.00055	<0.0001
2	Intercept	1.049288	0.22272	<0.0001
2	AmbT	0.006192	0.00209	0.003
2	ExhT	-0.01059	0.00688	0.1236
2	Inv	5.007765	0.14404	<0.0001
3	Intercept	2.079784	0.14511	<0.0001
3	ExhT	0.007943	0.00315	0.0119
3	LAW	0.019339	0.0005	<0.0001
4	Intercept	2.077258	0.12093	<0.0001
4	AmbT	0.003547	0.00098	0.0003
4	LAW	0.019862	0.00053	<0.0001
5	Intercept	0.803968	0.17442	<0.0001
5	ExhT	0.007805	0.0031	0.012
5	Inv	4.955695	0.1336	<0.0001
6	Intercept	0.788813	0.16547	<0.0001
6	AmbT	0.003397	0.00097	0.0005
6	Inv	5.070146	0.14418	<0.0001

Table 5-10. Fit and evaluation statistics for the gestation barn H_2S models developed for the no pit model.

Model	2LogL	AIC	AICc	BIC	Corr.	LNME[a] (%)	NME[b] (%)	ME[b] (g day^{-1})	MB[b] (g day^{-1})	NMB[b] (%)
1	1,241	1,273	1,273	1,270	0.851	8.682	68.727	1580.5	-520.1	-22.62
2	1,265	1,297	1,297	1,293	0.467	13.124	123.96	2850.6	389.82	16.95
3	1,556	1,586	1,586	1,583	0.847	9.004	69.458	1523.2	-518.7	-23.65
4	1,244	1,274	1,274	1,271	0.848	8.792	69.332	1594.4	-514.8	-22.39
5	1,575	1,605	1,605	1,602	0.471	13.201	124.38	2727.6	343.1	15.65
6	1,267	1,297	1,297	1,293	0.446	13.286	126.82	2916.5	450.49	19.589

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

For the “pit” model set, EPA again found the exhaust temperature to be insignificant when used in combination with the ambient temperatures, as in models 1 and 2. All other models had significant coefficients for all parameters (Table 5-11). As with the NH_3 models, the parameters had significant positive correlations with H_2S emissions.

Table 5-12 provides the model fit statistics and the model evaluation statistics for the six models. Focusing on the four models with significant parameters, models 4 and 6 had the lowest model fit statistic values. Across the four models, the model evaluation statistics were similar. Therefore, EPA selected the model with parameters that were readily available to the producers and did not require additional monitoring. EPA selected model 4 for further analysis, which is consistent with the “no pit” version of the model. Model 4 for the different pit types is as follows:

$$Gestation\ Barn,\ Shallow\ Pit: ln(H_2S) = 2.1305 + 0.0038 * Amb_T + 0.0196 * LAW \qquad \text{Equation 7}$$

$$Gestation\ Barn,\ Deep\ Pit: ln(H_2S) = 3.1785 + 0.0038 * Amb_T + 0.0196 * LAW \qquad \text{Equation 8}$$

Where:

$ln(H2S)$ = the natural log transformed predicted H_2S emissions in grams per day (g day^{-1}).
Amb_T = ambient temperature (^oC).
LAW = live animal weight in thousands of kilograms (Mg).

Table 5-11. Parameters and estimates for the gestation barn H_2S models, with pit type.

Model	Parameter	Estimate	Standard Error	p-value
1	Deep	3.343724	0.20609	<0.0001
1	Shallow	2.320599	0.20474	<0.0001
1	AmbT	0.006075	0.00218	0.0053
1	ExhT	-0.00839	0.00728	0.2491
1	LAW	0.019413	0.00056	<0.0001
2	Deep	3.16381	0.21225	<0.0001
2	Shallow	1.015716	0.23834	<0.0001
2	AmbT	0.005911	0.00218	0.0069
2	ExhT	-0.00832	0.0073	0.254
2	Inv	4.996525	0.14574	<0.0001
3	Deep	3.163799	0.1596	<0.0001
3	Shallow	2.094309	0.14531	<0.0001
3	ExhT	0.009296	0.00319	0.0037
3	LAW	0.01913	0.00051	<0.0001
4	Deep	3.171852	0.1471	<0.0001
4	Shallow	2.130472	0.12289	<0.0001
4	AmbT	0.003844	0.00098	0.0001
4	LAW	0.019592	0.00054	<0.0001
5	Deep	2.975309	0.16444	<0.0001
5	Shallow	0.797081	0.17776	<0.0001
5	ExhT	0.008994	0.0032	0.0051
5	Inv	4.938084	0.13301	<0.0001
6	Deep	2.990124	0.15311	<0.0001
6	Shallow	0.813576	0.16124	<0.0001
6	AmbT	0.003696	0.00099	0.0002
6	Inv	5.043545	0.14044	<0.0001

Table 5-12. Fit and evaluation statistics for the gestation barn H_2S models, with pit type.

Model	2LogL	AIC	AICc	BIC	Corr.	LNME[a] (%)	NME[b] (%)	ME[b] (g day^{-1})	MB[b] (g day^{-1})	NMB[b] (%)
1	1,197	1,231	1,231	1,227	0.913	6.079	50.904	1170.6	-241.9	-10.52
2	1,208	1,242	1,242	1,238	0.911	6.134	51.24	1178.4	-245.6	-10.68
3	1,509	1,541	1,542	1,538	0.912	6.258	50.252	1102	-233.6	-10.65
4	1,198	1,230	1,230	1,227	0.913	6.078	50.681	1165.5	-241.1	-10.49
5	1,517	1,549	1,550	1,546	0.91	6.302	50.592	1109.4	-238	-10.85
6	1,209	1,241	1,241	1,237	0.911	6.135	51.032	1173.6	-244.7	-10.64

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

5.1.3 PM_{10} Model Results and Evaluation

EPA developed 11 different models based on the seven predictor variables identified for farrowing rooms—cycle day, ambient temperature, exhaust temperature, ambient relative humidity, exhaust relative humidity, inventory, and LAW. Models 4 and 7 each had at least one coefficient that was insignificant ($p > 0.05$); these are in boldface in Table 5-13. Overall, ambient relative humidity and exhaust relative humidity had a negative correlation with PM_{10} concentration. This was expected, as the literature review (Section 3) noted that increased moisture generally prevents surface material disruption, so less material is entrained into the air. The ambient temperature and exhaust temperature also had a negative correlation with PM_{10} concentration, which was noted in literature to be due in part to decreased animal activity resulting in decreased disruption of material in the barn as temperatures increase.

Table 5-14 provides the model fit statistics and the model evaluation statistics for these models. Models 11 and 9, which had exhaust temperature and exhaust relative humidity, had the best model fit statistics. Scatter plots of the observed emissions versus the EEM predicted values are in Figures F-3 and F-4. The model evaluation statistics were relatively similar across the models. Therefore, EPA considered the potential ease of data collection and concluded that models that only used ambient parameters would be preferable. Of the models with only ambient parameters, EPA selected model 2 for further analysis. Model 2 is as follows:

$$Farrowing\ room, ln(\mathrm{PM}_{10}) = 2.490 + 0.0558 * cycleday\ + 0.1063 * LAW - 0.0034\ Amb_{RH} \qquad \text{Equation 9}$$

Where:

$ln(PM_{10})$ = the natural log transformed predicted PM_{10} emissions in grams per day (g day^{-1}).
cycleday = the day of the animal placement cycle (e.g., the day the sow is moved to the barn is cycle day 1).
LAW = live animal weight in thousands of kilograms (Mg).
AmbRH = average daily relative humidity (percent of water vapor in the air).

For the gestation barns, EPA developed 11 different models with different combinations of the six predictor variables—ambient temperature, exhaust temperature, ambient relative humidity, exhaust relative humidity, inventory, and LAW). Models 3, 6, 9, and 11 had coefficients that EPA found to be insignificant ($p > .05$). For all other models, all the parameter coefficients were significant. As with the farrowing rooms, ambient relative humidity, exhaust relative humidity, and exhaust temperature had a negative correlation with PM_{10} concentration. However, the relationship between ambient temperature and PM_{10} emissions was positive across all the models evaluated (see Table 5-13, Table 5-14, and Table 5-15). Table 5-16 provides the model fit statistics and the model evaluation statistics for the models. As with the farrowing rooms, the models produced relatively similar model fit statistics and evaluation statistics. EPA concluded that ambient temperature data would be potentially easier to obtain than exhaust temperature, so EPA selected model 2 for further analysis. Model 2 is as follows:

$$Gestation\ barns, ln(PM_{10}) = 5.1868 - 0.0078 * Amb_{RH} + 0.0055 * LAW \qquad \text{Equation 10}$$

Where:

$ln(PM_{10})$ = the natural log transformed predicted PM_{10} emissions in grams per day ($g\ day^{-1}$).

LAW = live animal weight in thousands of kilograms (Mg).

Amb_{RH} = average daily relative humidity (percent).

Table 5-13. Parameters and estimates for the farrowing barn PM_{10} models.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	2.31939	0.08016	<0.0001
1	cycleday	0.05454	0.00362	<0.0001
1	LAW	0.09776	0.01175	<0.0001
2	Intercept	2.489915	0.09914	<0.0001
2	cycleday	0.055625	0.00366	<0.0001
2	LAW	0.106263	0.01302	<0.0001
2	AmbRH	-0.00344	0.00066	<0.0001
3	Intercept	2.631802	0.10743	<0.0001
3	cycleday	0.059459	0.0037	<0.0001
3	AmbT	-0.00756	0.00192	<0.0001
3	LAW	0.106851	0.01316	<0.0001
3	AmbRH	-0.00407	0.0007	<0.0001
4	Intercept	3.062805	0.11999	<0.0001
4	cycleday	0.059061	0.00367	<0.0001
4	AmbT	-0.00132	0.00189	**0.4868**
4	LAW	0.100043	0.01303	<0.0001
4	Exh_RH	-0.01287	0.00135	<0.0001
5	Intercept	3.103209	0.11574	<0.0001
5	cycleday	0.059367	0.00367	<0.0001
5	LAW	0.088094	0.01244	<0.0001
5	Exh_RH	-0.01285	0.00126	<0.0001
6	Intercept	2.584906	0.10593	<0.0001
6	cycleday	0.061876	0.00389	<0.0001
6	AmbT	-0.00697	0.00193	0.0003
6	Inv	2.347235	0.2836	<0.0001
6	AmbRH	-0.00415	0.0007	<0.0001
7	Intercept	3.005011	0.12027	<0.0001
7	cycleday	0.061125	0.00384	<0.0001
7	AmbT	-0.00061	0.0019	**0.7489**
7	Inv	2.291581	0.28682	<0.0001
7	Exh_RH	-0.0132	0.00135	<0.0001
8	Intercept	3.52795	0.26291	<0.0001
8	cycleday	0.058797	0.00368	<0.0001
8	ExhT	-0.04199	0.00953	<0.0001
8	LAW	0.102848	0.01333	<0.0001
8	AmbRH	-0.00361	0.00065	<0.0001
9	Intercept	3.672323	0.24689	<0.0001
9	cycleday	0.060507	0.00363	<0.0001
9	ExhT	-0.02458	0.00924	0.008
9	LAW	0.08629	0.01269	<0.0001
9	Exh_RH	-0.0123	0.00126	<0.0001
10	Intercept	3.459979	0.26643	<0.0001

Model	Parameter	Estimate	Standard Error	p-value
10	cycleday	0.061093	0.00386	<0.0001
10	ExhT	-0.04036	0.00962	<0.0001
10	Inv	2.252306	0.2923	<0.0001
10	AmbRH	-0.00368	0.00065	<0.0001
11	Intercept	3.534881	0.24964	<0.0001
11	cycleday	0.062781	0.00376	<0.0001
11	ExhT	-0.02262	0.00927	0.0148
11	Inv	2.144946	0.28392	<0.0001
11	Exh_RH	-0.01253	0.00126	<0.0001

Table 5-14. Fit and evaluation statistics for the farrowing barn PM_{10} models.

Model	2LogL	AIC	AICc	BIC	Corr.	LNME[a] (%)	NME[b] (%)	ME[b] (kg day-1)	MB[b] (kg day-1)	NMB[b] (%)
1	-29	-11	-11	11	0.61	10.122	40.649	14.187	0.689	1.975
2	-52	-32	-31	-7	0.632	9.813	39.112	13.585	0.834	2.400
3	-40	-18	-18	9	0.606	10.205	40.789	14.260	1.759	5.032
4	-104	-82	-82	-55	0.624	10.067	40.087	14.076	1.762	5.019
5	-140	-120	-120	-95	0.63	10.034	40.062	14.040	1.508	4.302
6	-41	-19	-19	8	0.649	9.774	38.576	13.486	0.996	2.850
7	-108	-86	-86	-59	0.668	9.584	37.937	13.320	1.018	2.900
8	-71	-49	-49	-22	0.624	10.029	39.944	13.874	1.647	4.742
9	-147	-125	-125	-98	0.623	10.185	40.6	14.228	1.981	5.652
10	-71	-49	-49	-22	0.656	9.721	38.311	13.307	1.064	3.062
11	-156	-134	-133	-106	0.657	9.823	38.951	13.651	1.491	4.254

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

Table 5-15. Parameters and estimates for the gestation barn PM_{10} models.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	4.746812	0.18103	<0.0001
1	LAW	0.005227	0.00077	<0.0001
2	Intercept	5.186761	0.17987	<0.0001
2	LAW	0.005472	0.00076	<0.0001
2	AmbRH	-0.00766	0.00053	<0.0001
3	Intercept	5.197462	0.19044	<0.0001
3	AmbT	0.001332	0.00143	**0.3515**
3	LAW	0.005432	0.00077	<0.0001
3	AmbRH	-0.00794	0.00056	<0.0001
4	Intercept	6.009517	0.16609	<0.0001
4	AmbT	0.006093	0.00134	<0.0001
4	LAW	0.005005	0.00064	<0.0001
4	ExhRH	-0.02175	0.00094	<0.0001
5	Intercept	6.222609	0.15542	<0.0001
5	LAW	0.004471	0.00061	<0.0001
5	ExhRH	-0.02213	0.00096	<0.0001
6	Intercept	5.513233	0.32609	<0.0001
6	AmbT	0.001056	0.00143	**0.4592**
6	Inv	0.835821	0.28124	0.0048
6	AmbRH	-0.00785	0.00057	<0.0001
7	Intercept	5.935606	0.28506	<0.0001
7	AmbT	0.005531	0.00134	<0.0001
7	Inv	1.109027	0.24632	<0.0001
7	ExhRH	-0.02162	0.00096	<0.0001
8	Intercept	5.562154	0.22881	<0.0001
8	ExhT	-0.01149	0.00423	0.0068
8	LAW	0.004915	0.00077	<0.0001
8	AmbRH	-0.00791	0.00054	<0.0001
9	Intercept	6.240271	0.20282	<0.0001
9	ExhT	-0.00055	0.00407	**0.8919**
9	LAW	0.004443	0.00064	<0.0001
9	ExhRH	-0.02213	0.00096	<0.0001
10	Intercept	5.794705	0.30808	<0.0001
10	ExhT	-0.01587	0.00406	0.0001
10	Inv	0.8952	0.26107	0.0012
10	AmbRH	-0.00783	0.00055	<0.0001
11	Intercept	6.145041	0.28393	<0.0001
11	ExhT	-0.0057	0.0039	**0.1444**
11	Inv	1.127905	0.2377	<0.0001
11	ExhRH	-0.02209	0.00097	<0.0001

Table 5-16. Fit and evaluation statistics for the gestation barn PM_{10} models.

Model	2LogL	AIC	AICc	BIC	Corr.	LNME[a] (%)	NME[b] (%)	ME[b] (g day-1)	MB[b] (g day-1)	NMB[b] (%)
1	847	875	875	872	0.319	6.67	34.975	142.81	3.394	0.831
2	607	637	638	634`	0.374	6.584	34.958	143.33	9.142	2.230
3	589	621	621	617	0.371	6.58	34.954	143.81	9.278	2.255
4	303	335	335	331	0.439	6.419	35.11	143.87	13.961	3.407
5	372	402	402	399	0.425	6.608	36.336	147.8	15.586	3.832
6	613	645	646	642	0.259	6.948	37.79	155.48	7.89	1.918
7	328	360	360	356	0.357	6.893	38.845	159.18	17.876	4.362
8	601	633	633	629	0.377	6.566	34.895	143.07	9.68	2.361
9	372	404	404	400	0.425	6.61	36.349	147.85	15.648	3.847
10	620	652	652	649	0.309	6.86	37.24	152.68	7.038	1.717
11	390	422	422	419	0.369	7.031	39.845	162.07	20.546	5.051

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

5.1.4 $PM_{2.5}$ Model Results and Evaluation

As noted in Section 6.4 of the Overview Report, the $PM_{2.5}$ procedure is based on the PM_{10} results. The same 11 models using the seven predictor variables—cycle day, ambient temperature, exhaust temperature, ambient relative humidity, exhaust relative humidity, inventory, and LAW—were evaluated. All the models except model 1 had at least one coefficient that was insignificant ($p > 0.05$); these are in boldface in Table 5-17. Across all the models, ambient relative humidity and exhaust temperature both had a negative correlation with $PM_{2.5}$ emissions. Exhaust relative humidity and ambient temperature correlated positively with $PM_{2.5}$ emissions. All negative relationships were expected, as they are consistent with PM_{10}. The difference in the exhaust relative humidity and ambient temperature relationships between the parameters and emissions could be due to the additional chemical pathways for $PM_{2.5}$ development, and the effects of the emissions of other pollutants on secondary formation, or an artifact of the limited dataset. More $PM_{2.5}$ emissions measurements, taken in concert with ambient and barn parameters, would help identify additional parameters to characterize this relationship.

Table 5-18 provides the model fit statistics and the model evaluation statistics for the models. Model 1 performed reasonably well, ranking best across all model evaluation statistics. The ME for model 1 was 1.9 g day^{-1} with an NME of 53.65%. The model had a MB of 0.364 g day^{-1} and an NMB of 10.266%. Scatter plots of the observed emissions versus the EEM predicted values are in Figures F-5 and F-6.

EPA selected model 1 for further analysis because this was the only model with significant coefficients for all parameters, while also consisting of parameters easily obtained by the producer. Model 1 is as follows:

$$Farrowing\ Room, ln(PM_{2.5}) = -1.2146 + 0.0759 * cycleday\ + 0.2564 * LAW \qquad \text{Equation 11}$$

Where:

ln($PM_{2.5}$) = the natural log transformed predicted $PM_{2.5}$ emissions in grams per day (g day^{-1}).

cycleday = day of the animal placement cycle (e.g., the day the sow is moved to the barn is cycle day 1).

LAW = live animal weight in thousands of kilograms (Mg).

For the gestation barns, the same 11 models evaluated for PM_{10} were applied to $PM_{2.5}$. As with the farrowing rooms, all the models had at least one coefficient that EPA found to be insignificant. Model 1, which only used LAW as a parameter, was the only model with no insignificant parameters (Table 5-19). The models showed the same relationships between the predictive parameters as in the farrowing rooms.

Table 5-20 provides the model fit statistics and the model evaluation statistics for the gestation barn models. Model 1 performed reasonably well, ranking at or near the top across all model evaluation statistics. Scatter plots of the observed emissions versus the EEM predicted values are in Figures F-15 and F-16. Again, EPA selected model 1 for further analysis because this was the only model with significant coefficients for all parameters and that consisted of parameters easily obtained by the producer. Model 1 is as follows:

$$Gestation\ Barn, ln(PM_{2.5}) = 4.88715 + 0.0007 * LAW \qquad \text{Equation 12}$$

Where:

ln($PM_{2.5}$) = the natural log transformed predicted $PM_{2.5}$ emissions in grams per day (g day^{-1}).

LAW = live animal weight in thousands of kilograms (Mg).

Table 5-17. Parameters and estimates for the farrowing barn $PM_{2.5}$ models.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	-1.21456	0.19779	<0.0001
1	cycleday	0.075902	0.00225	<0.0001
1	LAW	0.256357	0.03492	<0.0001
2	Intercept	-1.22295	0.20482	<0.0001
2	cycleday	0.075309	0.00212	<0.0001
2	LAW	0.254803	0.03335	<0.0001
2	AmbRH	0.000573	0.00294	**0.8465**
3	Intercept	-0.96654	0.29083	0.0015
3	cycleday	0.065442	0.0091	<0.0001
3	AmbT	-0.01808	0.01225	**0.1524**
3	LAW	0.242206	0.05058	<0.0001
3	AmbRH	0.001018	0.00159	**0.5268**
4	Intercept	-0.10714	0.53486	**0.8423**
4	cycleday	0.072982	0.00857	<0.0001
4	AmbT	-0.01472	0.00893	**0.1074**
4	LAW	0.211476	0.04989	0.0001
4	ExhRH	-0.01609	0.00784	0.0475
5	Intercept	-0.57278	0.47918	**0.2381**
5	cycleday	0.077513	0.00748	<0.0001
5	LAW	0.249139	0.06454	0.0009
5	ExhRH	-0.01397	0.00775	**0.0822**
6	Intercept	-1.24104	0.27014	<0.0001
6	cycleday	0.087952	0.00353	<0.0001
6	AmbT	-0.01262	0.00751	0.1
6	Inv	4.939231	0.7756	<0.0001
6	AmbRH	0.001565	0.00224	**0.4913**
7	Intercept	-0.68262	0.34997	**0.0607**
7	cycleday	0.093276	0.0079	<0.0001
7	AmbT	-0.00831	0.00905	**0.3637**
7	Inv	4.70608	0.85298	<0.0001
7	ExhRH	-0.01089	0.0049	0.0347
8	Intercept	-5.44691	1.24162	<0.0001
8	cycleday	0.066785	0.02129	0.006
8	ExhT	0.179198	0.05016	0.0009
8	LAW	0.166968	0.01505	<0.0001
8	AmbRH	0.003391	0.00639	**0.5997**
9	Intercept	-4.07391	1.18021	0.001
9	cycleday	0.086992	0.0045	<0.0001
9	ExhT	0.168803	0.04758	0.0007
9	LAW	0.155647	0.03003	<0.0001
9	ExhRH	-0.01415	0.00868	**0.112**
10	Intercept	-5.38343	0.86921	<0.0001

Model	Parameter	Estimate	Standard Error	p-value
10	cycleday	0.100078	0.00518	<0.0001
10	ExhT	0.167264	0.03988	<0.0001
10	Inv	5.092094	0.82731	<0.0001
10	AmbRH	0.000251	0.00367	**0.9461**
11	Intercept	-4.61514	0.96869	<0.0001
11	cycleday	0.101842	0.00367	<0.0001
11	ExhT	0.162427	0.03734	<0.0001
11	Inv	4.743317	0.81837	<0.0001
11	ExhRH	-0.01232	0.00645	**0.0664**

Table 5-18. Fit and evaluation statistics for the farrowing barn $PM_{2.5}$ models.

Model	2LogL	AIC	AICc	BIC	Corr.	LNME[a] (%)	NME[b] (%)	ME[b] (kg day^{-1})	MB[b] (kg day^{-1})	NMB[b] (%)
1	21	39	42	62	0.578	58.639	53.647	1.9	0.364	10.266
2	21	41	45	66	0.576	59.273	53.886	1.908	0.357	10.081
3	16	38	43	66	0.45	61.574	64.181	2.273	0.738	20.827
4	12	34	38	61	0.494	56.046	61.838	2.19	0.768	21.687
5	18	36	39	59	0.594	52.603	52.929	1.875	0.432	12.189
6	18	40	44	67	0.546	57.112	63.524	2.298	0.825	22.793
7	16	36	39	61	0.577	53.159	64.322	2.327	0.903	24.962
8	23	45	50	72	0.754	40.756	42.546	1.507	-0.111	-3.13
9	11	33	37	60	0.748	51.083	43.368	1.536	0.094	2.655
10	7	29	33	56	0.725	50.388	58.836	2.129	0.774	21.392
11	2	24	28	52	0.734	46.771	56.986	2.062	0.761	21.027

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

[b] Based on back-transformed data.

Table 5-19. Parameters and estimates for the gestation barn $PM_{2.5}$ models.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	4.88715	0.07109	<0.0001
1	LAW	0.0007	0.00031	0.027
2	Intercept	4.824807	0.08396	<0.0001
2	LAW	0.000689	0.00031	0.0281
2	AmbRH	0.001005	0.00074	0.1745
3	Intercept	4.880687	0.09764	<0.0001
3	AmbT	-0.00111	0.0011	0.3165
3	LAW	0.0006	0.00031	0.0592
3	AmbRH	0.000681	0.00079	0.3921
4	Intercept	4.749922	0.11574	<0.0001
4	AmbT	-0.00129	0.00102	0.2118
4	LAW	0.000536	0.00031	0.0884
4	ExhRH	0.003155	0.00158	0.0484
5	Intercept	4.712665	0.1142	<0.0001
5	LAW	0.00064	0.00031	0.0404
5	ExhRH	0.00309	0.0016	0.0553
6	Intercept	4.896295	0.17405	<0.0001
6	AmbT	-0.00152	0.00109	0.168
6	Inv	0.10554	0.12992	0.4193
6	AmbRH	0.000885	0.00089	0.3194
7	Intercept	4.79353	0.16774	<0.0001
7	AmbT	-0.00173	0.00103	0.0967
7	Inv	0.05847	0.11824	0.6227
7	ExhRH	0.003508	0.00161	0.0313
8	Intercept	5.078659	0.14699	<0.0001
8	ExhT	-0.0063	0.00306	0.0425
8	LAW	0.000344	0.00034	0.3117
8	AmbRH	0.000265	0.0008	0.7409
9	Intercept	4.923306	0.14416	<0.0001
9	ExhT	-0.00605	0.00274	0.0306
9	LAW	0.000307	0.00033	0.3526
9	ExhRH	0.002892	0.00155	0.0644
10	Intercept	5.132446	0.19452	<0.0001
10	ExhT	-0.0076	0.00274	0.0068
10	Inv	0.047445	0.12546	0.7064
10	AmbRH	0.000259	0.00089	0.771
11	Intercept	4.969183	0.16959	<0.0001
11	ExhT	-0.00721	0.00245	0.0044
11	Inv	0.036209	0.11101	0.7454
11	ExhRH	0.003035	0.00156	0.0545

Table 5-20. Fit and evaluation statistics for the gestation barn $PM_{2.5}$ models.

Model	2LogL	AIC	AICc	BIC	Corr.	LNME[a] (%)	NME[b] (%)	ME[b] (g day^{-1})	MB[b] (g day^{-1})	NMB[b] (%)
1	-192	-184	-184	-185	0.176	2.167	39.471	17.033	-0.012	-0.028
2	-194	-184	-183	-185	0.204	2.146	39.23	16.929	-0.009	-0.020
3	-191	-179	-179	-180	0.214	2.149	39.332	17.044	-0.001	-0.002
4	-189	-177	-177	-179	0.236	2.135	39.528	16.941	0.009	0.021
5	-191	-181	-181	-182	0.218	2.127	39.178	16.721	0.002	0.004
6	-188	-176	-176	-177	0.167	2.178	39.906	17.293	0.002	0.005
7	-187	-175	-174	-176	0.201	2.156	40.056	17.167	0.014	0.032
8	-198	-186	-185	-187	0.264	2.122	39.145	16.893	0.002	0.005
9	-196	-184	-183	-185	0.28	2.116	39.379	16.806	0.011	0.026
10	-197	-185	-184	-186	0.255	2.123	39.284	16.953	0.004	0.010
11	-195	-183	-183	-184	0.273	2.118	39.543	16.877	0.013	0.031

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

5.1.5 TSP Model Results and Evaluation

As noted in Section 6.4 of the Overview Report, the analysis for TSP evaluated the same 11 models as the analysis for PM_{10}. All the TSP models had at least one coefficient that was insignificant ($p > 0.05$); these are in boldface in Table 5-21. The lack of significant parameters might be due to the smaller number of observations available for TSP in the NAEMS dataset. Across all the models, ambient relative humidity and exhaust relative humidity both correlated negatively with TSP emissions, as anticipated. Across the models, exhaust temperature and ambient temperature showed inconsistent relationships with TSP, likely owing to the limited data available.

Table 5-22 provides the model fit statistics and the model evaluation statistics for the models. Scatter plots of the observed emissions versus the EEM predicted values are in Figures F-7 and F-8. The ME and NME values were relatively consistent across the models, while MB and NMB demonstrated more variability. Because all of the models contained insignificant parameters, with relatively similar evaluation statistics, EPA selected model 2 for further analysis, based on the PM_{10} results. Model 2 is as follows:

$$Farrowing\ room, ln(TSP) = 2.8589 + 0.0706 * cycleday\ + 0.1473 * LAW\ - 0.0049\ Amb_{RH} \quad \text{Equation 13}$$

Where:

$ln(TSP)$ = the natural log transformed predicted TSP emissions in grams per day (g day^{-1}).
$cycleday$ = day of the animal placement cycle (e.g., the day the sow is moved to the barn is cycle day 1).
LAW = live animal weight in thousands of kilograms (Mg).
Amb_{RH} = daily average ambient relative humidity (percent).

For the gestation barns, the same 11 models were evaluated, and most models had at least one coefficient that was insignificant. The exceptions were models 1, 2, and 5 (see Table 5-23). Across all the models, ambient relative humidity, ambient temperature, exhaust relative humidity, and exhaust temperature correlated negatively with TSP emissions, outcomes consistent with the PM_{10} models. The only exception was the ambient temperature in model 4. Scatter plots of the observed emissions versus the EEM predicted values are in Figures F-17 and F-18.

The model fit statistics and the model evaluation statistics in Table 5-24 are relatively similar across models. Based on the PM_{10} results for gestation barns, EPA selected Model 2 for further analysis, which is as follows:

$$Gestation\ Barn, ln(TSP) = 5.53397 + 0.0080 * Amb_{RH} + 0.0066 * LAW \quad \text{Equation 14}$$

Where:

ln(TSP) = the natural log transformed predicted TSP emissions in grams per day (g day^{-1}).

Amb_{RH} = average daily ambient relative humidity (percent).

LAW = live animal weight in thousands of kilograms (Mg).

Table 5-21. Parameters and estimates for the farrowing barn TSP models.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	2.510049	0.44876	<0.0001
1	cycleday	0.075409	0.01396	<0.0001
1	LAW	0.147389	0.07907	**0.0679**
2	Intercept	2.858928	0.47281	<0.0001
2	cycleday	0.070551	0.01348	<0.0001
2	LAW	0.147305	0.07879	**0.0679**
2	AmbRH	-0.00491	0.00263	**0.0644**
3	Intercept	2.801817	0.53016	<0.0001
3	cycleday	0.070724	0.01347	<0.0001
3	AmbT	0.001602	0.0066	**0.8086**
3	LAW	0.152652	0.08146	**0.0663**
3	AmbRH	-0.0049	0.00264	**0.0654**
4	Intercept	3.621464	0.56437	<0.0001
4	cycleday	0.069119	0.01319	<0.0001
4	AmbT	0.009349	0.00686	**0.1758**
4	LAW	0.124026	0.0784	**0.1201**
4	ExhRH	-0.01866	0.00497	0.0003
5	Intercept	3.56584	0.52094	<0.0001
5	cycleday	0.074342	0.01373	<0.0001
5	LAW	0.117031	0.07536	**0.1271**
5	ExhRH	-0.01586	0.00485	0.0014
6	Intercept	3.136307	0.38035	<0.0001
6	cycleday	0.080618	0.01299	<0.0001
6	AmbT	-0.00014	0.00638	**0.9821**
6	Inv	1.823107	0.92016	0.0497
6	AmbRH	-0.0047	0.00264	**0.0771**
7	Intercept	3.946555	0.43644	<0.0001
7	cycleday	0.076822	0.01279	<0.0001
7	AmbT	0.007496	0.00661	**0.2603**
7	Inv	1.31966	0.92362	**0.1558**
7	ExhRH	-0.01857	0.00501	0.0003
8	Intercept	3.341498	0.98955	0.001
8	cycleday	0.070461	0.01342	<0.0001
8	ExhT	-0.01684	0.03054	**0.5824**
8	LAW	0.136466	0.08079	**0.0971**
8	AmbRH	-0.0049	0.00263	**0.065**
9	Intercept	3.261496	0.97183	0.0011
9	cycleday	0.074396	0.01371	<0.0001
9	ExhT	0.01196	0.03205	**0.7096**
9	LAW	0.123135	0.077	**0.116**
9	ExhRH	-0.01638	0.00502	0.0014
10	Intercept	3.64785	0.87406	<0.0001

Model	Parameter	Estimate	Standard Error	p-value
10	cycleday	0.079772	0.01283	<0.0001
10	ExhT	-0.01918	0.03003	**0.5242**
10	Inv	1.716278	0.92608	**0.0661**
10	AmbRH	-0.00469	0.00262	**0.0762**
11	Intercept	3.575734	0.85828	<0.0001
11	cycleday	0.082153	0.0127	<0.0001
11	ExhT	0.010094	0.03162	**0.7501**
11	Inv	1.525284	0.86906	**0.0821**
11	ExhRH	-0.01665	0.00503	0.0012

Table 5-22. Fit and evaluation statistics for the farrowing barn TSP models.

Model	2LogL	AIC	AICc	BIC	Corr.	LNME[a] (%)	NME[b] (%)	ME[b] (kg day-1)	MB[b] (kg day-1)	NMB[b] (%)
1	76	86	87	99	0.647	11.557	46.236	45.176	4.221	4.320
2	67	79	80	94	0.678	10.953	41.732	40.709	1.883	1.930
3	67	81	82	99	0.682	10.938	41.595	40.576	1.594	1.634
4	56	70	71	87	0.749	10.391	38.741	39.115	-0.36	-0.357
5	64	76	77	91	0.712	10.885	42.398	42.834	3.573	3.536
6	67	81	82	98	0.695	10.636	40.967	39.963	1.224	1.255
7	57	71	72	88	0.759	10.347	38.636	39.009	-0.656	-0.650
8	67	81	82	98	0.684	10.824	41.148	40.139	1.97	2.02
9	64	78	79	95	0.711	10.88	42.533	42.97	3.328	3.295
10	67	81	82	98	0.701	10.53	40.322	39.333	1.357	1.391
11	64	78	79	95	0.735	10.605	41.237	41.662	2.121	2.099

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

[b] Based on back-transformed data.

Table 5-23. Parameters and estimates for the gestation barn TSP models.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	5.047799	0.50254	<0.0001
1	LAW	0.006649	0.00206	0.0048
2	Intercept	5.533966	0.56243	<0.0001
2	LAW	0.006601	0.0023	0.012
2	AmbRH	-0.008	0.00126	<0.0001
3	Intercept	5.718378	0.61185	<0.0001
3	AmbT	-0.003629	0.00358	**0.3121**
3	LAW	0.006107	0.00242	0.0228
3	AmbRH	-0.008349	0.00129	<0.0001
4	Intercept	6.587825	0.50241	<0.0001
4	AmbT	0.001207	0.00295	**0.6835**
4	LAW	0.005874	0.00189	0.0071
4	ExhRH	-0.02364	0.00236	<0.0001
5	Intercept	6.500666	0.42744	<0.0001
5	LAW	0.006073	0.00166	0.0021
5	ExhRH	-0.022781	0.00222	<0.0001
6	Intercept	6.375716	0.8023	<0.0001
6	AmbT	-0.005564	0.00341	**0.1041**
6	Inv	0.7009	0.74125	**0.36**
6	AmbRH	-0.008471	0.0013	<0.0001
7	Intercept	7.043938	0.69332	<0.0001
7	AmbT	-0.000342	0.00247	**0.89**
7	Inv	0.813449	0.63836	**0.2241**
7	ExhRH	-0.023564	0.0024	<0.0001
8	Intercept	6.336514	0.69604	<0.0001
8	ExhT	-0.019719	0.00831	0.0189
8	LAW	0.005016	0.0025	**0.0607**
8	AmbRH	-0.008459	0.00126	<0.0001
9	Intercept	6.863691	0.54038	<0.0001
9	ExhT	-0.009764	0.00659	**0.141**
9	LAW	0.005357	0.00186	0.0094
9	ExhRH	-0.022867	0.00224	<0.0001
10	Intercept	7.09542	0.64832	<0.0001
10	ExhT	-0.027513	0.00711	0.0002
10	Inv	0.515996	0.65632	**0.444**
10	AmbRH	-0.008555	0.00127	<0.0001
11	Intercept	7.443337	0.46078	<0.0001
11	ExhT	-0.017032	0.00268	<0.0001
11	Inv	0.722282	0.49451	**0.1627**
11	ExhRH	-0.022716	0.00226	<0.0001

Table 5-24. Fit and evaluation statistics for the gestation barn TSP models.

Model	2LogL	AIC	AICc	BIC	Corr.	LNME[a] (%)	NME[b] (%)	ME[b] (g day^{-1})	MB[b] (g day^{-1})	NMB[b] (%)
1	57	85	86	82	0.371	7.136	39.7	282	6.29	0.886
2	20	50	52	47	0.414	7.147	39.89	281	9.735	1.381
3	19	51	53	48	0.435	6.984	38.89	274	6.308	0.895
4	-29	3	5	0	0.621	6.19	34.7	247	1.107	0.156
5	-37	-7	-5	-10	0.621	6.046	33.77	242	2.378	0.332
6	25	57	59	54	0.388	7.306	40.9	288	-0.695	-0.099
7	-21	11	13	8	0.588	6.505	37.23	264	-1.382	-0.194
8	17	49	51	46	0.449	6.796	37.58	265	3.475	0.493
9	-38	-6	-4	-9	0.622	5.933	33.04	236	3.145	0.440
10	21	53	55	50	0.443	6.976	38.63	272	-7.087	-1.005
11	-31	1	3	-2	0.614	6.097	34.26	245	-4.521	-0.632

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

5.2 Grow-Finish Barns

For the grow-finish models, EPA explored two sets of models for NH_3 and H_2S. The first set consisted of a single model that did not make a distinction between manure management systems (the no pit model); the second set of models accounted for different manure management systems (pit models). The exploratory data analysis suggested that ambient temperature, exhaust temperature, inventory, and LAW should be considered in developing the models.

The types of manure management and storage systems used at the farm did not appear to have an impact on PM emissions. The exploratory data analysis suggested that EPA should consider ambient temperature, ambient relative humidity, exhaust temperature, exhaust temperature, exhaust relative humidity, inventory and LAW in the development of the models.

5.2.1 NH_3 Model Results and Evaluation

EPA developed six different models using a combination of four predictor variables—ambient temperature, exhaust temperature, inventory, and LAW. For both the "no pit" and "pit" model sets, the activity and temperature variables correlated positively with NH_3 emissions, as has been indicated in literature.

For the "no pit" models, all coefficients were significant ($p < 0.05$), see Table 5-25. The model fit statistics (-2 log Likelihood, AIC, AICc, and BIC) and the model evaluation statistics (ME, NME, MB, NMB) are provided in Table 5-26. Models 1, 3, and 4, which all contained LAW, and either the ambient temperature or exhaust temperature, had the lowest model fit values. The exhaust temperature and LAW models (models 1 and 3) had the two lowest mean

MEs, followed by models 3 and 5. Models 2 and 6 had the highest ME values, but were not very different from the other models.

EPA concluded that all six of the "no pit" models produced comparable model fit statistics and evaluation statistics. Therefore, EPA selected model 4 for further analysis because ambient temperature and LAW would be potentially easier to obtain than exhaust temperature. Model 4 is as follows:

$$ln(\mathrm{NH_3}) = 1.2363 + 0.00895 * Amb_T + 0.0089 * LAW \qquad \text{Equation 15}$$

Where:

$ln(NH_3)$ = the natural log transformed predicted NH_3 emissions in kilograms per day (kg day^{-1}).
Amb_T = ambient temperature (°C).
LAW = live animal weight in thousands of kilograms (Mg).

Table 5-27 and Table 5-28 provides the model fit statistics and the model evaluation statistics for the six "pit" models. Overall, the "pit" model rankings were similar to the "no pit" versions, with the models that contained LAW and either of the two temperature variables (i.e., models 1, 3, and 4) having the lowest model fit values. All six models produced comparable model fit statistics and evaluation statistics. EPA concluded that ambient temperature and LAW would be potentially easier to obtain and therefore selected model 4 for further analysis. Model 4 is as follows:

$$Shallow\ Pit: ln(y_p) = 1.1422 + 0.0091 * Amb_T + 0.0085 * LAW \qquad \text{Equation 16}$$

$$Deep\ Pit: ln(y_p) = 1.3424 + 0.0091 * Amb_T + 0.0085 * LAW \qquad \text{Equation 17}$$

Where:

Shallow pit $ln(y_p)$ = the natural log transformed predicted NH_3 emissions in shallow pit facilities in kilograms per day (kg day^{-1}).
Deep Pit: $ln(y_p)$= the natural log transformed predicted NH_3 emissions in deep pit facilities in kilograms per day (kg day^{-1}).
Amb_T = ambient temperature (°C).
LAW = live animal weight in thousands of kilograms (Mg).

Because the "no pit" and "pit" versions of the model performed similarly, EPA decided to further evaluate and consider both sets of EEMs.

Table 5-25. Parameters and estimates for the no pit grow-finish NH_3 models developed.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	1.028629	0.06199	<0.0001
1	Ambient Temp	0.004347	0.00132	*0.0010*
1	ExhsT	0.013342	0.00314	<0.0001
1	LAW	0.008451	0.00052	<0.0001
2	Intercept	1.267617	0.07386	<0.0001
2	Ambient Temp	0.004228	0.00137	*0.0020*
2	ExhsT	0.015666	0.00328	<0.0001
2	Inv	0.177549	0.04043	<0.0001
3	Intercept	0.913240	0.05235	<0.0001
3	ExhsT	0.021452	0.00185	<0.0001
3	LAW	0.008360	0.00051	<0.0001
4	Intercept	1.236262	0.03916	<0.0001
4	Ambient Temp	0.008953	0.00081	<0.0001
4	LAW	0.008939	0.00051	<0.0001
5	Intercept	1.171164	0.06556	<0.0001
5	ExhsT	0.023489	0.00195	<0.0001
5	Inv	0.154185	0.03880	<0.0001
6	Intercept	1.492383	0.05647	<0.0001
6	Ambient Temp	0.009613	0.00084	<0.0001
6	Inv	0.235848	0.03939	<0.0001

Table 5-26. Fit and evaluation statistics for the no pit grow-finish NH_3 models developed.

Model	2LogL	AIC	AICc	BIC	Corr.	LNME[a] (%)	NME[b] (%)	ME[b] (kg day^{-1})	MB[b] (kg day^{-1})	NMB[b] (%)
1	-2,883	-2,847	-2,847	-2,848	0.681	13.232	27.129	1.654	0.013	0.206
2	-2,755	-2,719	-2,719	-2,720	0.238	17.861	36.314	2.214	0.029	0.470
3	-2,968	-2,934	-2,934	-2,935	0.693	13.309	27.009	1.632	-0.008	-0.129
4	-2,866	-2,832	-2,832	-2,833	0.674	13.338	27.435	1.673	0.027	0.439
5	-2,831	-2,797	-2,797	-2,798	0.304	17.949	36.344	2.196	0.000	0.008
6	-2,734	-2,700	-2,700	-2,701	0.188	18.066	36.727	2.240	0.045	0.733

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

Table 5-27. Parameters and estimates for the pit grow-finish NH_3 models developed.

Model	Parameter	Estimate	Standard Error	p-value
1	Deep	1.124059	0.06400	<0.0001
1	Shallow	0.920418	0.06548	<0.0001
1	Ambient Temp	0.004275	0.00132	0.0012
1	ExhsT	0.013952	0.00313	<0.0001
1	LAW	0.008080	0.00052	<0.0001
2	Deep	1.415308	0.08386	<0.0001
2	Shallow	1.151833	0.07895	<0.0001
2	Ambient Temp	0.003980	0.00137	0.0037
2	ExhsT	0.016534	0.00329	<0.0001
2	Inv	0.144983	0.04258	0.0007
3	Deep	1.007922	0.05438	<0.0001
3	Shallow	0.809468	0.05609	<0.0001
3	ExhsT	0.021950	0.00185	<0.0001
3	LAW	0.007990	0.00050	<0.0001
4	Deep	1.342386	0.04249	<0.0001
4	Shallow	1.142239	0.04362	<0.0001
4	Ambient Temp	0.009077	0.00081	<0.0001
4	LAW	0.008545	0.00051	<0.0001
5	Deep	1.327761	0.07679	<0.0001
5	Shallow	1.062030	0.07049	<0.0001
5	ExhsT	0.023880	0.00195	<0.0001
5	Inv	0.122264	0.04096	0.0029
6	Deep	1.644386	0.07165	<0.0001
6	Shallow	1.398875	0.06257	<0.0001
6	Ambient Temp	0.009662	0.00084	<0.0001
6	Inv	0.208959	0.04138	<0.0001

Table 5-28. Fit and evaluation statistics for the pit grow-finish NH_3 models developed.

Model	2LogL	AIC	AICc	BIC	Corr.	LNME[a] (%)	NME[b] (%)	ME[b] (kg day^{-1})	MB[b] (kg day^{-1})	NMB[b] (%)
1	-2,903	-2,865	-2,865	-2,866	0.719	12.231	25.503	1.555	0.037	0.606
2	-2,767	-2,729	-2,729	-2,730	0.402	16.584	33.264	2.028	0.019	0.315
3	-2,988	-2,952	-2,952	-2,953	0.731	12.297	25.373	1.533	0.018	0.294
4	-2,885	-2,849	-2,848	-2,850	0.712	12.346	25.799	1.573	0.049	0.798
5	-2,844	-2,808	-2,808	-2,809	0.450	16.592	33.105	2	-0.008	-0.131
6	-2,744	-2,708	-2,708	-2,709	0.353	16.957	34.126	2.081	0.041	0.67

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

5.2.2 H_2S Model Results and Evaluation

EPA developed six different models based on the four identified predictor variables—ambient temperature, exhaust temperature, inventory, and LAW. For all models, LAW and inventory have a significant ($p < 0.05$) positive correlation with H_2S emissions. This was expected based on the literature reviews and analysis. The ambient temperature has a significant negative correlation with H_2S emissions, meaning that as ambient temperature decreases, emissions increase. This runs counter to observations on barn sources reported in Section 3.1, but is consistent with the linear regressions of H_2S emissions from finishing sites reported in Section 4.3. Across the models, exhaust temperature shows both a positive and negative relationship with emissions.

For the "no pit" version of the models (Table 5-29), the exhaust temperature coefficients were not significant ($p > 0.05$) in models 2 and 3. Because the coefficient was found insignificant in models 2 and 3, EPA removed these two models from further consideration. In models 1 and 5, the exhaust temperature coefficients remained significant and EPA retained them for further consideration.

Table 5-30 provides the model fit statistics and the model evaluation statistics for the six H_2S models. EPA concluded that the four models remaining under consideration (1, 4, 5, and 6) produced comparable model fit statistics and evaluation statistics. NME values varied between 83.94 and 90.85%, and NMB ranged from 0.535% to 4.912%. With similar model fit and evaluation statistics, EPA selected model 4 because its parameters are easily obtainable by users. These inputs for model 4 are the same as the selected NH_3 model, which further reduces the input gathering burden. Model 4 is as follows:

$$ln(H_2S) = 4.0820 - 0.0066 * Amb_T + 0.0172 * LAW \quad \text{Equation 18}$$

Where:

ln(H₂S) = the natural log transformed predicted H_2S emissions in grams per day (g day^{-1}).
Amb_T = ambient temperature (°C).
LAW = live animal weight in thousands of kilograms (Mg).

For the "pit" model set, all exhaust temperature coefficients were insignificant ($p > 0.05$). (see Table 5-31 and Table 5-32). The two models that contained ambient temperature variables and inventory or LAW (i.e., models 1 and 6) were the only models with significant coefficients for all parameters. Model 4 had slightly better fit statistics and evaluation statistics; therefore, EPA decided to review model 4 further as a potential EEM. Model 4 is as follows:

$$Shallow\ Pit: ln(H_2S) = 4.1905 - 0.0055 * Amb_T + 0.0133 * LAW \quad \text{Equation 19}$$

$$Deep\ Pit: ln(H_2S) = 4.9916 + 0.0055 * Amb_T + 0.0133 * LAW \quad \text{Equation 20}$$

Where:

$ln(H_2S)$ = the natural log transformed predicted H_2S emissions in grams per day (g day^{-1}).

Amb_T = ambient temperature (°C).

LAW = live animal weight in thousands of kilograms (Mg).

The "pit" model performed slightly better with respect to model fit statistics, than the "no pit" version of the model. However, EPA decided to perform model validation on both sets of models and further consideration as an EEM.

Table 5-29. Parameters and estimates for the no pit H_2S finishing models developed.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	3.828226	0.15457	<0.0001
1	Ambient Temp	-0.010738	0.00256	<0.0001
1	Exhaust Temp	0.014873	0.00716	0.0380
1	LAW	0.016662	0.00153	<0.0001
2	Intercept	4.352401	0.15505	<0.0001
2	Ambient Temp	-0.010445	0.00264	<0.0001
2	Exhaust Temp	0.012584	0.00750	**0.0936**
2	Inv	0.479303	0.07728	<0.0001
3	Intercept	4.114478	0.13359	<0.0001
3	Exhaust Temp	-0.007280	0.00442	**0.0997**
3	LAW	0.017307	0.00153	<0.0001
4	Intercept	4.081979	0.09500	<0.0001
4	Ambient Temp	-0.006592	0.00161	<0.0001
4	LAW	0.017163	0.00151	<0.0001
5	Intercept	4.637743	0.13164	<0.0001
5	Exhaust Temp	-0.009723	0.00454	0.0324
5	Inv	0.538907	0.07433	<0.0001
6	Intercept	4.559343	0.09387	<0.0001
6	Ambient Temp	-0.006960	0.00163	<0.0001
6	Inv	0.519982	0.07361	<0.0001

Table 5-30. Fit and evaluation statistics for the no pit H_2S finishing models developed.

Model	2LogL	AIC	AICc	BIC	Corr.	LNME[a] (%)	NME[b] (%)	ME[b] (g day^{-1})	MB[b] (g day^{-1})	NMB[b] (%)
1	3,110	3,146	3,146	3,145	0.377	17.443	83.944	294.42	15.792	4.503
2	3,174	3,210	3,210	3,209	0.225	18.090	89.751	314.79	1.876	0.535
3	3,207	3,241	3,241	3,240	0.369	17.658	84.291	294.15	15.140	4.339
4	3,114	3,148	3,148	3,147	0.371	17.483	84.295	295.66	17.283	4.927
5	3,270	3,304	3,304	3,303	0.188	18.326	90.851	317.04	4.912	1.408
6	3,177	3,211	3,211	3,210	0.205	18.111	90.378	316.99	4.146	1.182

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

Table 5-31. Parameters and estimates for the pit grow-finish H_2S models developed.

Model	Parameter	Estimate	Standard Error	p-value
1	Deep	4.881262	0.20312	<0.0001
1	Shallow	4.076802	0.20572	<0.0001
1	Ambient Temp	-0.007641	0.00330	0.0205
1	Exhaust Temp	0.006977	0.00859	**0.4169**
1	LAW	0.013027	0.00176	<0.0001
2	Deep	5.194357	0.20687	<0.0001
2	Shallow	4.361626	0.21300	<0.0001
2	Ambient Temp	-0.007357	0.00335	0.0284
2	Exhaust Temp	0.005595	0.00883	**0.5262**
2	Inv	0.507381	0.10628	<0.0001
3	Deep	5.055498	0.18008	<0.0001
3	Shallow	4.226298	0.18395	<0.0001
3	Exhaust Temp	-0.007016	0.00514	**0.1728**
3	LAW	0.013636	0.00174	<0.0001
4	Deep	4.991579	0.15159	<0.0001
4	Shallow	4.190492	0.15138	<0.0001
4	Ambient Temp	-0.005539	0.00202	0.0062
4	LAW	0.013317	0.00173	<0.0001
5	Deep	5.369327	0.18585	<0.0001
5	Shallow	4.513433	0.19158	<0.0001
5	Exhaust Temp	-0.007894	0.00521	**0.1299**
5	Inv	0.536013	0.10299	<0.0001
6	Deep	5.277375	0.16029	<0.0001
6	Shallow	4.450293	0.16093	<0.0001
6	Ambient Temp	-0.005676	0.00203	0.0052
6	Inv	0.527087	0.10200	<0.0001

Table 5-32. Fit and evaluation statistics for the pit grow-finish H_2S models developed.

Model	2LogL	AIC	AICc	BIC	Corr.	LNME[a] (%)	NME[b] (%)	ME[b] (g day^{-1})	MB[b] (g day^{-1})	NMB[b] (%)
1	3656	3670	3670	3669	0.466	16.216	76.237	267.39	2.398	0.684
2	3686	3700	3700	3699	0.357	17.314	85.62	300.3	10.25	2.922
3	3766	3778	3778	3778	0.474	16.237	75.648	263.98	1.605	0.46
4	3656	3668	3669	3668	0.463	16.247	76.412	268	3.241	0.924
5	3798	3810	3810	3810	0.361	17.39	85.544	298.52	10.012	2.869
6	3686	3698	3698	3698	0.352	17.362	86.135	302.11	11.613	3.311

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

5.2.3 PM_{10} Model Results and Evaluation

The exploratory data analysis suggested that EPA should consider ambient temperature, ambient relative humidity, exhaust temperature, exhaust relative humidity, inventory, and LAW in the development of the PM_{10} models. EPA evaluated 13 models, each with a different combination of the six predictor variables (Figures F-23 and F-24). For all models, as expected, LAW and inventory again had significant positive correlations with emissions (Table 5-33). Similar to the breeding and gestation barns, the ambient and exhaust relative humidity and temperature parameters have a significant negative correlation with PM_{10} emissions.

The ambient temperature coefficients in Table 5-33 proved to be insignificant ($p > 0.05$) for models 3 and 4, so EPA removed these two models from further consideration. The coefficients for all other models were significant ($p < 0.05$). Table 5-34 provides the model fit statistics and the model evaluation statistics for the 11 models considered. Out of these 11 models considered, models 9 and 5 had the lowest model fit values. Models 5 and 4 had the two lowest mean MEs, followed by models 9 and 2. Models 11 and 6 had the highest ME values. Across the 11 models, ME ranged from 66.387 g day^{-1} (for model 5) to 99.401 g day^{-1} (for model 11), which produced NME values of 35.715% and 53.476%, respectively, a difference of 17.76%. Across the 11 models, MB ranged from 3.419 g day^{-1} (model 5) to 13.52 g day^{-1} (model 11). The corresponding NMBs ranged from 1.84% (model 5) to 7.274% (model 11). The positive values indicate that the model is over-predicting compared to measured (observed) values.

To pare down the 11 models and select a candidate EEM, EPA limited the set to those models with an NME less than 40%. This criterion left models 1, 2, 3, 4, 5, 8, and 9. Most of these seven best-fitting models included exhaust relative humidity (models 4, 5, 8, and 9), which is not a routinely collected parameter. EPA concluded that the remaining three models (1, 2, and 3) produced comparable model fit statistics and evaluation statistics. EPA selected model 2 for further analysis, because it included a readily available moisture parameter. Model 2 is as follows:

$$ln(PM_{10}) = 5.5039 - 0.0094 * Amb_{RH} + 0.0104 * LAW \quad \text{Equation 21}$$

Where:

$ln(PM_{10})$ = the natural log transformed predicted PM_{10} emissions in grams per day (g day^{-1}).
Amb_{RH} = ambient relative humidity (percent).
LAW = live animal weight in thousands of kilograms (Mg).

Table 5-33. Parameters and estimates for the PM_{10} finishing models developed.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	4.827106	0.03924	<0.0001
1	LAW	0.011002	0.00067	<0.0001
2	Intercept	5.503943	0.04999	<0.0001
2	LAW	0.010447	0.00066	<0.0001
2	Ambient RH	-0.009403	0.00044	<0.0001
3	Intercept	5.559664	0.05575	<0.0001
3	Ambient Temp	-0.002254	0.00122	**0.0656**
3	LAW	0.010372	0.00068	<0.0001
3	Ambient RH	-0.009606	0.00046	<0.0001
4	Intercept	6.212768	0.06174	<0.0001
4	Ambient Temp	-0.001257	0.00112	**0.2623**
4	LAW	0.009975	0.00063	<0.0001
4	Exhaust RH	-0.021830	0.00074	<0.0001
5	Intercept	6.196228	0.05891	<0.0001
5	LAW	0.010083	0.00062	<0.0001
5	Exhaust RH	-0.021951	0.00073	<0.0001
6	Intercept	5.601306	0.07235	<0.0001
6	Ambient Temp	-0.003847	0.00127	0.0025
6	Inv	0.611182	0.06029	<0.0001
6	Ambient RH	-0.009735	0.00046	<0.0001
7	Intercept	6.345648	0.07928	<0.0001
7	Ambient Temp	-0.003070	0.00117	0.0090
7	Inv	0.501598	0.05839	<0.0001
7	Exhaust RH	-0.021901	0.00074	<0.0001
8	Intercept	5.677437	0.07953	<0.0001
8	Exhaust Temp	-0.007965	0.00279	0.0044
8	LAW	0.010555	0.00068	<0.0001
8	Ambient RH	-0.009319	0.00044	<0.0001
9	Intercept	6.406988	0.08168	<0.0001
9	Exhaust Temp	-0.009524	0.00254	0.0002
9	LAW	0.010212	0.00065	<0.0001
9	Exhaust RH	-0.021880	0.00073	<0.0001
10	Intercept	5.736529	0.09043	<0.0001
10	Exhaust Temp	-0.011636	0.00289	<0.0001
10	Inv	0.673236	0.05806	<0.0001
10	Ambient RH	-0.009382	0.00043	<0.0001
11	Intercept	6.544987	0.09438	<0.0001
11	Exhaust Temp	-0.013957	0.00264	<0.0001
11	Inv	0.607481	0.05467	<0.0001
11	Exhaust RH	-0.022011	0.00073	<0.0001

Table 5-34. Fit and evaluation statistics for the PM_{10} finishing models developed.

Model	2LogL	AIC	AICc	BIC	Corr.	LNME[a] (%)	NME[b] (%)	ME[b] (kg day^{-1})	MB[b] (kg day^{-1})	NMB[b] (%)
1	-380	-348	-348	-349	0.587	5.336	39.511	73.327	3.936	2.121
2	-765	-731	-731	-732	0.618	5.126	37.858	70.505	4.299	2.308
3	-693	-657	-657	-658	0.609	5.210	38.540	71.922	4.631	2.437
4	-1024	-988	-988	-989	0.638	5.008	36.294	67.858	3.451	1.819
5	-1098	-1064	-1063	-1064	0.641	4.929	35.715	66.387	3.419	1.840
6	-587	-551	-551	-552	0.274	6.988	51.916	96.883	9.185	4.791
7	-896	-860	-859	-861	0.296	6.960	51.805	96.860	10.050	5.315
8	-773	-737	-737	-738	0.611	5.185	38.316	71.359	4.567	2.452
9	-1111	-1075	-1075	-1076	0.629	5.032	36.441	67.737	3.955	2.128
10	-671	-635	-635	-636	0.266	6.986	52.055	96.947	10.301	5.531
11	-995	-959	-959	-960	0.277	7.098	53.476	99.401	13.520	7.274

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

5.2.4 $PM_{2.5}$ Model Results and Evaluation

During initial EEM development, results suggested that there were a few outliers in the $PM_{2.5}$ emissions data. These data were particularly low (negative) and were impacting the likelihood of finding significant relationships with the predictive parameters. To mitigate this, EPA removed the bottom 5% of the data. From the revised dataset, EPA developed 13 models based on different combinations of the 6 predictor variables—ambient temperature, exhaust temperature, ambient relative humidity, exhaust relative humidity, inventory, and LAW (Figures F-25 and F-26). Table 5-35 shows that the inventory coefficients were not significant ($p > 0.05$) across the models where they were included (models 7, 8, 9, 11, 12, and 13). Models 3 and 10 also had insignificant coefficients for two of its three parameters. EPA removed from consideration eight models that had at least one non-significant parameter. For the models with significant coefficients, the parameters have relationships that are consistent with the PM_{10} models.

Table 5-36 provides the model fit statistics and the model evaluation statistics for the models. Out of the five models still under consideration, models 5 and 4 had the lowest model fit statistic values. For the evaluation statistics, all five models produced comparable model fit statistics and evaluation statistics. Therefore, EPA selected model 2 for further analysis because it is consistent with the parameters for the PM_{10}. Model 2 is as follows:

$$ln(PM_{2.5}) = 2.4954 - 0.0023 * Amb_{RH} + 0.01095 * LAW \qquad \text{Equation 22}$$

Where:

$ln(PM_{2.5})$ = the natural log transformed predicted $PM_{2.5}$ emissions in grams per day (g day^{-1}).

Amb_{RH} = ambient relative humidity (percent).

LAW = live animal weight in thousands of kilograms (Mg).

Table 5-35. Parameters and estimates for the $PM_{2.5}$ finishing models developed.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	2.302348	0.11809	<0.0001
1	LAW	0.011715	0.00236	0.0001
2	Intercept	2.495430	0.19623	<0.0001
2	LAW	0.010950	0.00334	0.0041
2	Ambient RH	-0.002279	0.00086	0.0089
3	Intercept	2.537710	0.19484	<0.0001
3	Ambient Temp	0.009621	0.00485	**0.0514**
3	LAW	0.008145	0.00432	**0.0697**
3	Ambient RH	-0.003306	0.00102	0.0017
4	Intercept	2.288922	0.12719	<0.0001
4	LAW	0.009030	0.00405	0.0338
4	Ambient Temp	0.007974	0.00484	**0.1041**
5	Intercept	2.663306	0.21940	<0.0001
5	Ambient Temp	0.010045	0.00452	0.0296
5	LAW	0.009193	0.00382	0.0225
5	Exhaust RH	-0.006906	0.00200	0.0008
6	Intercept	2.622421	0.18732	<0.0001
6	LAW	0.011931	0.00267	0.0004
6	Exhaust RH	-0.005534	0.00156	0.0006
7	Intercept	3.005931	0.51392	<0.0001
7	Ambient Temp	0.012476	0.00222	<0.0001
7	Inventory	0.002496	0.71390	**0.9972**
7	Ambient RH	-0.004533	0.00083	<0.0001
8	Intercept	3.342486	0.63180	<0.0001
8	Ambient Temp	0.011141	0.00257	<0.0001
8	Inventory	-0.000151	0.91844	**0.9999**
8	Exhaust RH	-0.009457	0.00078	<0.0001
9	Intercept	3.425887	0.56136	<0.0001
9	Inventory	-0.068691	0.83535	**0.9355**
9	Exhaust RH	-0.006851	0.00119	<0.0001
10	Intercept	2.166443	0.26835	<0.0001
10	Exhaust Temp	0.026396	0.02002	**0.1941**
10	LAW	0.009100	0.00556	**0.1142**
10	Exhaust RH	-0.006921	0.00229	0.0031
11	Intercept	2.340817	0.45361	<0.0001
11	Exhaust Temp	0.034826	0.00664	<0.0001
11	Inventory	-0.092030	0.62158	**0.8838**
11	Ambient RH	-0.003798	0.00077	<0.0001
12	Intercept	2.683586	0.58096	<0.0001
12	Exhaust Temp	0.033497	0.01025	0.0017

Model	Parameter	Estimate	Standard Error	p-value
12	Inventory	-0.094859	0.78141	**0.9045**
12	Exhaust RH	-0.008958	0.00110	<0.0001
13	Intercept	3.425856	0.50153	<0.0001
13	Inventory	-0.068685	0.66384	**0.9190**
13	Exhaust RH	-0.006851	0.00205	0.0011

Table 5-36. Fit and evaluation statistics for the $PM_{2.5}$ finishing models developed.

Model	2LogL	AIC	AICc	BIC	Corr.	LNME[a] (%)	NME[b] (%)	ME[b] (kg day^{-1})	MB[b] (kg day^{-1})	NMB[b] (%)
1	-134	-102	-100	-103	0.528	9.599	52.191	6.173	0.556	4.702
2	-143	-109	-107	-110	0.515	9.852	52.742	6.123	0.442	2.362
3	-173	-137	-134	-138	0.596	9.925	48.760	5.660	-0.355	-3.055
4	-157	-123	-121	-124	0.600	9.594	48.491	5.629	-0.288	-2.480
5	-175	-139	-136	-140	0.559	10.066	49.101	5.729	-0.211	-1.807
6	-141	-107	-104	-108	0.493	10.123	54.031	6.304	0.709	6.078
7	-142	-106	-103	-107	0.063	13.036	64.663	7.507	0.294	2.532
8	-141	-105	-102	-106	-.077	13.132	66.716	7.784	0.458	3.923
9	-115	-81	-79	-82	-.209	13.095	67.272	7.849	0.114	0.978
10	-163	-127	-124	-128	0.499	11.022	52.957	6.179	-0.018	-0.156
11	-132	-96	-93	-97	0.046	13.818	65.828	7.642	0.313	2.697
12	-132	-96	-93	-97	-.086	13.980	67.534	7.880	0.457	3.921
13	-115	-81	-79	-82	-.209	13.095	67.272	7.849	0.114	0.978

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

5.2.5 TSP Models Results and Evaluation

For TSP, EPA evaluated the same 13 models as were evaluated for PM_{10} (Table 5-37, Figures F-27 and F-28). The correlations between predictor variables and emissions were consistent with the PM_{10} results. All the coefficients proved to be significant ($p < 0.05$) across all the models. Table 5-38 provides the model fit statistics and the model evaluation statistics for the 13 models. All 13 models produced comparable model fit statistics and evaluation statistics. When selecting a model for further analysis, EPA again considered ease of use and the model selected for PM_{10}, and selected model 2 for further analysis. Model 2 is as follows:

$$ln(TSP) = 6.266 - 0.0088 * Amb_{RH} + 0.0118 * LAW \qquad \text{Equation 23}$$

Where:

$ln(TSP)$ = the natural log transformed predicted TSP emissions in grams per day (g day^{-1}).
Amb_{RH} = ambient relative humidity (percent).
LAW = live animal weight in thousands of kilograms (Mg).

Table 5-37. Parameters and estimates for the TSP finishing models developed.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	5.815769	0.18411	<0.0001
1	LAW	0.009746	0.00262	0.0005
2	Intercept	6.266140	0.23119	<0.0001
2	LAW	0.011813	0.00296	0.0007
2	Ambient RH	-0.008831	0.00185	<0.0001
3	Intercept	6.559145	0.27572	<0.0001
3	Ambient Temp	-0.009011	0.00442	0.0430
3	LAW	0.010805	0.00357	0.0059
3	Ambient RH	-0.009409	0.00203	<0.0001
4	Intercept	6.039034	0.20592	<0.0001
4	LAW	0.009656	0.00273	0.0010
4	Ambient Temp	-0.012453	0.00421	0.0035
5	Intercept	7.245363	0.22578	<0.0001
5	Ambient Temp	-0.008719	0.00366	0.0184
5	LAW	0.010740	0.00200	<0.0001
5	Exhaust RH	-0.023151	0.00305	<0.0001
6	Intercept	7.136576	0.21238	<0.0001
6	LAW	0.010837	0.00188	<0.0001
6	Exhaust RH	-0.023971	0.00300	<0.0001
7	Intercept	6.399395	0.33301	<0.0001
7	Ambient Temp	-0.011020	0.00415	0.0086
7	Inv	0.791571	0.28704	0.0074
7	Ambient RH	-0.006994	0.00209	0.0010
8	Intercept	7.180636	0.34955	<0.0001
8	Ambient Temp	-0.009588	0.00394	0.0157
8	Inv	0.613911	0.27245	0.0273
8	Exhaust RH	-0.019279	0.00317	<0.0001
9	Intercept	6.799693	0.40577	<0.0001
9	Inv	1.028981	0.27200	0.0006
9	Exhaust RH	-0.020994	0.00403	<0.0001
10	Intercept	8.191352	0.35972	<0.0001
10	Exhaust Temp	-0.033454	0.01041	0.0016
10	LAW	0.010413	0.00231	0.0003
10	Exhaust RH	-0.027139	0.00342	<0.0001
11	Intercept	6.850755	0.40872	<0.0001
11	Exhaust Temp	-0.030522	0.01080	0.0051
11	Inv	0.842748	0.27876	0.0035
11	Ambient RH	-0.006462	0.00195	0.0011
12	Intercept	7.673387	0.58625	<0.0001
12	Exhaust Temp	-0.027327	0.01192	0.0232
12	Inv	0.851755	0.31108	0.0090
12	Exhaust RH	-0.022106	0.00421	<0.0001
13	Intercept	6.799693	0.40577	<0.0001

Model	Parameter	Estimate	Standard Error	p-value
13	Inv	1.028981	0.27200	0.0006
13	Exhaust RH	-0.020994	0.00403	<0.0001

Table 5-38. Fit and evaluation statistics for the TSP finishing models developed.

Model	2LogL	AIC	AICc	BIC	Corr.	LNME[a] (%)	NME[b] (%)	ME[b] (kg day^{-1})	MB[b] (kg day^{-1})	NMB[b] (%)
1	-4	4	4	3	0.416	6.568	37.64	261.54	8.336	1.200
2	-56	-22	-19	-23	0.565	5.932	34.59	240.34	3.082	0.444
3	-35	1	5	0	0.614	5.885	33.718	241.72	-4.063	-0.567
4	10	20	20	19	0.436	6.78	39.849	285.67	16.214	2.262
5	-38	-26	-25	-26	0.773	4.759	28.35	203.24	-16.39	-2.286
6	-56	-46	-46	-46	4.753	27.844	193.47	-20.26	-2.915	4.753
7	2	14	14	13	6.183	34.935	250.44	-16.01	-2.234	6.183
8	-22	-10	-9	-10	5.536	31.604	226.57	-16.13	-2.250	5.536
9	-89	-55	-52	-55	5.818	34.114	237.04	-4.862	-0.700	5.818
10	-107	-71	-68	-72	4.456	26.624	185	-21.12	-3.040	4.456
11	-21	-9	-9	-10	6.05	35.242	244.87	-16.32	-2.349	6.05
12	-96	-60	-56	-61	5.074	30.063	208.89	-7.858	-1.131	5.074
13	-89	-55	-52	-55	0.748	4.907	28.69	199.35	-13.86	-1.995

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

5.3 Lagoons

The exploratory data analysis suggested that EPA should consider ambient temperature, lagoon temperature, wind speed, pH, and LAW in the development of the models. Differences in animal management practices, including feed composition, can affect the nitrogen and sulfur load to the lagoons; this was supported by differences in emissions trends across the sites. Based on this information from the literature review and exploratory data analysis, EPA decided to develop separate EEMs for lagoons at different types of swine farms (i.e., breeding and gestation, and grow-finish farms).

Because emissions emanate from the surface of the lagoon, the size of the surface area of the lagoon will affect emissions. Additionally, the size of the lagoon is often proportional to the number of animals the lagoon services. For these reasons, EPA normalized the lagoon emissions by the surface area (Table C-6) to better account for size variations, both in surface area and animals serviced, across the farms.

5.3.1 NH_3 Model Results and Evaluation

For breeding and gestation lagoons, EPA developed 12 models based on different combinations of the four predictor variables—ambient temperature, lagoon temperature, wind speed, and pH (Figures F-29 and F-30). Only the first six models had coefficients that were all significant ($p< 0.05$), and none of them included pH. Across all the models, the parameters correlated positively with NH_3 emissions, meaning that as temperature, wind speed, or pH increase, so do the emissions (Table 5-39). The only exceptions were pH in models 8 and 11. These positive relationships are consistent with the typical trends reported in literature.

Table 5-40 provides the model fit statistics (-2 log Likelihood, AIC, AICc, and BIC) and the model evaluation statistics (ME, NME, MB, and NMB) for the models. Of the six models with significant coefficients, the ME ranged from 1.434 g $day^{-1}m^{-2}$ (model 5) to 2.68 g $day^{-1}m^{-2}$ (model 3), which produced NME values of 23.847% and 40.226%, respectively. The MB of these models ranged from -0.427 to 0.187 g $day^{-1}m^{-2}$ (for models 2 and 3, respectively), which resulted in NMBs of -7.097% and 2.803%. The positive (or negative) NMB values indicate that the model is over- or under-predicting emissions relative to measured (observed) values.

Overall, model 5 had superior model evaluation statistics, and its parameters are easily obtained by operators; EPA therefore selected model 5 for further analysis. Model 5 is as follows:

$$Breeding\ Gestation\ Lagoon, ln(NH_3) = 0.5821 + 0.0557 * Amb_T + 0.0914 * ws \qquad \text{Equation 24}$$

Where:

$ln(NH_3)$ = the natural log transformed predicted NH_3 emissions in grams per day per square meter of surface area (g day^{-1} m^{-2}).
Amb_T = average daily ambient temperature (°C).
ws = average daily wind speed in meters per second (m/s) at a height of 2.5 meters.

For the grow-finish lagoons, EPA evaluated the same 12 models developed for the breeding and gestation lagoons (Table 5-41, Figures F-31 and F-32). Only models 3, 5, 6, and 12 had coefficients that were all significant ($p < 0.05$). Across all the models, the parameters correlate positively with NH_3 emissions, meaning that as temperature, wind speed, or pH increase, so do the emissions (Table 5-41). The only exception was pH in model 11. These positive relationships are consistent with the typical trends reported in literature.

Table 5-42 provides the model fit statistics and model evaluation statistics. Of the four models with significant coefficients, the ME ranged from 0.845 g $day^{-1}m^{-2}$ (model 12) to 1.781 g $day^{-1}m^{-2}$ (model 3), which produced NME values of 21.941% and 45.432%, respectively. The models had an MB range of -0.208 to 0.083 g $day^{-1}m^{-2}$, with NMBs of -4.913 to 1.974%, for models 5 and 3, respectively.

Overall, model statistics were inconsistently robust, with some models performing well on some statistics and worse on others. Therefore, when selecting a model for further analysis, EPA considered potential ease of use and concluded that ambient temperatures are easier to obtain than lagoon temperatures. Therefore, EPA selected model 5 for further analysis. Model 5 is as follows:

$$Grow\ Finish\ Lagoon, ln(NH_3) = -0.6801 + 0.0854 * Amb_T + 0.1319 * ws \quad \text{Equation 25}$$

Where:

$ln(NH_3)$ = the natural log transformed predicted NH_3 emissions in grams per day per square meter of surface area (g day^{-1} m^{-2}).
Amb_T = the average daily ambient temperature (°C).
ws = average daily wind speed in meters per second (m/s) at a height of 2.5 meters.

Table 5-39. Parameters and estimates for the swine breeding and gestation lagoon NH_3 models developed.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	0.875636	0.18288	0.0001
1	Air Temp	0.023209	0.0073	0.0021
1	Lagoon Temp	0.031408	0.01196	0.0115
2	Intercept	1.344128	0.11277	<0.0001
2	Air Temp	0.029756	0.00492	<0.0001
3	Intercept	0.771804	0.19814	0.0009
3	Lagoon Temp	0.057949	0.00946	<0.0001
4	Intercept	0.556905	0.16137	0.0023
4	Air Temp	0.012147	0.00565	0.0346
4	Lagoon Temp	0.045369	0.00987	<0.0001
4	WS	0.062766	0.00781	<0.0001
5	Intercept	0.582053	0.07702	<0.0001
5	Air Temp	0.055673	0.00268	<0.0001
5	WS	0.091428	0.01123	<0.0001
6	Intercept	0.486491	0.16366	0.0072
6	Lagoon Temp	0.059394	0.00766	<0.0001
6	WS	0.066408	0.00778	<0.0001
7	Intercept	1.335634	1.97264	**0.5006**
7	Air Temp	0.0646	0.01385	<0.0001
7	Lagoon Temp	-0.018755	0.01441	**0.1974**
7	pH	-0.022843	0.24719	**0.9266**
8	Intercept	1.965956	2.47673	**0.4301**
8	Air Temp	0.027168	0.00701	0.0002
8	pH	-0.074201	0.31181	**0.8126**
9	Intercept	0.265574	2.55621	**0.9176**
9	Lagoon Temp	0.052431	0.0123	0.0004
9	pH	0.073016	0.31363	**0.8166**
10	Intercept	-0.860651	1.95067	**0.6604**
10	Air Temp	0.010235	0.00606	**0.097**
10	Lagoon Temp	0.045602	0.01183	0.0005
10	WS	0.05794	0.00855	<0.0001
10	pH	0.181902	0.23885	**0.4488**
11	Intercept	1.492571	1.38919	**0.2863**
11	Air Temp	0.055412	0.00409	<0.0001
11	WS	0.108678	0.01318	<0.0001
11	pH	-0.128854	0.17588	**0.4662**
12	Intercept	-0.759231	1.9849	**0.7032**
12	Lagoon Temp	0.056318	0.01014	<0.0001
12	WS	0.060473	0.00861	<0.0001
12	pH	0.164322	0.24292	**0.501**

Table 5-40. Fit and evaluation statistics for the swine breeding and gestation lagoon NH_3 models developed.

Model	2LogL	AIC	AICc	BIC	Corr.	LNME[a] (%)	NME[b] (%)	ME[b] (g day^{-1}m^{-2})	MB[b] (g day^{-1}m^{-2})	NMB[b] (%)
1	-18	-8	-8	-13	0.766	16.295	35.896	2.392	0.022	0.333
2	-17	-9	-9	-13	0.827	18.015	41.954	2.523	-0.427	-7.097
3	-9	-1	0	-4	0.706	18.238	40.226	2.68	0.187	2.803
4	-67	-55	-54	-61	0.859	13.151	28.712	1.913	-0.184	-2.766
5	22	30	30	26	0.894	10.626	23.847	1.434	-0.001	-0.009
6	-63	-53	-52	-57	0.838	13.975	30.47	2.03	-0.136	-2.045
7	59	69	70	65	0.731	15.613	37.344	2.199	-0.013	-0.215
8	-4	6	6	1	0.721	17.35	43.439	2.558	-0.281	-4.771
9	-5	5	6	0	0.626	19.201	45.922	2.704	0.229	3.895
10	-45	-31	-30	-38	0.804	14.232	32.578	1.918	-0.102	-1.727
11	13	23	24	19	0.87	10.135	24.827	1.462	0.027	0.462
12	-43	-31	-29	-36	0.787	14.884	33.651	1.982	-0.069	-1.18

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

Table 5-41. Parameters and estimates for the swine growing and finishing lagoon NH_3 models developed.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	-0.566633	0.2496	**0.0593**
1	AirTemp	0.023119	0.01253	0.0717
1	LagnTemp	0.087319	0.01867	<0.0001
2	Intercept	-0.049884	0.67955	**0.942**
2	AirTemp	0.038719	0.01238	0.0027
3	Intercept	-0.603991	0.24051	0.0407
3	LagnTemp	0.112214	0.01316	<0.0001
4	Intercept	-1.128417	0.1993	<0.0001
4	AirTemp	0.016087	0.01227	**0.1974**
4	LagnTemp	0.09329	0.01491	<0.0001
4	WS	0.13032	0.03173	0.0002
5	Intercept	-0.680078	0.24813	0.0169
5	AirTemp	0.085372	0.01423	0.0033
5	WS	0.131932	0.05442	0.02
6	Intercept	-1.171433	0.18552	<0.0001
6	LagnTemp	0.109863	0.00817	<0.0001
6	WS	0.138518	0.03068	<0.0001
7	Intercept	-5.963413	3.94171	**0.1557**
7	AirTemp	0.021854	0.01447	**0.1385**
7	LagnTemp	0.125063	0.02234	<0.0001
7	pH	0.638838	0.48002	**0.2076**
8	Intercept	-0.836278	11.0659	**0.9412**
8	AirTemp	0.045035	0.01714	0.0113
8	pH	0.096251	1.41519	**0.9471**
9	Intercept	-6.654716	3.89618	**0.1143**
9	LagnTemp	0.150671	0.01457	<0.0001
9	pH	0.718096	0.47492	**0.1574**
10	Intercept	-7.928994	2.74523	0.0095
10	AirTemp	0.00609	0.01416	**0.6696**
10	LagnTemp	0.13598	0.01904	<0.0001
10	WS	0.157811	0.03288	<0.0001
10	pH	0.80741	0.33239	0.0256
11	Intercept	6.210049	5.48066	**0.2827**
11	AirTemp	0.019652	0.01157	0.0963
11	WS	0.076797	0.03599	0.0393
11	pH	-0.758828	0.70323	**0.3056**
12	Intercept	-8.252853	2.65417	0.0068
12	LagnTemp	0.143149	0.00982	<0.0001
12	WS	0.162008	0.03126	<0.0001
12	pH	0.843797	0.3231	0.019

Table 5-42. Fit and evaluation statistics for the swine growing and finishing lagoon NH_3 models developed.

Model	2LogL	AIC	AICc	BIC	Corr.	LNME[a] (%)	NME[b] (%)	ME[b] (kg $day^{-1}m^{-2}$)	MB[b] (kg $day^{-1}m^{-2}$)	NMB[b] (%)
1	53	67	69	58	0.845	42.59	39.524	1.666	0.027	0.629
2	55	67	68	59	0.867	74.251	52.802	2.16	-15.06	-15.06
3	57	69	70	61	0.82	45.432	42.25	1.781	0.083	1.974
4	26	42	45	32	0.93	28.226	29.839	1.307	-0.064	-1.463
5	64	74	75	67	0.91	34.087	28.822	1.223	-0.208	-4.913
6	28	42	44	33	0.926	28.844	30.255	1.326	-0.083	-1.889
7	52	68	71	58	0.824	55.311	36.98	1.363	0.217	5.885
8	54	68	70	58	0.845	78.857	57.059	2.091	-0.641	-17.500
9	55	69	71	60	0.801	58.121	39.615	1.46	0.262	7.104
10	24	42	46	30	0.933	32.017	22.087	0.851	0.04	1.037
11	51	63	65	55	0.82	66.418	58.211	2.228	-0.609	-15.91
12	24	40	44	30	0.932	32.283	21.941	0.845	0.033	0.848

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

5.3.2 H_2S Models Results and Evaluation

For the breeding and gestation lagoons, EPA developed 13 H_2S models based on different combinations of the four predictor variables—ambient temperature, lagoon temperature, wind speed, and pH (Table 5-43, Figures F-34 and F-35). Only models 1, 4, and 13 had coefficients that were all significant ($p < 0.05$), but none included pH. Across all the models, wind speed and temperature had relationships consistent with the literature review.

Table 5-44 provides the model fit statistics and the model evaluation statistics for the models. Of the three models with significant coefficients, the ME ranged from 131.990 g $day^{-1}m^{-2}$ (model 4) to 269.800 g $day^{-1}m^{-2}$ (model 13), which produced NME values of 78.233% and 117.86%, respectively. The models had MBs ranging from -23.980 to -23.280 g $day^{-1}m^{-2}$, with NMBs ranging from -14.210% to -10.170% (models 1 and 13, respectively). Overall, the model evaluation statistics were inconsistently robust, with some models doing well on the error statistics, but worse on the bias statistics, or vice versa. Therefore, when selecting a model for further analysis, EPA considered the potential ease of use and concluded that ambient temperatures would be easier to obtain than lagoon temperatures, as ambient temperatures could be obtained from a local weather station. Therefore, EPA selected model 13 for further analysis. Model 13 is as follows:

$$Breeding\ \&\ Gestation\ Lagoons, ln(H_2S) = 4.6796 + 0.11516 * ws \qquad \text{Equation 26}$$

Where:

$ln(H_2S)$ = the natural log transformed predicted H_2S emissions per square meter of surface area (mg day^{-1} m^{-2}).
ws = average daily wind speed in meters per second (m/s) at a height of 2.5 meters.

For the grow-finish lagoons, EPA evaluated the same 13 models as were evaluated for the breeding and gestation lagoons (Figures F-36 and F-37). Table 5-45 indicates that models 2, 5, 8, 9, 10, 11, 12, and 13 had coefficients that were all significant ($p < 0.05$). Across all the models, the relationships for ambient temperature, lagoon temperature, and wind speed were consistent with the typical trends seen in literature.

Table 5-46 provides the model fit statistics and the model evaluation statistics for the models. Of the eight models with significant coefficients, the ME ranged from 163.85 g $day^{-1}m^{-2}$ (model 12) to 402.02 g $day^{-1}m^{-2}$ (model 9), which produced NME values of 40.323% and 98.935%, respectively. The models had MBs ranging from -45.25 to 162.61 g $day^{-1}m^{-2}$, with NMBs ranging from -11.560 to 40.018 (models 13 and 9, respectively). As with some of the other lagoon models, the evaluation statistics were inconsistently robust, with some models performing well with respect to error, but not well with bias, and vice versa. Therefore, when selecting a model for further analysis, EPA considered the potential ease of use and concluded that ambient temperature and wind speed could be easily obtained from local weather stations, whereas lagoon temperature and pH are not routinely monitored. EPA therefore selected model 13 for further analysis, for both ease of use and for consistency with the breeding and gestation model. Model 13 is as follows:

$$Grow - Finish\ Lagoons, ln(H_2S) = 3.6948 + 0.2790 * ws \quad \text{Equation 27}$$

Where:

$ln(H_2S)$ = the natural log transformed predicted H_2S emissions per square meter of surface area (mg day^{-1} m^{-2}).
Amb_T = average daily ambient temperature in °C.
ws = average daily wind speed in meters per second (m/s) at a height of 2.5 meters.

Table 5-43. Parameters and estimates for the H_2S swine gestation lagoon models.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	6.478992	0.3387	<0.0001
1	AirTemp	0.119184	0.02631	<0.0001
1	LagnTemp	-0.173902	0.03106	<0.0001
2	Intercept	6.428343	0.23161	<0.0001
2	AirTemp	-0.02363	0.0111	0.0379
3	Intercept	6.196805	0.44893	<0.0001

Model	Parameter	Estimate	Standard Error	p-value
3	LagnTemp	-0.050033	0.02127	0.0315
4	Intercept	5.022463	0.36237	<0.0001
4	AirTemp	0.094013	0.03212	0.0065
4	LagnTemp	-0.111776	0.03607	0.0035
4	WS	0.168391	0.04212	0.0004
5	Intercept	6.52387	0.31046	<0.0001
5	AirTemp	-0.024557	0.01148	0.0377
5	WS	-0.006003	0.03223	0.853
6	Intercept	5.410901	0.43287	<0.0001
6	LagnTemp	-0.03885	0.01718	0.0362
6	WS	0.129965	0.03991	0.0017
7	Intercept	10.448431	6.025	0.0951
7	AirTemp	0.070218	0.02918	0.0221
7	LagnTemp	-0.169165	0.03307	<0.0001
7	pH	-0.401988	0.76214	0.6023
8	Intercept	-1.986147	6.45492	0.7604
8	AirTemp	-0.007457	0.0233	0.751
8	pH	0.959146	0.83502	0.2595
9	Intercept	5.691389	6.28786	0.3721
9	LagnTemp	-0.097135	0.0202	0.0014
9	pH	0.188021	0.79272	0.814
10	Intercept	9.548496	6.33186	0.1478
10	AirTemp	0.075029	0.03012	0.018
10	LagnTemp	-0.167581	0.03433	<0.0001
10	WS	0.022008	0.03533	0.5395
10	pH	-0.312304	0.79045	0.697
11	Intercept	-1.061752	6.97035	0.8799
11	AirTemp	-0.00625	0.02337	0.7908
11	WS	-0.0109	0.03269	0.7416
11	pH	0.843677	0.89476	0.3528
12	Intercept	5.355561	6.73864	0.4328
12	LagnTemp	-0.09578	0.02179	0.001
12	WS	0.005886	0.03421	0.8648
12	pH	0.224932	0.83865	0.7903
13	Intercept	4.833256	0.25025	<0.0001
13	WS	0.099772	0.04391	0.0253

Table 5-44. Fit and evaluation statistics for the H_2S swine gestation lagoon models.

Model	2LogL	AIC	AICc	BIC	Corr.	LNME[a] (%)	NME[b] (%)	ME[b] (g day^{-1} m^{-2})	MB[b] (g day^{-1} m^{-2})	NMB[b] (%)
1	130	140	141	136	0.582	8.754	80.366	135.590	-23.980	-14.210
2	163	179	180	171	-0.177	21.321	129.280	290.340	-1.231	-0.548
3	148	156	157	152	0.369	11.441	113.030	190.700	-7.692	-4.559
4	116	136	139	127	0.649	8.604	78.233	131.990	-23.690	-14.040
5	159	177	179	169	0.422	21.661	128.370	293.870	-1.208	-0.528
6	139	149	150	144	0.553	10.151	100.300	169.210	-14.820	-8.786
7	25	37	40	31	0.659	5.498	44.493	86.622	-15.580	-8.000
8	39	49	51	44	0.501	14.121	122.060	237.640	-5.118	-2.629
9	30	40	42	35	0.636	7.120	66.732	129.920	-19.410	-9.971
10	25	39	43	32	0.67	5.353	44.321	86.286	-13.470	-6.919
11	39	51	54	45	0.576	14.782	127.820	248.860	1.017	0.523
12	30	42	45	37	0.646	7.108	66.745	129.940	-18.600	-9.556
13	213	221	221	217	0.472	13.718	117.860	269.800	-23.280	-10.170

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

Table 5-45. Parameters and estimates for the H_2S swine growing lagoon models.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	2.73314	1.04953	0.0248
1	Air Temp	0.083699	0.03236	0.0141
1	Lagoon Temp	0.041352	0.06788	**0.5489**
2	Intercept	3.735991	0.60044	<0.0001
2	Air Temp	0.084295	0.02491	0.0014
3	Intercept	2.54563	1.16909	0.0553
3	Lagoon Temp	0.131182	0.06277	**0.061**
4	Intercept	1.458511	0.92977	**0.1337**
4	Air Temp	0.049379	0.03397	**0.1581**
4	Lagoon Temp	0.078182	0.05821	**0.1918**
4	WS	0.263928	0.09545	0.008
5	Intercept	3.166201	0.54568	<0.0001
5	Air Temp	0.052501	0.02584	0.0481
5	WS	0.221709	0.08295	0.0099
6	Intercept	1.261412	0.87337	**0.1675**
6	Lagoon Temp	0.12634	0.04316	0.0126
6	WS	0.303785	0.08537	0.0009
7	Intercept	22.901945	4.09576	<0.0001
7	Air Temp	0.116961	0.02952	0.0004
7	Lagoon Temp	0.055851	0.0407	**0.1784**
7	pH	-2.574006	0.50141	<0.0001
8	Intercept	25.573479	3.83417	<0.0001
8	Air Temp	0.150334	0.01514	<0.0001
8	pH	-2.869505	0.47948	<0.0001
9	Intercept	18.670458	4.80653	0.0015
9	Lagoon Temp	0.193279	0.02407	<0.0001
9	pH	-2.080679	0.59078	0.0031
10	Intercept	24.000677	4.08593	<0.0001
10	Air Temp	0.092797	0.02822	0.0033
10	Lagoon Temp	0.043962	0.03778	**0.2534**
10	WS	0.26001	0.09257	0.0071
10	pH	-2.831053	0.50683	<0.0001
11	Intercept	26.266885	3.81109	<0.0001
11	Air Temp	0.115684	0.01854	<0.0001
11	WS	0.279819	0.09384	0.0045
11	pH	-3.09202	0.48223	<0.0001
12	Intercept	21.446313	4.66658	0.0003
12	Lagoon Temp	0.139203	0.02672	<0.0001
12	WS	0.342479	0.09143	0.0005
12	pH	-2.575565	0.58147	0.0004
13	Intercept	3.694758	0.49199	<0.0001
13	WS	0.279011	0.0731	0.0004

Table 5-46. Fit and evaluation statistics for the H_2S swine growing lagoon models.

Model	2LogL	AIC	AICc	BIC	Corr.	LNME[a] (%)	NME[b] (%)	ME[b] (g day^{-1} m^{-2})	MB[b] (g day^{-1} m^{-2})	NMB[b] (%)
1	173	187	189	178	0.512	27.635	94.597	349.48	33.493	9.066
2	193	205	207	197	0.354	30.692	98.557	385.62	95.359	24.372
3	179	191	193	183	0.47	28.625	99.14	366.26	31.839	8.618
4	165	181	184	170	0.668	23.766	74.5	275.23	34.591	9.363
5	186	200	202	190	0.578	28.198	74.927	293.16	10.768	2.752
6	167	181	183	172	0.686	23.504	69.554	256.96	5.571	1.508
7	121	137	140	126	0.797	18.15	80.697	327.91	110.06	27.085
8	123	137	139	128	0.8	18.354	75.985	308.76	85.848	21.127
9	135	149	152	140	0.739	20.094	98.935	402.02	162.61	40.018
10	113	131	135	119	0.876	15.075	47.018	191.05	53.974	13.283
11	115	131	134	120	0.878	15.294	48.742	198.06	57.991	14.271
12	123	139	142	128	0.872	14.583	40.323	163.85	32.622	8.028
13	189	201	203	193	0.602	29.034	71.652	280.35	-45.25	-11.56

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

5.4 Basins

5.4.1 NH_3 Model Results and Evaluation

For the basin, EPA evaluated three models that used combinations of ambient temperature and wind speed, because NAEMS did not measure the temperature or pH of the basin liquid (Table 5-47). Two of the three models had insignificant parameters, highlighted in bold in Table 5-47. The model with significant parameters, model 1, did not include wind speed as a parameter. The models produced comparable model fit statistics and evaluation statistics (Table 5-48). After consideration, EPA selected model 1, which was the only model with significant coefficients for all parameters and had parameters easily obtained. Model 1 is as follows:

$$Basin, ln(NH_3) = 1.5049 + 0.01171 * Amb_T$$ Equation 28

Where:

$ln(NH_3)$ = the natural log transformed predicted NH_3 emissions in grams per day per square meter of surface area (g day^{-1} m^{-2}).
Amb_T = average daily ambient temperature (°C).

Table 5-47. Parameters and estimates for the swine basin NH_3 models developed.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	1.504932	0.18455	<0.0001
1	AmbT	0.075879	0.01171	<0.0001

Model	Parameter	Estimate	Standard Error	p-value
2	Intercept	1.901887	0.31764	<0.0001
2	AmbT	0.071725	0.0109	<0.0001
2	ws	-0.079949	0.05457	**0.1512**
3	Intercept	2.774765	0.36936	<0.0001
3	ws	-0.070246	0.05977	**0.2484**

Table 5-48. Fit and evaluation statistics for the swine basin NH_3 models developed.

Model	2LogL	AIC	AICc	BIC	Corr.	LNME[a] (%)	NME[b] (%)	ME[b] (kg day^{-1})	MB[b] (kg day^{-1})	NMB[b] (%)
1	56	64	66	71	0.837	17.022	38.221	5.219	0.493	3.609
2	54	64	66	72	0.851	16.449	35.901	4.903	0.624	4.568
3	72	80	81	87	0.449	34.744	66.457	9.075	-0.422	-3.088

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

[b] Based on back-transformed data.

5.4.2 H_2S Model Results and Evaluation

For the basin, EPA evaluated three models that used combinations of ambient temperature and wind speed, as NAEMS did not collect temperature or pH measurements of the basin liquid. All three models had insignificant parameters, highlighted in bold in Table 5-49. The models produced comparable model fit statistics and evaluation statistics (Table 5-50). EPA selected model 1 because it was consistent with the NH_3 model selected, which did have significant coefficients. Model 1 is as follows:

$$Basin, ln(H_2S) = 0.4689 + 0.0270 * Amb_T$$ Equation 29

Where:

$ln(H_2S)$ = the natural log transformed predicted H_2S emissions in grams per square meter of surface area (g day^{-1} m^{-2}).

Amb_T = the average daily ambient temperature (°C).

Table 5-49. Parameters and estimates for the H_2S swine basin models.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	0.468899	0.28738	**0.1406**
1	Air Temp	0.026991	0.01578	**0.103**
2	Intercept	0.362633	0.32848	**0.2876**
2	Air Temp	0.023929	0.01637	**0.1619**
2	ws	0.029956	0.04085	**0.4702**
3	Intercept	0.573781	0.34208	**0.1262**
3	ws	0.050215	0.03903	**0.2115**

Table 5-50. Fit and evaluation statistics for the H_2S swine basin models.

Model	2LogL	AIC	AICc	BIC	Corr.	LNME[a] (%)	NME[b] (%)	ME[b] (g day^{-1} m^{-2})	MB[b] (g day^{-1} m^{-2})	NMB[b] (%)
1	23	31	33	37	0.583	69.794	80.738	1.403	-0.134	-7.731
2	23	33	36	39	0.555	74.185	84.669	1.472	-0.137	-7.868
3	25	33	35	38	-0.322	97.083	106.94	1.859	0.061	3.531

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

[b] Based on back-transformed data.

6 MODEL COEFFICENT EVALUATION

To ensure reliable prediction of the emissions, the model coefficients were evaluated with the jackknife method (Christensen et al., 2014; Leeden et al., 2008), which examined the cumulative effect on coefficient estimates of multiple "minus-one" runs. The jackknife approach called for removing one of the independent sample units from the dataset. For NAEMS, the individual barns at each site and the monitored lagoons are the mutually exclusive independent sample units. EPA then determined the associated parameter estimates for the selected model based on this dataset. This was repeated for each of the sample units. These results were then compared to the model coefficients based on the full dataset (full model). For each jackknife model, the ME, NME, MB, and NMB were calculated, based on Equations 5 through 10, to facilitate comparison.

EPA also prepared plots showing the variation in coefficients and standard errors for the selected model and compared the plots 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 consistent with one another. If the omission of one monitoring unit (e.g., a barn or lagoon) resulted in a coefficient that was outside ± 1 standard error of the full model, the sample unit was reviewed to determine if a specific characteristic of that unit (e.g., animal placement strategy, manure handling system) might have caused the inconsistency. If the difference could not be ascribed to an operational characteristic of the unit, the data were reviewed for outliers that could be trimmed, and other potential remediation measures considered.

6.1 Breeding and Gestation Barns

6.1.1 NH_3 Model Evaluation

For the farrowing rooms, the model coefficients from the jackknife approach were comparable across the withheld sets. Table 6-1 shows the variation in coefficients and standard errors for the selected model 4 and each of the jackknife models and Table 6-2 presents the model fit and evaluation statistics. The plots in Figure 6-1 show that the results for all jackknife models overlap the full model estimate ± 1 standard error, except sites IA4B and NC4B were outside of this range for the intercept and cycle day. In comparison to the full model, that is where the site removed is "None", the maximum percent differences for parameter estimates across the six models were 15%, 133%, 83%, and 36% for intercept, cycle day, ambient temperature, and LAW, respectively. Across all models, the difference in NME and NMB percentages in comparison to the selected model were moderate, with NME values differing by less than 10.83% and NMB by less than 0.003%.

For the gestation barns, the coefficients developed using the jackknife approach were comparable for the "no pit" model set (Table 6-3, Table 6-4, and Figure 6-2), as well as for the "pit" model set (Table 6-5, Table 6-6, and Figure 6-3). The "no pit" plots show that the results for all jackknife models overlap the full model estimate ± 1 standard error, except for one barn per parameter. Site NC4BB1 falls outside the ± 1 standard error for the intercept and LAW, while site OK4BB2 falls outside for ambient temperature. Comparing the average values to the selected model, the maximum percentage differences for parameter estimates across the "no pit" models were 30%, 40%, and 10% for intercept, ambient temperature and LAW, respectively.

For the pit model, coefficients differed by as much as 60%, 148%, 28%, and 23% for deep model intercept, shallow model intercept, ambient temperature, and LAW, respectively. The largest percentage differences are associated with NC4BB1, except for the ambient temperature, which was associated with IA4BB1. The differences in process and operations between the pit types, and the nominally improved fit statistics, prompted EPA to select the "pit" version of the models over the "no pit" version.

Table 6-1. Parameters and estimates using the jackknife approach for NH_3 emissions from farrowing barns.

Site Out	Parameter	Estimate	Standard Error	p-value
None	Intercept	0.68875	0.01775	<0.0001
None	cycleday	0.001961	0.0008	0.0157
None	AmbT	0.000581	0.00029	0.0449
None	LAW	0.008405	0.00154	<0.0001
IA4BF	Intercept	0.784435	0.01932	<0.0001
IA4BF	cycleday	0.003193	0.00056	<0.0001
IA4BF	AmbT	0.000101	0.0002	0.6032
IA4BF	LAW	0.005396	0.00276	0.0509
NC4BF	Intercept	0.791997	0.04058	<0.0001
NC4BF	cycleday	0.004576	0.00161	0.0049
NC4BF	AmbT	0.000276	0.00022	0.2136
NC4BF	LAW	0.009463	0.00137	<0.0001
OK4BF	Intercept	0.678472	0.0123	<0.0001
OK4BF	cycleday	0.001467	0.00056	0.0105
OK4BF	AmbT	0.001227	0.00024	<0.0001
OK4BF	LAW	0.009068	0.00144	<0.0001

Table 6-2. Fit and evaluation statistics using the jackknife approach for NH_3 emissions from farrowing barns.

Site Out	LNME (%)	NME (%)	ME (kg day^{-1})	MB (kg day^{-1})	NMB (%)	Corr.
None	9.086	55.927	0.169	-0.00119	-0.39215	0.498
IA4BF	9.295	54.942	0.184	-0.00044	-0.13226	0.331
NC4BF	8.898	45.099	0.1697	-0.00044	-0.11624	0.402
OK4BF	4.949	47.966	0.092	-0.00075	-0.38973	0.5

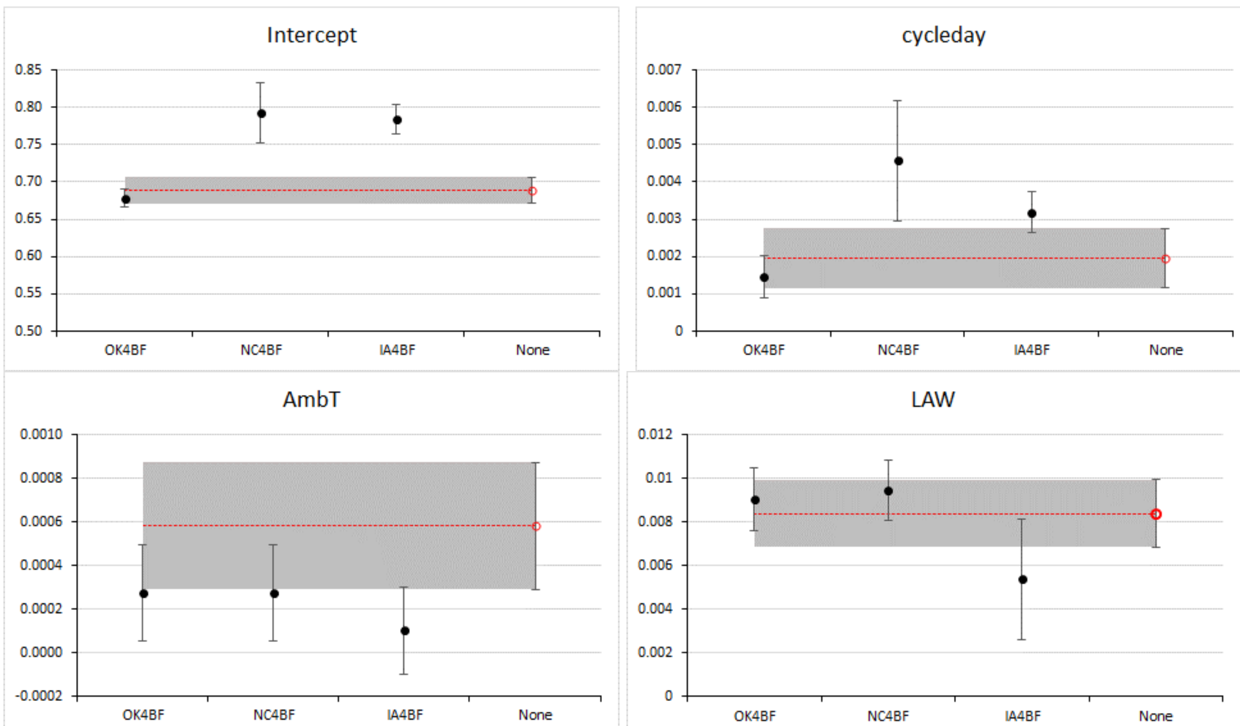

Figure 6-1. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected NH_3 farrowing model coefficient ("None," gray band for ± SE) for each model parameter.

Table 6-3. Parameters and estimates using the jackknife approach for NH_3 emissions from gestation barns, no pit model.

Site Out	Parameter	Estimate	Standard Error	p-value
None	Intercept	0.1548	0.1186	0.1972
None	AmbT	0.0069	0.0006	<0.0001
None	LAW	0.0091	0.0005	<0.0001
IA4BB1	Intercept	0.1850	0.1017	0.0741
IA4BB1	AmbT	0.0058	0.0006	<0.0001
IA4BB1	LAW	0.0091	0.0004	<0.0001
IA4BB2	Intercept	0.1834	0.1209	0.1354
IA4BB2	AmbT	0.0071	0.0006	<0.0001
IA4BB2	LAW	0.0090	0.0005	<0.0001
NC4BB1	Intercept	0.4524	0.1390	0.0028
NC4BB1	AmbT	0.0067	0.0006	<0.0001
NC4BB1	LAW	0.0079	0.0006	<0.0001
NC4BB2	Intercept	-0.0657	0.1341	0.6273
NC4BB2	AmbT	0.0065	0.0006	<0.0001
NC4BB2	LAW	0.0101	0.0006	<0.0001
OK4BB1	Intercept	0.1254	0.1237	0.3146
OK4BB1	AmbT	0.0065	0.0007	<0.0001
OK4BB1	LAW	0.0093	0.0005	<0.0001
OK4BB2	Intercept	0.0697	0.1306	0.5957
OK4BB2	AmbT	0.0097	0.0007	<0.0001
OK4BB2	LAW	0.0092	0.0006	<0.0001

Table 6-4. Fit and evaluation statistics using the jackknife approach for NH_3 emissions from gestation barns, no pit model.

Site Out	LNME (%)	NME (%)	ME (kg day^{-1})	MB (kg day^{-1})	NMB (%)	Corr.
None	12.461	36.699	4.755	-0.652	-5.033	0.546
IA4BB1	10.499	23.485	2.480	-0.155	-1.467	0.774
IA4BB2	11.930	36.821	4.392	-0.708	-5.935	0.540
NC4BB1	11.784	38.524	5.503	-0.638	-4.467	0.502
NC4BB2	11.691	37.576	5.336	-0.648	-4.565	0.511
OK4BB1	14.286	40.398	5.474	-0.854	-6.303	0.562
OK4BB2	14.699	40.699	5.452	-0.914	-6.822	0.581

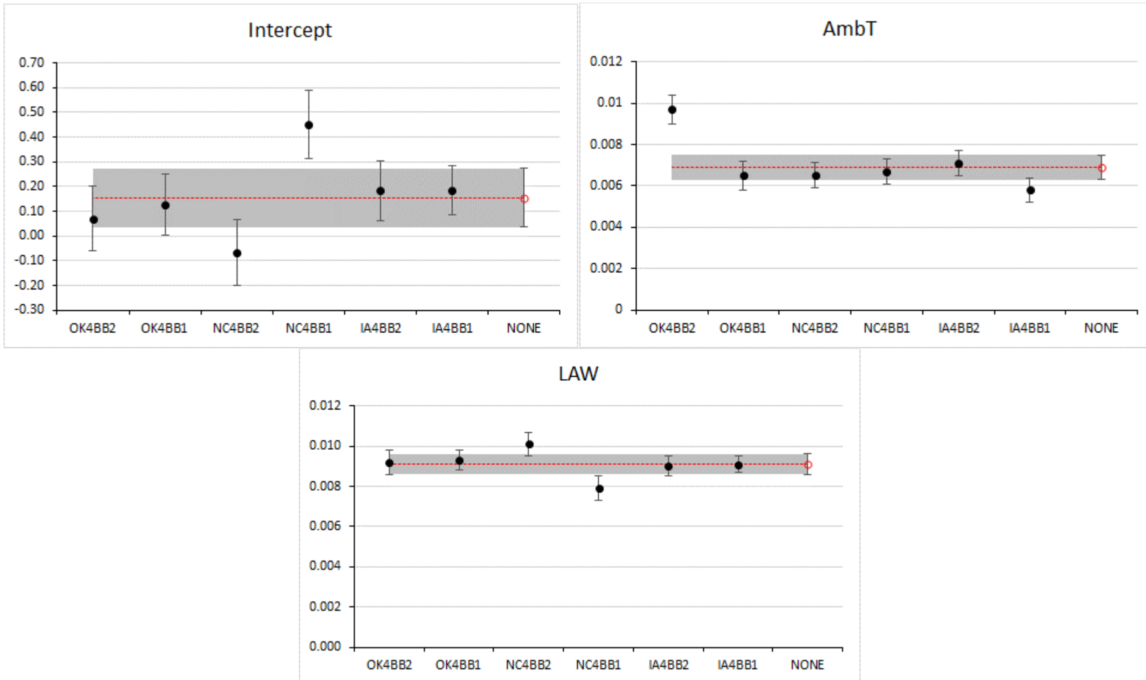

Figure 6-2. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected NH_3 gestation "no pit" model coefficient ("None," gray band for ± SE) for each model parameter.

Table 6-5. Parameters and estimates using the jackknife approach for NH_3 emissions from gestation barns, pit model.

Site Out	Parameter	Estimate	Standard Error	p-value
None	Deep	0.834777	0.26817	0.0025
None	Shallow	0.30747	0.20558	0.1382
None	AmbT	0.011778	0.00085	<0.0001
None	LAW	0.007899	0.001	<0.0001
IA4BB1	Deep	0.357293	0.18567	0.057
IA4BB1	Shallow	0.168421	0.13529	0.2158
IA4BB1	AmbT	0.008475	0.00087	<0.0001
IA4BB1	LAW	0.008873	0.00065	<0.0001
IA4BB2	Deep	0.721361	0.226	0.002
IA4BB2	Shallow	0.001492	0.17789	0.9933
IA4BB2	AmbT	0.013103	0.00092	<0.0001
IA4BB2	LAW	0.009311	0.00086	<0.0001
NC4BB1	Deep	1.331542	0.34521	0.0003
NC4BB1	Shallow	0.762074	0.2798	0.0082
NC4BB1	AmbT	0.010919	0.00084	<0.0001
NC4BB1	LAW	0.006047	0.00129	<0.0001
NC4BB2	Deep	0.794288	0.34624	0.0245
NC4BB2	Shallow	0.270919	0.28157	0.339
NC4BB2	AmbT	0.01065	0.00085	<0.0001

Site Out	Parameter	Estimate	Standard Error	p-value
NC4BB2	LAW	0.008105	0.0013	<0.0001
OK4BB1	Deep	0.88397	0.34063	0.0113
OK4BB1	Shallow	0.31036	0.24715	0.213
OK4BB1	AmbT	0.013658	0.00107	<0.0001
OK4BB1	LAW	0.007643	0.00128	<0.0001
OK4BB2	Deep	0.993592	0.33709	0.0042
OK4BB2	Shallow	0.369208	0.24456	0.1352
OK4BB2	AmbT	0.014208	0.00104	<0.0001
OK4BB2	LAW	0.007204	0.00126	<0.0001

Table 6-6. Fit and evaluation statistics using the jackknife approach for NH_3 emissions from gestation barns, pit model.

Site Out	LNME (%)	NME (%)	ME (kg day^{-1})	MB (kg day^{-1})	NMB (%)	Corr.
None	11.622	31.205	4.043	-0.361	-2.7861	0.653
IA4BB1	10.278	22.109	2.335	-0.021	-0.1996	0.807
IA4BB2	11.126	29.146	3.477	-0.405	-3.3943	0.762
NC4BB1	10.575	31.011	4.43	-0.493	-3.4496	0.633
NC4BB2	10.919	31.725	4.505	-0.446	-3.1441	0.621
OK4BB1	13.577	35.233	4.774	-0.419	-3.0893	0.661
OK4BB2	13.343	34.723	4.651	-0.459	-3.4235	0.671

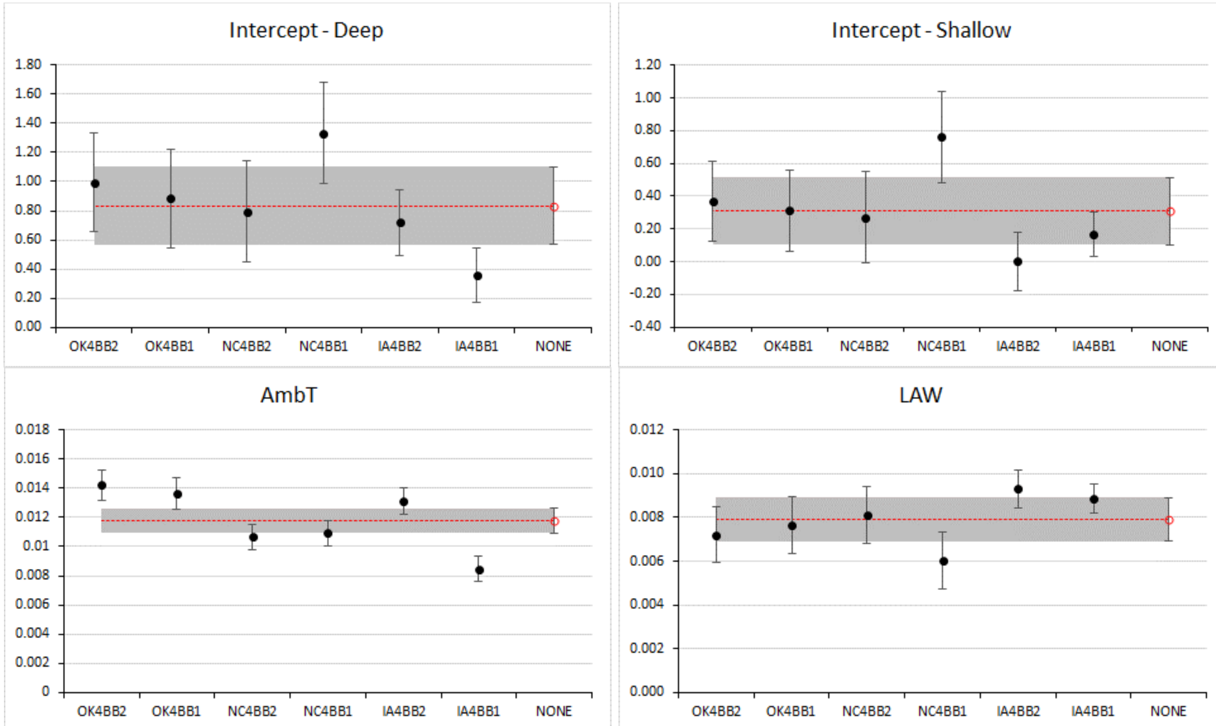

Figure 6-3. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected NH_3 gestation "pit" model coefficient ("None," gray band for ± SE) for each model parameter.

6.1.2 H_2S Model Evaluation

For the farrowing rooms, the coefficients for the jackknife models were fairly consistent across the withheld sets (Table 6-7 and Table 6-8). Figure 6-4 shows the variation in coefficients and standard errors for the selected model 4 and each of the jackknife models. The plots in Figure 10-4 show that the results for all jackknife models, ± 1 standard error, overlap the full model estimate, except that OK4B is outside of this range for the intercept and cycle day. In comparison to the selected model (i.e., site out is "None"), the maximum percentage differences for parameter estimates across the six models were 24%, 21%, and 17% for intercept, cycle day, and LAW, respectively. Across all models, the difference in NME and NMB percentages in comparison to the selected model were moderate, with NME values differing by less than 7.5% and NMB less than 0.101%.

For the gestation barns, the coefficients developed using the jackknife approach were fairly consistent for the "no pit" (Table 6-9, Table 6-10, and Figure 6-5) and "pit" (Table 6-11, Table 6-12, and Figure 6-6) model sets. The plots for the "no pit" model set show that the results for all jackknife models overlap the full model estimate ± 1 standard error. In some cases, the overlap is on the edge of the ± 1 standard error band. Comparing the average values to the selected model 4, the maximum percentage differences for parameter estimates across the "no pit" models were 17%, 64%, and 6% for intercept, ambient temperature and LAW, respectively.

For the pit model, coefficients differed by 21%, 23%, 64%, and 8% for the deep model intercept, shallow model intercept, ambient temperature, and LAW, respectively. The large percentage differences are associated with NC4BB2, except for the ambient temperature, which was associated with OK4BB2. Because of the process and operational differences between the pit types and the nominally improved fit statistics, EPA selected the “pit” version of the models over the “no pit” version.

Table 6-7. Parameters and estimates using the jackknife approach for H_2S emissions from farrowing barns.

Site Out	Parameter	Estimate	Standard Error	p-value
None	Intercept	2.142329	0.12728	<0.0001
None	cycleday	0.129797	0.00562	<0.0001
None	LAW	0.061406	0.01641	0.0002
IA4BF	Intercept	1.98399	0.19918	<0.0001
IA4BF	cycleday	0.141673	0.00612	<0.0001
IA4BF	LAW	0.071958	0.03561	0.0438
NC4BF	Intercept	2.142329	0.12728	<0.0001
NC4BF	cycleday	0.129797	0.00562	<0.0001
NC4BF	LAW	0.061406	0.01641	0.0002
OK4BF	Intercept	2.650861	0.15832	<0.0001
OK4BF	cycleday	0.102079	0.00788	<0.0001
OK4BF	LAW	0.063076	0.01794	0.0005

Table 6-8. Fit and evaluation statistics using the jackknife approach for H_2S emissions from farrowing barns.

Site Out	LNME (%)	NME (%)	ME (g day-1)	MB (g day-1)	NMB (%)	Corr.
None	19.73	70.283	73.785	20.322	19.357	0.521
IA4BF	13.545	62.794	74.321	34.576	29.213	0.642
NC4BF	22.472	70.131	63.162	9.889	10.980	0.523
OK4BF	23.343	76.795	81.23	9.789	9.255	0.45

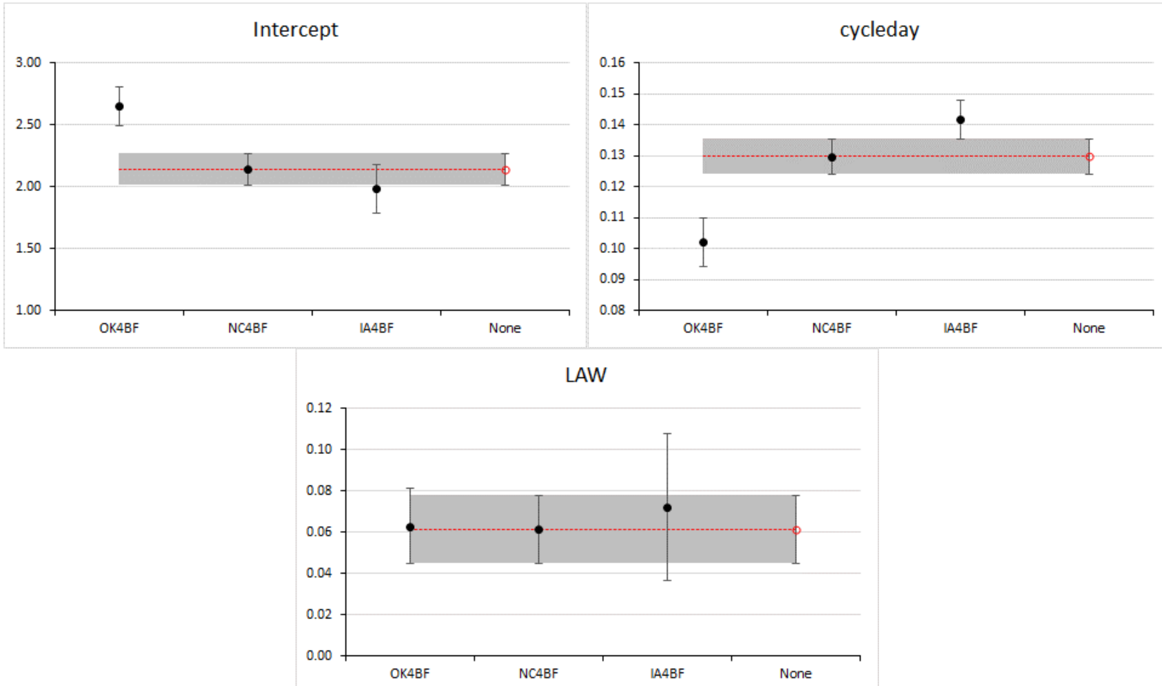

Figure 6-4. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected H^2S farrowing model coefficient ("None," gray band for ± SE) for each model parameter.

Table 6-9. Parameters and estimates using the jackknife approach for H_2S emissions from gestation sites, with no pit.

Site Out	Parameter	Estimate	Standard Error	p-value
None	Intercept	2.0773	0.1209	<0.0001
None	AmbT	0.0035	0.0010	0.0003
None	LAW	0.0199	0.0005	<0.0001
IA4BB1	Intercept	2.1231	0.1183	<0.0001
IA4BB1	AmbT	0.0019	0.0010	0.0623
IA4BB1	LAW	0.0198	0.0005	<0.0001
IA4BB2	Intercept	2.0702	0.1219	<0.0001
IA4BB2	AmbT	0.0043	0.0010	<0.0001
IA4BB2	LAW	0.0198	0.0005	<0.0001
NC4BB1	Intercept	1.9357	0.1415	<0.0001
NC4BB1	AmbT	0.0036	0.0010	0.0003
NC4BB1	LAW	0.0205	0.0006	<0.0001
NC4BB2	Intercept	2.3780	0.1888	<0.0001
NC4BB2	AmbT	0.0033	0.0010	0.0009
NC4BB2	LAW	0.0186	0.0008	<0.0001
OK4BB1	Intercept	2.0518	0.1262	<0.0001
OK4BB1	AmbT	0.0032	0.0012	0.0106
OK4BB1	LAW	0.0200	0.0006	<0.0001
OK4BB2	Intercept	2.0303	0.1300	<0.0001
OK4BB2	AmbT	0.0058	0.0013	<0.0001
OK4BB2	LAW	0.0199	0.0006	<0.0001

Table 6-10. Fit and evaluation statistics using the jackknife approach for H_2S emissions from gestation sites, with no pit.

Site Out	LNME[a] (%)	NME[b] (%)	ME[b] (kg day^{-1})	MB[b] (kg day^{-1})	NMB[b] (%)	Corr.
None	8.792	69.332	1594.40	-514.8	-22.387	0.573
IA4BB1	6.667	51.874	733.33	-298.1	-21.089	0.735
IA4BB2	8.346	79.777	1,386.20	-438.1	-25.213	0.548
NC4BB1	8.568	69.715	1,869.00	-491.4	-18.329	0.542
NC4BB2	8.778	71.326	1,951.70	-482.9	-17.649	0.536
OK4BB1	10.219	66.319	1,775.10	-651.5	-24.340	0.587
OK4BB2	10.401	66.966	1,772.50	-656.7	-24.812	0.594

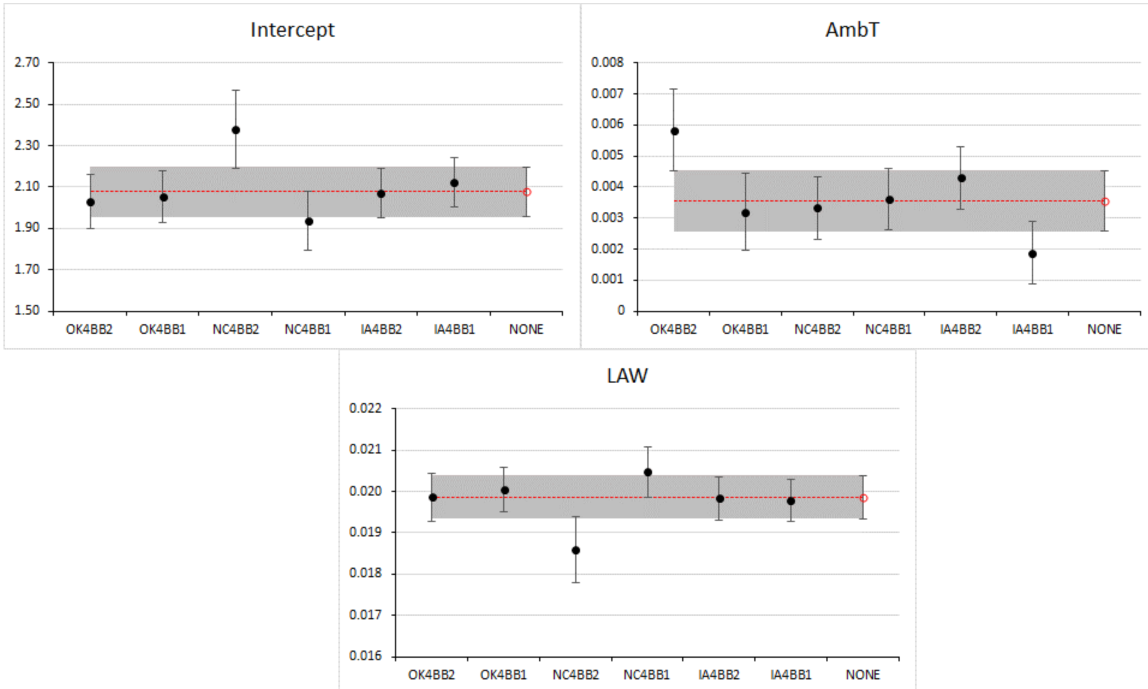

Figure 6-5. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected H_2S gestation "no pit" model coefficient ("None," gray band for ± SE) for each model parameter.

Table 6-11. Parameters and estimates using the jackknife approach for H_2S emissions from gestation sites, with pit.

Site Out	Parameter	Estimate	Standard Error	p-value
None	Deep	3.171852	0.1471	<0.0001
None	Shallow	2.130472	0.12289	<0.0001
None	AmbT	0.003844	0.00098	0.0001
None	LAW	0.019592	0.00054	<0.0001
IA4BB1	Deep	3.110121	0.15481	<0.0001
IA4BB1	Shallow	2.153327	0.12341	<0.0001
IA4BB1	AmbT	0.002188	0.001	0.0295
IA4BB1	LAW	0.019606	0.00054	<0.0001
IA4BB2	Deep	3.851503	0.10637	<0.0001
IA4BB2	Shallow	2.069741	0.12368	<0.0001
IA4BB2	AmbT	0.004546	0.00102	<0.0001
IA4BB2	LAW	0.019814	0.00054	<0.0001
NC4BB1	Deep	3.031241	0.16843	<0.0001
NC4BB1	Shallow	2.011579	0.1451	<0.0001
NC4BB1	AmbT	0.003921	0.00099	<0.0001
NC4BB1	LAW	0.020098	0.00063	<0.0001
NC4BB2	Deep	3.617535	0.21637	<0.0001
NC4BB2	Shallow	2.508618	0.19514	<0.0001
NC4BB2	AmbT	0.003652	0.00099	0.0003

Site Out	Parameter	Estimate	Standard Error	p-value
NC4BB2	LAW	0.017988	0.00084	<0.0001
OK4BB1	Deep	3.134284	0.16218	<0.0001
OK4BB1	Shallow	2.10801	0.12746	<0.0001
OK4BB1	AmbT	0.003664	0.00124	0.0032
OK4BB1	LAW	0.019735	0.00056	<0.0001
OK4BB2	Deep	3.174794	0.16916	<0.0001
OK4BB2	Shallow	2.097823	0.1319	<0.0001
OK4BB2	AmbT	0.006314	0.00131	<0.0001
OK4BB2	LAW	0.019485	0.0006	<0.0001

Table 6-12. Fit and evaluation statistics using the jackknife approach for H_2S emissions from gestation sites, with pit.

Site Out	LNME (%)	NME (%)	ME (g day^{-1})	MB (g day^{-1})	NMB (%)	Corr.
None	6.078	50.681	1,165.5	-241.1	-10.485	0.666
IA4BB1	5.538	38.483	544.03	36.985	2.616	0.791
IA4BB2	5.674	44.325	770.2	-46.66	-2.685	0.814
NC4BB1	5.565	50.892	1,364.4	-276.5	-10.314	0.639
NC4BB2	5.415	49.723	1,360.6	-295.1	-10.787	0.649
OK4BB1	6.896	53.649	1,436	-237.7	-8.881	0.651
OK4BB2	6.883	52.622	1,392.9	-248.8	-9.398	0.663

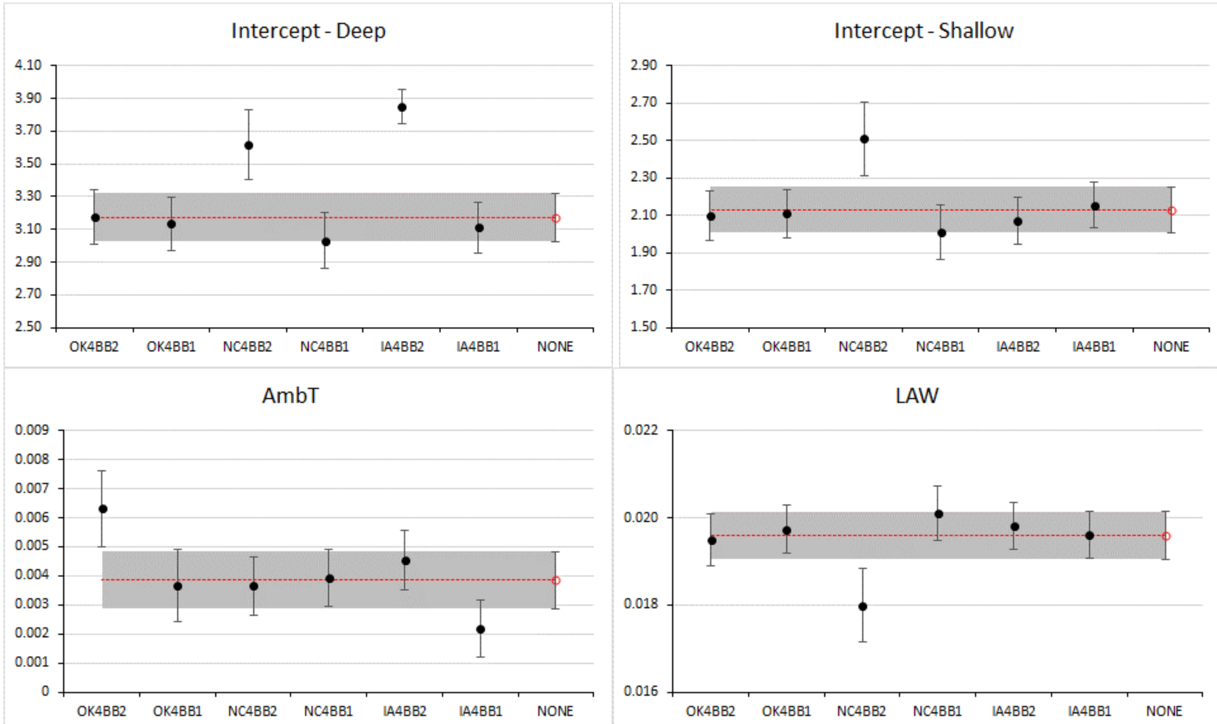

Figure 6-6. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected H_2S gestation "pit" model coefficient ("None," gray band for ± SE) for each model parameter.

6.1.3 PM_{10} Model Evaluation

For the farrowing rooms, the model coefficients from the jackknife approach were all significant and fairly consistent across the withheld sets (Table 6-13 and Table 6-14). Figure 6-7 shows the variation in coefficients and standard errors for the selected model and each of the jackknife models. The plots in Figure 6-7 show that the results for all jackknife models overlap the full model estimate ± 1 standard error, except that OK4B is outside of this range for cycle day. In comparison to the selected model (i.e., site out is "None"), the maximum percentage differences for parameter estimates across the six models were 9%, 30%, 19%, and 18% for intercept, cycle day, LAW, and ambient relative humidity, respectively. Across all models, the difference in NME and NMB percentages in comparison to the selected model were moderate, with NME values differing by less than 7.72% and NMB less than 7.903%.

For the gestation barns, Tables 6-15 and Tables 6-16 present the results of the "minus-one" jackknife approach. Figure 6-8 shows that the results for all jackknife models overlap the full model estimate ± 1 standard error, except for NC4BB1, which falls outside the standard error for the intercept and LAW. Comparing the withheld models to the selected model, the maximum percentage differences for parameter estimates were 10%, 37%, and 9% for the intercept, ambient temperature, and LAW parameters, respectively.

Table 6-13. Parameters and estimates using the jackknife approach for PM_{10} emissions from farrowing barns.

Site Out	Parameter	Estimate	Standard Error	p-value
None	Intercept	2.489915	0.09914	<0.0001
None	cycleday	0.055625	0.00366	<0.0001
None	LAW	0.106263	0.01302	<0.0001
None	AmbRH	-0.003436	0.00066	<0.0001
IA4BF	Intercept	2.526142	0.15529	<0.0001
IA4BF	cycleday	0.068382	0.00424	<0.0001
IA4BF	LAW	0.085696	0.02531	0.0011
IA4BF	AmbRH	-0.002824	0.00072	0.0001
NC4BF	Intercept	2.274249	0.12651	<0.0001
NC4BF	cycleday	0.069256	0.00429	<0.0001
NC4BF	LAW	0.126377	0.01783	<0.0001
NC4BF	AmbRH	-0.003002	0.00089	0.0008
OK4BF	Intercept	2.700754	0.11819	<0.0001
OK4BF	cycleday	0.039055	0.00458	<0.0001
OK4BF	LAW	0.075749	0.01415	<0.0001
OK4BF	AmbRH	-0.003791	0.00082	<0.0001

Table 6-14. Fit and evaluation statistics using the jackknife approach for PM_{10} emissions from farrowing barns.

Site Out	LNME (%)	NME (%)	ME (g day-1)	MB (g day-1)	NMB (%)	Corr.
None	9.813	39.112	13.585	0.834	2.400	0.596
IA4BF	7.551	31.397	12.171	0.664	1.713	0.734
NC4BF	10.914	43.422	16.071	2.925	7.903	0.544
OK4BF	10.199	38.91	10.79	0.578	2.085	0.478

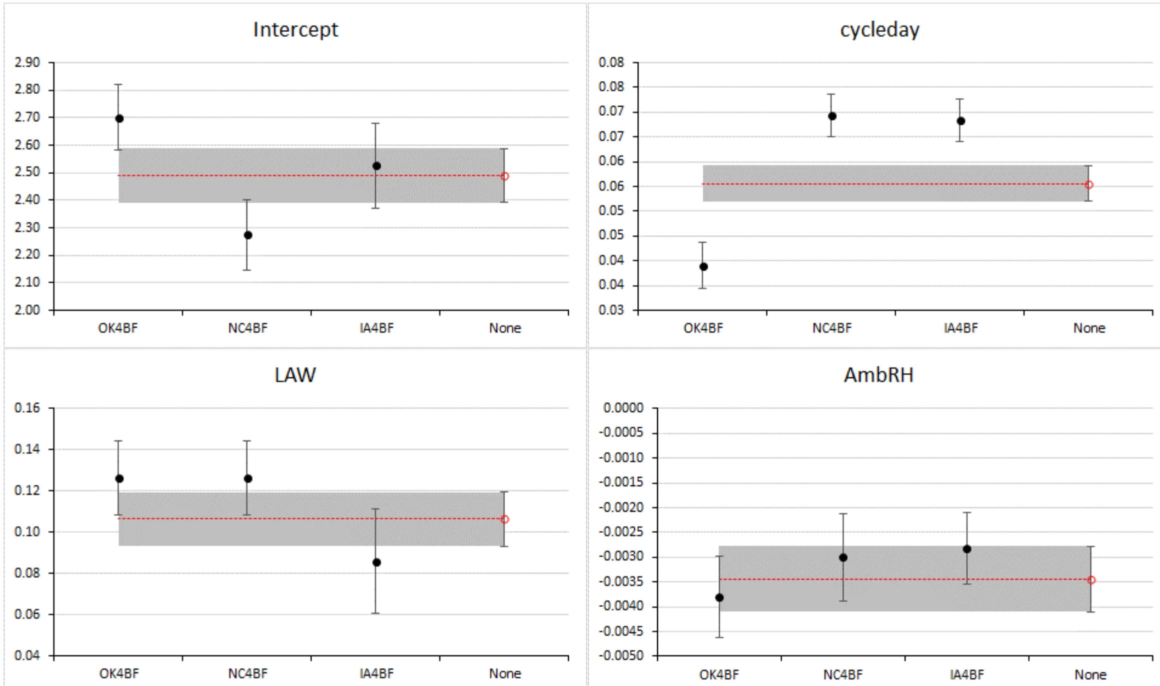

Figure 6-7. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected PM_{10} farrowing model coefficient ("None," gray band for ± SE) for each model parameter.

Table 6-15. Parameters and estimates using the jackknife approach for PM_{10} emissions from gestation sites.

Site Out	Parameter	Estimate	Standard Error	p-value
None	Intercept	5.186761	0.17987	<0.0001
None	LAW	0.005472	0.00076	<0.0001
None	AmbRH	-0.007661	0.00053	<0.0001
IA4BB1	Intercept	5.140164	0.19635	<0.0001
IA4BB1	LAW	0.005613	0.00084	<0.0001
IA4BB1	AmbRH	-0.007407	0.00058	<0.0001
IA4BB2	Intercept	5.290841	0.20881	<0.0001
IA4BB2	LAW	0.004953	0.0009	<0.0001
IA4BB2	AmbRH	-0.007869	0.00055	<0.0001
NC4BB1	Intercept	5.683417	0.26176	<0.0001
NC4BB1	LAW	0.003426	0.00109	0.0035
NC4BB1	AmbRH	-0.007389	0.00058	<0.0001
NC4BB2	Intercept	5.035882	0.18558	<0.0001
NC4BB2	LAW	0.006124	0.00078	<0.0001
NC4BB2	AmbRH	-0.007867	0.00057	<0.0001
OK4BB1	Intercept	5.248244	0.18492	<0.0001
OK4BB1	LAW	0.005539	0.00077	<0.0001
OK4BB1	AmbRH	-0.008026	0.00062	<0.0001
OK4BB2	Intercept	5.209886	0.18475	<0.0001
OK4BB2	LAW	0.004424	0.00078	<0.0001
OK4BB2	AmbRH	-0.007	0.00064	<0.0001

Table 6-16. Fit and evaluation statistics using the jackknife approach for PM_{10} emissions from gestation sites.

Site Out	LNME (%)	NME (%)	ME (g day^{-1})	MB (g day^{-1})	NMB (%)	Corr.
None	2.167	39.471	17.033	-0.012	-0.028	0.201
IA4BB1	2.335	43.415	18.252	-0.019	-0.044	0.189
IA4BB2	1.945	36.679	15.027	-0.007	-0.017	0.132
NC4BB1	2.299	41.154	18.320	-0.007	-0.016	0.151
NC4BB2	2.338	42.093	18.313	-0.012	-0.028	0.229
OK4BB1	1.920	33.104	15.659	-0.017	-0.037	0.263
OK4BB2	2.043	38.978	15.856	-0.006	-0.015	0.221

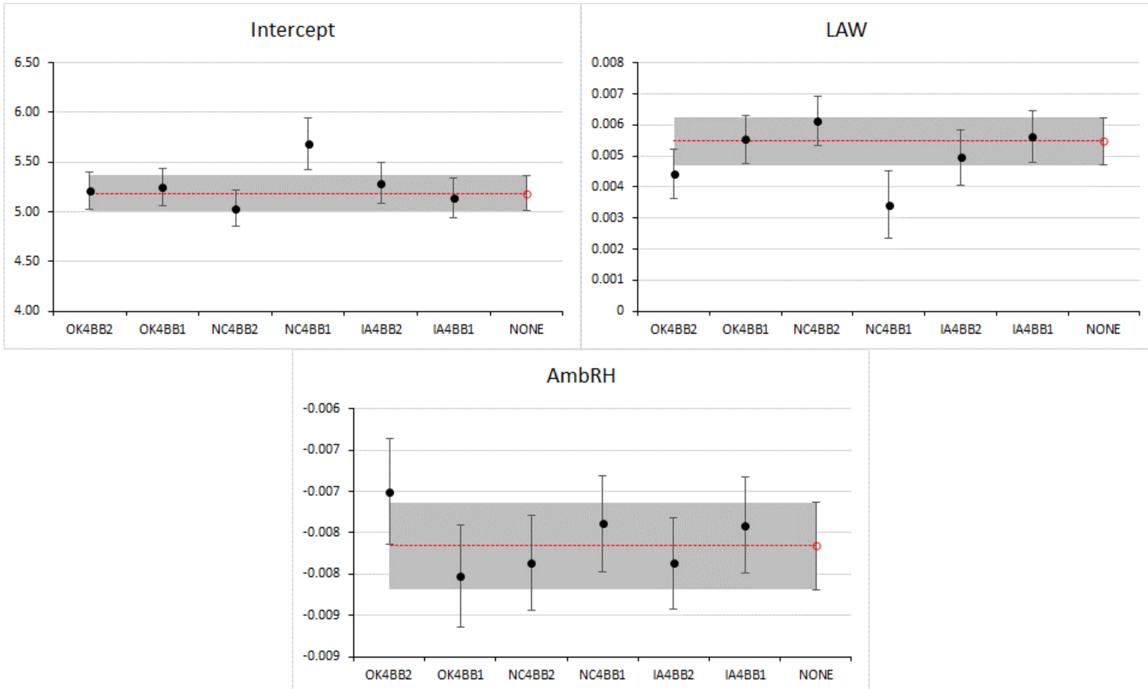

Figure 6-8. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected PM_{10} gestation model coefficient ("None," gray band for ± SE) for each model parameter.

6.1.4 $PM_{2.5}$ Model Evaluation

For the farrowing rooms, the model coefficients from the jackknife approach were all significant and comparable across the withheld sets (Table 6-17 and Table 6-18). The plots in Figure 6-9 show that the results for all jackknife models overlap the full model estimate ± 1 standard error, except for IA4B, which is outside of this range for the intercept and LAW parameters. In comparison to the selected model (i.e., site out is "None"), the maximum percentage differences for parameter estimates across the six models were 75%, 9%, and 67% for intercept, cycle day, and LAW, respectively. Across all models, the differences in NME and NMB percentages in comparison to the selected model were moderate, with NME values differing by less than 66.67% and NMB less than 13.615%.

For the gestation barns, Table 6-19 and Table 6-20 present the results of the "minus-one" jackknife approach. The plots (Figure 6-10) show that the results for all the jackknife models overlap the full model estimate ± 1 standard error. Comparing the withheld models to the selected model, the maximum percentage differences for parameter estimates were 2% and 44% for intercept and LAW parameters, respectively. Across all models, the differences in NME and NMB percentages in comparison to the selected model were moderate, with NME values differing by less than 6.4% and NMB by less than 0.069%.

Table 6-17. Parameters and estimates using the jackknife approach for $PM_{2.5}$ emissions from farrowing barns.

Site Out	Parameter	Estimate	Standard Error	p-value
None	Intercept	-1.21456	0.19779	<0.0001
None	cycleday	0.075902	0.00225	<0.0001
None	LAW	0.256357	0.03492	<0.0001
IA4BF	Intercept	-2.128576	0.36318	0.0027
IA4BF	cycleday	0.068876	0.00542	<0.0001
IA4BF	LAW	0.421707	0.06499	0.0017
NC4BF	Intercept	-0.951649	0.22029	<0.0001
NC4BF	cycleday	0.077615	0.0023	<0.0001
NC4BF	LAW	0.212175	0.0392	<0.0001
OK4BF	Intercept	-1.385241	0.16117	<0.0001
OK4BF	cycleday	0.074381	0.00859	<0.0001
OK4BF	LAW	0.230567	0.02857	<0.0001

Table 6-18. Fit and evaluation statistics using the jackknife approach for $PM_{2.5}$ emissions from farrowing barns.

Site Out	LNME (%)	NME (%)	ME (g day^{-1})	MB (g day^{-1})	NMB (%)	Corr.
None	58.639	53.647	1.900	0.364	10.266	0.548
IA4BF	18.786	18.716	0.691	0.053	1.429	0.948
NC4BF	66.67	64.214	2.596	0.55	13.615	0.504
OK4BF	57.594	60.33	1.86	0.416	13.481	0.19

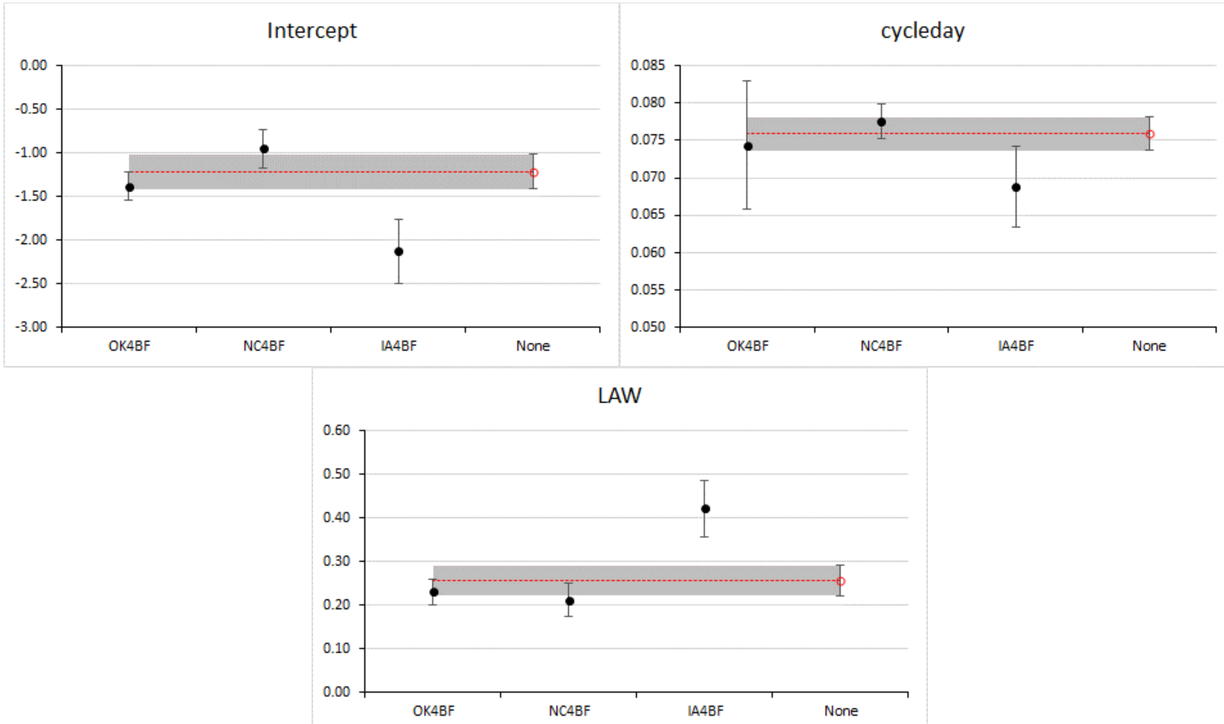

Figure 6-9. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected $PM_{2.5}$ farrowing model coefficient ("None," gray band for ± SE) for each model parameter.

Table 6-19. Parameters and estimates using the jackknife approach for $PM_{2.5}$ emissions from gestation barns.

Site Out	Parameter	Estimate	Standard Error	p-value
None	Intercept	4.88715	0.07109	<0.0001
None	LAW	0.0007	0.00031	0.027
IA4BB1	Intercept	4.900209	0.07571	<0.0001
IA4BB1	LAW	0.000623	0.00034	0.0712
IA4BB2	Intercept	4.935704	0.06516	<0.0001
IA4BB2	LAW	0.00045	0.0003	0.1353
NC4BB1	Intercept	4.905205	0.09643	<0.0001
NC4BB1	LAW	0.000629	0.0004	0.126
NC4BB2	Intercept	4.809812	0.09443	<0.0001
NC4BB2	LAW	0.001008	0.0004	0.0138
OK4BB1	Intercept	4.890792	0.06903	<0.0001
OK4BB1	LAW	0.000809	0.0003	0.0099
OK4BB2	Intercept	4.878499	0.07977	<0.0001
OK4BB2	LAW	0.000679	0.00035	0.0574

Table 6-20. Fit and evaluation statistics using the jackknife approach for $PM_{2.5}$ emissions from gestation barns.

Site Out	LNME (%)	NME (%)	ME (g day^{-1})	MB (g day^{-1})	NMB (%)	Corr.
None	2.167	39.471	17.033	-0.012	-0.0283	0.201
IA4BB1	2.335	43.415	18.252	-0.019	-0.0440	0.189
IA4BB2	1.945	36.679	15.027	-0.007	-0.0167	0.132
NC4BB1	2.299	41.154	18.32	-0.007	-0.0156	0.151
NC4BB2	2.338	42.093	18.313	-0.012	-0.0282	0.229
OK4BB1	1.92	33.104	15.659	-0.017	-0.0368	0.263
OK4BB2	2.043	38.978	15.856	-0.006	-0.0147	0.221

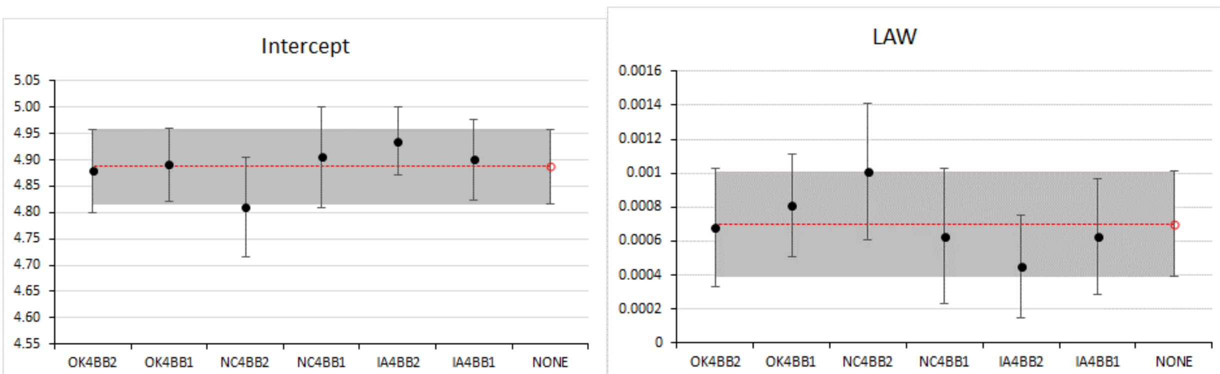

Figure 6-10. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected $PM_{2.5}$ gestation model coefficient ("None," gray band for ± SE) for each model parameter.

6.1.5 TSP Model Evaluation

For the farrowing rooms, the model coefficients from the jackknife approach were all significant and comparable across the withheld sets (Table 6-21 and Table 6-22). The plots in Figure 6-11 show that the results for all jackknife models overlap the full model estimate ± 1 standard error, except for IA4B, which is outside of this range for LAW. In comparison to the selected model (i.e., site out is "None"), the maximum percentage differences for parameter estimates across the six models were 39%, 21%, 142%, and 56% for intercept, cycle day, LAW, and ambient relative humidity, respectively. Across all models, the differences in NME and NMB percentages in comparison to the selected model were moderate, with NME values differing by less than 8.86% and NMB by less than 5.929%.

For the gestation barns, Table 6-23 and Table 6-24 present the results of the jackknife approach. The plot (Figure 6-12) shows that the results for all jackknife models overlap the full model estimate ± 1 standard error. Comparing the withheld models to the selected model, the maximum percentage differences for parameter estimates were 8%, 31%, and 20% for intercept, LAW, and ambient relative humidity, respectively. Across all models, the differences in NME and NMB percentages in comparison to the selected model were moderate, with NME values differing by less than 3.4% and NMB by less than 2.342%.

Table 6-21. Parameters and estimates using the jackknife approach for TSP emissions from farrowing barns.

Site Out	Parameter	Estimate	Standard Error	p-value
None	Intercept	2.858928	0.47281	<0.0001
None	cycleday	0.070551	0.01348	<0.0001
None	LAW	0.147305	0.07879	0.0679
None	AmbRH	-0.004908	0.00263	0.0644
IA4BF	Intercept	1.740335	0.6517	0.0105
IA4BF	cycleday	0.077898	0.0139	<0.0001
IA4BF	LAW	0.356794	0.10285	0.0014
IA4BF	AmbRH	-0.004685	0.00301	0.1236
NC4BF	Intercept	3.186904	0.64065	<0.0001
NC4BF	cycleday	0.085413	0.01804	<0.0001
NC4BF	LAW	0.043285	0.1202	0.7205
NC4BF	AmbRH	-0.002136	0.00264	0.4208
OK4BF	Intercept	3.294123	0.51839	<0.0001
OK4BF	cycleday	0.059449	0.01675	0.0016
OK4BF	LAW	0.081324	0.08216	0.3306
OK4BF	AmbRH	-0.00668	0.00468	0.1583

Table 6-22. Fit and evaluation statistics using the jackknife approach for TSP emissions from farrowing barns.

Site Out	LNME[a] (%)	NME (%)	ME (kg day^{-1})	MB (kg day^{-1})	NMB (%)	Corr.
None	10.953	41.732	40.709	1.883	1.930	0.618
IA4BF	8.823	32.868	37.179	6.706	5.929	0.811
NC4BF	10.192	41.883	40.973	3.472	3.549	0.62
OK4BF	11.831	43.321	34.273	0.894	1.130	0.532

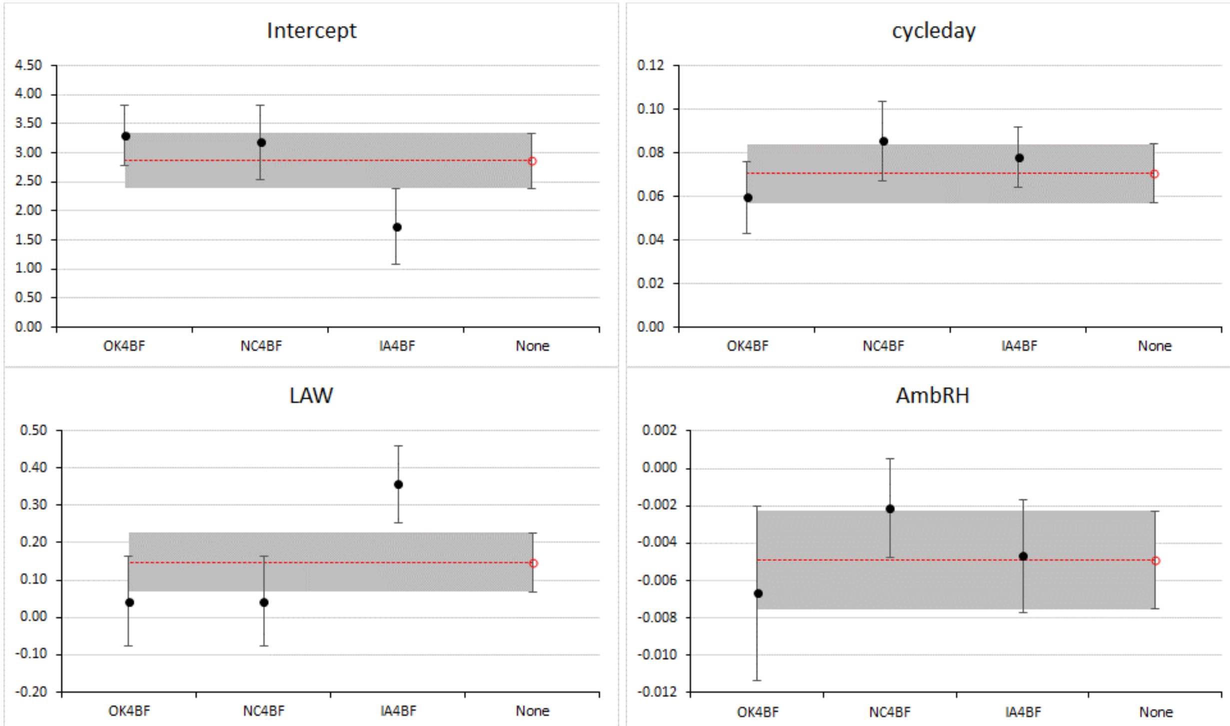

Figure 6-11. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected TSP farrowing model coefficient ("None," gray band for ± SE) for each model parameter.

Table 6-23. Parameters and estimates using the jackknife approach for TSP emissions from gestation barns.

Site Out	Parameter	Estimate	Standard Error	p-value
None	Intercept	5.533966	0.56243	<0.0001
None	LAW	0.006601	0.0023	0.012
None	AmbRH	-0.008	0.00126	<0.0001
IA4BB1	Intercept	5.498281	0.70079	<0.0001
IA4BB1	LAW	0.006729	0.00306	0.0449
IA4BB1	AmbRH	-0.007809	0.0013	<0.0001
IA4BB2	Intercept	5.959879	0.56781	<0.0001
IA4BB2	LAW	0.004523	0.00231	0.0727
IA4BB2	AmbRH	-0.008112	0.00129	<0.0001
NC4BB1	Intercept	5.766295	0.63247	<0.0001
NC4BB1	LAW	0.005532	0.00258	0.0712
NC4BB1	AmbRH	-0.007425	0.00127	<0.0001
NC4BB2	Intercept	5.096022	0.57473	<0.0001
NC4BB2	LAW	0.00827	0.00235	0.0041
NC4BB2	AmbRH	-0.007702	0.0013	<0.0001
OK4BB1	Intercept	5.657414	0.55129	<0.0001
OK4BB1	LAW	0.006356	0.00221	0.0116
OK4BB1	AmbRH	-0.007913	0.00167	<0.0001

Site Out	Parameter	Estimate	Standard Error	p-value
OK4BB2	Intercept	5.595466	0.59389	<0.0001
OK4BB2	LAW	0.006677	0.00239	0.0149
OK4BB2	AmbRH	-0.009585	0.00154	<0.0001

Table 6-24. Fit and evaluation statistics using the jackknife approach for TSP emissions from gestation barns.

Site Out	LNME (%)	NME (%)	ME (g day^{-1})	MB (g day^{-1})	NMB (%)	Corr.
None	7.147	39.887	281.19	9.735	1.381	0.399
IA4BB1	6.695	38.083	267.26	11.2	1.596	0.434
IA4BB2	7.216	39.657	255.65	2.54	0.394	0.373
NC4BB1	6.918	39.513	292.4	5.315	0.718	0.315
NC4BB2	7.044	39.328	284.86	6.745	0.931	0.409
OK4BB1	7.193	38.896	286.84	5.434	0.737	0.452
OK4BB2	7.76	43.236	294.98	15.978	2.342	0.401

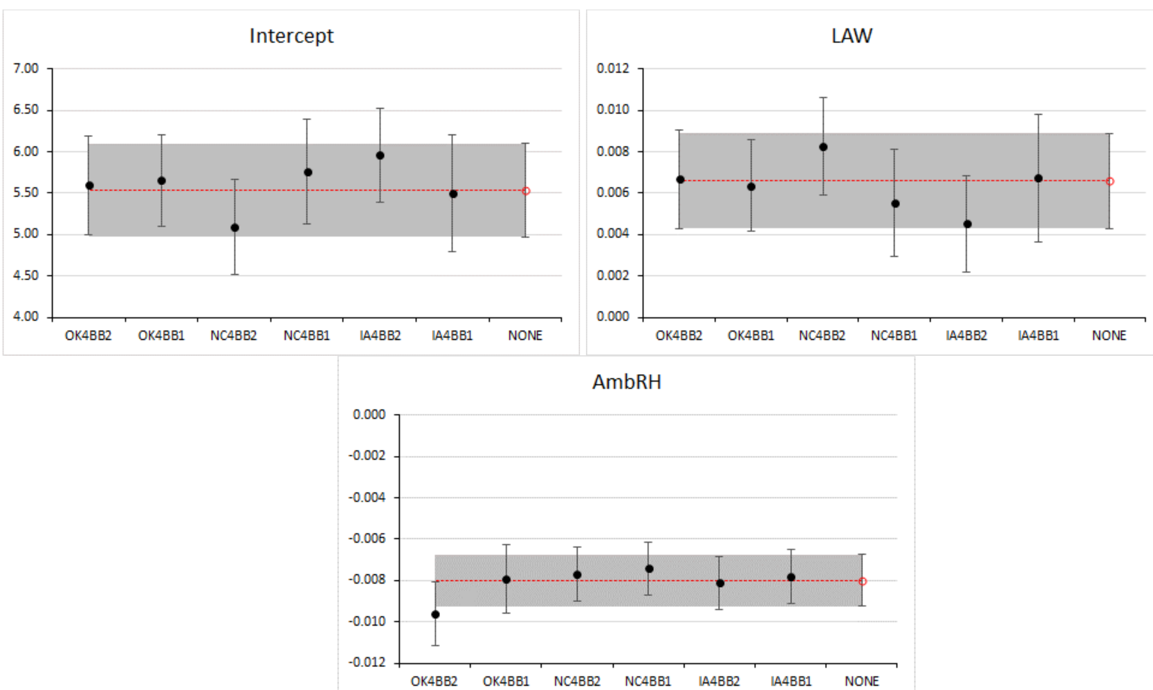

Figure 6-12. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected TSP gestation model coefficient ("None," gray band for ± SE) for each model parameter.

6.2 Grow-Finish Barns

For the grow-finish models, EPA explored two sets of models for NH_3 and H_2S. The first set consisted of a single model that did not make a distinction between manure management systems. For the second set, EPA developed a model for each manure management system. The exploratory data analysis suggested that EPA should consider ambient temperature, exhaust temperature, inventory, and LAW in the development of the models.

The type of manure management and storage system employed at the farm did not appear to have an impact on PM emissions. The exploratory data analysis suggested that EPA should consider ambient temperature, ambient relative humidity, exhaust temperature, exhaust relative humidity, inventory, and LAW in the development of the models.

6.2.1 NH_3 Model Evaluation

The model coefficients developed for the "no pit" (Table 6-25 and Table 6-26) and "pit" (Table 6-27 and Table 6-28) model sets using the jackknife approach were comparable. Figure 6-13 shows the mean plot plus standard error for each coefficient for the selected model (i.e., site out is "None") and each of the jackknife models for the "no pit" and "pit" model sets. The plots show that the results for all jackknife models overlap the full model estimate ± 1 standard error, except for the IN3BR5 model for ambient temperature. Comparing the average values to the selected model, the maximum percentage differences for parameter estimates across the "no pit" models were 6.2%, 24.4%, and 5.9% for intercept, ambient temperature, and LAW, respectively. For the deep pit model, coefficients differed by 5.5%, 24.4%, and 6.1% for intercept, ambient temperature, and LAW, respectively. Results for the shallow pit model were similar: 4.8%, 24.4%, and 5.2% for intercept, ambient temperature, and LAW, respectively. EPA identified the 24.4% difference for each model set with the IN3BR5-out models.

Because of the superior fit statistics relative to the "no pit" model, and the process and operational differences between the pit types, EPA selected the "pit" version of the models.

Table 6-25. Parameters and estimates using the jackknife approach for NH_3 emissions from grow-finish sites, no pit.

Site Out	Parameter	Estimate	Standard Error	p-value
None	Intercept	1.236262	0.03916	<0.0001
None	Ambient Temp	0.008953	0.00081	<0.0001
None	LAW	0.008939	0.00051	<0.0001
IN3BR5	Intercept	1.159515	0.04028	<0.0001
IN3BR5	Ambient Temp	0.011134	0.00086	<0.0001
IN3BR5	LAW	0.009210	0.00054	<0.0001
IN3BR6	Intercept	1.205131	0.04076	<0.0001
IN3BR6	Ambient Temp	0.008839	0.00085	<0.0001
IN3BR6	LAW	0.008823	0.00054	<0.0001
IN3BR7	Intercept	1.279189	0.04393	<0.0001
IN3BR7	Ambient Temp	0.008970	0.00084	<0.0001
IN3BR7	LAW	0.008414	0.00058	<0.0001
IN3BR8	Intercept	1.218012	0.04373	<0.0001
IN3BR8	Ambient Temp	0.010143	0.00085	<0.0001
IN3BR8	LAW	0.008719	0.00058	<0.0001
NC3BB1	Intercept	1.244118	0.04194	<0.0001
NC3BB1	Ambient Temp	0.007587	0.00088	<0.0001
NC3BB1	LAW	0.009461	0.00055	<0.0001
NC3BB2	Intercept	1.265149	0.04267	<0.0001
NC3BB2	Ambient Temp	0.007875	0.00092	<0.0001
NC3BB2	LAW	0.009192	0.00055	<0.0001
NC3BB3	Intercept	1.308254	0.04299	<0.0001
NC3BB3	Ambient Temp	0.007772	0.00091	<0.0001
NC3BB3	LAW	0.008520	0.00055	<0.0001

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

[b] Based on back-transformed data.

Table 6-26. Fit and evaluation statistics using the jackknife approach for NH_3 emissions from grow-finish sites, no pit.

Site Out	LNME (%)	NME (%)	ME (kg day^{-1})	MB (kg day^{-1})	NMB (%)	Corr.
None	13.338	27.435	1.673	0.027	0.439	0.661
IN3BR5	13.370	27.375	1.615	0.009	0.149	0.686
IN3BR6	13.516	27.961	1.641	0.017	0.283	0.643
IN3BR7	13.715	28.179	1.697	0.007	0.122	0.629
IN3BR8	13.778	28.367	1.704	0.025	0.422	0.636
NC3BB1	12.532	26.149	1.644	0.073	1.163	0.682
NC3BB3	13.010	26.639	1.684	0.011	0.172	0.674

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

[b] Based on back-transformed data.

Table 6-27. Parameters and estimates using the jackknife approach for NH_3 emissions from grow-finish sites.

Site Removed	Parameter	Estimate	Standard Error	p-value
None	Deep	1.342386	0.04249	<0.0001
None	Shallow	1.142239	0.04362	<0.0001
None	Ambient Temp	0.009077	0.00081	<0.0001
None	LAW	0.008545	0.00051	<0.0001
IN3BR5	Deep	1.268263	0.04527	<0.0001
IN3BR5	Shallow	1.087888	0.04289	<0.0001
IN3BR5	Ambient Temp	0.011289	0.00086	<0.0001
IN3BR5	LAW	0.008858	0.00054	<0.0001
IN3BR6	Deep	1.301069	0.04798	<0.0001
IN3BR6	Shallow	1.150047	0.04535	<0.0001
IN3BR6	Ambient Temp	0.008912	0.00085	<0.0001
IN3BR6	LAW	0.008442	0.00056	<0.0001
IN3BR7	Deep	1.400621	0.04613	<0.0001
IN3BR7	Shallow	1.163358	0.04533	<0.0001
IN3BR7	Ambient Temp	0.009068	0.00084	<0.0001
IN3BR7	LAW	0.008101	0.00056	<0.0001
IN3BR8	Deep	1.384624	0.04800	<0.0001
IN3BR8	Shallow	1.136793	0.04572	<0.0001
IN3BR8	Ambient Temp	0.010155	0.00085	<0.0001
IN3BR8	LAW	0.008252	0.00057	<0.0001
NC3BB1	Deep	1.326421	0.04361	<0.0001
NC3BB1	Shallow	1.133037	0.04857	<0.0001
NC3BB1	Ambient Temp	0.007736	0.00088	<0.0001
NC3BB1	LAW	0.009070	0.00054	<0.0001
NC3BB2	Deep	1.335902	0.04440	<0.0001
NC3BB2	Shallow	1.152681	0.05139	<0.0001
NC3BB2	Ambient Temp	0.008016	0.00092	<0.0001
NC3BB2	LAW	0.008872	0.00055	<0.0001
NC3BB3	Deep	1.380227	0.04424	<0.0001
NC3BB3	Shallow	1.180283	0.05007	<0.0001
NC3BB3	Ambient Temp	0.007897	0.00090	<0.0001
NC3BB3	LAW	0.008250	0.00054	<0.0001

Table 6-28. Fit and evaluation statistics using the jackknife approach for NH_3 emissions from grow-finish sites.

Site Removed	LNME (%)	NME (%)	ME (kg day^{-1})	MB (kg day^{-1})	NMB (%)	Corr.
None	12.346	25.799	1.573	0.049	0.798	0.696
IN3BR5	12.533	25.892	1.527	0.034	0.581	0.712
IN3BR6	12.905	26.982	1.583	0.023	0.397	0.667
IN3BR7	12.325	25.860	1.557	0.034	0.562	0.682
IN3BR8	12.476	26.094	1.567	0.054	0.899	0.684

Site Removed	LNME (%)	NME (%)	ME (kg day^{-1})	MB (kg day^{-1})	NMB (%)	Corr.
NC3BB1	11.641	24.657	1.550	0.095	1.512	0.716
NC3BB2	12.257	25.646	1.623	0.067	1.058	0.702
NC3BB3	12.037	25.025	1.582	0.037	0.578	0.705

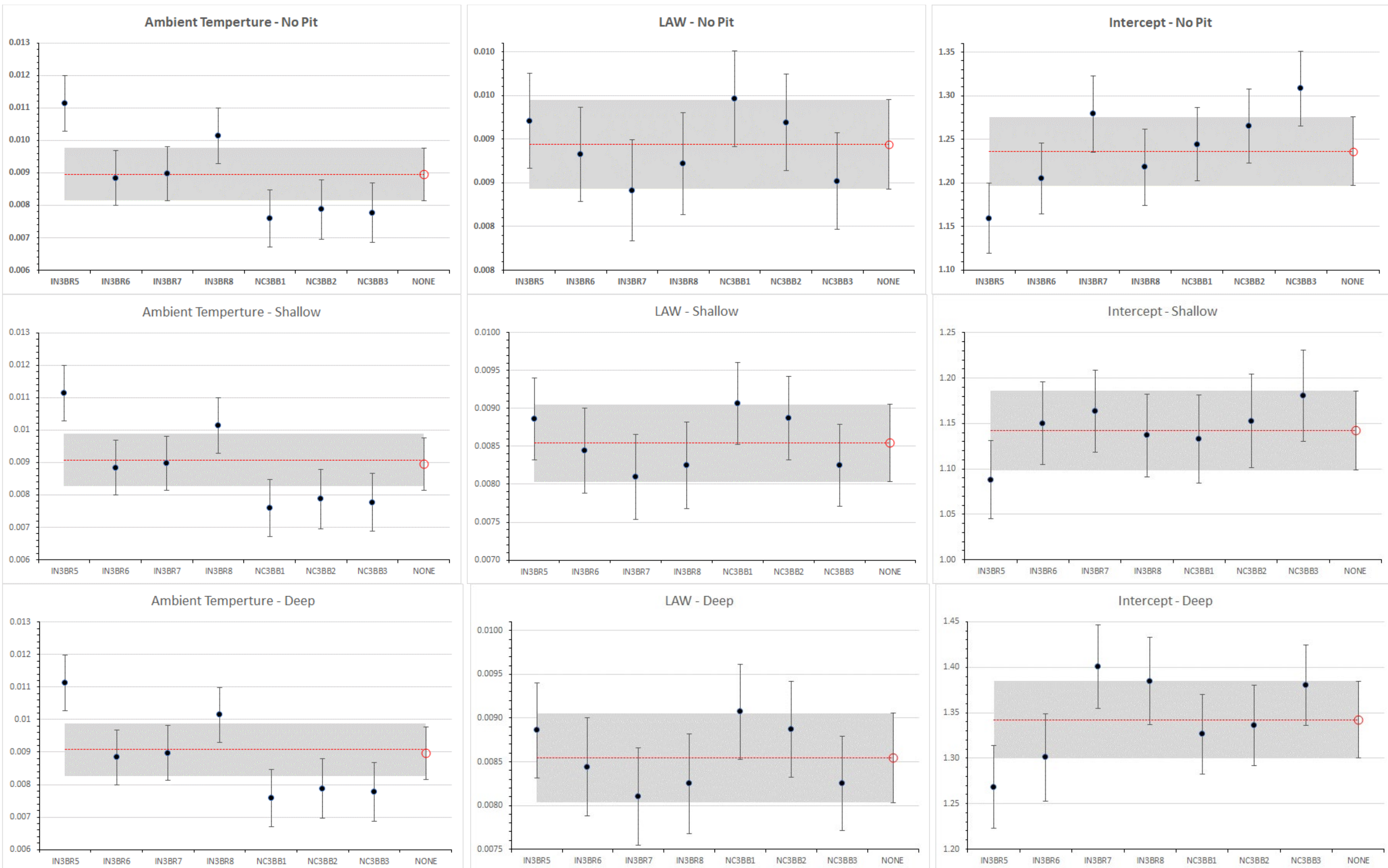

Figure 6-13. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected NH_3 Grow-Finish model coefficient (“None,” gray band for ± SE) for each model parameter. Plots are for the ambient temperature (left column), and LAW (center column), and intercept (right column). No pit results are in the top row, shallow pit results in the middle row, and deep pit results in the bottom row.

6.2.2 H_2S Model Evaluation

EPA developed the jackknife model coefficients by removing one barn/room from the dataset and re-running the model. Table 6-29 and Table 6-30 show the results for the “no pit” model sets and Table 6-31 and Table 6-32 show the “pit” model sets. Figure 6-14 shows the mean plot for each model coefficient, for the selected model (i.e., site out is “None”) and each of the jackknife models for the “no pit” and “pit” model sets. The plots show that the results for all jackknife models overlap the full model estimate ± 1 standard error, except for the IN3BR8 model for ambient temperature for the “no pit” version of the model. Comparing the average values to the selected model, the maximum percentage differences for parameter estimates across the “no pit” models were 2.4%, 53.8%, and 6.2% for the intercept, ambient temperature, and LAW, respectively. For the deep pit model, coefficients differed by 2.5%, 46.7% and 8.5% for the intercept, ambient temperature, and LAW, respectively. EPA identified similar results for the shallow pit model: 1.6%, 46.7%, and 8.5% for the intercept, ambient temperature and LAW, respectively. Each model set with IN3BR8 withheld showed a large percentage difference for ambient temperature. IN3B was the quad-room barn where piglets were initially held in Rooms 5 and 6 (with Rooms 7 and 8 held empty) and then distributed evenly across the four rooms as the animals grew. IN3BR8, along with R7, received the older pigs for the second half of their growth cycle. This may account for the differences seen in these two rooms.

Overall, neither H_2S model performed particularly well. This could be because the nature of H_2S emissions makes them more difficult to model. For example, H_2S is more likely to be influenced by management activities that disturb manure, such as pit flushing and bubbling of the pit liquid. Similar to methane, changes in barn pressure could correlate to H_2S ebullitions; however, barn pressure is not routinely measured, and daily average values of atmospheric pressure may not capture barn changes. To provide an initial EEM of H_2S, EPA selected the “pit” version of the models because it showed better fit statistics than the “no pit” model, and because of the process and operational differences between the pit types.

Table 6-29. Parameters and estimates using the jackknife approach for H_2S emissions from grow-finish sites, no pits.

Site Out	Parameter	Estimate	Standard Error	p-value
None	Intercept	4.081979	0.09500	<0.0001
None	Ambient Temp	-0.006592	0.00161	<0.0001
None	LAW	0.017163	0.00151	<0.0001
IN3BR5	Intercept	4.091295	0.10141	<0.0001
IN3BR5	Ambient Temp	-0.007782	0.00193	<0.0001
IN3BR5	LAW	0.017289	0.00165	<0.0001
IN3BR6	Intercept	4.058112	0.10045	<0.0001
IN3BR6	Ambient Temp	-0.008481	0.00183	<0.0001
IN3BR6	LAW	0.018223	0.00162	<0.0001
IN3BR7	Intercept	4.051440	0.09861	<0.0001
IN3BR7	Ambient Temp	-0.005896	0.00169	0.0005
IN3BR7	LAW	0.017365	0.00160	<0.0001
IN3BR8	Intercept	3.983525	0.09837	<0.0001
IN3BR8	Ambient Temp	-0.003048	0.00182	**0.0948**
IN3BR8	LAW	0.017642	0.00158	<0.0001
NC3BB1	Intercept	4.181300	0.10874	<0.0001
NC3BB1	Ambient Temp	-0.006764	0.00166	<0.0001
NC3BB1	LAW	0.016476	0.00169	<0.0001
NC3BB2	Intercept	4.117450	0.10952	<0.0001
NC3BB2	Ambient Temp	-0.006868	0.00166	<0.0001
NC3BB2	LAW	0.016516	0.00168	<0.0001
NC3BB3	Intercept	4.113334	0.10710	<0.0001
NC3BB3	Ambient Temp	-0.007277	0.00167	<0.0001
NC3BB3	LAW	0.016486	0.00166	<0.0001

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

Table 6-30. Fit and evaluation statistics using the jackknife approach for H_2S emissions from grow-finish sites, no pits.

Site Out	LNME (%)	NME (%)	ME (g day^{-1})	MB (g day^{-1})	NMB (%)	Corr.
None	17.483	84.295	295.66	17.283	4.927	0.384
IN3BR5	17.227	82.090	280.39	9.454	2.768	0.413
IN3BR6	16.490	83.607	258.10	17.010	5.51	0.382
IN3BR7	16.986	81.873	280.31	13.208	3.858	0.413
IN3BR8	17.034	84.137	257.99	14.075	4.59	0.376
NC3BB1	17.875	84.646	329.79	23.598	6.057	0.364
NC3BB2	18.355	85.228	328.52	22.167	5.751	0.368
NC3BB3	18.289	85.889	330.34	22.018	5.725	0.366

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

Table 6-31. Parameters and estimates using the jackknife approach for H_2S emissions from grow-finish sites, deep and shallow pits.

Site Out	Parameter	Estimate	Standard Error	p-value
None	Deep	4.991579	0.15159	<0.0001
None	Shallow	4.190492	0.15138	<0.0001
None	Ambient Temp	-0.005539	0.00202	0.0062
None	LAW	0.013317	0.00173	<0.0001
IN3BR5	Deep	5.079570	0.16063	<0.0001
IN3BR5	Shallow	4.214277	0.14627	<0.0001
IN3BR5	Ambient Temp	-0.006483	0.00234	0.0057
IN3BR5	LAW	0.013275	0.00184	<0.0001
IN3BR6	Deep	4.878786	0.16019	<0.0001
IN3BR6	Shallow	4.159743	0.14659	<0.0001
IN3BR6	Ambient Temp	-0.006517	0.00228	0.0042
IN3BR6	LAW	0.014453	0.00183	<0.0001
IN3BR7	Deep	5.116008	0.15622	<0.0001
IN3BR7	Shallow	4.190931	0.14172	<0.0001
IN3BR7	Ambient Temp	-0.004186	0.00218	**0.0555**
IN3BR7	LAW	0.012858	0.00181	<0.0001
IN3BR8	Deep	4.807978	0.16395	<0.0001
IN3BR8	Shallow	4.122399	0.15098	<0.0001
IN3BR8	Ambient Temp	-0.002952	0.00228	**0.1956**
IN3BR8	LAW	0.013816	0.00187	<0.0001
NC3BB1	Deep	4.982270	0.17095	<0.0001
NC3BB1	Shallow	4.221809	0.19706	<0.0001
NC3BB1	Ambient Temp	-0.005709	0.00204	0.0052
NC3BB1	LAW	0.013452	0.00194	<0.0001
NC3BB2	Deep	5.022033	0.16888	<0.0001
NC3BB2	Shallow	4.189982	0.19648	<0.0001
NC3BB2	Ambient Temp	-0.006173	0.00205	0.0026
NC3BB2	LAW	0.012906	0.00189	<0.0001
NC3BB3	Deep	5.038359	0.16491	<0.0001
NC3BB3	Shallow	4.216006	0.19177	<0.0001
NC3BB3	Ambient Temp	-0.006697	0.00210	0.0014
NC3BB3	LAW	0.012768	0.00186	<0.0001

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

Table 6-32. Fit and evaluation statistics using the jackknife approach for H_2S emissions from grow-finish sites, deep and shallow pits.

Site Out	LNME (%)	NME (%)	ME (g day^{-1})	MB (g day^{-1})	NMB (%)	Corr.
None	16.247	76.412	268.00	3.241	0.924	0.469
IN3BR5	15.663	72.420	247.36	-0.820	-0.24	0.515
IN3BR6	15.899	77.493	239.23	5.368	1.739	0.46
IN3BR7	15.350	72.071	246.75	2.553	0.746	0.516
IN3BR8	16.295	77.335	237.14	-0.540	-0.176	0.457
NC3BB1	16.618	77.963	303.75	10.534	2.704	0.435
NC3BB2	16.910	78.055	300.87	6.635	1.721	0.444
NC3BB3	16.751	78.111	300.42	3.904	1.015	0.444

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

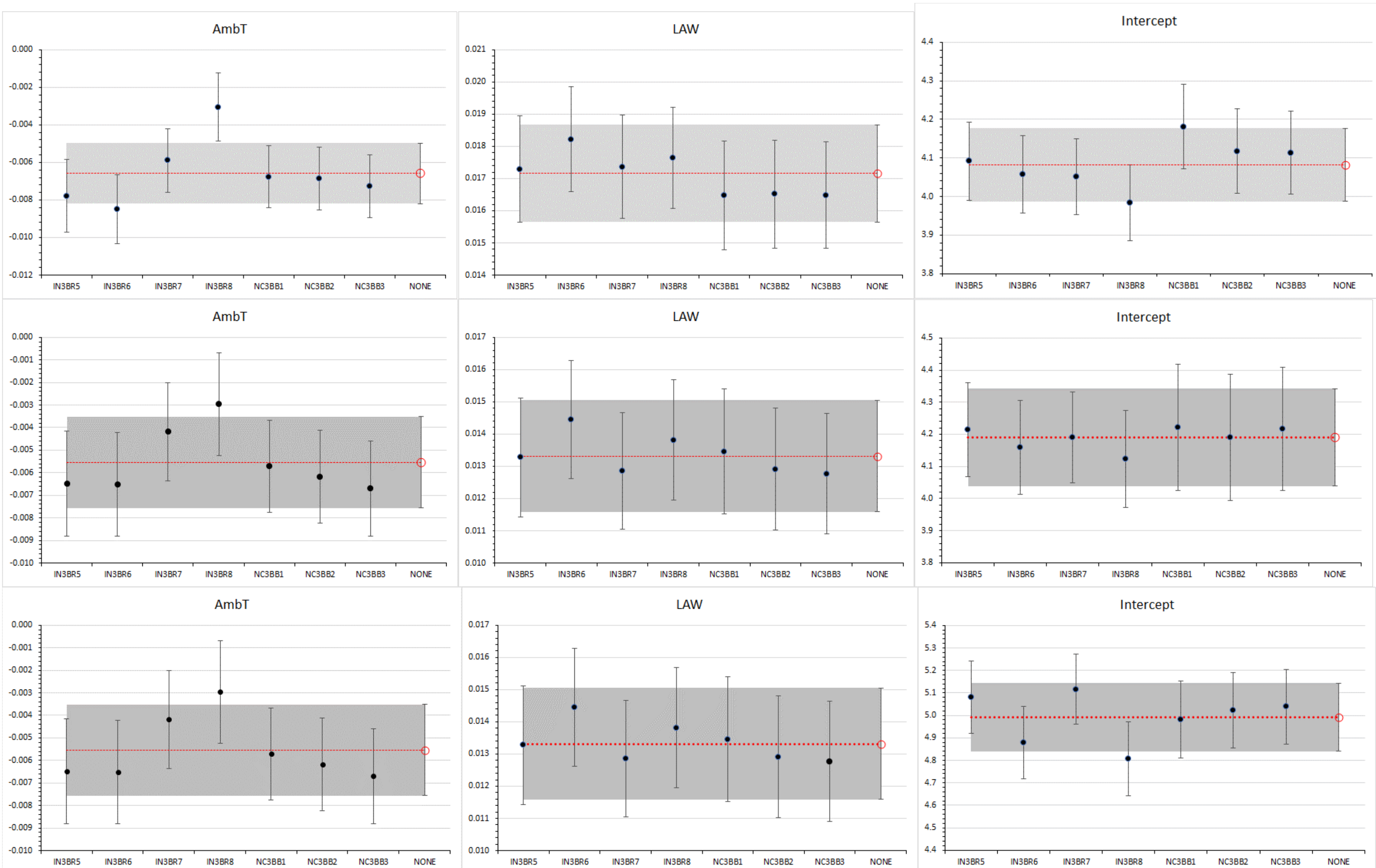

Figure 6-14. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected H_2S Grow-Finish model coefficient ("None," gray band for ± SE) for each model parameter. Plots are for the ambient temperature (left column), and LAW (center column), and intercept (right column). No pit results are in the top row, shallow pit middle row, and deep pit in the bottom row.

6.2.3 PM_{10} Model Evaluation

The model coefficients developed using the jackknife approach were comparable (Table 6-33 and Table 6-34). Figure 6-15 shows the variation in coefficients and standard errors for the selected model 2 and each of the jackknife models. All runs overlap the selected model, suggesting no significant differences in coefficients. Compared to the selected model (model 2), the maximum percentage differences for parameter estimates across the six models were 1.0%, 7.2%, and 8.4% for the intercept, ambient relative humidity, and LAW, respectively. Across all models, the differences in NME and NMB percentages in comparison to the selected model were also small, with NME values differing by less than 2.3% and NMBs by less than 2.892%.

Table 6-33. Parameters and estimates using the jackknife approach for PM_{10} emissions from grow-finish sites.

Site Out	Parameter	Estimate	Standard Error	p-value
None	Intercept	5.503943	0.04999	<0.0001
None	LAW	0.010447	0.00066	<0.0001
None	Ambient RH	-0.009403	0.00044	<0.0001
IN3BR5	Intercept	5.526831	0.05124	<0.0001
IN3BR5	LAW	0.010664	0.00068	<0.0001
IN3BR5	Ambient RH	-0.009915	0.00046	<0.0001
IN3BR6	Intercept	5.498268	0.05156	<0.0001
IN3BR6	LAW	0.010654	0.00069	<0.0001
IN3BR6	Ambient RH	-0.009537	0.00045	<0.0001
IN3BR7	Intercept	5.511390	0.05231	<0.0001
IN3BR7	LAW	0.011075	0.00072	<0.0001
IN3BR7	Ambient RH	-0.009645	0.00045	<0.0001
IN3BR8	Intercept	5.510694	0.04989	<0.0001
IN3BR8	LAW	0.010640	0.00064	<0.0001
IN3BR8	Ambient RH	-0.009542	0.00045	<0.0001
NC3BB1	Intercept	5.457815	0.05712	<0.0001
NC3BB1	LAW	0.010223	0.00073	<0.0001
NC3BB1	Ambient RH	-0.009031	0.00051	<0.0001
NC3BB2	Intercept	5.450092	0.05567	<0.0001
NC3BB2	LAW	0.010414	0.00071	<0.0001
NC3BB2	Ambient RH	-0.008723	0.00050	<0.0001
NC3BB3	Intercept	5.552647	0.05751	<0.0001
NC3BB3	LAW	0.009572	0.00072	<0.0001
NC3BB3	Ambient RH	-0.009218	0.00050	<0.0001

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

Table 6-34. Fit and evaluation statistics using the jackknife approach for PM_{10} emissions from grow-finish sites.

Site Out	LNME (%)	NME (%)	ME (kg day^{-1})	MB (kg day^{-1})	NMB (%)	Corr.
None	5.126	37.858	70.505	4.299	2.308	0.560
IN3BR5	5.229	38.870	70.954	4.109	2.251	0.546
IN3BR6	5.082	37.792	68.485	3.790	2.091	0.573
IN3BR7	5.014	36.951	68.849	4.538	2.435	0.574
IN3BR8	4.729	35.576	66.230	3.637	1.954	0.601
NC3BB1	5.305	39.238	72.748	5.183	2.796	0.542
NC3BB2	5.212	38.166	72.232	5.473	2.892	0.550
NC3BB3	5.309	38.314	74.010	3.219	1.667	0.540

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

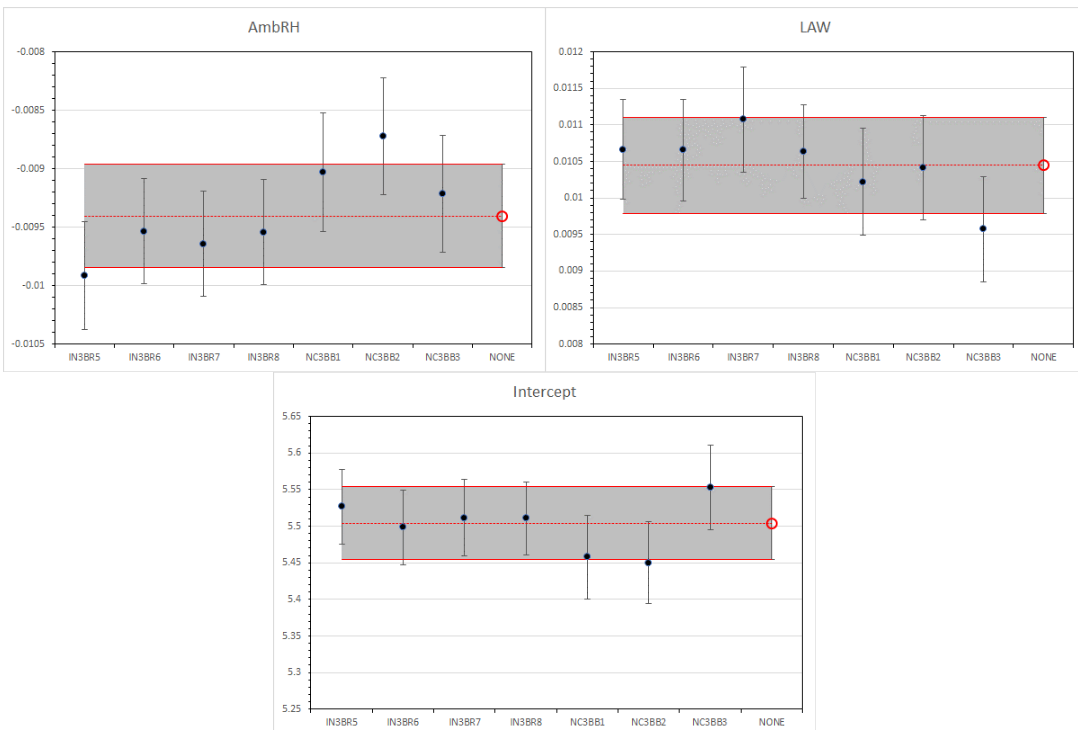

Figure 6-15. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected PM_{10} Grow-Finish model coefficient ("None," gray band for ± SE) for each model parameter.

6.2.4 $PM_{2.5}$ Model Evaluation

The model coefficients developed using the jackknife approach were comparable (Table 6-35 and Table 6-36). Figure 6-16 shows the variation in coefficients and standard errors for the selected model 2 and each of the jackknife models. All runs overlap the selected model, suggesting no significant differences in coefficients. In comparison to the selected model (model

2), the maximum percentage differences for parameter estimates across the seven models were 1.8%, 21.4%, and 22.6% for the intercept, ambient relative humidity, and LAW, respectively. Across all models, the difference in NME and NMB percentages in comparison to the selected model were also small, with NME values differing by less than 7.5% and NMB by less than 3.967%.

Table 6-35. Parameters and estimates using the jackknife approach for $PM_{2.5}$ emissions from grow-finish sites.

Site Out	Parameter	Estimate	Standard Error	p-value
None	Intercept	2.495430	0.19623	<0.0001
None	LAW	0.010950	0.00334	0.0041
None	Ambient RH	-0.002279	0.00086	0.0089
IN3BR5	Intercept	2.458096	0.09846	<0.0001
IN3BR5	LAW	0.011681	0.00134	<0.0001
IN3BR5	Ambient RH	-0.002199	0.00086	0.0117
IN3BR6	Intercept	2.505692	0.11620	<0.0001
IN3BR6	LAW	0.010972	0.00172	<0.0001
IN3BR6	Ambient RH	-0.002429	0.00091	0.0085
IN3BR7	Intercept	2.482571	0.19437	<0.0001
IN3BR7	LAW	0.011272	0.00328	0.0030
IN3BR7	Ambient RH	-0.002300	0.00092	0.0134
IN3BR8	Intercept	2.484291	0.18428	<0.0001
IN3BR8	LAW	0.011254	0.00308	0.0018
IN3BR8	Ambient RH	-0.002320	0.00092	0.0133
NC3BB1	Intercept	2.467530	0.14746	<0.0001
NC3BB1	LAW	0.010743	0.00217	0.0001
NC3BB1	Ambient RH	-0.001791	0.00106	0.0952
NC3BB2	Intercept	2.502909	0.21884	<0.0001
NC3BB2	LAW	0.010815	0.00377	0.0122
NC3BB2	Ambient RH	-0.002400	0.00068	0.0007
NC3BB3	Intercept	2.540677	1.17482	0.0438
NC3BB3	LAW	0.008480	0.01858	0.6637
NC3BB3	Ambient RH	-0.002357	0.00243	0.3347

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

Table 6-36. Fit and evaluation statistics using the jackknife approach for $PM_{2.5}$ emissions from grow-finish sites.

Site Out	LNME (%)	NME (%)	ME (kg day^{-1})	MB (kg day^{-1})	NMB (%)	Corr.
None	9.852	52.742	6.123	0.442	3.805	0.473
IN3BR5	9.848	51.629	6.187	0.475	3.967	0.43
IN3BR6	9.343	50.917	6.031	0.374	3.156	0.472
IN3BR7	9.460	50.172	6.106	0.529	4.348	0.478
IN3BR8	8.752	45.319	5.744	0.329	2.596	0.533
NC3BB1	9.560	56.578	4.990	0.641	7.272	0.499
NC3BB2	11.114	60.194	6.781	0.448	3.976	0.478
NC3BB3	11.950	55.149	6.671	0.018	0.146	0.475

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

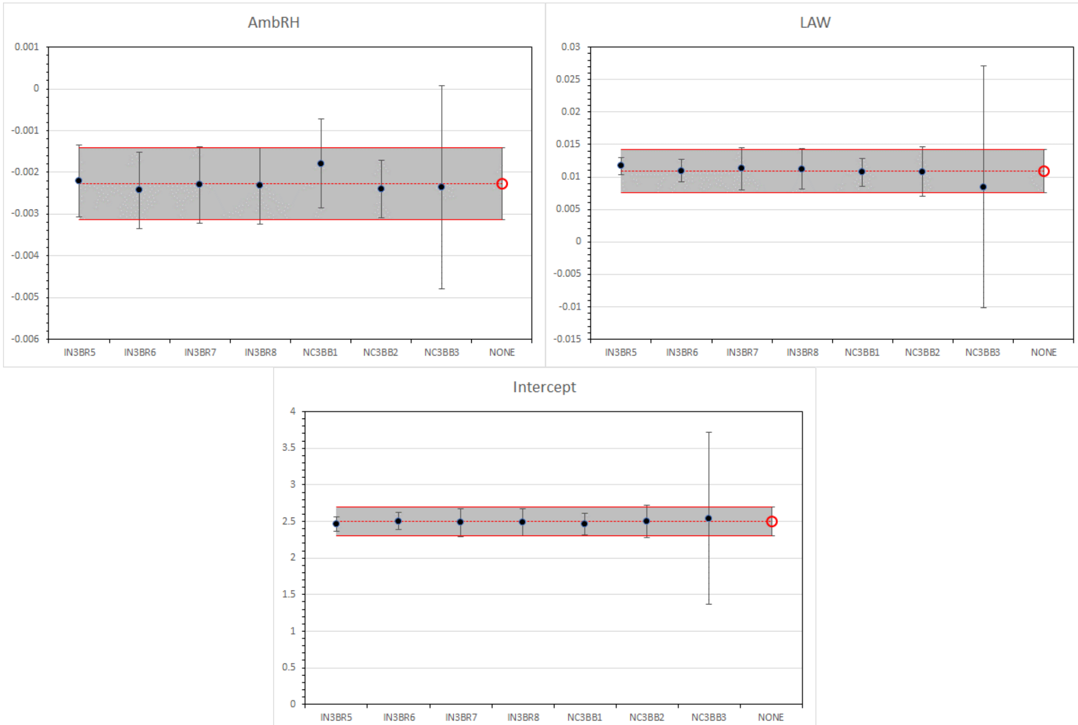

Figure 6-16. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected $PM_{2.5}$ Grow-Finish model coefficient ("None," gray band for ± SE) for each model parameter.

6.2.5 TSP Model Evaluation

The TSP model coefficients developed using the jackknife approach were not as consistent as those developed for the other PM species (see Table 6-37 and Table 6-38). Figure 6-17 shows the variation in coefficients and standard errors for the selected model 2 and each of the jackknife models. All runs overlap the selected model for relative humidity, suggesting no significant differences in the relative humidity coefficients. However, the runs for the NC3B barns fall outside of the ±1 standard error of the selected model.

In comparison to the selected model (model 2), the maximum percentage differences for parameter estimates across the six models were 14.6%, 19.9%, and 71.9% for the intercept, ambient relative humidity, and LAW, respectively. This could be due to differences in management between the sites. As discussed previously, IN3B is a "quad-barn," where each of the four rooms is treated as a separate barn.

Across all models, the differences in NME and NMB percentages in comparison to the selected model were small, with NME values differing by less than 3.51% and NMB by less than 0.03%.

Table 6-37. Parameters and estimates using the jackknife approach for TSP emissions from grow-finish sites.

Site Out	Parameter	Estimate	Standard Error	p-value
None	Intercept	6.266140	0.23119	<0.0001
None	Ambient Temp	0.011813	0.00296	0.0007
None	LAW	-0.008831	0.00185	<0.0001
IN3BR5	Intercept	6.321492	0.22403	<0.0001
IN3BR5	Ambient Temp	0.010197	0.00298	0.0008
IN3BR5	LAW	-0.009144	0.00182	<0.0001
IN3BR6	Intercept	6.204000	0.23819	<0.0001
IN3BR6	Ambient Temp	0.012636	0.00324	0.0010
IN3BR6	LAW	-0.009863	0.00187	<0.0001
IN3BR7	Intercept	6.060494	0.24017	<0.0001
IN3BR7	Ambient Temp	0.013710	0.00322	0.0006
IN3BR7	LAW	-0.008590	0.00191	<0.0001
IN3BR8	Intercept	6.142430	0.24171	<0.0001
IN3BR8	Ambient Temp	0.012712	0.00327	0.0011
IN3BR8	LAW	-0.008868	0.00186	<0.0001
NC3BB1	Intercept	7.174425	0.34089	<0.0001
NC3BB1	Ambient Temp	0.003708	0.00400	0.3671
NC3BB1	LAW	-0.008333	0.00279	0.0035
NC3BB2	Intercept	7.120128	0.26170	<0.0001
NC3BB2	Ambient Temp	0.003323	0.00299	0.2827
NC3BB2	LAW	-0.007071	0.00253	0.0061
NC3BB3	Intercept	7.178959	0.12129	<0.0001
NC3BB3	Ambient Temp	0.003742	0.00117	0.0053
NC3BB3	LAW	-0.008464	0.00161	<0.0001

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

Table 6-38. Fit and evaluation statistics using the jackknife approach for TSP emissions from grow-finish sites.

Site Out	LNME (%)	NME (%)	ME (kg day^{-1})	MB (kg day^{-1})	NMB (%)	Corr.
None	5.932	34.590	240.34	3.083	0.444	0.565
IN3BR5	6.244	36.717	246.74	-2.826	-0.421	0.517
IN3BR6	5.844	35.367	230.00	4.806	0.739	0.554
IN3BR7	5.609	31.941	206.84	-3.085	-0.476	0.669
IN3BR8	5.762	33.551	221.41	1.617	0.245	0.600
NC3BB1	7.118	36.539	280.47	-15.72	-2.048	0.595
NC3BB2	7.412	37.958	288.12	-14.08	-1.854	0.580
NC3BB3	7.838	38.100	275.80	-17.45	-2.410	0.632

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

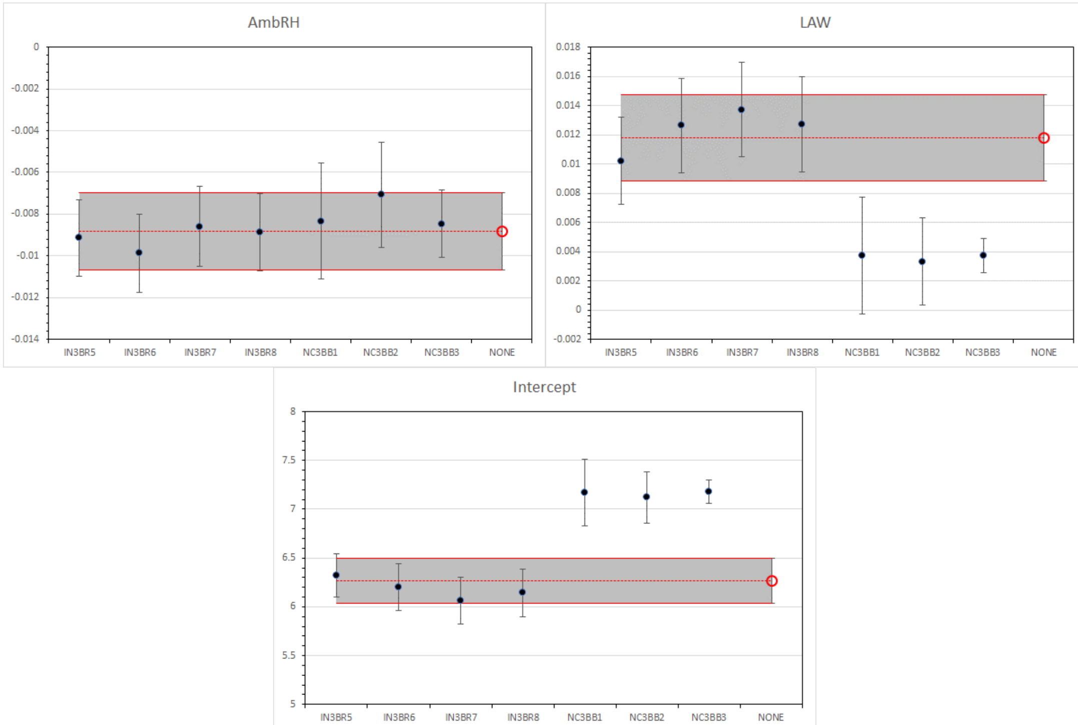

Figure 6-17. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected TSP Grow-Finish model coefficient ("None," gray band for ± SE) for each model parameter.

6.3 Lagoons

The exploratory data analysis suggested that EPA should consider ambient temperature, lagoon temperature, wind speed, pH, and LAW in the development of the models. Based on the exploratory data analysis, EPA decided to develop EEMs for breeding and gestation farm lagoons separately from grow-finish farm lagoons.

Because emissions emanate from the surface of a lagoon, the size of the lagoon affects emissions, and the size of the lagoon is often proportional to the number of animals the lagoon services. For these reasons, EPA normalized lagoon emissions (using the lagoon surface area) to better account for the variations across farms.

6.3.1 NH_3 Model Evaluation

For the breeding and gestation lagoons model, the coefficients from the jackknife approach were all significant and comparable across the withheld sets (see Table 6-39 and Table 6-40). The plots in Figure 6-18 show the results for all jackknife models compared to the full model ± 1 standard error. OK4A does not overlap the full model estimate for any of the parameters, and NC4A does not overlap for the intercept or wind speed. In comparison to the selected model (i.e., site out is "None"), the maximum percentage differences for parameter estimates across the sites were 53%, 16%, and 132% for the intercept, ambient temperature, and wind speed, respectively. Across all models, the differences in NME and NMB percentages in comparison to the selected model were moderate, with NME values differing by less than 4.35% and NMB by less than 0.023%.

For the grow-finish lagoon model, Table 6-41 and Table 6-42 present the results of the jackknife approach. The plots (Figure 6-19) show that the results for all jackknife models overlap the full model estimate ± 1 standard error, except for NC3A. Numerically comparing the withheld models to the selected model, the maximum percentage difference for parameters estimates were 200%, 70%, and 129% for intercept, ambient temperature, and wind speed, respectively. Across all models, the difference in NME and NMB percentages in comparison to the selected model were moderate, with NME values differing by less than 21.74% and NMB less than 0.006%.

Table 6-39. Parameters and estimates using the jackknife approach for NH_3 emissions from breeding-gestation farm lagoons.

Site Out	Parameter	Estimate	Standard Error	p-value
None	Intercept	0.582053	0.07702	<0.0001
None	AirTemp	0.055673	0.00268	<0.0001
None	WS	0.091428	0.01123	<0.0001
NC4A	Intercept	0.810115	0.08773	<0.0001
NC4A	AirTemp	0.056123	0.0026	<0.0001
NC4A	WS	0.06094	0.01223	<0.0001
OK4A	Intercept	0.890644	0.15759	<0.0001
OK4A	AirTemp	0.047354	0.00512	<0.0001
OK4A	WS	-0.029071	0.03857	0.456

Table 6-40. Fit and evaluation statistics using the jackknife approach for NH_3 emissions from breeding-gestation farm lagoons.

Site Out	LNME (%)	NME (%)	ME (kg day^{-1})	MB (kg day^{-1})	NMB (%)	Corr.
None	10.626	23.847	1.434	-0.001	-0.009	0.896
NC4A	8.632	19.497	1.392	0.059	0.821	0.919
OK4A	11.313	25.309	0.881	-0.031	-0.887	0.88

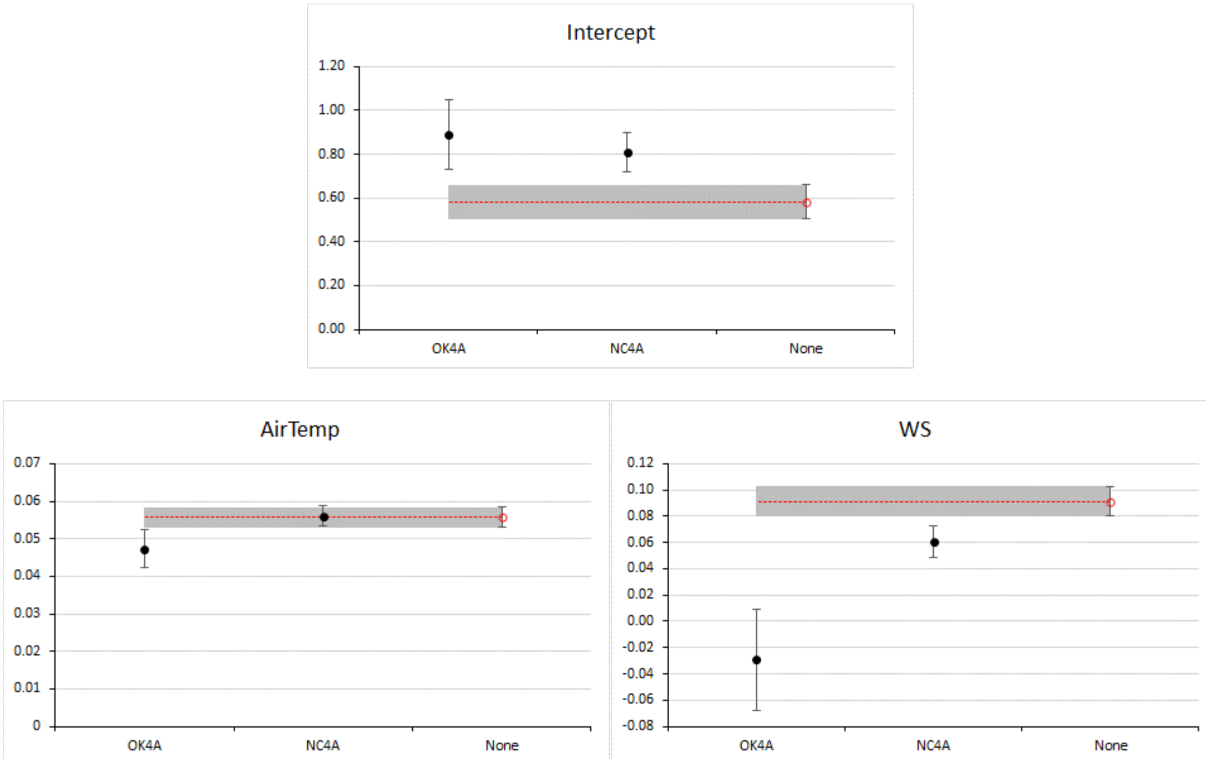

Figure 6-18. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected NH_3 Grow-Finish lagoon model coefficient ("None," gray band for ± SE) for each model parameter.

Table 6-41. Parameters and estimates using the jackknife approach for NH_3 emissions from grow-finish farm lagoons.

Site Out	Parameter	Estimate	Standard Error	p-value
None	Intercept	-0.680078	0.24813	0.0169
None	AirTemp	0.085372	0.01423	0.0033
None	WS	0.131932	0.05442	0.02
NC3A	Intercept	0.680268	0.37354	0.1155
NC3A	AirTemp	0.025556	0.01087	0.0233
NC3A	WS	0.073289	0.03001	0.0192
OK3A	Intercept	-0.238145	0.32152	0.4684
OK3A	AirTemp	0.065001	0.01577	0.0006
OK3A	WS	-0.037631	0.11655	0.7507

Table 6-42. Fit and evaluation statistics using the jackknife approach for NH_3 emissions from grow-finish farm lagoons.

Site Out	LNME (%)	NME (%)	ME (kg day^{-1})	MB (kg day^{-1})	NMB (%)	Corr.
None	34.087	28.822	1.223	-0.208	-4.913	0.895
NC3A	56.959	50.559	2.642	-0.665	-12.73	0.889
OK3A	71.985	27.796	0.497	-0.022	-1.204	0.896

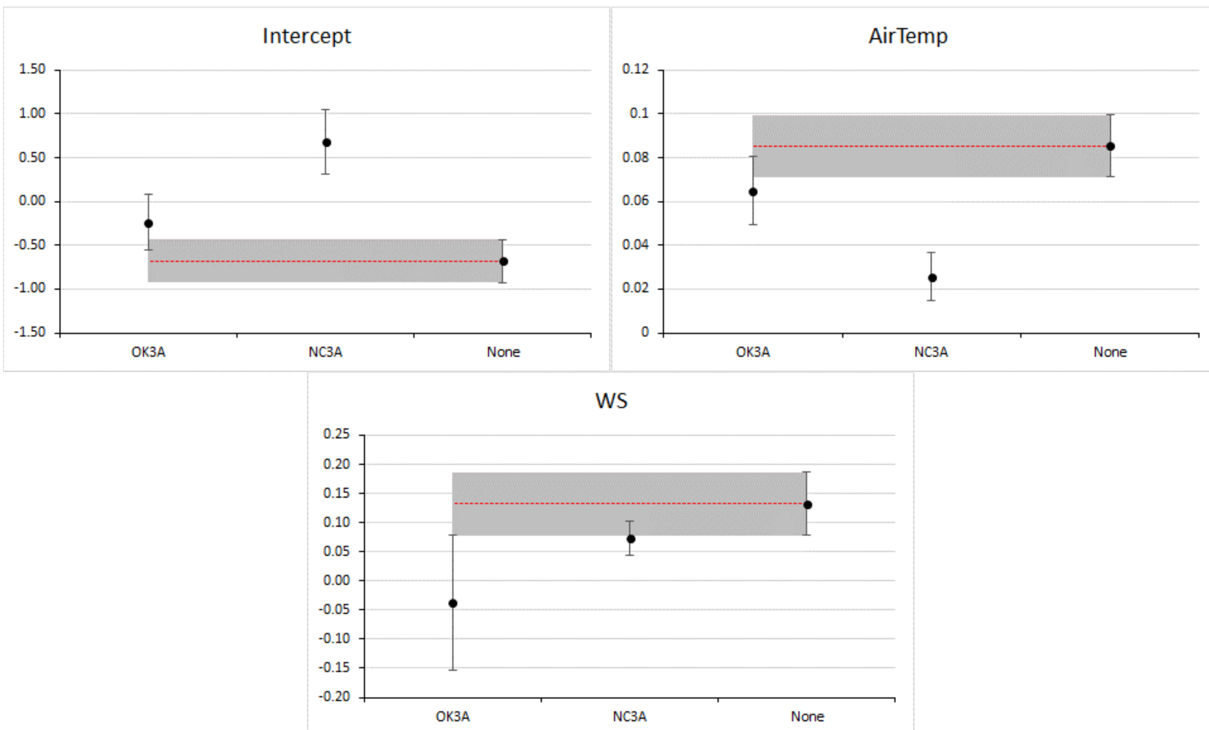

Figure 6-19. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected NH_3 Grow-Finish lagoon model coefficient ("None," gray band for ± SE) for each model parameter.

6.3.2 H_2S Model Evaluation

For the breeding and gestation lagoons model, Table 6-43 and Table 6-44 show the coefficients from the jackknife models. The plots in Figure 6-20 show that the results for all jackknife models compared to the full model ± 1 standard error. IN4A does not overlap the full model estimate for wind speed and had a p-value > 0.05, suggesting some data differences for this site. In comparison to the selected model (i.e., site out is "None"), the maximum percentage difference for parameters estimates across the sites were 12% and 105% for intercept and wind speed, respectively. Across all models, the difference in NME and NMB percentages in comparison to the selected model were moderate, with NME values differing by less than 59.21% and NMB less than 0.086%.

For the grow-finish lagoon model, Table 6-45 and Table 6-46 present the results of the jackknife approach. The plots (Figure 6-21) show that all "minus-one-barn" results overlap the model estimate ± 1 standard error, except for OK3A. Numerically comparing the withheld models to the selected model ("NONE") the maximum percentage difference for parameters estimates were 54%, and 177% for intercept, and wind speed, respectively. Across all models, the difference in NME and NMB percentages in comparison to the selected model were moderate, with NME values differing by less than 88.5% and NMB less than 0.665%.

For the basin model, as with the NH_3 model, EPA did not complete a jackknife analysis because there was only one site in the dataset, and EPA did not pursue an alternate evaluation using k-fold cross validation based on SAB comments.

Table 6-43. Parameters and estimates using the jackknife approach for H_2S emissions from breeding-gestation farm lagoons.

Site Out	Parameter	Estimate	Standard Error	p-value
None	Intercept	4.36054	0.2695	<0.0001
None	WS	0.23571	0.052	<0.0001
NC4A	Intercept	4.86592	0.3785	<0.0001
NC4A	WS	-0.0922	0.1297	0.483
OK4A	Intercept	4.36054	0.2695	<0.0001
OK4A	WS	0.23571	0.052	<0.0001

Table 6-44. Fit and evaluation statistics using the jackknife approach for H_2S emissions from breeding-gestation farm lagoons.

Site Out	LNME (%)	NME (%)	ME ($g\ d^{-1}m^{-2}$)	MB ($g\ d^{-1}m^{-2}$)	NMB (%)	Corr.
None	13.662	117.64	265.37	-24.48	-10.17	0.35
NC4A	16.252	110.69	346.14	-12.27	-3.922	0.267
OK4A	5.869	176.85	59.61	-1.228	-3.888	0.153

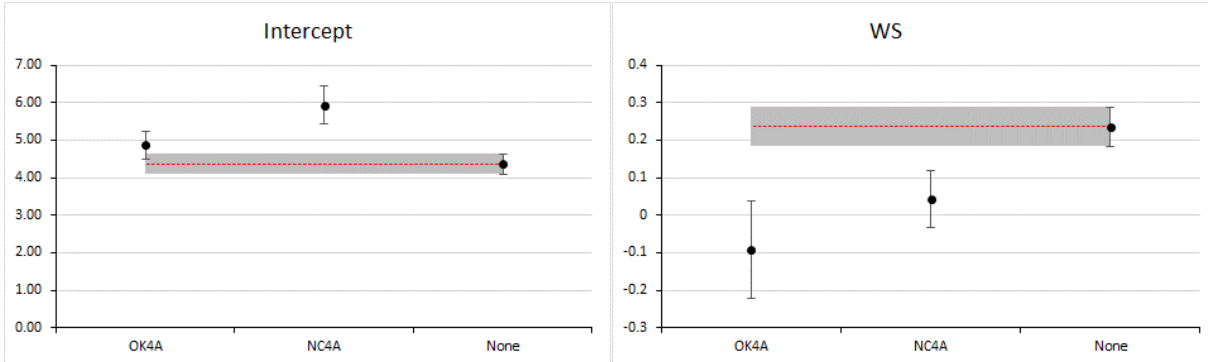

Figure 6-20. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected H_2S grow-finish lagoon model coefficient ("None," gray band for ± SE) for each model parameter.

Table 6-45. Parameters and estimates using the jackknife approach for H_2S emissions from grow-finish farm lagoons.

Site Out	Parameter	Estimate	Standard Error	p-value
None	Intercept	3.694758	0.49199	<0.0001
None	WS	0.279011	0.0731	0.0004
NC3A	Intercept	4.087401	0.56644	<0.0001
NC3A	WS	0.241888	0.07215	0.0017
OK3A	Intercept	1.690553	1.06612	0.1493
OK3A	WS	0.773746	0.31543	0.0377

Table 6-46. Fit and evaluation statistics using the jackknife approach for H_2S emissions from grow-finish farm lagoons.

Site Out	LNME (%)	NME (%)	ME ($g\ d^{-1}m^{-2}$)	MB ($g\ d^{-1}m^{-2}$)	NMB (%)	Corr.
None	29.034	71.652	280.35	-45.25	-0.116	0.689
NC3A	24.145	67.549	312.94	-43.7	-0.094	0.662
OK3A	46.409	160.19	165.33	18.405	0.178	0.024

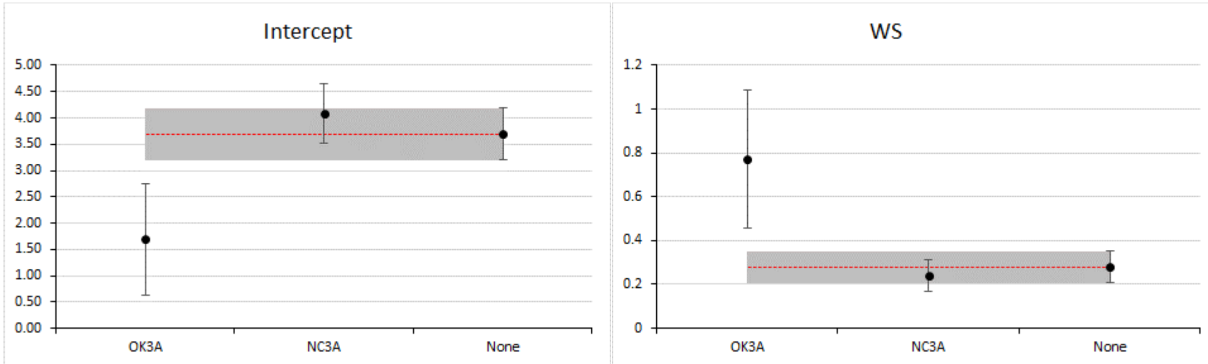

Figure 6-21. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each the jackknife model with the selected H_2S grow-finish lagoon model coefficient ("None," gray band for ± SE) for each model parameter.

6.4 Basins

For the basin models, EPA did not complete jackknife analysis for NH_3 or H_2S because there was only one site in the dataset. EPA also did not pursue a model evaluation using a k-fold cross validation technique based on SAB comments.

7 ANNUAL EMISSIONS ESTIMATES AND MODEL UNCERTAINTY

To estimate annual pollutant emissions, the results of the daily EEMs are summed over the number of operating days per year. This approach requires values for the necessary ambient, barn, and open source parameters. For an actual emissions estimate, the daily estimates are based on meteorology from nearby monitors and barn occupancy and animal weight records and open source surface area values 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., barns, lagoons), annual emissions are determined for individual sources and summed together to calculate total annual farm-scale emissions.

As noted in Section 6 of the Overview Report, the model results are transformed values resulting from emissions models. To convert to the native emissions units (e.g., kg or g), Equation 8 would be 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	Source Type	Manure Management System	Pollutant	e_i	C
Breeding-gestation	Farrowing Room	Unspecified	H_2S	1.4588	3
Breeding-gestation	Farrowing Room	Unspecified	NH_3	1.06677	0
Breeding-gestation	Farrowing Room	Unspecified	PM_{10}	1.05116	2
Breeding-gestation	Farrowing Room	Unspecified	$PM_{2.5}$	0.86487	6
Breeding-gestation	Farrowing Room	Unspecified	TSP	1.17091	0
Breeding-gestation	Gestation Barn	Deep Pit/Shallow Pit	H_2S	1.28254	29
Breeding-gestation	Gestation Barn	Deep Pit/Shallow Pit	NH_3	1.06524	0
Breeding-gestation	Gestation Barn	Unspecified	H_2S	2.1131	29
Breeding-gestation	Gestation Barn	Unspecified	NH_3	1.2156	0
Breeding-gestation	Gestation Barn	Unspecified	PM_{10}	1.09772	0
Breeding-gestation	Gestation Barn	Unspecified	$PM_{2.5}$	1.01188	114
Breeding-gestation	Gestation Barn	Unspecified	TSP	1.02075	0
Breeding-gestation	Lagoon	Unspecified	H_2S	1.48373	100
Breeding-gestation	Lagoon	Unspecified	NH_3	1.03459	2
Grow-finish	Barn	Deep Pit/Shallow Pit	H_2S	1.52598	13
Grow-finish	Barn	Deep Pit/Shallow Pit	NH_3	1.06222	1
Grow-finish	Barn	Unspecified	H_2S	2.37261	13
Grow-finish	Barn	Unspecified	NH_3	1.04371	1
Grow-finish	Barn	Unspecified	PM_{10}	1.05297	67
Grow-finish	Barn	Unspecified	$PM_{2.5}$	1.08403	10
Grow-finish	Barn	Unspecified	TSP	1.09602	0
Grow-finish	Basin	Unspecified	H_2S	1.1225	1
Grow-finish	Basin	Unspecified	NH_3	1.16858	2
Grow-finish	Lagoon	Unspecified	H_2S	2.04143	7

Animal Type	Source Type	Manure Management System	Pollutant	***e***	C
Grow-finish	Lagoon	Unspecified	NH_3	1.09967	0
Unspecified	Lagoon	Unspecified	H_2S	1.12375	100
Unspecified	Lagoon	Unspecified	NH_3	1.46057	0

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:

$$S_{an} = \sqrt{(S_{r1})^2 + (S_{r2})^2 + \ldots (S_{rn})^2} \qquad \text{Equation 30}$$

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 30 simplifies to:

$$S_{an} = S_r n^{0.5} \qquad \text{Equation 31}$$

Table 7-2 lists the S_r values for swine barns and open sources 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:

$$U_{an} \approx 1.96\, S_{an} \qquad \text{Equation 32}$$

Combining Equations 31 and 32 with an n value of 365 (representing the number of days in the annual uncertainty calculation) yields:

$$U_{an} \approx 1.96\, S_{an} \approx 1.96\, S_r n^{0.5} \approx 1.96\, S_r * (365)^{0.5} \approx 37.45\, S_r \qquad \text{Equation 33}$$

Table 7-2. Daily residual standard deviation values for swine barns and open sources.

Process	Pollutant	S_r	Emissions Units
Farrowing Barn	NH_3	0.199	
Farrowing Barn	H_2S	111.4	
Farrowing Barn	PM_{10}	18.299	
Farrowing Barn	$PM_{2.5}$	2.609	
Farrowing Barn	TSP	53.848	
Gestation barn, no pit	NH_3	10.346	kg/d
Gestation barn, no pit	H_2S	3,292	g/d
Gestation barn, no pit	PM_{10}	182.57	g/d
Gestation barn, no pit	$PM_{2.5}$	22.211	g/d
Gestation barn, no pit	TSP	351.87	g/d
Gestation barn, shallow pit	NH_3	9.123	kg/d
Gestation barn, shallow pit	H_2S	2,876.3	g/d
Gestation barn, shallow pit	PM_{10}	182.57	g/d
Gestation barn, shallow pit	$PM_{2.5}$	22.211	g/d
Gestation barn, shallow pit	TSP	351.87	g/d
Gestation barn, deep pit	NH_3	9.123	kg/d
Gestation barn, deep pit	H_2S	2,876.3	g/d
Gestation barn, deep pit	PM_{10}	182.57	g/d
Gestation barn, deep pit	$PM_{2.5}$	22.211	g/d
Gestation barn, deep pit	TSP	351.87	g/d
Finishing barn, no pit	NH_3	2.139	kg/d
Finishing barn, no pit	H_2S	205.55	g/d
Finishing barn, no pit	PM_{10}	96.621	g/d
Finishing barn, no pit	$PM_{2.5}$	4.269	g/d
Finishing barn, no pit	TSP	229.25	g/d
Finishing barn, shallow pit	NH_3	2.088	kg/d
Finishing barn, shallow pit	H_2S	246.73	g/d
Finishing barn, shallow pit	PM_{10}	96.621	g/d
Finishing barn, shallow pit	$PM_{2.5}$	4.269	g/d
Finishing barn, shallow pit	TSP	229.25	g/d
Finishing barn, deep pit	NH_3	2.088	kg/d
Finishing barn, deep pit	H_2S	246.73	g/d
Finishing barn, deep pit	PM_{10}	96.621	g/d
Finishing barn, deep pit	$PM_{2.5}$	4.269	g/d
Finishing barn, deep pit	TSP	229.25	g/d
Gestation, lagoon	NH_3	2.517	
Gestation, lagoon	H_2S	605.67	
Finishing, lagoon	NH_3	3.903	
Finishing, lagoon	H_2S	379	
Basin	NH_3	0.008	
Basin	H_2S	3.225	

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

$$Total\ farm\ uncertainty = \sqrt{(U_{B1})^2 + \cdots + (U_{Bi})^2 + (U_{L1})^2 + \cdots + \left(U_{Lj}\right)^2} \qquad \text{Equation 34}$$

Where:

Total farm uncertainty = total uncertainty for the total emissions from all farm sources.
UBi = the resulting uncertainty for barns, and i represents the total number of barns on the farm,
ULi = the resulting uncertainty for open sources, and j represents 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 EEMs, 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 EEM. Section 8 provides example calculations showing how the daily, annual, and annual uncertainty calculations are completed.

8 MODEL APPLICATION AND ADDITIONAL TESTING

Key to the development of any model is the demonstration of its 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 model (Section 8.1), the sensitivity of the models to their inputs (Section 8.2), a comparison of the models developed to existing emissions factors in literature, and a test of model performance against an independent dataset (Section 8.3).

8.1 Model Application Example

This section demonstrates how the daily EEMs from Section 5 and the annual uncertainty from Section 7 would be used to calculate emissions for a sample farm. These example calculations demonstrate how to use the system of equations to estimate emissions.

The example calculates NH_3 emissions for a finishing farm on a single day. For the hypothetical farm, consider 1,400 pigs placed in a shallow pit barn on January 1, 2019, in Bladen County, NC. The average weight of each pig is 14 kg. therefore, our LAW for the day is:

LAW(day 1) = 1,400 * 14 = 19,600 kg

The EEM uses thousands of kg (Mg) of LAW, so this value will be divided by 1,000 for use in the EEM. The next component of the calculation is the ambient weather data. Ambient weather data 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 NCEI site shows a location near Bladen County at Turnbull Creek, NC, which is a Global Historical Climate Network (GHCN) site, that already has the daily average temperatures calculated. It reports that the average temperature on January 1, 2019, was 20.56 °C. Based on Equation 16, our log transformed NH_3 emissions are equal to:

$$\text{Shallow Pit: } \ln(NH_3)=1.1422+0.0091*Amb_T+0.0085*LAW$$

Substituting for the temperature and LAW, the equation becomes:

$$\ln(NH_3) = 1.1422+0.0091*(20.56) +0.0085*(19600 /1000)$$

$$\ln(NH_3) = 1.4959$$

To back-transform the results to NH_3 in kg, use Equation 7 from the Overview Report and the values for e_i and C provided in Table 7-1. For a shallow pit grow-finish barn, e_i is 1.06222 and C is 1.

$$NH_3 = e^{1.4959} \times 1.06222 - 1$$

This comes to 3.74 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. For this example, we used the for Turnbull Creek, NC, which are summarized in Table 8-1. After considering the values for each day in 2019, the total annual emissions for the barn was calculated at 2,935.80 kg. To calculate the uncertainty associated with this estimate, use Equation 33 with the Sr value from Table 7-2. This results in an annual uncertainty of ± 78.20 kg. Thus, the final annual estimate for this barn is 2,935.80 kg ± 78.20 kg. This calculation would be repeated for any other grow-finish barns at the site. This example assumes there is a second barn, with an initial placement of 1,100 pigs. Using the same meteorology, the annual emissions are estimated at 2,360.13 kg ± 78.20 kg of NH_3.

Table 8-1. Summary of annual input parameters for Bladen County, NC.

Summary Statistic	Ambient Temperature (°C)	Wind Speed (mph @ 10 m)	Inventory (head)	Average Animal Mass (kg)	LAW (kg)
Minimum	-2.22	0.00	0	0.00	0.00
Average	17.86	3.32	1,400	62.98	88,166.7
Maximum	30.56	15.78	1,400	124.93	174,900.5

Finally, assume there is a 20,000 m^2 lagoon on the farm. The emissions from the lagoon are calculated from Equation 25:

$$Grow\ Finish\ Lagoon, ln(NH_3) = -0.6801 + 0.0854 \times Amb_T + 0.1319 \times ws$$

The height at which wind speed is measured influences the observation as friction with the surface will affect the observation. That is the closer to the ground the measurement is made, the more friction will act to slow the speed. NAEMS winds were monitored at a height of approximately 2.5 meters at swine open sources, while the National Weather Service (NWS) sites archived at NCEI are typically monitored at 10 m. Therefore, the difference in measurement heights between NAEMS and NWS requires an adjustment to the wind speed values used in the daily emissions models. The relationship between wind speed and height is well established and can be written as:

$$\frac{V}{V_r} = \left(\frac{Z}{Z_r}\right)^m \qquad \text{Equation 35}$$

Where m is the friction coefficient 0.125 for water surfaces (Arya, 1999; Masters, 2013), V_r is the wind velocity at a height of 10 m (Z_r) and V is the wind velocity height at 2.5 m (Z). Assuming a value of 0.125 for m, this results in the following equation:

$$V_{2.5m} = \left(\frac{2.5}{10}\right)^{0.125} \times V_{10m} = 0.840896 \times V_{10m}$$ Equation 36

Using this formula, a 10-m wind speed of 1.3 ms^{-1} would be 1.09 ms^{-1} at 2.5 m. Inserting Equation 36 into Equation 25 yields the following modification:

$$Grow\ Finish\ Lagoon, ln(NH_3) = -0.6801 + 0.0854 \times Amb_T + 0.1319 \times (0.840896 \times ws)$$

For a temperature of 20.56 °C and a 10-m wind speed of 1.3 ms^{-1},

$$Grow\ Finish\ Lagoon, ln(NH_3) = -0.6801 + 0.0854 \times 20.56 + 0.1319 \times (0.840896 \times 1.3)$$

$$Grow\ Finish\ Lagoon, ln(NH_3) = 1.22$$

Like with the barn emissions, back transform this result using values from Table 8-1.

$$NH_3 = e^{1.22} \times 1.09967 - 0$$

$$NH_3 = 3.72\ gd^{-1}m^{-2}$$

To get an emissions estimate for the whole lagoon, the result is multiplied by the surface area (20,000 m^2) for a final estimate of 74,126.86 g or 74.13 kg. Across the year, the lagoon is estimated to produce 1,351.1 gm^{-2}, or 27,021.55 kg of NH_3. To calculate the uncertainty associated with this estimate, use Equation 33 with the Sr value from Table 7-2. This results in an annual uncertainty of ± 146.17 gm^{-2}. Thus, the final annual estimate for this lagoon is 27,021.55 kg ± 146.17 kg. This calculation would be repeated for any other lagoons on the site.

To calculate total emissions from these three sources, the emissions from each unit are added. As a reminder, NH_3 emissions from barn 1 were 2,935.80 kg ± 78.20 kg, NH_3 emissions from barn 2 were 2,360.13 kg ± 78.20 kg, and NH_3 emissions from the lagoon were 27,021.55 kg ± 146.17 kg. The annual NH_3 emissions estimate from the confinement and open sources is:

$$Farm\ Total\ Emissions = 2{,}935.80 + 2{,}360.13 + 27{,}021.55 = 32{,}317.47\ kg\ NH_3$$

To estimate the total farm uncertainty, use Equation 34:

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

$$Total\ Farm\ Uncertainty = \sqrt{78.20^2 + 78.20^2 + 146.17^2}$$

$$Total\ Farm\ Uncertainty = 183.29$$

The final annual NH_3 estimate for the farm is 32,317.47 ± 183.29 kg.

8.2 Model Sensitivity Testing

In the previous example we calculated NH_3 emissions for a farm with two barns of varying sizes. The first barn had an initial placement of 1,400 pigs at an initial weight of 14 kg. Using a temperature of 20.56 for January 1, 2019, yielded NH_3 emissions of 3.74 kg NH_3 for the day.

The second barn had an initial placement of 1,100 pigs. Applying the same assumptions as barn 1, the NH_3 emissions for barn 2 on January 1, 2019, are as follows:

$$LAW(barn2, day\ 1) = 1{,}100 * 14 = 15{,}400\ kg$$

$$\ln(NH_3) = 1.1422+0.0091 * (20.56) +0.0085 * (15{,}400 /1000)$$

$$\ln(NH_3) = 1.4602$$

$$NH_3 = e^{1.4602} \times 1.06222 - 1$$

This results in daily NH_3 emissions of 3.57 kg NH_3. This is 0.17 kg less than barn 1 for the same day, which demonstrates the model's sensitivity to the number of animals in the barn. While this is a small number for a single day, the difference becomes 575.66 kg when the annual emissions for 2019 are calculated for each barn.

To further test model sensitivity (specifically, to demonstrate that climate differences produce different emissions results, EPA calculated the emissions for the same farm in two distinctly different climate regions. The first was the farm from the previous example that is in eastern North Carolina. Then the NH_3 emissions for this same farm setup (i.e., shallow pit grow-finish farm with two barns and a single lagoon) were calculated using meteorology from Crosby, North Dakota. A summary of the conditions in Crosby, ND is provided in Table 8-2.

Table 8-2. Summary of annual input parameters for Crosby, ND.

Summary Statistic	Ambient Temperature (°C)	Wind Speed (mph @ 10 m)	Inventory (head)	Average Animal Mass (kg)	LAW (kg)
Minimum	-31.62	2.59	0	0.00	0.00
Average	3.10	10.86	1,400	62.98	88,166.7
Maximum	25.64	24.68	1,400	124.93	174,900.5

For our test sites, the temperatures from the North Dakota site were always less than the North Carolina site (Figure 8-1). Temperatures in North Dakota varied from as little as 0.5 °C to as much as 51.6°C from North Carolina on the same day (Figure 8-2). On average, the North Dakota temperatures were 14 °C less than those in North Carolina. Divide County, ND has substantially higher average wind speeds than the North Carolina site (Figure 8-3). Winds are on average 2.7 ms^{-1} higher at the North Dakota site than the North Carolina site.

The annual NH_3 emissions estimate for the farm using meteorology from North Dakota was 19,656.46 kg; approximately 12,661 kg lower NH_3 emissions than when using meteorology from North Carolina. This is consistent with the trend of lower temperatures yielding lower emissions portrayed in the data exploration in Section 4, despite the higher wind speeds. This suggests that the EEMs are robust enough to account for the climatic differences of the different growing regions.

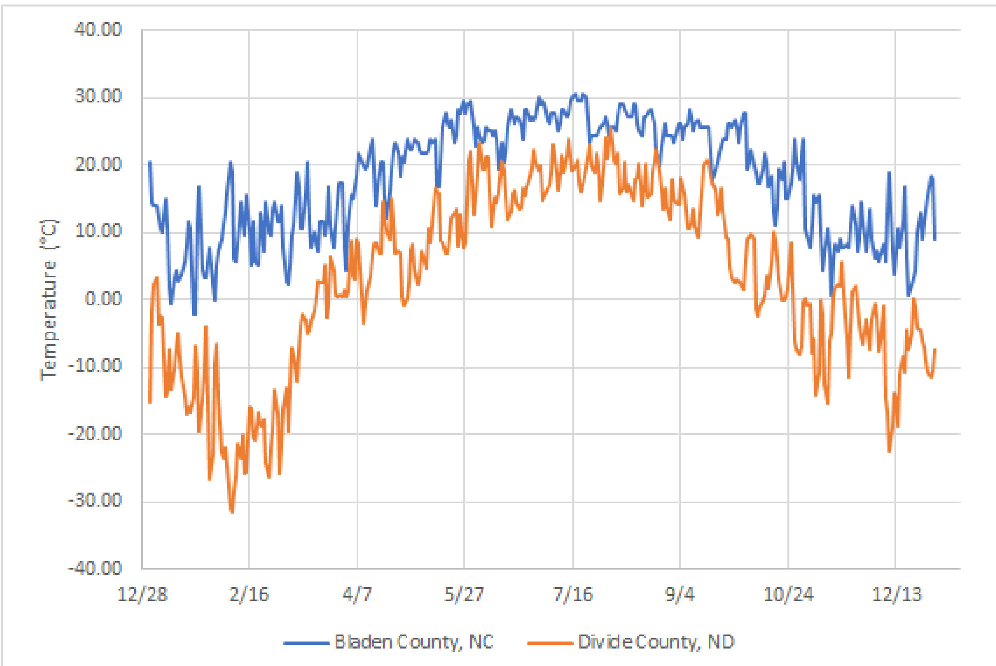

Figure 8-1. Comparison of temperature from test sites.

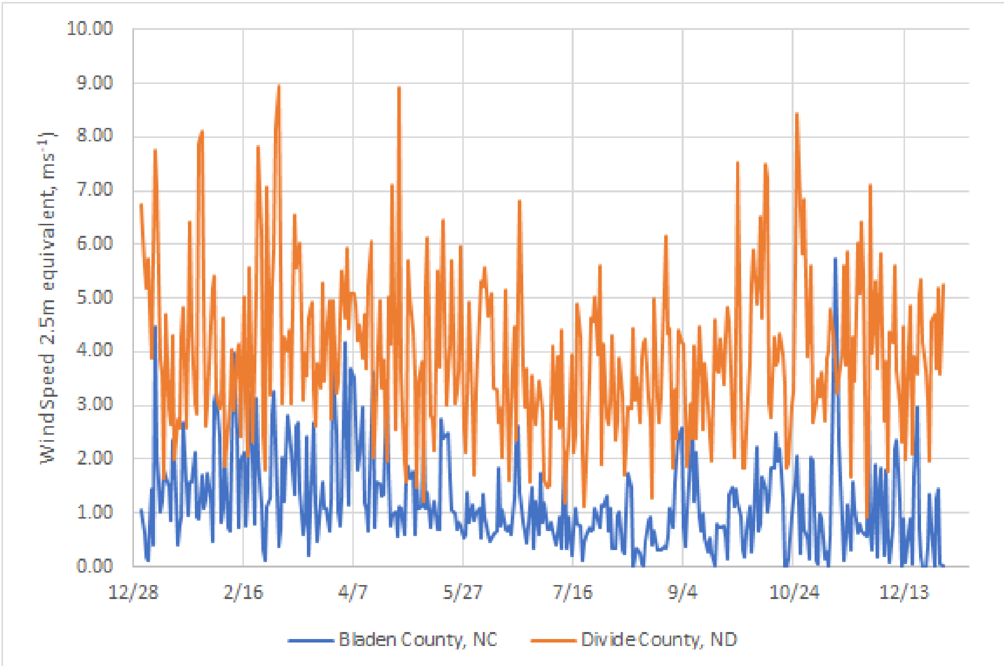

Figure 8-2. Comparison of 2.5 meter equivalent wind speed from test sites.

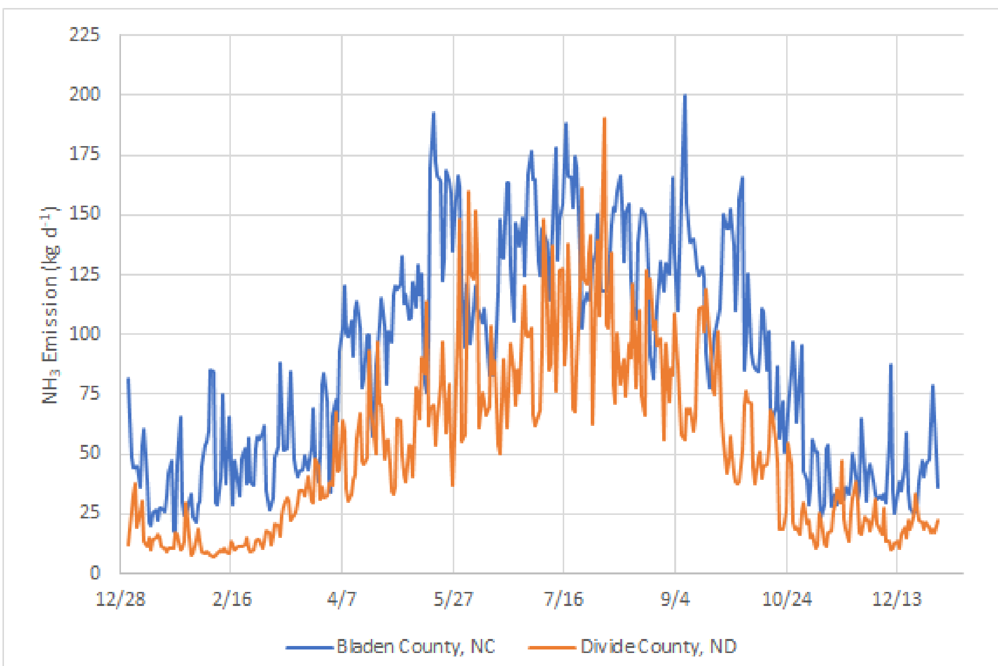

Figure 8-3. Comparison of total NH_3 emissions from test sites.

8.3 Model Limitation Testing

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

The swine equations included some combination of ambient temperature, ambient relative humidity, and wind speed. The ranges of ambient parameters are based on the NAEMS dataset. The range values tested for each parameter are in Table 8-3. Confinement models allow used the live animal weight to estimate emissions. For testing, the number of animals in a single barn or farrowing room are based on barn capacity numbers provided by consent agreement participants, while average weight were developed based on NAEMS study data. A range was developed for both weight and inventory. These values were then multiplied to develop a range of LAW values to test the models. Table 8-4 and Table 8-5 show the ranges used for breeding and gestation barns, and grow-finish barns, respectively.

Table 8-3. Parameter ranges tested for the swine models.

Parameter	Upper Limit	Lower Limit	Average Value	Increment
Ambient temperature (°C)	32.0	-23	10.0	0.8
Ambient relative humidity (%)	93	24	68.1	1
Wind speed (ms^{-1})	11.2	0.00	2.3	0.15

Table 8-4. LAW ranges tested for the swine breeding and gestation barn models.

Parameter	Upper Limit	Lower Limit	Average Value	Increment
Inventory (hd)	3360	8	744	25
Average animal weight (kg)	249	181	210	1
LAW (Mg)	865.81	1.45	385.56	--

Table 8-5. LAW ranges tested for the grow -finish barn models.

Parameter	Upper Limit	Lower Limit	Average Value	Increment
Inventory (hd)	3000	48	744	50
Average animal weight (kg)	130	20	70	1.5
LAW (Mg)	6.80	4.4	4.33	--

In the instance of farrowing rooms, LAW was derived from the weight and inventory are the combined values for sows and piglets in the room. The LAW for piglet and swine were calculated separately, assuming a piglet weight that increased over a growing cycle at a constant rate between the minimum and maximum values. The LAW for both piglets and swine were then combined for a room total LAW. Table 8-6 summarize the ranges for both sows and piglets.

Table 8-6. LAW ranges tested for the swine farrowing room models.

Parameter	Upper Limit	Lower Limit	Average Value
Inventory (hd), sow	24	0	21
Average animal weight (kg), sow	299	0	203
Inventory (hd), piglet	328	0	216 (Or 14 piglets per sow)
Average animal weight (kg), piglet	9	0	4.5
LAW (Mg), room	6.8	4.4	5.62

This analysis does not account for interaction between multiple terms within an equation, which could further affect the results. For example, in the case of particulate emissions where relative humidity can decrease emissions, higher ambient temperatures could allow for a wider range of inventory before potentially producing negative emissions. Conversely, a barn with lower ambient temperatures would cover a smaller range of inventory before potentially producing negative emission values. However, the analysis does provide a general range where the model produces reasonable results.

8.3.1 Breeding and Gestation Barns

The initial analysis for breeding and gestation barns is presented in Figure 8-4 and Figure 8-5. Neither the H_2S (Figure 8-4) nor NH_3 (Figure 8-5) models produce negative emissions under average conditions. The model did produce a rapid increase in emissions when estimating barns with LAW greater than approximately 250 Mg (roughly 1,200 head at 226 kg each). The average LAW the NAEMS data set was 219.62 Mg. It is encouraging that extreme extrapolation only starts to occur, which would account for the unrealistic behavior with extreme inventory numbers. Based on the consent agreement participant data, more than 90% of the participating barns fall below a capacity of 1,200 head. This suggests the model would still be appropriate for the bulk of the participants.

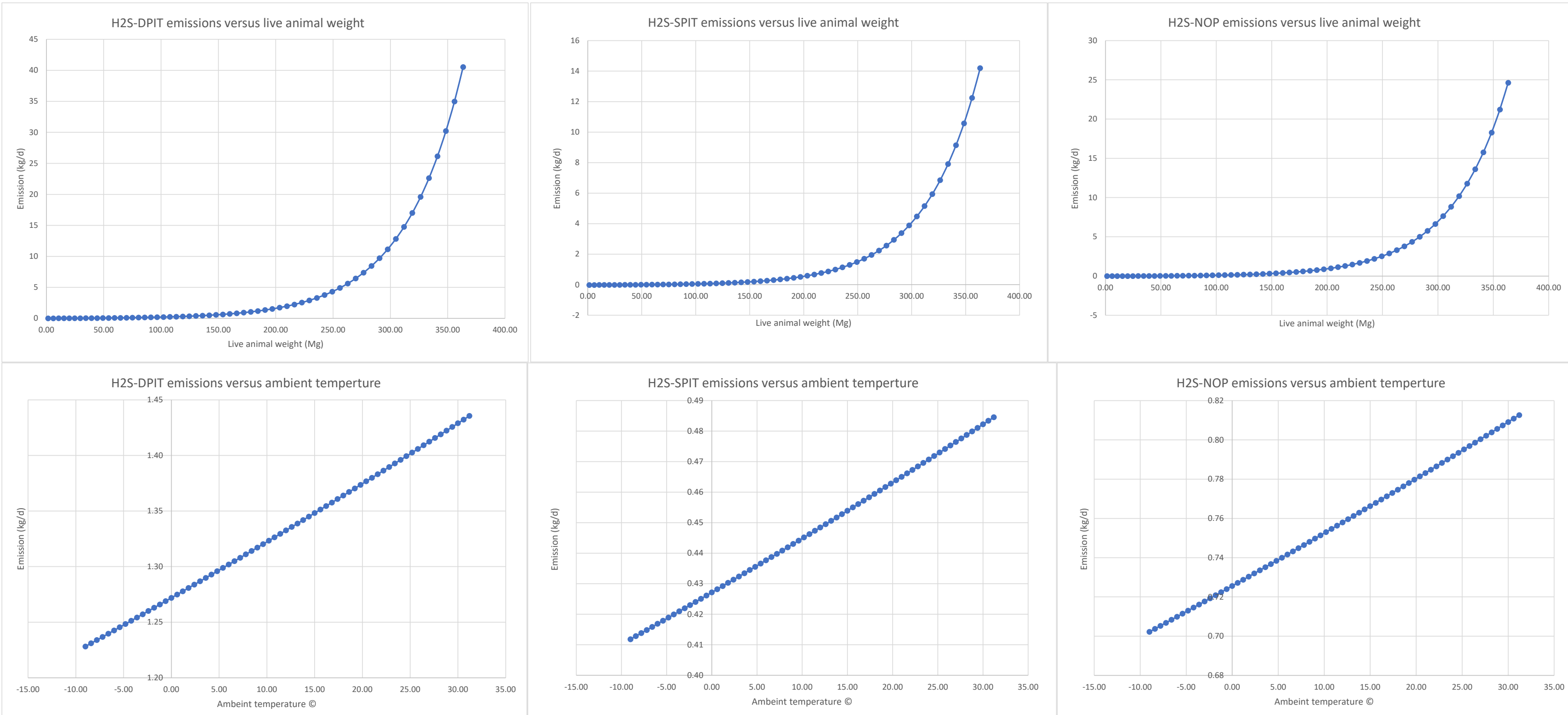

Figure 8-4. Breeding and gestation barn limitation tests for H_2S.

Visualization of the results for H_2S. – live animal weight (top row) and temperature (bottom row) tests for the deep pit (left), shallow pit (center) and pit type not specified (i.e., no pit) model (right).

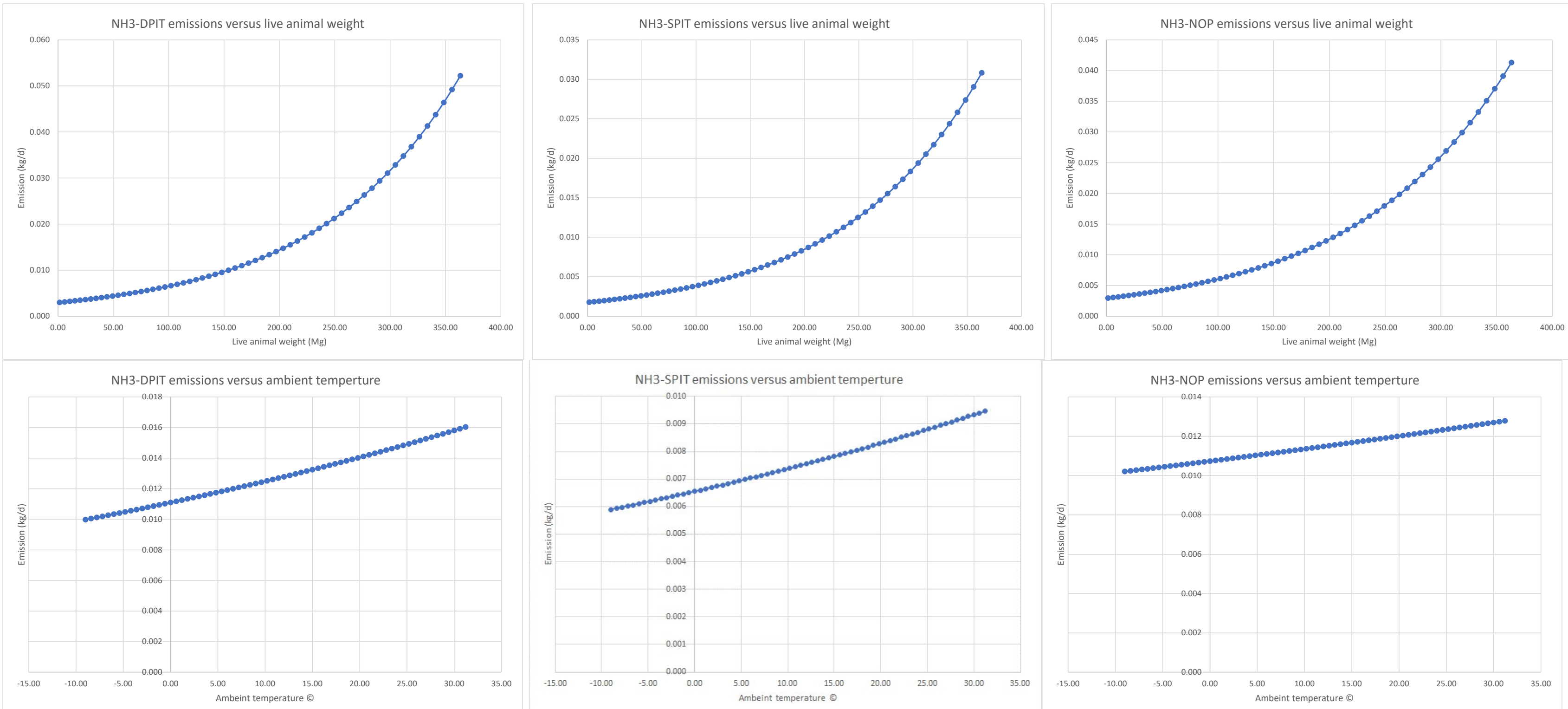

Figure 8-5. Breeding and gestation barn limitation tests for NH_3.

Visualization of the results for NH_3 – live animal weight (top row) and temperature (bottom row) tests for the deep pit (left), shallow pit (center) and pit type not specified (i.e., no pit) model (right).

The PM_{10}, $PM_{2.5}$, and TSP models (Figure 8-6) do not produce negative emission values. PM_{10} shows a slight rate increase after a law of 250 Mg, like H_2S and NH_3. However, the rate is not as severe. Again, based on the consent agreement participant data, more than 90% of the participating barns fall below a capacity of 1,200 head. This suggests the model would still be appropriate for the bulk of the participants.

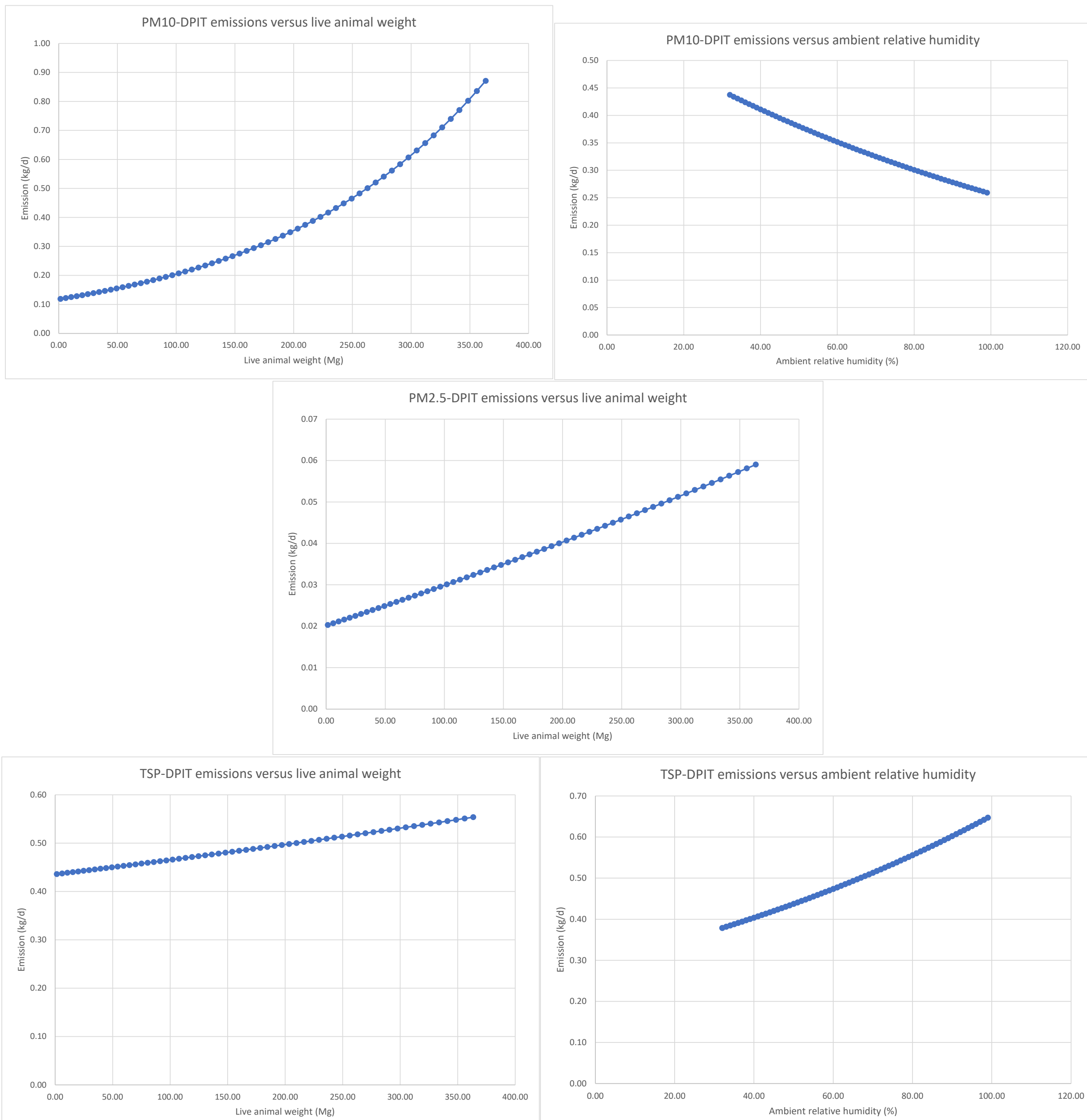

Figure 8-6. Breeding and gestation barn limitation tests for particulate matter.
Visualization of the results for PM_{10} (top row), $PM_{2.5}$ (bottom row), and TSP (center row), for tests of live animal weight (left) and ambient relative humidity (right).

8.3.2 Farrowing Rooms

The initial analysis for farrowing rooms is presented in Figure 8-7 and Figure 8-8. Neither the H_2S (Figure 8-7) nor NH_3 (Figure 8-8) models produce negative emissions under average conditions. The models do produce a rapid increase in emissions with respect to increasing LAW. However, the model also estimates only small amounts of emissions less than 1 kg for any of the pollutants on any day. The steep increase seems plausible, given the rapid growth of the piglets over the growth cycle.

With the PM_{10}, $PM_{2.5}$, and TSP models (Figure 8-9) we again see a rapid increase in emissions with respect to increasing LAW. We also saw linear trends with relative humidity for PM_{10} and TSP. The $PM_{2.5}$ model does produce negative emissions for LAWs less than 5.55 Mg, which roughly corresponds for the first 20 days of the growth cycle. The negative values are very small (less than 6 gram), which is well within the previously noted model uncertainty.

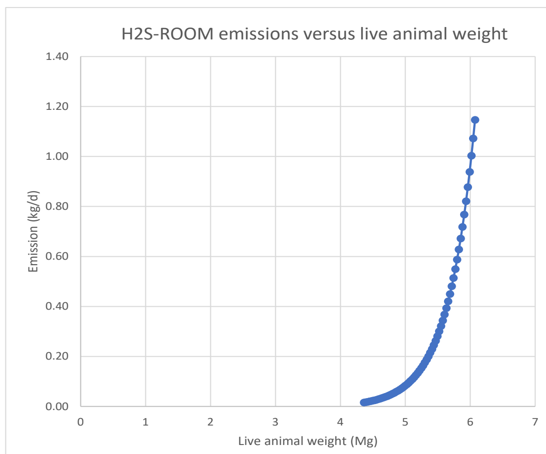

Figure 8-7. Farrowing room limitation tests for H_2S.
Visualization of the results for H_2S sensitivity to live animal weight.

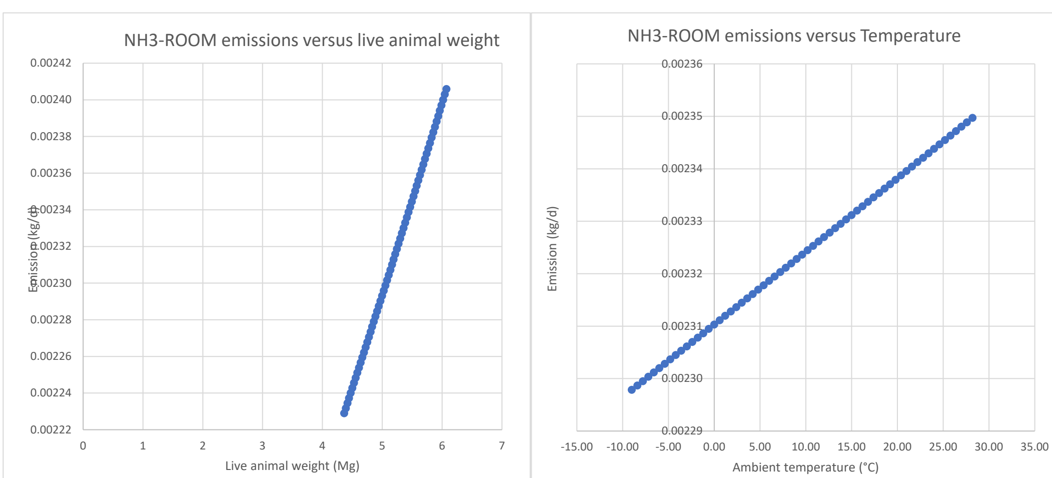

Figure 8-8. Farrowing room limitation tests for NH_3.
Visualization of the results for NH_3 sensitivity to live animal weight (right) and temperature (left).

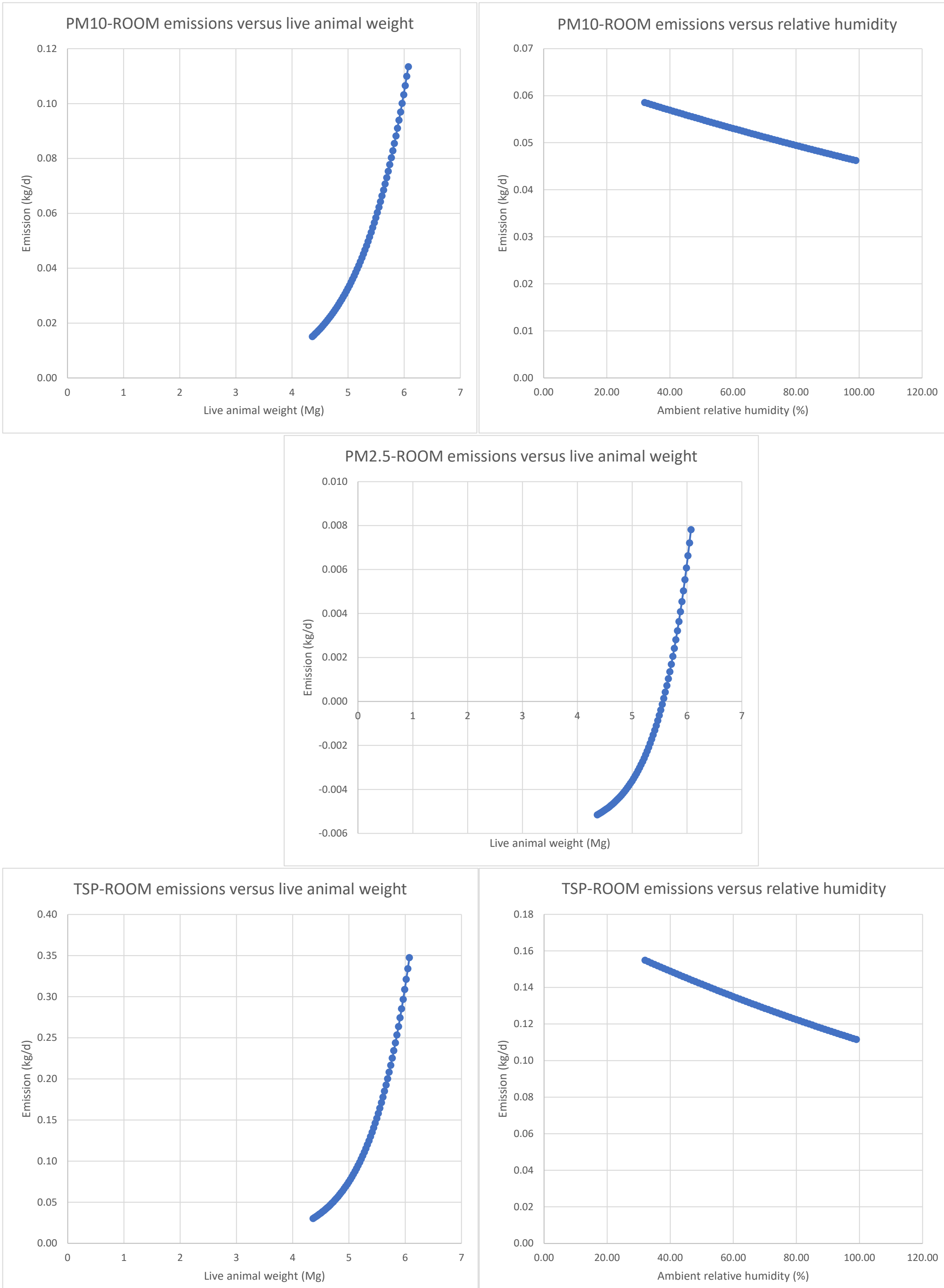

Figure 8-9. Farrowing room limitation tests for particulate matter.

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

8.3.3 Grow Finish Barns

The initial analysis for breeding and gestation barns is presented in Figure 8-5. Neither the H_2S (Figure 8-10) nor NH_3 (Figure 8-11) models produce negative emissions under average conditions. Relationships with temperature are linear across a range reasonable for the continental United States. The model did produce a rapid increase in emissions when estimating barns with LAW greater than approximately 200 Mg (roughly 1,500 head at 130 kg each). Based on the consent agreement participant data, more than ~92% of the participating barns fall below a capacity of 1,500 head. This suggests the model would still be appropriate for the bulk of the participants.

The PM_{10}, $PM_{2.5}$, and TSP models (Figure 8-12) do not produce negative emission values. Relationships with relative humidity are roughly linear across a range of values. PM_{10} shows a slight rate increase after a law of 200 Mg, like H_2S and NH_3. Again, based on the consent agreement participant data, more than 90% of the participating barns fall below a capacity of 1,500 head. This suggests the model would still be appropriate for the bulk of the participants.

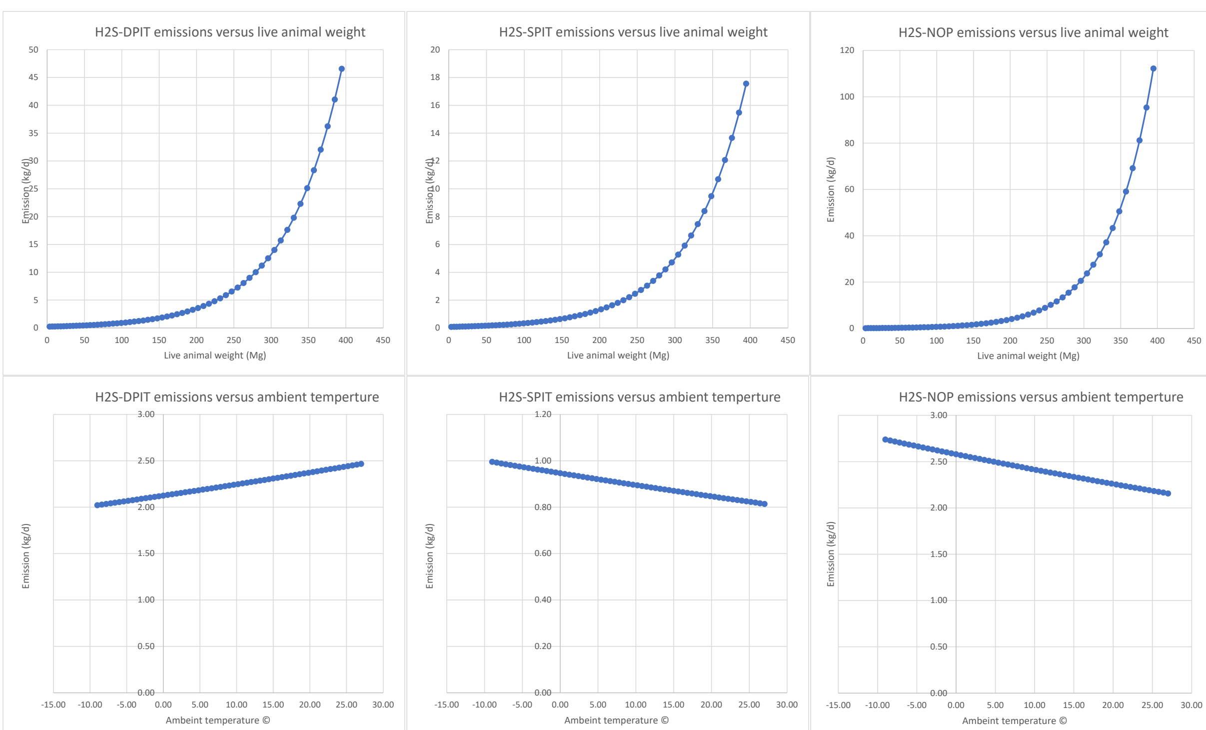

Figure 8-10. Grow-finish barns limitation tests for H_2S.
Visualization of the results for H_2S – live animal weight (top row) and temperature (bottom row) tests for the deep pit (left), shallow pit (center) and pit type not specified (i.e., no pit) model (right).

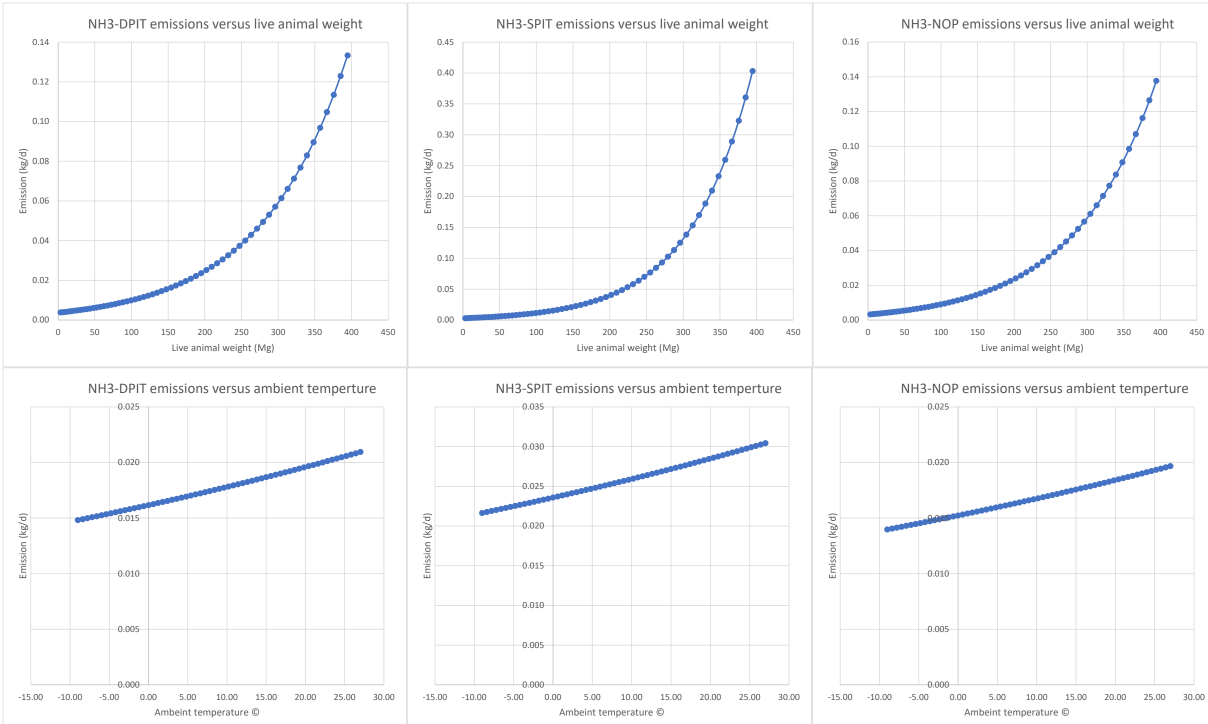

Figure 8-11. Grow-finish barns limitation tests for NH_3.

Visualization of the results for NH_3 – live animal weight (top row) and temperature (bottom row) tests for the deep pit (left), shallow pit (center) and pit type not specified (i.e., no pit) model (right).

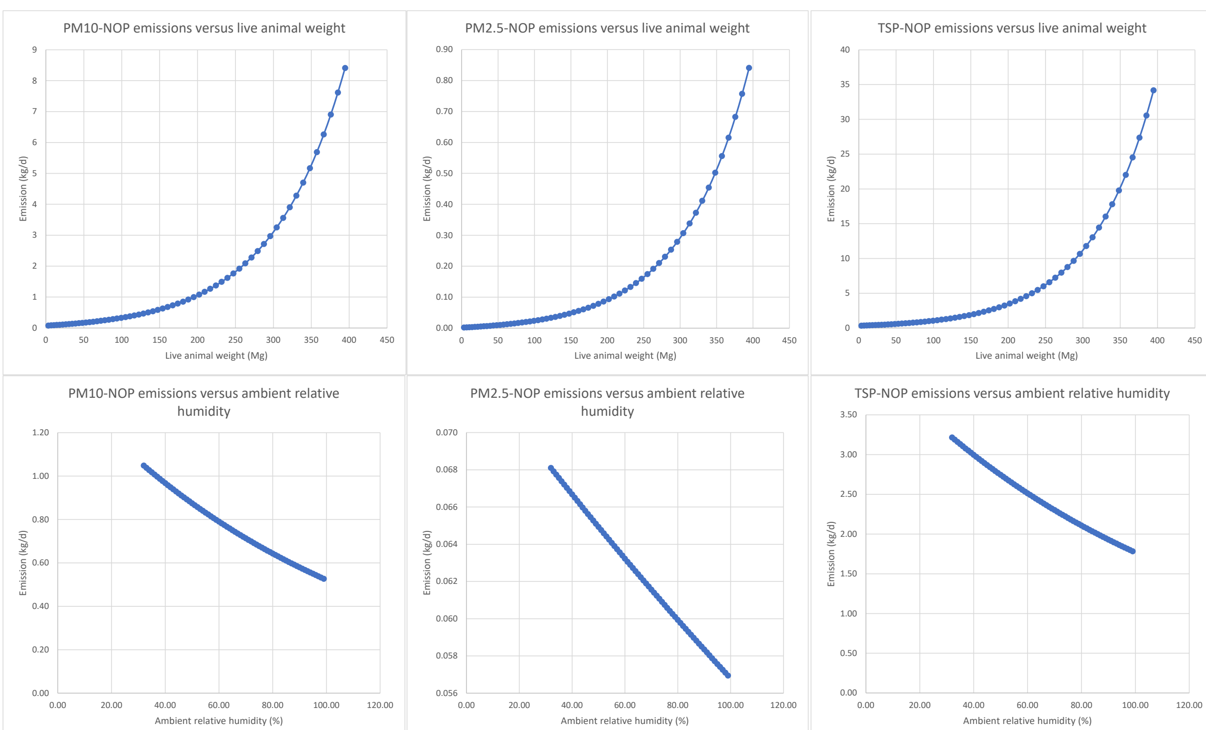

Figure 8-12. Grow-finish barns limitation tests for particulate matter.

Visualization of the results for PM_{10} (left), $PM_{2.5}$ (Center), and TSP (right), for tests of live animal weight (top) and ambient relative humidity (bottom).

8.3.4 Lagoons

Analysis for lagoons is presented in Figure 8-13 and Figure 8-14. The H_2S models (Figure 8-13) produce negative emissions under average conditions. Relationships with wind speed are not quite linear, but do not suggest issues with extrapolation.

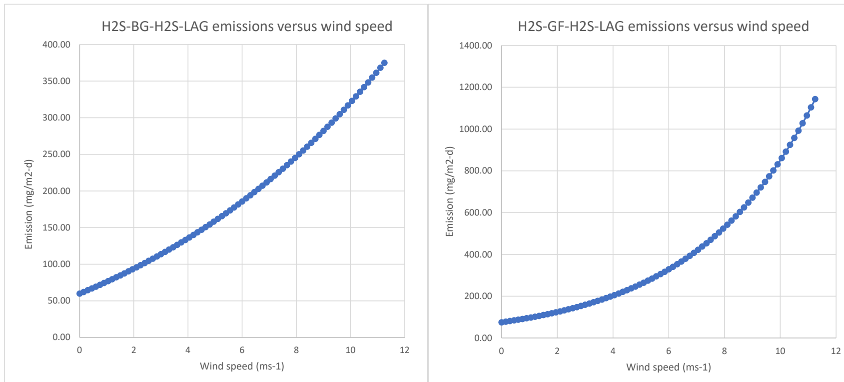

Figure 8-13. Lagoon tests for H_2S.
Visualization of the results for H_2S sensitivity breeding and gestation lagoons (left) and growing and finishing lagoons (right) to wind speed.

For NH_3 (Figure 8-14), the breeding and gestation model will produce negative emissions for temperatures below -3 °C. The negative emissions estimated by the model are less than 1 gram per m^2 of surface area, which is well within the uncertainty estimate for the model. The relationships with temperature and winds speed are not linear, but do not suggest there are issued with extrapolation.

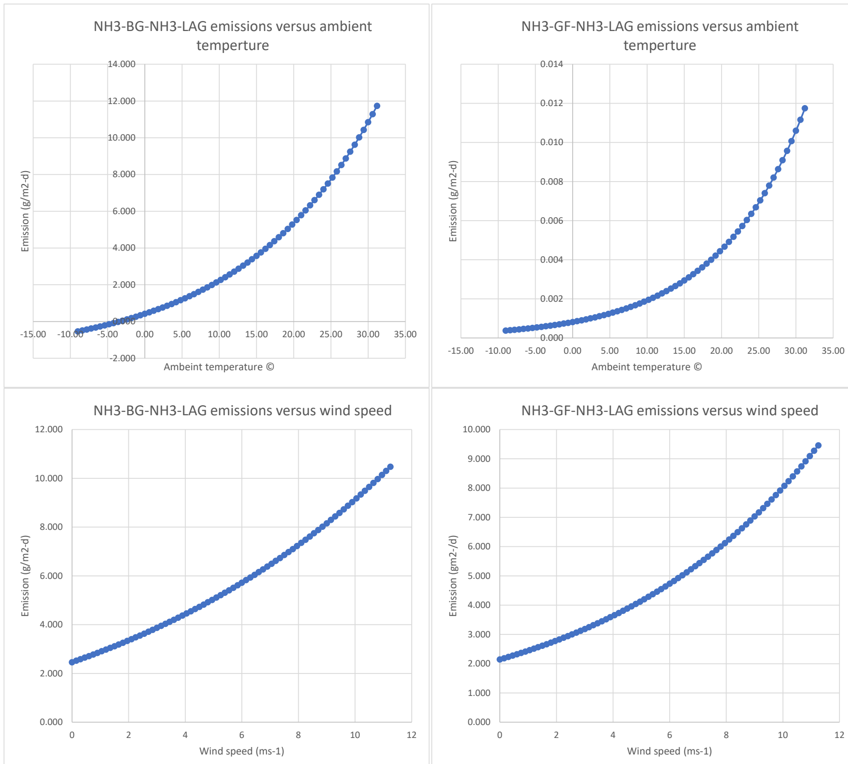

Figure 8-14. Lagoon limitation tests for NH_3.

Visualization of the results for NH_3 – ambient temperature (top row) and wind speed (bottom row) tests for breeding and gestation lagoons (left) and growing and finishing lagoons (right).

8.3.5 Basins

Basin limitation testing is summarized in Figure 8-15 and Figure 8-16 for H_2S and NH_3, respectively. Both plots are fairly linear and do not suggest the model will produce extreme emission estimates across the range of temperatures seen in the continental United States.

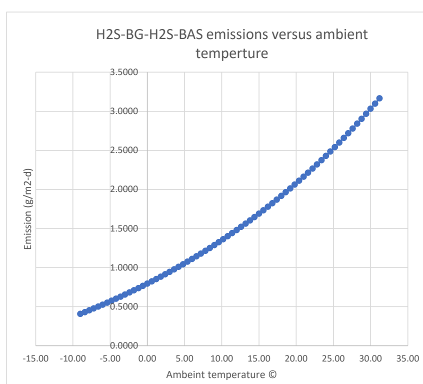

Figure 8-15. Basin limitation test for H_2S.

Visualization of the results for H_2S sensitivity of breeding and gestation basins to ambient temperature.

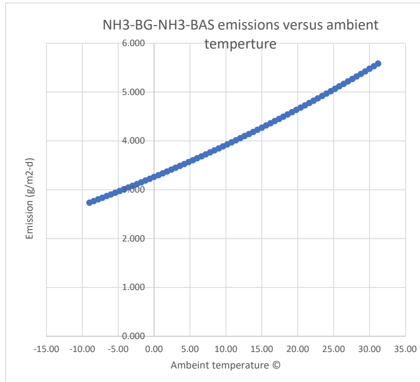

Figure 8-16. Basin limitation test for NH_3.

Visualization of the results for NH_3 sensitivity of breeding and gestation basins to ambient temperature.

8.4 Comparison to Literature and Replication of Independent Measurements

To further validate the EEMs developed under this effort, EPA compared the results for the EEMs to the emissions calculated using emission factors found in literature. EPA scanned the literature for a variety of emission factors. Ni et al. (2012) contained a review of emission factors. EPA selected the three most recent factors for comparison, which are summarized in Table 8-7.

These emission factors were then applied to the theoretical finishing barns from the example calculation in Section 8.1 (i.e., warm climate farm, starting weight of 14 kg). EPA also calculated the emissions for a theoretical farrowing room with an initial placement of 36 sows in a shallow pit room, which yielded 412 piglets, for comparison. The EEMs estimate for the farrowing room was based on the same meteorology used for the grow-finish barn from the example in Section 8.1. The results for both the grow-finish barns and a farrowing room are presented in Table 8-8. For the farrowing room, the emission factors from Arogo et al. (2006) and Battye et al. (2003) use only the number of sow present, while the composite emission factor from Faulkner and Shaw (2008) uses both sow and piglet inventory, like the EEM.

Overall, the EEMs described in this paper result in emission estimates that are lower than previous emission factors. The exceptions are for the farrowing room where the emission factor only considered the sow inventory. One reason for the lower values could be the due to the study duration. Arogo (2006) noted that a flaw in emission factors is that they are usually developed from measurements taken over short periods of time, which may not represent average annual conditions of weather, operating conditions, and animal sizes and numbers. Arogo (2006) posited that the extrapolation of these short term measurements might lead to under or over estimation of ammonia emissions. As the EEMs are based on two years of consecutive measurements from the barns, they should be more reflective of the actual average emissions since they are based on a wider variety of meteorological and house conditions.

The disparity in the emissions compared to the composite emission factor developed by Faulkner and Shaw is also due to the increased complexity of the EEM. A composite emission is developed to represent the mix of animal type, size, and production conditions. The composite emission factor is a weighted average of emission factors for several sizes and types of swine, including sows, gilts, boars, piglets, and growing (finishing) pigs. So not only is the composite emission factor derived from short term studies, but it is also an average of emission factors for all the phases of swine production and manure management systems, and not specific to the source being estimated here.

For the farrowing rooms, the EEMs presented in this paper appear to be a compromise between previously released emission factors. The EEMs fall in the middle of the previous methods, likely to the increased variability of conditions captured in the EEMs.

Table 8-7. NH_3 emission factors (kg NH_3 hd^{-1} yr^{-1}) from literature.

Source	Grow-Finish	Sow/Farrow	Composite
Faulkner and Shaw (2008)	--	--	5.8
Arogo et al. (2006)	6.98	16.13	--
Battye et al. (2003)	6.4	16.4	--

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

Barn Type	Inventory (hd)	2020 EEMs	Faulkner and Shaw (2008)	Arogo et al. (2006)	Battye et al. (2003)
Grow-Finish, Barn 1	1,400	2,935.80	8,120.00	9,772.00	8,960.00
Grow-Finish, Barn 2	1,100	2,360.13	6,380.00	7,678.00	7,040.00
Farrowing Room	Total: 448 Sows: 36	1,203.61[a]	2,598.40[a]	580.68[b]	590.40[b]

[a] Estimate based on total animal inventory (i.e., sows and piglets)
[b] Estimate based on sow inventory only.

EPA also tested the EEMs against the Michigan Department of Environment, Great Lakes, and Energy (EGLE) calculations worksheet for EPCRA and CERCLA compliance. The worksheet lays out calculations for minimum and maximum daily emissions values based on the head count. Table 8-9 presents the results for NH_3. For all the structures tested, the head count was allowed to drop to zero to replicate periods when the structure is empty for management purposes (e.g., cleaning). In these minimum instances, the EEMs do predict some nominal emissions for the structure, unlike the MI EGLE worksheet. For the grow-finish maximum daily emissions calculations, the EEMs predict approximately half the emissions as the worksheet. For the farrowing room, the EEMs estimate slightly more emissions than the worksheet. Similar to the previous example, the minimum and maximum emission estimates are based, in part, on emission factors from more limited data sets. The added consideration for meteorological variables is likely contributing to the lower maximum emissions for the source and higher minimum emissions.

Table 8-9. Comparison of resulting NH_3 emissions (kg d^{-1}) from various estimation methods.

Barn	Inventory (hd)	2020 EEM	MI EGLE 2009
Grow-Finish, Barn 1 Min	0	2.82	0
Grow-Finish, Barn 1 Max	1,400	17.95	34.93
Grow-Finish, Barn 2 Min	0	2.82	0
Grow-Finish, Barn 2 Max	1,100	12.78	27.44
Farrowing Room, Min	0	1.23	0
Farrowing Room, Max	Total: 448 Sow: 36	3.41[a]	2.61 [b]

[a] Estimate based on total animal inventory (i.e., sows and piglets)
[b] Estimate based on sow inventory only.

A final test of the developed EEMs 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 a 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 EEMs can be applied and then compared to the observed emissions.

The APECAB project included a farrowing buildings (IL site), gestation buildings (MN site), and grow-finish buildings (IA and TX sites). EPA was able to obtain data for the IL, MN, and IA sites for testing. However, the farrowing site did not include cycle day as a parameter, which is needed for the developed EEMs. The site reported a constant inventory and average animal mass for the duration of the study, which made it impossible to determine the cycle day from those values. As a result, EPA could only test the two gestation barns from the MN site and the two grow-finish barns from the IA site.

For the available site, the ambient and barn parameters were used in the EEMs to estimate the emissions from the barns. These estimates were then compared to the observed values, when available, using the same model performance statistics noted in Section 9.

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 observation has been used as a model performance metric in air quality modeling as 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.

For the grow-finish barns NH_3 was under predicted, while H_2S, and PM_{10} were over predicted (Table 8-10, Figure 8-17). For NH_3, the model has a 6% negative bias with a 20% error. The scatter plots (Figure 8-17) show that a vast majority of the NH_3 values fall within a factor of two of the observation. For H_2S and PM_{10}, the percent error values are larger than seen with NH_3. However, the values of mean bias and error in terms of emissions are much lower than NH_3. This is a function of the emission values being an order of magnitude smaller, so small errors and bias represent a large percentage of the overall values.

Table 8-10. Model performance evaluation statistics grow-finish barns.

Pollutant	n	MB (kg)	ME (kg)	NMB (%)	NME (%)	r
NH_3	449	-0.4001	1.3899	-6%	20%	0.5442
H_2S	403	0.0433	0.2709	9%	55%	0.2895
PM_{10}	495	0.1033	0.1147	95%	106%	0.3694

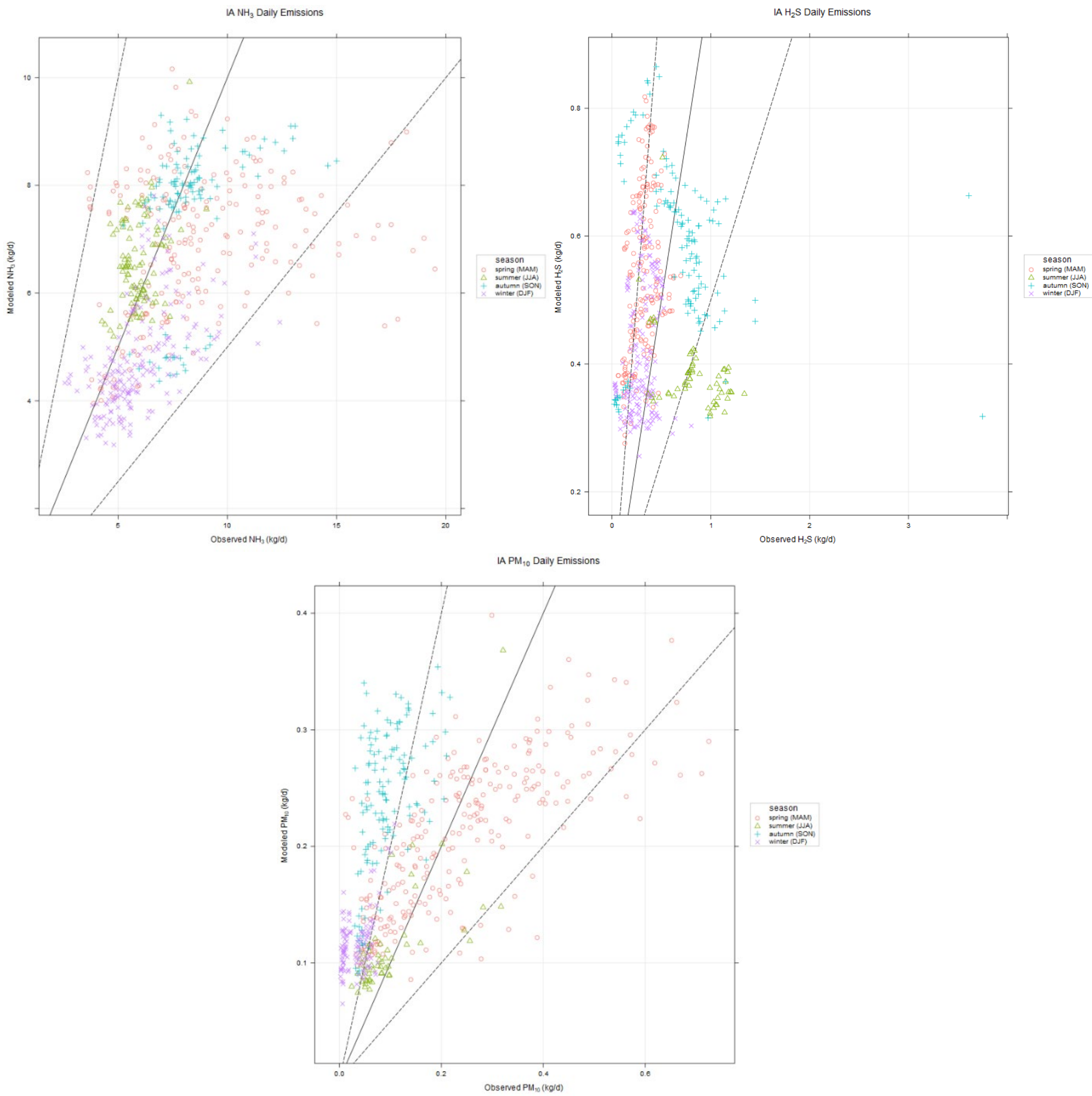

Figure 8-17. Scatter plots of observed versus predicted emissions for the grow-finish site (IA).

For the gestation barns, the EEMs under predicted NH_3, H_2S, and PM_{10} (Table 8-11). Most notably is the under prediction for H_2S, where most of the predicted values fall outside a factor of two of the observed values (Figure 8-18). As with the grow-finish barns, the percentage error and bias are large, but represent small practical emission values. Results for PM_{10} are better, with NMB and NME at -29% and 32%, respectively. The scatter plots show more values falling within a factor of two of the observations. For NH_3, the scatter plots (Figure 8-18) are even better, with most predictions within a factor of two of the observation, which is also reflected in the NMB and NME of -2% and 35%, respectively.

Table 8-11. Model performance evaluation statistics gestation barns.

Pollutant	n	MB (kg)	ME (kg)	NMB (%)	NME (%)	r
NH_3	580	-0.0684	1.4063	-2%	35%	-0.1527
H_2S	521	-0.2555	0.2572	-76%	77%	0.2144
PM_{10}	657	-0.0868	0.0966	-29%	32%	0.3045

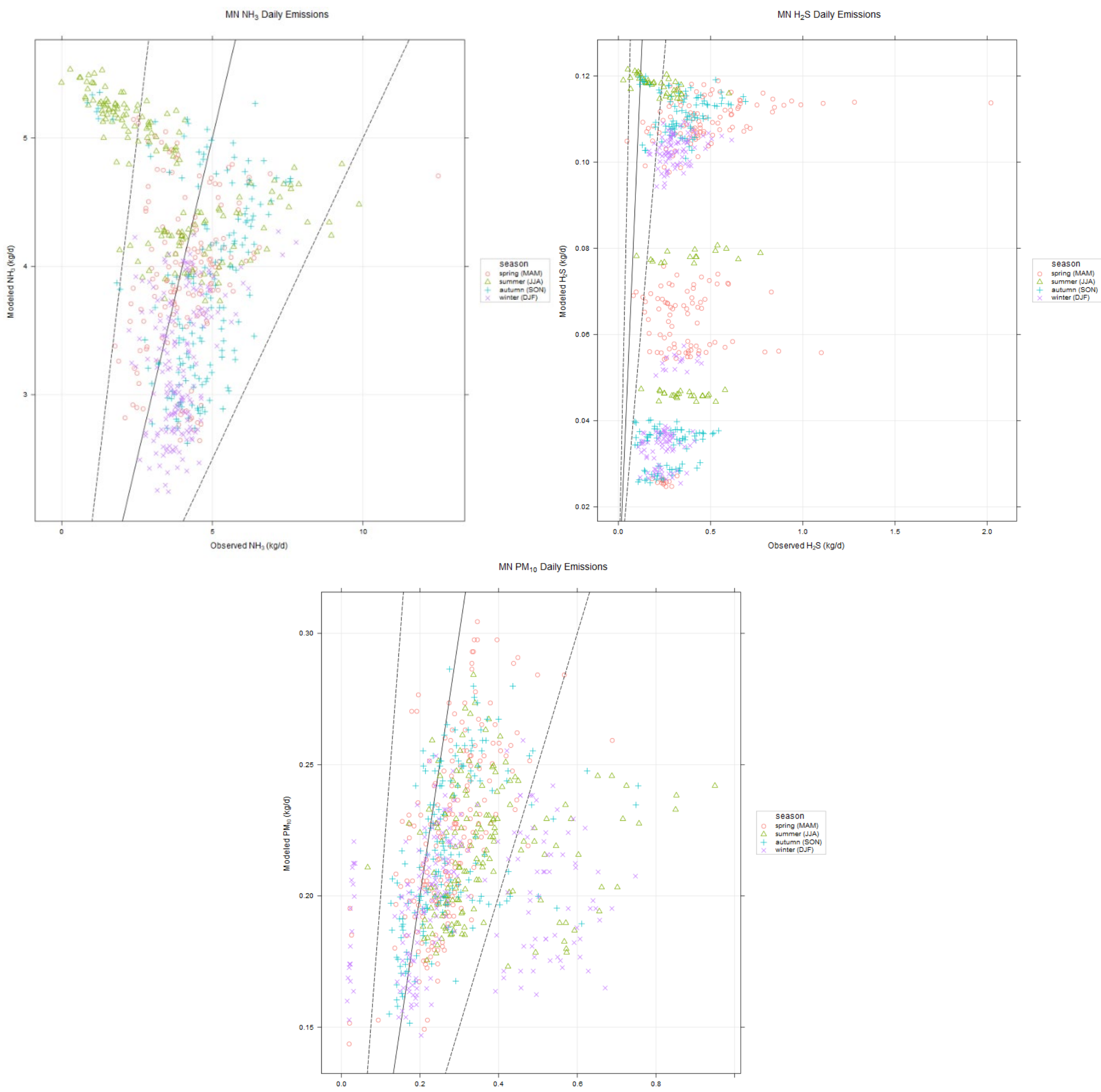

Figure 8-18. Scatter plots of observed versus predicted emissions for gestation barns (MN site).

9 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 swine operations. These interim 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 EEM development. EPA also considered which variables could be measured or obtained with minimal effort.

Overall, LAW (inventory × average animal weight) was identified as a key parameter and is used in most confinement 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 EEMs. For breeding and gestation sites, cycle day also proved to be an essential parameter in predicting emissions. Relative humidity parameters proved to be key for PM prediction, as the higher moisture levels keep barn materials from entraining into the air with mechanical disruptions. Confinement parameters specific to the barn, like ventilation rate and exhaust temperate, 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 EEMs put forward for use in this document use parameters that are already routinely collected as part of the standard farm operation (e.g., inventory and animal weight) or are ambient meteorological parameters, which freely available from public sources such National Center for Environmental Information (NCEI, https://gis.ncdc.noaa.gov/maps/).

For the open source EEMs, temperature and wind speed proved to be key parameters for EEM development. Additional lagoon specific parameters, such as lagoon temperature, were shown to have predictive capabilities. However, they are not routinely collected by producers and would represent an increased burden if required for emissions estimation. Therefore, EPA opted to utilize ambient parameters that are readily available from public sources such as the NCEI.

The method used to develop the EEMs allows for the incorporation of additional emissions and monitoring datasets from other studies, should they become available after the release of the EEMs. Revised EEMs for any individual farm type could be issued once significant additional data becomes available. Similarly, if monitoring options for barn or lagoon parameters become more widespread as automation options grow, future evaluations could assess whether EEMs 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 swine 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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