Development of Emissions Estimating Methodologies for Swine Barns and Lagoons

Draft

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TABLE OF CONTENTS

Page

CONTENTS (Continued)

CONTENTS (Continued)

CONTENTS (Continued)

CONTENTS (Continued)

LIST OF TABLES

Page

LIST OF TABLES (Continued)

Page

LIST OF TABLES (Continued)

Page

LIST OF TABLES (Continued)

Page

LIST OF TABLES (Continued)

Page

LIST OF TABLES (Continued)

Page

LIST OF TABLES (Continued)

Page

LIST OF FIGURES

Page

LIST OF FIGURES (Continued)

Page

LIST OF FIGURES (Continued)

Page

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
bLS	backward Lagrangian Stochastic
CAA	Clean Air Act
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
EEM	emissions-estimating methodologies
EPCRA	Emergency Planning and Community Right-to-Know Act
FANS	Fan Assessment Numeration System
FARM Act	Fair Agricultural Reporting Method Act
FTIR	Fourier transform infrared spectroscopy
H_2S	hydrogen sulfide
MB	mean bias
ME	mean error
NAEMS	National Air Emissions Monitoring Study
NAS	National Academy of Sciences
NH_3	ammonia
NMB	normalized mean bias
NME	normalized mean error
NRCS	Natural Resources Conservation Service
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
PREF	primary representative exhaust fan
PSB	purple sulfur bacteria
QAPP	quality assurance project plan
QC	quality control
RH/T	relative humidity and temperature
S-OPS	synthetic open path systems
TAN	total ammoniacal nitrogen
TDLAS	tunable-diode laser absorption spectroscopy
TEOM	tapered element oscillating microbalance
TKN	total Kjeldahl nitrogen
TSP	total suspended particulate
USDA	U.S. Department of Agriculture
UV–DOAS	ultraviolet differential optical absorption spectroscopy
VOCs	volatile organic compounds
VRPM	vertical radial plume mapping

1.0 INTRODUCTION

Farms in the United States contain approximately 900,000 livestock and poultry operations (USDA, 2019). About half of these operations raise animals in confinement, which qualifies them as Animal Feeding Operations (AFOs) (USDA, 2019). AFOs are complex operations comprising multiple emission sources including animal confinement, manure storage, feed storage, boilers and generators, farm vehicles and equipment, and waste application. These varied sources make AFOs potential sources of a variety of air pollutants including ammonia (NH_3), hydrogen sulfide (H_2S), total suspended particulate matter (TSP), particulate matter with aerodynamic diameters less than 10 micrometers (PM_{10}), particulate matter with aerodynamic diameters less than 2.5 micrometers ($PM_{2.5}$), and volatile organic compounds (VOCs).

A number of factors influence air emissions from individual animal feeding operations. EPA agrees with the National Academy of Sciences and other experts that process-based models allow operators to model the complex interactions affecting emissions at individual operations. However, following their recommendations, this report presents EPA's interim efforts to develop statistical models that describe emissions from swine-raising operations. Specifically, this report presents emissions-estimating methodologies (EEMs) for estimating the uncontrolled emissions from swine operations' confinement and manure storage sources. EPA developed the EEMs based on data collected in the National Air Emissions Monitoring Study (NAEMS) and other relevant information obtained through EPA's January 19, 2011, *Call for Information* (76 FR 3060). This report is organized as follows:

- Section 1.1 of this report describes EPA's previous effort to quantify potential emissions from this sector and the evolution of the Air Compliance Agreement.
- Section 1.2 outlines NAEMS sites and briefly summarizes the data collected.
- Section 1.3 summarizes the initial efforts to develop broiler and open source EEMs.
- Section 1.4 summarizes the current efforts and how they have improved the process.

1.1 EPA's Consent Agreement for Animal Feeding Operations

In August 2001, EPA completed the draft report, *Emissions from Animal Feeding Operations*, which contains methodologies for estimating farm-level emissions from AFOs in the beef, dairy, swine, and poultry (broilers, layers, and turkeys) animal sectors (U.S. EPA, 2001). To develop the methodologies, EPA: (1) identified the manure management systems typically used by AFOs in each animal sector, (2) developed model farms, (3) conducted literature searches to identify emission factors related to model farm components (e.g., confinement, manure handling and treatment system), and (4) applied the emission factors to the model farms to estimate annual mass emissions.

After completion of the draft 2001 report, EPA and the U. S. Department of Agriculture (USDA) jointly requested that the National Academy of Sciences (NAS) evaluate the current knowledge base and the approaches for estimating air emissions from AFOs. In a 2003 report, *Air Emissions From Animal Feeding Operations: Current Knowledge, Future Needs* (NRC, 2003), NAS concluded the following: reliable emission factors for AFOs were not available at that time; additional data were needed to develop estimating methodologies; current methods for estimating emissions were not appropriate; and EPA should use a process-based approach to determine emissions from an AFO. Among the recommendations was that EPA should improve the emission factor approach in the short-term while researching the implementation of process-based models.

A process-based model is a mathematical representation of the biological processes occurring in a system. At its simplest, a process-based model traces the mass of an element through a biological process, ensuring the amount of that element leaving the system is consistent with the amount entering the system. With respect to AFOs, a process-based model would account for the nitrogen entering the system through feed, water, and the animals through the biological and chemical transformations that occur during the growing process; and ensuring this total mass equals the mass of nitrogen excreted in manure and urine, animals carcasses, and air emissions from the barn or farm. As noted in the 2003 NAS report, process-based models are data intensive, requiring material sampling at all phases of animal development in addition to air monitoring. Therefore, EPA has proceeded with an approach to estimate emissions from sources based on statistical relationships between air emissions and the meteorological and confinement parameters collected that are known to affect processes that generate emissions, as recommended for the near-term.

In January 2005, EPA announced the voluntary Air Compliance Agreement with the AFO industry. The goals of the Air Compliance Agreement were to reduce air pollution, monitor AFO emissions, promote a national consensus on methodologies for estimating emissions from AFOs and ensure compliance with the requirements of the Clean Air Act (CAA), the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), and the Emergency Planning and Community Right-to-Know Act (EPCRA).

To develop the Air Compliance Agreement, EPA worked with industry representatives, state and local governments, environmental groups, and other stakeholders. Approximately 2,600 AFOs, representing nearly 14,000 facilities that included broiler, dairy, egg layer, and swine operations, received EPA’s approval to participate in the Air Compliance Agreement. Participating AFOs paid a civil penalty, ranging from $200 to $100,000, based on the size and number of facilities covered by their respective Air Compliance Agreements. The AFO industry was also responsible for contributing approximately $14.6 million to fund NAEMS.

As part of the Air Compliance Agreement, EPA agreed not to sue participating AFOs for certain violations of the CAA, CERCLA, and EPCRA, provided that the AFOs comply with the Air Compliance Agreement's conditions. However, the Air Compliance Agreement does not limit EPA's ability to act in the event of imminent and substantial danger to public health, welfare, or the environment. The Air Compliance Agreement also preserves state and local authorities' ability to enforce local odor or nuisance laws. After EPA publishes the final EEMs for the broiler, swine, egg layer and dairy sectors, participating AFOs must apply the final methodologies for their respective sectors to determine what actions, if any, they must take to comply with applicable CAA, CERCLA, and EPCRA requirements.[1]

1.2 National Air Emissions Monitoring Study for AFOs

The purpose of the NAEMS was to collect data and aggregate it with appropriate existing emissions data; analyze the monitoring results; and create tools (e.g., tables and/or emission models) that AFOs could use to determine whether they emit pollutants at levels that require them to comply with the applicable regulatory requirements. The monitoring study was designed to generate scientifically credible data to provide for the characterization of emissions from all major types of AFOs in all geographic areas where they are located. NAEMS was conducted between 2007 and 2010, with data originally published in 2011 and finalized in 2012. Data were collected at 26 NAEMS study sites (Section 1.2.1) for two years, including various meteorological, environmental, and biological measurements (Section 1.2.2). The final reports for data gathered at each site monitored during NAEMS are available on EPA's website.

1.2.1 NAEMS Monitoring Sites

EPA provided oversight for NAEMS and a team of researchers assembled from the following eight universities: Purdue University, Iowa State University, University of California-Davis, Cornell University, University of Minnesota, North Carolina State University, Texas A&M University and Washington State University. The researchers conducted monitoring at 26 different sites in 10 states (California, Indiana, Iowa, Kentucky, New York, North Carolina, Oklahoma, Texas, Washington, and Wisconsin). Table 1-1 lists the monitoring sites that were established under NAEMS. As described in the quality assurance project plan (QAPP) for the NAEMS barn component (Heber et al, 2008), the study was designed to include monitoring sites representative of typical broiler, egg-layer, swine, and dairy operations. EPA reviewed and approved site selection and monitoring plans.

[1] In 2018, the Fair Agricultural Reporting Method Act (Title XI of Division S of the March 2018 Consolidated Appropriations Act), amended CERCLA to exempt air emissions from animal waste (including decomposing animal waste) at a farm from CERCLA reporting. Since that time, EPA has finalized rulemakings to provide a reporting exemption for air emissions from animal waste at farms from both CERCLA and EPCRA (84 FR 27533, June 13, 2019).

For the broiler sector portion of NAEMS, Tyson Foods sponsored an earlier monitoring study at two broiler farms in Kentucky (sites KY1B-1 and KY1B-2) from 2006 to 2007. The QAPP for the Tyson study (Burns et al, 2006) was developed by the researchers at Iowa State University and the University of Kentucky to be consistent with NAEMS. Therefore, EPA considered the data collected at the Tyson study sites to be an integral part of NAEMS. Although the Tyson study was funded by Tyson Foods and not pursuant to the Air Compliance Agreement, the resulting data were combined with the data from NAEMS sites and are considered to be part of the NAEMS dataset.

Open source monitoring (for emissions from lagoons, basins and corrals) was conducted at three dairies (IN5A, WA5A, and WI5A), three breeding and gestation swine farms (IN4A, NC4A, and OK4A), and three swine growing and finishing farms (IA3A, NC3A, and OK3A). All farms operated under the overarching QAPP for the open source portion of NAEMS.

Section 2.1 provides additional detail on NAEMS monitoring sites for swine operations and includes operational details such as ventilation types and manure management systems.

Table 1-1. NAEMS Monitoring Sites

State	County	Site Name	Type of Operation Monitored
California	Stanislaus	CA1B	Broiler (2 Houses)
California	San Joaquin	CA2B	Egg-Layer (2 High-Rise Houses)
California	San Joaquin	CA5B	Dairy (2 Barns)
Iowa	Marshall	IA4B	Swine Sow (2 Barns, 1 Gestation Room)
Iowa	Jefferson	IA3A	Swine Finisher (1 Lagoon)
Indiana	Wabash	IN2B[a]	Egg-Layer (2 Manure-Belt Houses)
		IN2H[a]	Egg-Layer (2 High-Rise Houses)
Indiana	Carroll	IN3B	Swine Finisher (1 "Quad" Barn)
Indiana	Clinton	IN4A	Swine Sow (1 Lagoon)
Indiana	Jasper	IN5B[b]	Dairy (2 Barns, 1 Milking Center)
Indiana	Jasper	IN5A[b]	Dairy (1 Lagoon)
North Carolina	Nash	NC2B	Egg-Layer (2 High-Rise Houses)
North Carolina	Duplin	NC3B	Swine Finisher (3 Barns)
North Carolina	Bladen	NC3A	Swine Finisher (1 Lagoon)
North Carolina	Duplin	NC4A[c]	Swine Sow (1 Lagoon)
		NC4B[c]	Swine Sow (2 Barns, 1 Gestation Room)
New York	Onondaga	NY5B	Dairy (1 Barn, 1 Milking Center)
Oklahoma	Texas	OK3A	Swine Finisher (1 Lagoon)
Oklahoma	Texas	OK4A[c]	Swine Sow (1 Lagoon)
		OK4B[c]	Swine Sow (2 Barns, 1 Gestation Room)
Texas	Deaf Smith	TX5A	Dairy (Corral)[d]
Washington	Yakima	WA5A[c]	Dairy (1 Lagoon)
		WA5B[c]	Dairy (2 Barns)
Wisconsin	Saint Croix	WI5A[c]	Dairy (2 Lagoons)[e]
		WI5B[c]	Dairy (2 Barns)
Kentucky [f]	Union	KY1B-1	Broiler (1 House)

Table 1-1. NAEMS Monitoring Sites

State	County	Site Name	Type of Operation Monitored
	Hopkins	KY1B-2	Broiler (1 House)

[a] Two different types of barns located at the same site were monitored.
[b] Monitoring occurred on two separate dairy farms in Jasper County, IN.
[c] Barns and lagoons were located at the same site.
[d] The reported emission estimates represent the entire corral.
[e] Instrumentation was deployed around two of the lagoons in the three-stage system. The emissions from the two lagoons were reported as a combined value.
[f] The Kentucky sites were part of an earlier Tyson Foods sponsored study, which was designed to be consistent with NAEMS.

1.2.2 Overview of Emissions and Process Parameters Monitored

In the early planning stages of NAEMS, representatives from EPA, USDA, the AFO industry, state and local air quality agencies, and environmental organizations met to discuss and define the parameters that would be collected by the study. The goal was to develop a comprehensive list of parameters that would provide a greater understanding and accurate characterization of the processes and activities at AFOs. By monitoring these parameters, EPA would have the necessary information to develop EEMs for uncontrolled emissions of particulate matter, ammonia, hydrogen sulfide and volatile organic compounds from animal feeding operations.

Attachment B to the Air Compliance Agreement (National Air Emissions Monitoring Protocol; Overview & Summary) (Attachment B) provided guidance on the emissions and process parameters to be monitored under NAEMS and the specific components that were to be included in the emissions monitoring plans. In addition, Attachment B identified the technologies and measurement methodologies to be used to measure emissions and process parameter data at each of the broiler, dairy, egg layer, and swine monitoring sites. The Air Compliance Agreement required that an on-farm instrument shelter for housing monitoring equipment be located at each site and that the following parameters be monitored for 24 months:

- NH_3 concentrations using a chemiluminescence or photoacoustic infrared gas analyzer;
- CO_2 concentrations using a photoacoustic infrared gas analyzer, or equivalent;
- H_2S concentrations using a pulsed fluorescence gas analyzer;
- $PM_{2.5}$ concentrations using a gravimetric, federal reference method for $PM_{2.5}$ for at least one month per site;
- PM_{10} concentrations using a tapered element oscillating microbalance (TEOM);
- TSP concentrations using an isokinetic, multipoint gravimetric method;

- VOC concentrations using a sampling method that captures a significant fraction of the 20 analytes determined by an initial characterization study of confinement VOC emissions to be the greatest contributors to total VOC mass;
- Animal activity, manure handling, feeding, and lighting operation;
- Total nitrogen and total sulfur concentrations determined by collecting and analyzing feed, water, and manure samples;
- Environmental parameters (heating and cooling operation, floor and manure temperatures, inside and outside air temperatures and humidity, wind speed and direction, and solar radiation); and
- Feed and water consumption, manure production and removal, animal mortalities, and production rates.

Attachment B also required sites to estimate the ventilation air flow rate of mechanically ventilated confinement structures by continuously measuring fan operational status and building static pressure, applying field-tested fan performance curves, and by directly measuring selected fan air flows using anemometers.

In addition, Attachment B identified the technologies and measurement methodologies to be used to measure emissions and process parameter data at dairy and swine open source monitoring sites. Attachment B required the use of optical remote sensing techniques upwind and downwind of the lagoon combined with three-dimensional wind velocity measurements. Attachment B required the following measurements:

- NH_3 and the various hydrocarbons concentration using open-path Fourier transform infrared spectroscopy (FTIR);
- H_2S and NH_3 concentration using collocated open-path ultraviolet differential optical absorption spectroscopy (UV–DOAS); and
- Environmental parameters (air and lagoon temperatures, humidity, wind speed and direction, atmospheric pressure, and solar radiation).

The NH_3 and H_2S emissions were to be calculated from the difference in upwind and downwind concentration measurements using two different methods: a Eulerian Gaussian approach [computed tomography (CT)], and a Lagrangian Stochastic approach [backward Lagrangian stochastic method (bLS)]. For the VOC emissions, samples of the lagoon liquid were to be collected and analyzed for VOC, and EPA model WATER9 used to estimate emissions based on measured VOC concentrations, pH, and other factors.

There were some variations in parameters collected, because not all were applicable to each animal type and/or site. Additionally, some of the principal investigators (PIs) may have opted to collect more than required by Attachment B. Section 2.2 discusses the data received for swine operations, including the amount of data received, in more detail.

To further supplement the NAEMS dataset, EPA published a *Call for Information* in January 2011 (76 FR 3060) to obtain emissions and process parameter datasets for animal confinement and manure storage and treatment operations at AFOs and supporting documentation. The *Call for Information* yielded 13 responses with reference to peer-reviewed journal articles or reports outlining other studies on AFO emissions. Because most of the data were not readily available in formats compatible with the NAEMS dataset, EPA used the data received from the *Call for Information* to inform decisions on parameter use. Additionally, values reported in literature are also helpful for comparison with the current EPA EEMs to evaluate the reasonableness of these results.

1.3 Previous Emission-Estimating Methodology Development

In February 2012, EPA developed draft EEMs for estimating air pollutant emissions from broiler confinement operations using the emissions and process data collected under NAEMS and other relevant information obtained through the 2011 *Call for Information*. The broiler draft EEMs included formulas to estimate NH_3, H_2S, PM_{10}, $PM_{2.5}$, TSP, and VOCs. EPA also developed an EEM to estimate daily and annual NH_3 emissions from swine and dairy lagoons.

For broilers, EPA divided the process data into the following three groups: inventory (e.g., number of birds and bird weight), ambient (e.g., ambient temperature, pressure, and relative humidity), and confinement (e.g., building temperature, pressure, and relative humidity). The process parameters were statistically evaluated to determine if they were predictor variables. In addition, EPA evaluated whether the predictor variable process data were readily available to the growers, state and local agencies, and other interested parties. Given that the EEMs developed from the NAEMS dataset will be used for site-specific permitting decisions by operations participating in the Air Compliance Agreement and other operations, it is important to consider both the science in decision making, and the practical burden of collecting, maintaining, and supplying data to support emission estimations.

Based on the results of EPA’s predictor variable evaluation process, three EEMs were developed using various process parameters. The three EEMs were: an EEM based on poultry inventory parameters (I EEMs); an EEM based on poultry inventory and ambient parameters (IA EEMs); and an EEM based on poultry inventory, ambient and confinement parameters (IAC EEMs). For the EEMs, EPA fit a polynomial mixed effects model (SAS version 9.2, Proc Mixed, SAS®) with an auto-regressive order 1 (AR(1)) covariance function.

At the time of its development, EPA explored the need for the model to include a random effect based on the barn(s) monitored at each site and decided it was not needed. EPA also considered whether different variance under different conditions were needed. The analysis suggested there was no evidence supporting an increase in the variance with increasing mean emissions. There was some indication of variance across the three sites, but it was not included in the model due to the limited data available.

EPA employed a backward elimination process to finalize the mean trend variables. To accomplish this, EPA started with an initial model run that included all variables (main effects and interactions). EPA then used the calculated p-values to eliminate the variables that were insignificant (p-value > 0.001). For this elimination process, the collection of cubic terms (e.g., [average mass, $(\text{average mass})^2$ and $(\text{average mass})^3$]) were considered the main effect/interaction term. This collection of terms could only be removed as a group if a test of the null hypothesis that all three regression coefficients equal zero could be rejected. This was repeated until all terms remaining were significant (all p-values (or p-values for collections) < 0.001). At this point, EPA examined the fit statistics for the base dataset and cross-validation dataset to determine the version of the model (i.e., the set of mean trend terms) with the best performance. EPA selected this model as the candidate EEM.

EPA followed a similar process to develop an EEM to estimate daily and annual NH_3 emissions from the combined swine and dairy lagoon dataset. EPA used ambient temperature, relative humidity, solar radiation (represented by Julian day), and wind speed. Due to the very limited amount of data received for the nitrogen concentration, solid content, and pH of the lagoon liquid, those data were not included in the EEM.

In February 2012, EPA requested the agency's Science Advisory Board (SAB) review and comment on these draft EEMs. Although the SAB reiterated that the models should be process-based, like the NAS 2003 report, they did acknowledge NAEMS data were not sufficient to produce a process-based model. With respect to the statistical model itself, the SAB noted that EPA should not use a polynomial model because it leads to poor predictions at the extremes of the experimental conditions.

1.4 Current Emission-Estimating Methodology Development

EPA agrees that the development of process-based models should be pursued with the long-term goal of improving the accuracy of emission estimates for the livestock and poultry sectors. However, as noted in the SAB report, process-based models "require extensive data beyond the range of values, conditions, and types of farms available in NAEMS dataset." Following the expert recommendations and consistent with the goals of the Air Compliance

Agreement, EPA has developed statistical based models as an interim emission estimation tool for AFOs until process-based models are developed.

Per the SAB recommendations, EPA adjusted the form of the modeling, variable selection, validation method used, and expanded residual analysis and evaluation of fit statistics. In this revised effort, EPA has discontinued the use of polynomial forms to combat issues with extrapolation on the extreme ends of the data. In response to SAB comments and to move from an emission factor approach toward a process-based model, EPA has attempted to represent the chemical, biological, and physical processes and constraints in the EEM through the selection of variables used. EPA conducted a rigorous analysis of the literature and data available to identify the data elements collected under NAEMS with known chemical, biological, and physical processes and constraints present at the monitoring sites. Those variables with the strongest connection to these processes were used in model development and selection was not completed strictly on significant p-values. For example, a primary driver of emissions is the volume of manure generated, as more manure has a higher emissions potential. The volume of manure generated is directly proportional to the number of animals present. Therefore, the inventory counts, or total live animal weight collected during NAEMS, are representative of this biological relationship. Section 8.0 of this report details this analysis and the resulting decisions for model development.

With respect to the validation method, the previous efforts employed a k-fold cross-validation method, where 20 percent of the data were withheld to test the model. The SAB recommended splitting the data based on factors related to study design, such as barn, to evaluate model predictive ability. In this current effort, EPA has shifted to a "jackknife" technique, which withholds each barn at a time for model testing and validation. This is discussed in more detail in Section 10.0.

For model fit evaluation, EPA expanded the use of residual diagnostic plots, with more of those images presented in Appendix F. EPA also expanded fit statistics to include Akaike information criteria (AIC), adjusted Akaike information criteria (AICc) for number of predictors, Schwarz Bayesian criteria (BIC), and negative twice the likelihood (-2LogL) to measure predictiveness and effectiveness of fitted model. EPA also enhanced the model validation process, adding several standard statistics and metrics used throughout EPA to validate modeling. The specific metrics are discussed in detail in Sections 9.3 and 10.0.

2.0 DATA COLLECTION

2.1 Sites

Swine operations breed and grow pigs for meat. Typical swine operations combine various stages of swine development. The number of swine operations in the United States has been steadily declining since 1959; however, the number of pigs marketed has increased. This is in part due to improvements in animal health (e.g., decrease in mortality rates) and increased sow fertility. It is also characteristic of the domestic swine industry becoming increasingly dominated by large totally enclosed confinement operations capable of handling 5,000 animals or more at a time.

The production cycle for swine has three phases: farrowing, nursing, and finishing. Some farms specialize in a single phase of the growth cycle, while other farms may handle two or all three phases. The first phase begins with breeding and gestation over a 114-day period followed by farrowing (giving birth). After farrowing, the newly born piglets normally are nursed for a period of three to four weeks until they reach a weight of 10 to 15 pounds. Sows can be bred again within a week after a litter is weaned. Sows normally produce five to six litters before they are sold for slaughter.

After weaning, pigs are relocated to a nursery where swine typically are fed a corn-soybean meal-based diet that may include small grains such as wheat and barley and other ingredients until slaughtered. Nursery operations receive weaned pigs and grow them to a weight of 40 to 60 pounds. The third phase of swine production is the growing-finishing phase where the gilts (young females) and young castrated boars (males) not retained for breeding are fed until they reach a market weight, typically between 240 and 280 pounds. Growing-finishing usually takes between 15 and 18 weeks, and animals normally are slaughtered at about 26 weeks of age.

Swine operations can be of several types. As of the 2017 USDA Census of Agriculture (USDA, 2019), the most common is the growing-finishing operation, followed by the farrow-to-finish operation that encompasses all three phase 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. Although not as common, some newer farms may operate only the farrowing phase or only the nursery phase.

At any enclosed confinement facilities, swine manure is handled as either a slurry or a liquid. 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. 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. These practices do not represent all of the practices in use today; however, they are the predominant practices currently used by swine operations.

Most large swine farms have from 6 to 12 months of manure storage capacity (Pfost et al., 2000). Storage is in either an anaerobic lagoon or a storage facility. Typical storage facilities include deep pits, tanks, and earthen ponds. Anaerobic lagoons provide both manure stabilization and storage. The use of storage tanks and ponds generally is limited to operations with deep pits and pull-plug pits where manure is handled as a slurry. Pit recharge and flush systems typically use anaerobic lagoons, because of the need for supernatant for use as recharge or flush water.

2.1.1 Confinement Sites Monitored

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 the piglets are provided 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 2-1 summarizes the sites and their characteristics. The following sections describe each site in more detail.

Table 2-1. 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]
		Farrowing	MV	1	PPR	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	Lagoon
NC4B[1]	12/15/07 - 12/14/09	Breeding/gestation	MV (tunnel)	2	PPR	Lagoon
		Farrowing	MV	1	PPR	Lagoon
OK4B[1]	7/19/07 - 7/19/09	Breeding/gestation	MV (tunnel)	2	PPR	Lagoon
		Farrowing	MV	1	PPR	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.
PPR = pull plug with recharge

2.1.1.1 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. 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 concrete slatted 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.

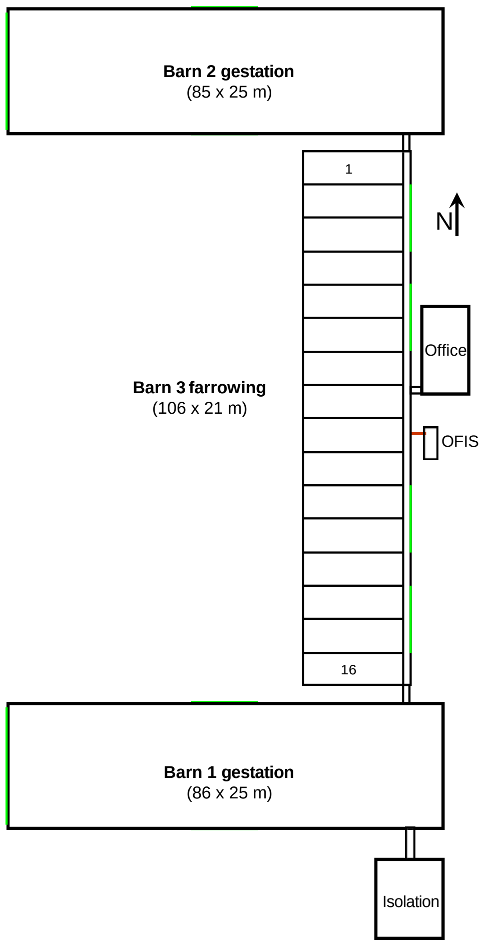

Figure 2-1. IA4B Farm layout.

2.1.1.2 IN3B

The finishing farm monitored in Indiana consisted of two "quad" barns with deep pits. 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.

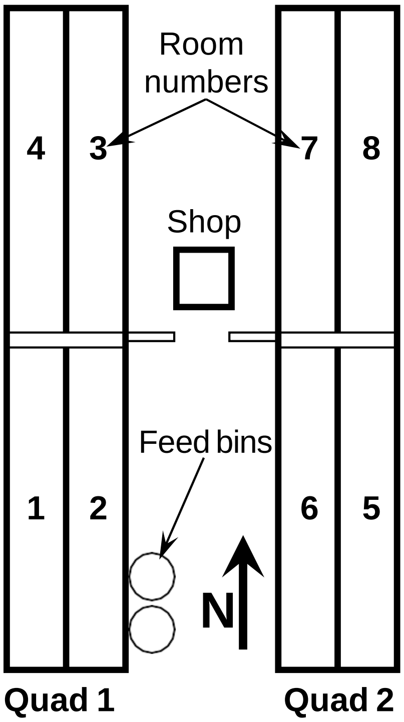

Figure 2-2. IN3B Facility layout. Rooms 5 through 8 in Quad 2 were monitored.

2.1.1.3 NC3B

The farm site consisted of nine finishing barns constructed in 1996, and a lagoon. The farm had a capacity of 7,200 head, which was divided among the nine barns. The finishing barns had concrete slatted 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; the opposite from 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).

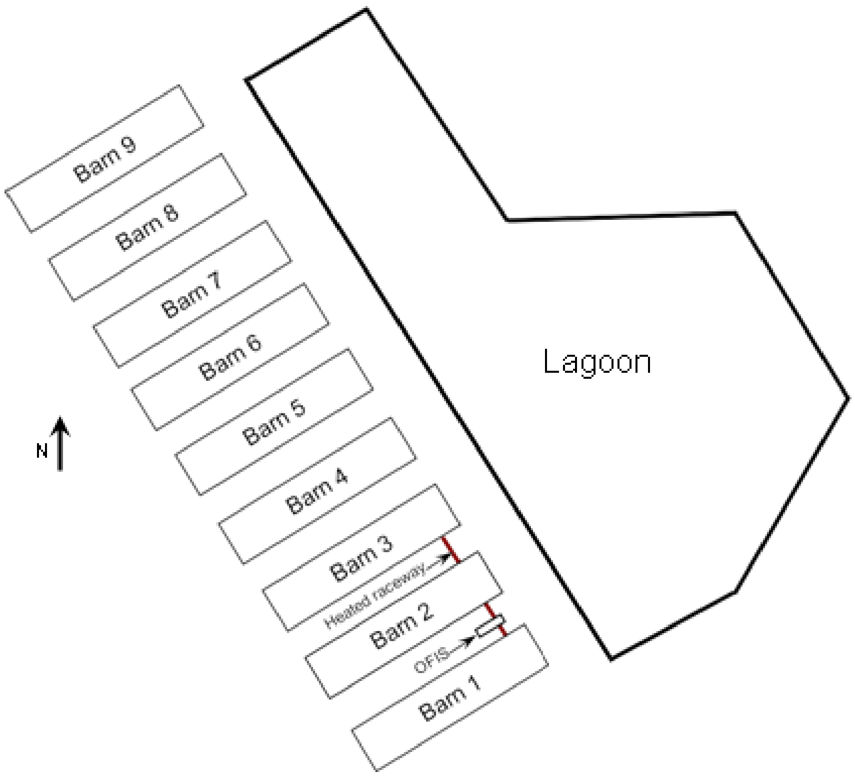

Figure 2-3. NC3B facility layout. Barns 1, 2 and 3 were monitored.

2.1.1.4 NC4B

This sow farm consisted of three barns, an office, and an anaerobic waste treatment lagoon. 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 2.1.2.4. Construction of the barns was completed in 1995. The farm had a capacity of 300 farrowing, 776 breeding, and 924 gestation 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; all 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).

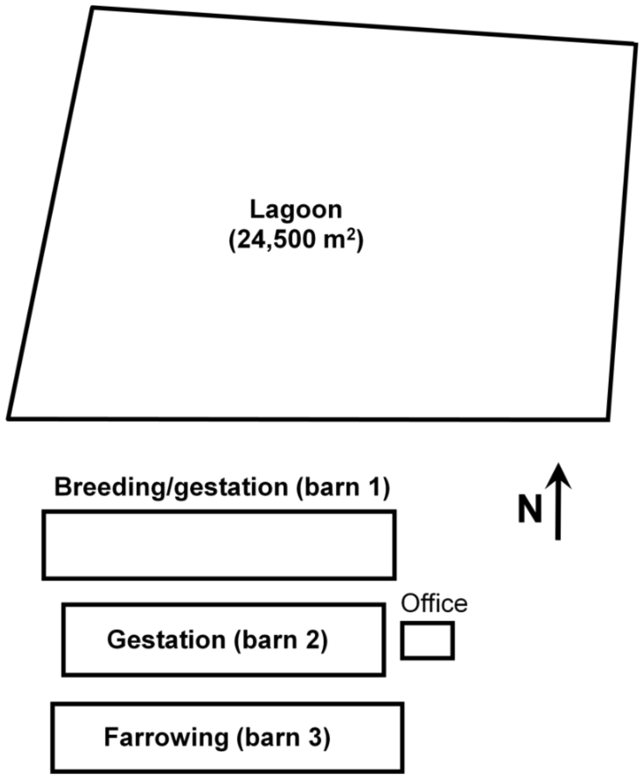

Figure 2-4. NC4B Farm layout showing the barns and lagoon.

2.1.1.5 OK4B

This sow farm consisted of the three barns, an office, and a waste lagoon. 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 2.1.2.1. 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. 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).

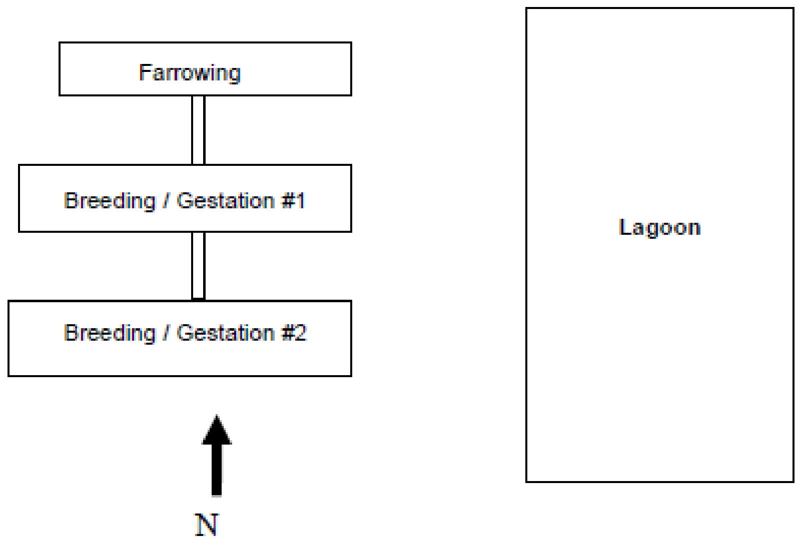

Figure 2-5. Farm layout showing the barns and lagoon.

2.1.2 Open Source Sites

Six swine farms had lagoons or basins monitored as part of NAEMS, as listed in Table 2-2. 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, OK4A). Table 2-3 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 2-2. 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 2-3. Summary of NAEMS Swine Open Source Monitoring Sites

Site	Phase[1]	Source Type	Manure Collection	Monitoring Period									
				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 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

2.1.2.1 IA3A

The grow-finish farm in Iowa consisted of four barns and a manure basin (Figure 2-6). 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 2-6. Aerial View of IA3A

2.1.2.2 IN4A

The Indiana farm consisted of nine barns and a lagoon (Figure 2-7) 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 from 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 surface area of 13,580 m^2 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 2-7. Aerial View of IN4A

2.1.2.3 NC3A

The North Carolina grow-finish farm consisted of five barns (Figure 2-8) 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 2-8. Aerial View of NC3A

2.1.2.4 NC4A

The breeding/gestation farm in North Carolina consisted of three barns, one each of gestation, breeding, and farrowing, and an office (Figure 2-9). 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 2-9). 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 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 2-9. Aerial View of NC4A

2.1.2.5 OK3A

The Oklahoma grow-finish farm consisted of three barns (Figure 2-10). 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 2-10. Aerial View of OK3A

2.1.2.1 OK4A

The Oklahoma breeding/gestation farm consisted of three barns and one office (Figure 2-11). 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 2-11. Aerial View of OK4A

2.2 Confinement Site Data Sampled

NAEMS collected a host of data from the sites. Data collected including gaseous concentrations, particulate matter samples, meteorological data, confinement parameters, and biomaterial samples (e.g., pit liquid, loadout manure). All procedures were outlined in the project QAPP (Heber et al., 2008) and are summarized in the following section.

2.2.1 Emissions Sampling

NH_3 and H_2S concentrations were continuously sampled from multiple gas sampling probes with a custom-designed gas sampling system (GSS). Three gas sampling probes were placed in each barn in front of the exhaust fans. The inlet air (ambient air entering the barn) was sampled as well.

Each exhaust location was sampled individually for 10 minutes. The ventilation inlet location was monitored at least twice daily, originally with a 10-minute sampling period. The inlet sampling period was increased to 20 minutes and then 30 minutes later in the study.

Real-time PM monitors (TEOM Model 1400a, Thermo Fisher Scientific, Waltham, MA) were located immediately upstream of an exhaust in each barn to continuously measure exhaust PM. A beta attenuation PM monitor (Beta Gage Model FH62C-14, Thermo Fisher Scientific, Franklin, MA) continuously measured barn inlet PM concentration. At any one time, the sampled PM size class was either PM_{10}, $PM_{2.5}$, or TSP at both TEOMs and the Beta Gage. The $PM_{2.5}$ size class was measured at least twice over the course of the study, for a period of 4 to 21 days. The sites with less frequent $PM_{2.5}$ observation periods were monitored for more days. In other words, a site that only monitored $PM_{2.5}$ twice recorded measurements for 15 to 20 days at a time, while other sites monitored more frequently for only 1 week at a time. The TSP inlet heads were placed on the TEOMs up to 10 times during the study duration, for 4- to 20-day periods. The PM_{10} concentration was measured at all other times. Appendix A contains summary tables (Tables A-1 through A-5), which note the PM sampling schedules for each site.

Grab samples of VOC were collected at the primary exhaust fans using methodology based on EPA Methods TO-15 and TO-16. Sampling was conducted multiple times over the course of the study at each site, with duplicate samples typically collected at each location. All canisters were cleaned and passed quality control (QC) before sample collection. Canister samples were then analyzed at Purdue University's Trace Contaminant Laboratory. Samples were analyzed on a thermodesorption-gas chromatograph-mass spectrometer (TDS-GC-MS), consisting of a gas chromatograph (Model 6890, Agilent Technologies, Palo Alto, CA) coupled with a Model 5795 mass spectrometer detector (Agilent Model 5795) and equipped with a thermal desorption system (Model TDS-G, Gerstel, Baltimore, MD) and a cooled injection system (Gerstel CIS). The analytical results were analyzed by ChemStation and all integrations were manually checked. This method used an external standard compound for instrument monitoring and quality assurance (QA) to avoid losses of low-molecular-weight analytes that would occur when purging solvent used with internal standard(s). Response curves were generated at both the beginning and the end of the VOC analysis period.

2.2.2 Environmental Parameters

Building environmental conditions were monitored throughout the study. Relative humidity and temperature (RH/T) probes were located at the primary representative exhaust fans (PREFs) for each barn. Additional thermocouples were used to measure temperatures inside the barns.

In-situ airflow measurements, or ventilation rate, were conducted with a 122-cm field-portable fan tester (Fan Assessment Numeration System (FANS), University of Kentucky, Lexington, KY), which was described by Gates et al. (2004). The field data were used to develop equations that would calculate airflow as a function of differential pressure and fan rotational speed, and to assess the uncertainty in airflow predictions.

Weather data were collected using a solar radiation shielded capacitance-type relative humidity and temperature probe (RH/T), a pyranometer, and a cup anemometer, which were attached to the roof of a barn or the instrument shelter installed for the study.

2.2.3 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.

2.2.4 Biomaterials Sampling Methods and Schedule

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).

2.3 Open Source Data Sampled

The Air Compliance Agreement provided guidance on the emissions and process parameters to be monitored under NAEMS and the specific components that were to be included in the emissions monitoring plans. In addition, the Air Compliance Agreement identified the technologies and measurement methodologies to be used to measure emissions and process parameter data at dairy and swine open source monitoring sites. The Air Compliance Agreement required the use of optical remote sensing techniques upwind and downwind of the lagoon combined with three-dimensional wind velocity measurements. The Air Compliance Agreement required the following measurements:

- NH_3 and the various hydrocarbons concentration using open-path Fourier transform infrared spectroscopy (FTIR).
- H_2S and NH_3 concentration using collocated open-path ultraviolet differential optical absorption spectroscopy (UV–DOAS).
- Environmental parameters (air and lagoon temperatures, humidity, wind speed and direction, atmospheric pressure, and solar radiation).

The NH_3 and H_2S emissions were to be calculated from the difference in upwind and downwind concentration measurements using two different methods: an Eulerian Gaussian approach [computed tomography (CT)], and a Lagrangian Stochastic approach [backward Lagrangian stochastic method (bLS)]. For the VOC emissions, samples of the lagoon liquid were to be collected and analyzed for VOC, and the EPA model WATER9 used to estimate emissions based on measured VOC concentrations, pH, and other factors.

There were some variations in process parameters collected, because not all were applicable to each animal type or site. Additionally, some of NAEMS researchers opted to collect more data than required by the Air Compliance Agreement. Table 2-4 lists the process parameters monitored at NAEMS open source sites. The data collection procedures are outlined in the open source project QAPP (Grant, 2008), and are summarized in the following section.

Table 2-4. Continuous Parameters Monitored at NAEMS Lagoon Sites

Parameter		Units
Lagoon conditions	Temperature (lagoon liquid)	ºC
	pH	pH
	Reduction/oxidation potential	millivolts
Meteorological conditions	Ambient temperature	ºC
	Ambient relative humidity	%

Table 2-4. Continuous Parameters Monitored at NAEMS Lagoon Sites

Parameter		Units
	Barometric pressure	kPa
	Surface wetness	millivolts
	Solar radiation	Watts/m^2
	Wind speed	ft/sec
	Wind direction	Degrees

2.3.1 Emissions

Atmospheric concentrations of NH_3 around the basin were measured using narrow-bandwidth open path tunable-diode laser absorption spectroscopy (TDLAS). Atmospheric measurements of H_2S concentrations were made using pulsed fluorescence technology from air collected from 50-m synthetic open path systems (S-OPS) and sampled from a GSS that drew the air through the S-OPS. Emissions of NH_3 were determined from the difference in upwind and downwind concentration measurements from the TDLAS open path systems using two emissions models: a Gaussian plume fit model (Radial Plume Mapping: *RPM*; Arcadis Inc, Denver, CO) and a backward Lagrangian Stochastic (bLS) model (*WindTrax*; Thunder Beach Scientific, http://www.thunderbeachscientific.com).

Emissions of H_2S were determined using the concentration measurements from the pulsed fluorescence analyzer from air sampled by the air inlets of the S-OPS using the bLS model. NAEMS also tested the viability of a second method, a Ratiometric model, which calculates the ratio of the H_2S concentrations to NH_3 concentrations along the path, then multiplies that ratio with the corresponding RPM NH_3 emissions measurement to estimate the H_2S emissions.

2.3.2 Weather Conditions

Measurements of the atmospheric temperature, relative humidity, barometric pressure, solar radiation, and surface wetness were measured and recorded at an automated weather station established on the basin rim.

2.3.3 Farm Activity

Additional information concerning farm operations was routinely collected from the producers. Pertinent activities affecting the basin include transfer of waste from barns into the basin and basin pump-outs for irrigation. Section 2.2.3 discusses the animal inventories used to calculate basin loading rates.

2.3.4 Basin Conditions and Biomaterial Sampling

For IA3A, the appearance of the basin was recorded on almost every site visit. Samples of the basin manure were collected during each measurement period at the basin and analyzed for pH, total and ammoniacal nitrogen, sulfur, and total solids by a commercial laboratory. For the lagoon sites, measurements of the lagoon pH, oxidation-reduction potential, and temperature at 0.3 m depth were also measured from a float located at least 30 m from the lagoon inlet.

3.0 REVISIONS TO DATASET AND EMISSIONS DATA SUMMARY

3.1 Revisions to the 2010 Dataset

NAEMS monitoring data was submitted to EPA in 2010 (henceforth referred to as the "2010 dataset"). More information about the QA associated with this dataset can be found in Grant et al. (2008) and Heber et al. (2008). Heber (Barn PI and overall NAEMS PI) and Grant (Open source PI) revised the barn and open source parts of the 2010 dataset, respectively. The revised dataset was used for EEM development. The following sections provide a summary of the revisions for the barn and open source parts of the 2010 dataset.

3.1.1 Revisions to the 2010 Barn Dataset

Heber provided a revised swine barn dataset to EPA in 2015. The dataset revised the method used to determine barn gas inlet concentrations, which affected the emissions calculations for NH_3 and H_2S. In short, the calculation was modified to allow more time for inlet gas concentrations to equilibrate from higher exhaust (outlet) concentrations. In addition, the calculation applied a 10-day running average of inlet concentrations (5 days before and 5 days after) to determine NH_3 and H_2S emissions. The 2010 dataset used an interpolated value between two individual measurements approximately 12 hours apart to determine NH_3 and H_2S emissions. This revision helped reduce the number of negative emission calculations due to occasionally high inlet concentrations. A more detailed description of the changes, as applied to layer houses, can be found in Liang (2015).

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 particulate matter 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.

3.1.2 Revisions to the 2010 Open Source Dataset

Grant provided a revised open source dataset to EPA in 2012. The revised dataset adjusted the bLS calculations, so they were reported at a standardized temperature of 20^oC. Three additional data validation criteria were applied to the bLS open source dataset beyond those laid out in the 2008 QAPP (Grant, 2008). The additional validation criteria were 1) the standard deviation of the wind direction had to be less than 30^{o}C, 2) the touchdown fraction had to be greater than 0.1, and, 3) for NH_3, the background concentration had to between -0.1 ppm and 0.1 ppm. These criteria for valid data and associated rationale can be found in Grant et al. (2013a), Grant et al. (2016), and Grant and Boehm (2018), which reported and analyzed NH_3 emissions from NAEMS swine open sources.

The vertical radial plume mapping (VRPM) dataset also had additional data validation criteria compared to the 2010 dataset. These criteria included: (1) the mean wind direction must be less than 60^{o} of the perpendicular of the measurement plane and (2) the upwind source fraction must be greater than 0.9. The rationale for and application of these criteria for data validity can be found in Grant et al. (2013a) and Grant et al. (2016).

The revised dataset also invalidated NH_3 emission estimates due to atmospheric moisture inference with TDLAS measurements (Grant and Boehm, 2018; Grant et al., 2016). The atmospheric moisture inference negatively affected the probability of concentration measurement being NH_3 and the magnitude of the instruments' response (Grant et al., 2016). Table 3-1 summarizes the days invalidated due to moisture for each site.

Some of the moisture interfered data was validated in a later study by examining the TDLAS concentration measurements, which were made at a temporal resolution of 1.2 second (Grant et al. (2016)). However, EPA did not make a similar adjustment to the EEM development dataset because the 1.2 second resolution data was not included in the 2010 or revised datasets could.

Table 3-1. Day invalidated due to moisture interference

Site	Start date	End date	Total number of days (percentage of dataset)
IN4A	All dates		49 (100%)
IA3A	December 19, 2008	January 15, 2008	21 (32%)
OK3A	January 24, 2008	February 19, 2008	5 (7%)
OK4A	April 23, 2008	May 6, 2008	9 (19%)

Further studies comparing the VRPM and bLS methods found the bLS method to be closer to the true emission value for lagoon sources and advanced an approach to adjust VRPM measurements based on bLS measurements (Grant et al. 2016). Grant el al. (2016) then averaged the bLS and adjusted VRPM estimate to calculate a final NH_3 emissions estimate. (

For IA3A, a different approach was used for adjusting NH_3 emissions. Grant and Boehm (2018) determined that the impact of nearby barn exhaust fans on measured NH_3 concentrations was greater in the bLS method than the VRPM method. For this site, the bLS emission estimates were adjusted to VRPM emission estimates using an equivalency ratio. Based on this work, EPA adjusted VRPM and bLS emission estimates for the EEM development dataset. In instances where only a bLS or VRPM emission values were available for the 30-minute time period, the individual adjustment, or non-adjusted VRPM/bLS, value was used. When both the bLS and VRPM estimate were valid, the values were averaged.

The 2010 dataset reported H_2S emissions using the bLS methodology and the ratiometric emissions methodology. The ratiometric methodology is essentially the ratio of measured H_2S to NH_3 concentrations multiplied by the NH_3 emission rate. Thus, this calculation assumes that the same factors have the same influence on NH_3 emissions and H_2S emissions. This assumption has not proven to be the case, and, the ratiometric methodology was not used for EEM development for H_2S.

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. This data were considered invalid because the pH probe failed accuracy calibration tests on July 14, 2009 and July 15, 2009 (Grant and Boehm, 2010f).

3.2 Data Completeness Criteria for the Revised Dataset

The appropriate data completeness criteria to use in a study depends on the size of the dataset and the accuracy needed. A study by Grant et al. (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 3-1). Using this relaxed daily completeness criteria resulted in a substantial increase in the size of the dataset.

Based on Figure 3-1 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.

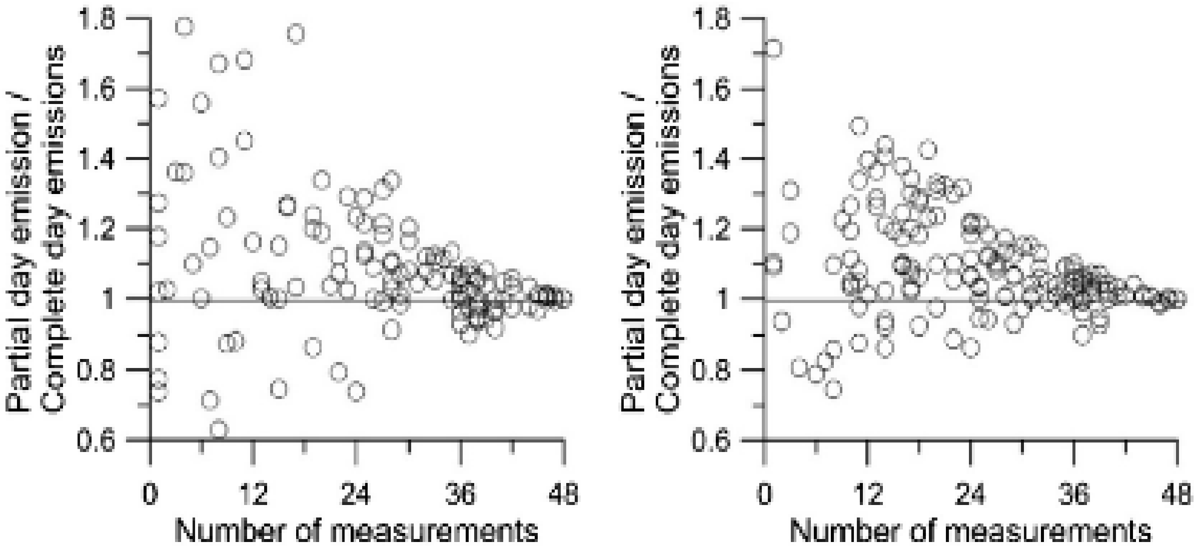

Figure 3-1. Ratio of mean predicted emissions for portion of day with valid emissions measurements to mean predicted emissions for the complete day at the finishing (A) and sow (B) farm. Error plotted against number of valid 30-minute measurements (from Grant et al., 2013c).

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 emission 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 criterion (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 3.2.3 will show, this revised method further improved the number of ADM available for EEM development.

3.2.1 Data Completeness Review and Conclusions for Sow Datasets

Table 3-1 and Table 3-2 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 3-2. 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 3-3. 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 3-4, 3-4 and 3-5 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 3-4. 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 3-5. 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 3-6. 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
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

3.2.2 Data Completeness Review and Conclusions for Grow-Finish Datasets

Table 3-7 and 3-7 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 3-7. 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 3-8. 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 3-9, Table 3-10, and Table 3-11, 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 particulate matter dataset. This value also matches the data completeness criteria used in the 2010 NAEMS datasets (Grant et al., 2008; Heber et al., 2008).

Table 3-9. 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 3-10. 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 3-11. 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
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

3.2.3 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. 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. Overall, for both pollutants, the number of ADM available more than doubles 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 3-12. Number of ADM for open source NH_3 at different percentages of data completeness.

Completeness criteria	NC3A			OK3A			NC4A			OK4A			IA3A		
	BLS	VRPM	Sum	BLS	VRPM	Sum	BLS	VRPM	Sum	BLS	VRPM	Sum	BLS	VRPM	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 3-13. Number of ADM for open source H_2S at different percentages of data completeness.

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

3.3 Comparison between the 2010 and Revised Datasets

The influence of all of the previously described revisions to the dataset can be observed by comparing the number of valid ADM and mean emission values between the 2010 and revised datasets. The following sections describe the differences in the ADM for each pollutant between the 2010 data and the revised dataset used in this analysis.

3.3.1 NH_3 Breeding and Gestation Data

At IA4B, the number of valid ADM decreased by 16 (3%), 1 (0.26%), and 1 (0.23%) for the farrowing room (F), barn 1 (B1), and barn 2 (B2), respectively, in the revised dataset. This resulted in an overall increase in estimated average NH_3 emissions in the revised dataset of 5.39%, 0.64%, and 1.49% for F, B1, and B2, respectively. At NC4B, the number of valid ADM increased by 106 (25.85%), 135 (32.22%), and 134 (30.18%) for F, B1, and B2, respectively. Mean NH_3 emissions for F, B1, and B2 in the revised dataset decreased by 5.88%, 5.42%, and 5.56%, respectively. At OK4B, the number of valid ADM decreased by 84 (14.71%), 2 (0.33%), and 2 (0.34%) for F, B1, and B2, respectively. The overall mean NH_3 emission for F increased by 10.48%, B1 showed no change, and B2 decreased by 0.62%. Table 3-14 provides a summary of the number of valid ADM (N of ADM) and the overall ADM for each site.

Table 3-14. Number of B&G site valid ADM and mean NH_3 emission values between the 2010 and revised datasets.

Dataset	Statistic	IA4B			NC4B			OK4B		
		F	B1	B2	F	B1	B2	F	B1	B2
2010	N of ADM	528	379	433	410	419	444	571	612	581
	Overall ADM (kg d^{-1})	0.241	31.3	20.1	0.136	5.9	7.2	0.458	10.8	11.3
Revised	N of ADM	512	378	432	516	554	578	487	610	579
	Overall ADM (kg d^{-1})	0.254	31.5	20.4	0.128	5.6	6.8	0.506	10.8	11.2

3.3.2 H_2S Breeding and Gestation Data

At IA4B, the number of valid ADM decreased by 16 (2.83%), 0 (0.00%), and 1 (0.22%) for the F, B1, and B2, respectively. Meanwhile, H_2S emissions increased by 1.45%, 0.07%, and 0.24% for F, B1, and B2, respectively. At NC4B, the number of valid ADM increased by 115 (25.73%), 140 (30.97%), and 147 (30.25%) for F, B1, and B2, respectively. Mean H_2S emissions for F, B1, and B2 decreased by 7.83%, 5.14% and 8.42%, respectively. At OK4B, the number of valid ADM decreased by 86 (14.73%), 2 (0.32%), and 2 (0.34%) for F, B1, and B2, respectively. Mean H_2S emissions for F increased by 13.52% and decreased for B1 by 0.19% and B2 by 0.10%. Table 3-15 provides a summary of the number of valid ADM (N of ADM) and the overall ADM for each site.

Table 3-15. Number of B&G site valid ADM and mean H_2S emission values between the 2010 and revised datasets.

Dataset	Statistic	IA4B			NC4B			OK4B		
		F	B1	B2	F	B1	B2	F	B1	B2
2010	N of ADM	566	391	464	447	452	486	584	621	591
	Overall ADM (g d^{-1})	89.7	8,585	5,722	143	294	240	91	864	885
Revised	N of ADM	550	391	463	562	592	633	498	619	589
	Overall ADM (g d^{-1})	91.0	8,591	5,736	132	279	220	103	862	884

3.3.3 PM Breeding and Gestation Data

At IA4B, the number of valid PM_{10} ADM decreased by 4 (1.00%), 0 (0.00%), and 1 (0.29%) for the F, B1, and B2, respectively. Overall meanPM_{10} emissions increased by 1.43% and 0.17% for F and B1, respectively, while for B2 emissions decreased by 0.11%. At NC4B, the number of valid ADM increased by 49 (27.07%), 64 (20.32%), and 49 (19.14%) for F, B1, and B2, respectively. Mean PM_{10} emissions for F, B1, and B2 decreased by 7.33%, 3.12% and 5.12%, respectively. At OK4B, the number of valid ADM decreased by 62 (14.39%), 1 (0.20%), and 1 (0.23%) for F, B1, and B2, respectively, while mean PM_{10} emissions for F and B1 increased by 15.50% and 0.14%, respectively. Mean PM_{10} emissions decreased for B2 by 0.12%. Table 3-16 provides a summary of the number of valid ADM (N of ADM) and the overall ADM for each site.

Table 3-16. Number of B&G site valid ADM and mean PM_{10} emission values between the 2010 and revised datasets.

Dataset	Statistic	IA4B			NC4B			OK4B		
		F	B1	B2	F	B1	B2	F	B1	B2
2010	N of ADM	399	359	342	181	315	256	431	495	435
	Overall ADM (g d^{-1})	28	466	526	30	260	406	40	345	494
Revised	N of ADM	395	359	341	230	379	305	369	494	434
	Overall ADM (g d^{-1})	28.4	465.5	526.9	27.8	251.9	385.2	46.2	345.5	493.4

At IA4B, the number of valid $PM_{2.5}$ ADM did not change for either at F, B1, or B2 and did not have an emissions change that was not attributable to the precision in the data sources. At NC4B, the number of valid ADM increased by 3 (14.29%), 8 (40.00%), and 13 (108.33%) for F, B1, and B2, respectively. Mean $PM_{2.5}$ emissions for F, B1, and B2 decreased by 9.29%, 11.28% and 15.21%, respectively. At OK4B, the number of valid ADM decreased by 7 (10.77%) for F, while there was no change in the ADM for B1 and B2. Mean $PM_{2.5}$ emissions for F increased by 36.00% and B1 and B2 did not have an emissions change that was not attributable to the precision in the data sources. Table 3-17 provides a summary of the number of valid ADM (N of ADM) and the overall ADM for each site.

Table 3-17. Number of B&G site valid ADM and mean $PM_{2.5}$ emission values between the 2010 and revised datasets.

Dataset	Statistic	IA4B			NC4B			OK4B		
		F	B1	B2	F	B1	B2	F	B1	B2
2010	N of ADM	51	36	39	21	20	12	11	43	42
	Overall ADM (g d^{-1})	3.1	48	52	2.8	39	48	5	28	49
Revised	N of ADM	51	36	39	24	28	25	9	43	42
	Overall ADM (g d^{-1})	3.13	48.3	52.4	2.54	34.6	40.7	6.8	27.7	49.0

At IA4B, the number of valid TSP ADM decreased by 3 (6.25%) for the farrowing room and resulted in increased TSP emissions by 4.33%. No change in the number of valid ADM or TSP emissions was seen at B1 and B2. At NC4B, the number of valid ADM increased by 3 (10.00%), 4 (11.43%), and 3 (9.38%) for F, B1, and B2, respectively. Mean TSP emissions for F decreased by 5.52%, while emissions for B1 and B2 increased by 1.00% and 1.42%, respectively. At OK4B, the number of valid ADM decreased by 7 (10.77%) for the farrowing room, which resulted in a 7.01% increase in TSP emissions while B1 and B2 showed no change in the number of valid ADM for TSP emissions. Table 3-18 provides a summary of the number of valid ADM (N of ADM) and the overall ADM for each site.

Table 3-18. Number of B&G site valid ADM and mean TSP emission values between the 2010 and revised datasets.

Dataset	Statistic	IA4B			NC4B			OK4B		
		F	B1	B2	F	B1	B2	F	B1	B2
2010	N of ADM	48	39	45	30	35	32	65	88	81
	Overall ADM (g d^{-1})	64.7	728	1,069	96	441	542	117	630	787
Revised	N of ADM	45	39	45	33	39	35	58	88	81
	Overall ADM (g d^{-1})	67.5	727.7	1,068.2	90.7	445.4	549.7	125.2	629.6	787.3

3.3.4 NH_3 Finisher Data

At IN3B, the number of valid ADM decreased by 2 (0.53%), 4 (1.18%), 3 (0.90%), and 30 (8.90%) for R5, R6, R7, and R8, respectively. Meanwhile, NH_3 emissions increased by 2.03%, 2.80%, 1.78%, and 11.31% for R5, R6, R7, and R8, respectively. At NC3B, the number of valid ADM increased by 43 (8.14%), 51 (10%), and 105 (23.28%) for B1, B2, and B3, respectively. Mean NH_3 emissions for B1, B2, and B3 decreased by 5.41%, 5.24% and 11.44%, respectively. Table 3-19 provides a summary of the number of valid ADM (N of ADM) and the overall ADM for each site.

Table 3-19. Number of Finisher site valid ADM and mean NH_3 emission values between the 2010 and revised datasets.

Dataset	Statistic	IN3B				NC3B		
		R5	R6	R7	R8	B1	B2	B3
2010	N of ADM	375	340	334	337	528	510	451
	Overall ADM (kg d^{-1})	7.35	7.66	6.63	6.23	5.49	5.24	5.64
Revised	N of ADM	373	336	331	307	571	561	556
	Overall ADM (kg d^{-1})	7.50	7.87	6.74	6.93	5.20	4.97	5.00

3.3.5 H_2S Finisher Data

At IN3B, the number of valid ADM decreased by 3 (0.60%), 3 (0.67%), 3 (0.68%), and 34 (8.11%) for R5, R6, R7, and R8, respectively. Mean H_2S emissions decreased for R5 (0.48%) but increased for R6 (1.01%), R7 (0.96%), and R8 (8.13%). At NC3B, the number of valid ADM increased by 46 (9.04%), 49 (9.92%), and 93 (20.76%) for B1, B2, and B3, respectively, with mean H_2S emissions decreasing by 7.72% for B1, 5.75% for B2, and 14.57% for B3. Table 3-20 provides a summary of the number of valid ADM (N of ADM) and the overall ADM for each site.

Table 3-20. Number of Finisher site valid ADM and mean H_2S emission values between the 2010 and revised datasets.

Dataset	Statistic	IN3B				NC3B		
		R5	R6	R7	R8	B1	B2	B3
2010	N of ADM	500	449	440	419	509	494	448
	Overall ADM (g d^{-1})	419.33	617.86	400.70	637.26	156.74	170.48	193.13
Revised	N of ADM	497	446	437	385	555	543	541
	Overall ADM (g d^{-1})	417.31	624.11	404.55	689.10	144.64	160.68	164.99

3.3.6 PM Finisher Data

At IN3B, the number of valid PM_{10} ADM decreased by 2 (0.66%) for R5 and 20 (8.70%) for R8 and increased by 1 (0.34%) for R7; the values for R6 were 0. Mean PM_{10} emissions increased by 0.41%, 1.06%, and 1.13% for R5, R6, and R7, respectively, and decreased by 7.56% for R8. At NC3B, the number of valid ADM was 0 for B1 and increased by 46 (10.77%) and 95 (38.46%) for B2 and B3 respectively. Mean PM_{10} emissions increased by 0.71% for B1 and decreased by 7.05% for B2 and 12.92% for B3. Table 3-12 provides a summary of the number of valid ADM (N of ADM) and the overall ADM for each site.

Table 3-21. Number of Finisher site valid ADM and mean PM_{10} emission values between the 2010 and revised datasets.

Data Set	Statistic	IN3B				NC3B		
		R5	R6	R7	R8	B1	B2	B3
2010	N of ADM	303	271	296	230	466	427	247
	Overall ADM (g d^{-1})	211.87	225.74	185.14	172.17	188.23	187.47	166.78
Revised	N of ADM	301	271	297	210	466	473	342
	Overall ADM (g d^{-1})	211.02	223.35	183.05	185.19	189.57	174.25	145.24

At IN3B, the number of valid $PM_{2.5}$ ADM increased by 4 (14.81%) for both R6 and R7 and by 5 (18.25%) and 4 (16.67%) for R5 and R8, respectively. Mean $PM_{2.5}$ emissions decreased by 32.59%, 5.0%, and 25.15% for R5, R6, and R7, respectively. R8 had a 29.13% increase in mean $PM_{2.5}$ emissions. At NC3B, the number of valid ADM increased by 11 (22.92%) for B1 and 3 (10%) for B3 and decreased by 2 (3.28%) for B2. Mean $PM_{2.5}$ emissions decreased 11.09% for B1 while B2 and B3 had the largest decreases in emissions with values of 74.79% and 73.27%, respectively. Table 3-22 provides a summary of the number of valid ADM (N of ADM) and the overall ADM for each site. It is worth noting that the emissions values include negative emission rates, as produced by the observation method.

Table 3-22. Number of Finisher site valid ADM and mean $PM_{2.5}$ emission values between the 2010 and revised datasets.

Data Set	Statistics	IN3B				NC3B		
		R5	R6	R7	R8	B1	B2	B3
2010	N of ADM	27	27	27	24	48	61	30
	Overall ADM (g d^{-1})	9.50	5.20	-14.88	2.35	24.14	51.50	32.09
Revised	N of ADM	32	31	31	28	59	59	33
	Overall ADM (g d^{-1})	6.41	4.94	-11.14	3.04	21.46	12.98	8.58

At IN3B, the number of valid TSP ADM did not change for R5, R6, R7, and R8, while mean TSP emissions decreased by 0.76%, 1.25%, 0.97%, and 1.44% for R5, R6, R7, and R8, respectively. While the number of valid days did not change between the 2010 dataset and the revised dataset, additional half-hour estimates were added to some of the daily averages. These additional half-hour estimates altered the daily averages for IN3B. At NC3B, the number of valid ADM decreased by 3 (5.45%), 11 (17.46%), and 4 (14.81%) for B1, B2, and B3, respectively. Mean TSP emissions decreased by 34.97% for B1 and 37.27% for B2 and increased by 15.15% for B3. Table 3-23 provides a summary of the number of valid ADM (N of ADM) and the overall ADM for each site.

Table 3-23. Number of Finisher site valid ADM and mean TSP emission values between the 2010 and revised datasets.

Data Set	Statistic	IN3B				NC3B		
		R5	R6	R7	R8	B1	B2	B3
2010	N of ADM	24	24	34	22	55	63	27
	Overall ADM (g d^{-1})	898.74	1092.62	978.22	1041.59	683.42	755.24	375.27
Revised	N of ADM	24	24	34	22	52	52	23
	Overall ADM (g d^{-1})	891.94	1078.95	968.73	1026.63	444.41	473.77	432.12

3.3.7 NH_3 Open Source Data

The data presented in the 2010 site reports is substantially different from the revised dataset for EEM development. EPA reprocessed the revised dataset to utilize a lower completeness criterion to develop the daily averages (see discussion in Section 3.2.3), for both methods used to estimate NH_3 emissions data. Each emission estimation method is presented separately in Table 3-24. For the bLS method, the number of valid ADM increased for NC3A (25%), NC4A (75%) and OK4A (15%) and decreased for IA3A (-3%) and OK3A (-18%). The North Carolina sites also saw an increase in the ADM of 3%, 7%, for NC3A and NC4A. The remaining sites saw decrease of 22% (IA3A), 31% (OK3A), and 21% (OK4A).

The VRPM method had increases in the number of valid ADM for all sites, with 11 (1100%) added days for IA3A, 5 (167%) for NC3A, 17 (189%) for OK3A, 9 (225%) for NC4A, and 12 (40%) for OK4A. These increases in the number of days available translated into increases in the ADM of 9% and 2% for IA3A and OK4A, respectively. The remaining sites saw decreases in ADM of 31% (NC3A), 26% (OK3A) and 6% (NC4A).

The most notable change is the removal of IN4A because all of its data was flagged as invalid due to moisture interference, as discussed in section 3.1.2.

Table 3-24. Number of open source valid ADM and mean NH_3 emission values between the 2010 (75% completeness) and revised (52% completeness) datasets.

Data Set	Statistic	IA3A		NC3A		OK3A		NC4A		OK4A	
		VRPM	bLS	VRPM	bLS	VRPM	bLS	VRPM	bLS	VRPM	bLS
2010	N of ADM	1	32	3	8	9	50	4	16	30	46
	Overall ADM (kg d^{-1})	47.08	14.21	58.23	28.31	102.80	55.44	70.78	62.35	177.15	171.83
Revised	N of ADM	12	31	8	10	26	41	13	28	42	53
	Overall ADM (kg d^{-1})	51.15	11.03	40.39	29.03	76.56	38.48	66.74	66.66	180.45	136.23

3.3.8 H_2S Open Source Data

Similar to the NH_3 for lagoons, the data presented in the 2010 reports is different from the revised dataset used for EEM development. Table 3-24 provides a summary of the ADM available in each dataset. For the most part, the revised dataset represents an increase in the number of ADM available for H_2S emissions. Most sites more than doubled the number of valid days with the change to a 52% criterion. IA3A increased by 21 days (350%), NC3A 9 days (150%), OK3A 29 days (121%), and IN4A 18 days (150%). The only exception was OK4A, which only increased by 12 days with a 50% change. These increases in number of ADM resulted in increases in the overall ADM for IA3A (88%), IN4A (33%), NC4A (57%) and OK4A (41%). A 13% decrease and 19% decrease in overall ADM occurred for NC3A and OK3A, respectively.

Table 3-25. Number of open source valid ADM and mean H_2S emission values between the 2010 (75% completeness) and revised (52% completeness) datasets.

Dataset	Statistic	IA3A	NC3A	OK3A	IN4A	NC4A	OK4A
2010	N of ADM	6	6	24	15	12	24
	Overall ADM (g d^{-1})	2.20	1.95	6.33	0.39	0.30	8.35
Revised	N of ADM	27	15	53	34	30	36
	Overall ADM (g d^{-1})	4.13	1.69	5.14	0.52	0.47	11.78

3.4 Comparison Between the Revised Datasets and NAEMS Datasets Used in Peer-Reviewed Published Papers

As a final check, a comparison of summary statistics of the revised dataset was made to peer-reviewed journal articles using the NAEMS data. This allowed EPA to evaluate how well the data revisions were replicated and identify any additional data processing revisions that may have been made. The following section summarizes the results of this analysis.

3.4.1 Barn Sources

Currently, there have been no peer-reviewed publications that report NAEMS emissions data from swine barns that will allow for a comparison.

3.4.2 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 (Table 3-26).The major difference in the datasets is related to the removal of data affected by moisture interference for the EPA revised dataset (see Section 3.1.2), 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 (Table 3-38), 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 of 75%. For comparison, EPA also used a data completeness of 75% (Table 3-26). While the count of valid days matched for IN4A, the daily average H_2S emissions are different, as the revised dataset has an average emission 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 are significantly smaller than at IN4A with values 38.6% higher for OK4A and 57.2% lower for NC4A.

Table 3-26. Comparison of EPA revised constructed NH_3 dataset to Grant publications (Grant et al., 2016; Grant and Boehm, 2018)

Dataset	NC3A				OK3A				IN4A				NC4A				OK4A				IA3A			
	# of valid days at 52%				# of valid days at 52%				# of valid days at 52%				# of valid days at 52%				# of valid days at 52%				# of valid days at 52%			
	B[a]	V[b]	Sum	ADM	B	V	Sum	ADM	B	V	Sum	ADM	B	V	Sum	ADM	B	V	Sum	ADM	B	V	Sum	ADM
EPA	10	8	21	1.66	22	24	45	5.23	0	0	0	0	28	13	35	3.48	48	42	80	7.05	31	12	38	13.66
Grant Pub.[c]	10	8	16	1.88	43	23	59	4.33	18	2	18	3.22	28	13	30	3.10	50	40	67	7.18	-	-	40	10.80
Diff (%)				-11.8				23.8				N/A				12.3				-1.7				26.4

[a] B is the BLS methodology
[b] V is the VRPM methodology
c All values from Grant et al. (2016) apart from site IA3A values, which are from Grant and Boehm (2018)
N/A = Not applicable
ADM = Average Daily Mean in units of g day^{-1} m^{-2}

Table 3-27. Comparison of EPA revised constructed H_2S dataset to Grant et al. (2013b) using the BLS methodology and a data completeness of 75%

Dataset	IN4A		OK4A		NC4A	
	# of valid days	ADM	# of valid days	ADM	# of valid days	ADM
EPA	15	1.9	18	114.1	14	2.1
Grant and Boehm (2018)	15	25.8	24	82.3	12	4.9
Diff (%)		92.6		38.6		-57.1

ADM = average daily mean in units of mg s^{-1}m^{-2}

4.0 AVAILABLE EMISSIONS AND PROCESS DATA FOR CONSIDERATION

Developing EEMs for AFOs is complex, since many variables potentially influence emissions. Therefore, EPA used a focused approach to develop EEMs for efficiency. The approach focused on variables that could have a major influence on air emissions, as established in previous studies. The following sections summarize the literature on the factors that are most influential on emissions from AFOs.

4.1 NH_3 and H_2S Emissions from Barn 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 (e.g., movement of gas from manure into the air). Proxies for the amount of manure produced at a swine barn are live animal weight and inventory. For model development, the EPA selected live animal weight and inventory as production predictor variables. This allows the influence of these variables to be quantified; it also allows the production predictor variable to potentially represent the pig rotation characteristics. For example, live animal weight 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. Live animal weight and inventory were determined daily during the NAEMS and are available 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 key concentrations and can also have a major influence on NH_3 and H_2S emissions from swine manure (Ni et al., 2009; 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, but the frequency of the measurements at each site varied greatly, ranging from none to a sample every two to three months. TKN and TAN were selected for further analysis, but 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). Manure temperature influences the microbial degradation of animal waste, with increasing temperatures resulting in increasing degradation rates (Zhang and Day, 1996). 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 that can be released from the manure into the air. However, for H_2S, an increasing Henry's law constant and dissociation have conflicting effects on the potential amount available, meaning that the overall influence of temperature on H_2S emissions may not be as strong as for NH_3. Increasing manure temperature and air temperature can also increase the transfer of NH_3 and H_2S across the manure-air interface (Ni et al., 2009, and references within; Montes et al., 2009, and references; Rumsey and Aneja, 2014). Note that while the release of NH_3 is controlled by the convective mass transfer release mechanism, the release of H_2S is additionally influenced by bubble-release (ebullition) mechanisms, which can be triggered by manure disturbances (Ni et al., 2009) from animal or management activities inside the barn. During NAEMS, researchers took continuous measurements of exhaust temperature (temperature at barn fan exhaust) and ambient temperature, and both were chosen 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 25°C varying from approximately 0.6 to 15% and approximately 2 to 44%, respectively. In NAEMS, barn manure pH was measured in collected manure samples, which were taken every two to three 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, thereby lowering the resistance to volatilization and causing an increase in the transfer of NH_3 and H_2S across the air-manure interface (Arogo et al., 1999; Rumsey and Aneja, 2014). Researchers measured the barn ventilation rate continuously during NAEMS, so it was chosen for further analysis.

As previously mentioned, the release of H_2S is additionally influenced by ebullition mechanisms, which can be triggered by manure disturbances (Ni et al., 2009) from animal or management activities inside the barn. However, EPA did not receive barn activity measurements, so it could not explore the influence of this variable further. In farrowing rooms at swine sow operations, there is likely to be an increase in piglet activity as piglets become older and, therefore, increased disturbance of manure on the farrowing room floor. Additionally, there will be more manure on the floor of the farrowing room to disturb as the cycle goes on. (Floors of farrowing rooms are typically clean at the beginning of the cycle since rooms are power-washed between cycles). These factors could result in increasing H_2S emissions throughout the approximately 21-day farrowing cycle. These hypotheses are supported by the observation of a regular cycle occurring in the H_2S emission trends at NC4A and OK4A (see Section 3.3.2).

Accordingly, EPA chose the variable “cycle day” 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 a trend related to the farrow cycle, EPA also chose the variable “cycle day” for NH_3 so that a consistent approach could be applied to the farrowing room methodology.

4.2 NH_3 and H_2S Emissions from Open Sources

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

As with 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 more information on how they influence emissions, refer to the previous section.) For NAEMS open source sites, there were limited measurements of TAN at three of the five sites (five, three, and one daily measurements at IA3A, OK3A, and OK4A, respectively), as a result EPA did not choose the influence of this variable for further analysis. TKN was measured more often, particularly at NC3A and NC4A, where it was measured approximately every two months. Therefore, TKN was chosen for further investigation. There were no measurements of sulfide in open source manure samples, so EPA could not investigate this parameter 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. Accordingly, these four variables were 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 manure samples and not continuously measured like it was for lagoons. As a result, pH was only measured during five events over the NAEMS sampling period. Therefore, EPA chose the continuously-measured air temperature and wind speed for further analysis at basins.

In literature, studies have suggested that additional factors 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., 2013b; Varadharajan and Hemond, 2012). Grant et al. (2013b) analyzed a swine sow lagoon dataset similar to the EPA revised dataset and commented that “bursts or episodes of high H_2S emissions at the Indiana and North Carolina lagoons were often associated with the passage of cold fronts.” However, further analysis in Grant et al. study concluded that changes in atmospheric pressure and lagoon depth did not correlate with periods of high H_2S emissions. Due to the Grant et al. analysis and because the influence of barometric pressure on H_2S emissions is unlikely to be determined in a daily averaged dataset, EPA did not choose barometric pressure change 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., 2013b). In the same analysis mentioned above, Grant et al. (2013b) hypothesized that H_2S emissions at the North Carolina and Indiana sow lagoons were an order of magnitude lower than at Oklahoma due to the presence of purple sulfur bacteria at North Carolina and Indiana, which have favorable conditions for growth at these sites due to the warmer temperatures. No measurements of purple sulfur bacteria in lagoons was made during NAEMS, so this variable was not explored further.

The presence of a crust or cover on a lagoon or basin will inhibit the transfer of NH_3 to the atmosphere, reducing emissions. Similarly, frozen lagoon surfaces will also stop emissions from the surface of the lagoon. The NAEMS made limited observation of the state of the lagoon (e.g., color, crust) during the study. The lack of daily observations would limit the number of days available for EEM development, as the dataset would be limited to only those days with lagoon surface observations. Due to the limited nature of the observations available, this variable was not explored further.

4.3 PM Emissions 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, the EPA chose live animal weight and inventory as predictor variables, as they are 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, the EPA did not receive barn activity measurements and could not explore the influence of this variable 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).

Observational studies of environmental variables’ influence on swine PM emissions have been limited; however, Haeussermann 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 $PM_{2.5}$ emission rates from animal houses including swine in the Netherlands using a statistical model. Winkel et al. (2015) did not include environmental variables in their models but do suggest based on preliminary analysis that ambient temperature is a promising predictor variable. Note 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 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 temp). Accordingly, EPA chose the variables barn RH, ambient RH, barn temperature, ambient temperature, and ventilation rate 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 approximately 21-day farrowing cycle. Similarly to H_2S, these hypotheses are supported by the observation of a regular cycle in the NC4A and OK4A PM_{10} farrowing room emission trends, although the cycle pattern (see Section 3.3.2) 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 Haeussermann et al. (2008) study, which reported that cycle day had an influence on PM concentrations in swine barns. There are not enough data to observe whether there is a regular cycle in TSP and $PM_{2.5}$ trends; however, because the emission 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.

4.4 Effect of Management Activities

As noted in section 2.1 the production cycle for swine has three phases: farrowing, nursing, and finishing. Some farms specialize in a single phase of the growth cycle, while other farms may handle 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 meat processing company, known as an 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 NAEMS either encompassed the farrowing-nursing phases (also referred to as breeding and gestation farms) or finishing farms.

Barns for farrowing and finishing have different concerns and management practices. Farrowing operations need 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, EPA developed separate EEMs for each phase.

The way manure is managed at the farm can also influence emissions. Four principal types of waste management systems are used with total and partially enclosed confinement housing in the swine industry: deep pit, pull-plug pit, pit recharge, and flush systems. Other practices are used, but these are the predominant practices. 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 wastes to an anaerobic lagoon. The pit may be flushed daily or as often as every two hours; the frequency depends on 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 four to 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 are emptied by pumping. To reduce odor, NH_3, and

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, H_2S, and VOC differently. Emissions of NH_3, H_2S, and VOC 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, H_2S, and VOC 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 differences between in-house manure management systems can affect emissions, the EPA developed separate EEMs for each system.

5.0 OVERVIEW OF EEM DEVELOPMENT APPROACH

EPA developed EEMs separately for different swine production types (i.e., grow-finish, gestation, and farrowing) due to the significant differences in pig characteristics and the associated production and management conditions, which can have a large influence on air emissions. In addition, EPA developed separate EEMs for different open source waste management systems (i.e., lagoon and basin), because lagoons and basins have different storage times, which influence biochemical processes and thus air emissions.

The EEM development approach consisted of seven steps:

1. Data processing.
2. Compare/contrast sites and review data plots to identify patterns.
3. Identify process and emissions variables for consideration.
4. Develop/refine/select daily emissions models.
5. Validation of daily emissions models.
6. Uncertainty estimates for annual emissions.
7. Model application.

The first step, data processing, consisted of loading and cleaning the dataset for use in the analysis. EPA started with the revised data developed by Heber, which adjusted the airflow and emission calculations for barn sources. This adjustment is described in more detail in Section 3.1, with the data cleaning process discussed in more detail in Section 6.

The second step of the EEM development process was to compare and contrast sites and identify patterns. The comparison of sites helped identify process differences that might be contributing to differences in emissions. For example, a site might have higher emissions values due to a different manure management system. This data exploration also helped to identify questionable data points for further review. This phase also included analysis to identify the strength of relationships between the available parameters and emissions. Section 7 shows the results of this analysis.

The third step identified the variables to consider in EEM development. This step started with a literature review to identify parameters with established relationships with emissions. This was coupled with the exploratory data analysis to assess the strength of these well-established relationships within NAEMS data. The final phase evaluated the quantity of data available, the potential ease of variable measurement for a producer, and the exploratory data analysis together to select the variables to use in model development. A summary of this selection process is provided in Section 8.

After the parameters were selected, EPA developed the daily models. All the parameters were tested in different combinations. Each combination was compared using model fit and evaluation statistics, as well as residual plots. EPA also examined the models for outliers or questionable results (e.g., relationships that were contrary to those found in literature). If any were found, EPA explored refinements to the data that would result in improvements in model performance (e.g., removal of outliers, addition of other variables). EPA then reran the models with this refined dataset and repeated the review process. Once data refinement was complete, EPA selected a final model. This process is outlined in Section 9 for each of the animal types.

This final model went through additional validation using a jackknife approach, which is discussed in more detail in Section 10. This validation step evaluated the model coefficients for consistency when a whole barn was removed from the dataset. This helped to identify any sites that might be strongly influencing the model.

Next, EPA developed annual emission and uncertainty estimates. Additional details on the approach are provided in Section 11. The final step is the application of the model to develop an emission estimate for a farm by a user. Section 12 presents the calculation, including combining multiple structures for a to sum emissions on a farm and calculating an uncertainty estimate.

6.0 DATA PROCESSING

For data processing, the EPA-ORD standard operating procedure EMAB-129.0 : *Procedures for Entering or Importing Electronic Sample Data into Study Database* was followed. EPA imported the data from MS Excel® spreadsheets and MS Access database files into SAS®, a statistical analysis software package. Data was imported using a number of steps associated with the loading and where necessary, transposing of the data. EPA made only minimal adjustments to the dataset to ensure proper uploading into SAS, including adjustment to column names to comply with SAS string length and character limitations, and replacement of "not a number" (NaN) flags and Excel data errors flags (e.g., #VALUE, #N/A) with empty (null) cells. EPA reviewed the data to ensure appropriate transformations into SAS format.

Additional variables were also created in the SAS dataset by combining existing variables (e.g., live animal weight, which is a combination of animal inventory and animal weight) and adjusting existing variables for unit change (e.g., normalizing open source emissions for surface area). Variables were also added to the dataset to facilitate analysis by site, barn, date, or day of test. For open sources, additional data processing was needed to create ADM from 30-minute averaged data. A description of the method and data completeness criteria for determining ADM emissions is provided in sections 3.1 and 3.2. For environmental data, a similar approach was used, with each 30-minute average considered valid if five or more of the six five-minute averages within the period were valid. ADM were calculated for environmental variables if 36 or more values were valid in a day (out of 48 total), representing a completeness criterion of 75%.

The datasets were also updated in accordance with revisions that were made to the dataset as a result of identifying invalid data during the EEM development process (see section 3.1 for more details).

7.0 SITE COMPARISON AND TRENDS ANALYSIS

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

7.1 Emissions Data

7.1.1 Breeding/Gestation

Table C-1 presents the summary statistics for daily average emissions of NH_3 and H_2S, by breeding and gestation site. Emissions of NH_3 from the farrowing rooms were substantially lower than those from the gestation barns. Across the sites, NC4B has the lowest farrowing room emissions, followed by IA4B and OK4B (which is consistent with NC4B having the lowest inventory.) The time series plot shown in Figure D-1 suggests more variation at IA4B, which is supported by IA4B having the largest standard deviation. Site NC4B also had the lowest NH_3 emissions, followed by OK4B and IA4B. Again, NC4B has the lowest inventory, consistent with having the lowest emissions among the sites. Similar to the farrowing rooms, IA4B has the largest standard deviation and apparent variability in the time series plot. The cyclical nature of the emissions for both the farrowing rooms and the gestation barns can be seen in the time series plot (Figure D-1). The cycle for the farrow room is shorter than the gestation barns, suggesting that the cyclical emissions are linked to the placement cycle, while the cyclic emissions observed in the gestation barns seem to be linked to season.

For H_2S emissions, the farrowing rooms had lower emissions than the gestation barns (Table C-1), which was expected due to the large difference in animal populations contained in each type of barn. However, site IA4B had the lowest H_2S emissions, followed by sites OK4B and NC4B. This is a reversal from the NH_3 emission rankings. Despite the lower emissions at IA4B, the time series plot (see Figure D-2) shows high variability in its emissions. The emissions are relatively low for most of the year with a spike during the summer months. The H_2S emissions from the other sites show the same emissions pattern as NH_3: initially low emissions that increase and then drop to a minimum value after a short period of time. As with NH_3, this short cycle is likely associated with animal placement and removal. Section 7.2 will explore this further.

Gestation barn emissions are lowest at NC4B, followed by OK4B, and IA4B, which also has the most variable emissions. The H_2S emissions from IA4B gestation barns are markedly higher than those from the other sites. This could be due to differences in the manure handling at the site. IA4B gestation barns use a deep pit system, which hold manure for up to six months, 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 also has slightly higher live animal weights than the other sites, which suggests more manure production and, therefore, higher H_2S emissions.

Table C-2 presents the summary statistics for daily average PM_{10}, $PM_{2.5}$, and TSP emissions from breeding and gestation sites. The farrowing rooms continued to have lower emissions of all three PM species. NC4B had the lowest emissions of PM_{10} from farrowing rooms, followed by IA4B and OK4B (see Table C-2). The emissions from NC4B and IA4B are comparable, while OK4B emissions average 50% higher. The emissions at OK4B are also more variable, with a standard deviation of 26.7 g day^{-1}, which is almost 80% higher than the standard deviation at other sites. For gestation barns, the ranks overlap across sites. NC4B B1 has the lowest emissions, followed by OK4B Barn 1, NC4B Barn 2, IA4B Barn 1, OK4B Barn 2, and finally IA4B Barn 2. The standard deviations for the IA4B barns are the highest, at 225 g day^{-1} and 224 g day^{-1}. Figure D-3 suggests that emissions from the gestation barn follow a seasonal pattern, while most of the farrowing rooms appear to follow a cycle tied to animal placement. The patterns of PM_{10}, $PM_{2.5}$, and TSP emissions for the farrowing room at OK4B are not consistent with the patterns seen with NH_3 and H_2S emissions.

For $PM_{2.5}$ emissions, the farrowing rooms at NC4B have the lowest emissions, followed by IA4B and OK4B (Table C-2). The OK4B farrowing room has nearly twice the $PM_{2.5}$ emissions as the other two sites, with the highest standard deviation. For the gestation barns, the summary statistics show a slightly different order of sites from PM_{10}, with the lowest average emissions of $PM_{2.5}$ at OK4B Barn 1, followed by the NC4B Barns 1 and 2, and the remaining barns in the same order as seen with PM_{10}. OK4B Barn 2 has the highest standard deviation for $PM_{2.5}$ emissions from gestation barns. With fewer emission measurements than PM_{10}, it is more difficult to discern a temporal pattern to the emissions of $PM_{2.5}$ shown in Figure D-4.

For TSP, site IA4B has the lowest emissions among farrowing rooms, followed by NC4B and OK4B (Table C-2). There is large variation in TSP emissions across sites; the average TSP emissions from OK4B are 85% higher than IA4B. For the gestation barns, NC4B Barn 1 has the lowest TSP emissions, followed by NC4B Barn 2 and OK4B Barn 1 (the largest emitters of TSP match the order of the largest emitters of $PM_{2.5}$ and PM_{10}). The spread in emissions is relatively large, with the average emissions from IA4B Barn 2 2.4 times higher than NC4B Barn 1. Any temporal pattern in the time series in Figure D-5 is not readily apparent.

7.1.2 Grow/finish

Table C-3 presents the summary statistics for daily average NH_3 and H_2S emissions at grow-finish sites. As shown in the table, site IN3B had slightly higher average NH_3 emissions than the NC3B site, which is likely due to the larger capacity of the Indiana barns. Both sites had a cyclical pattern to the emissions that is apparent in the time series plots (Figure D-6). This pattern of increasing emissions is likely related to the growing cycle within the barns. Figure D-6 also shows NC3B with a steady decrease in peak emissions over the monitoring period, as each iteration of the cycle produces lower emissions. IN3B had more consistent cycle NH_3 emissions over the course of the monitoring period. Site IN3B also had higher average 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, at NC3B, there were five negative H_2S emission values at Barn 1 and two negative H_2S values at Barn 2. There is also more variation in emissions between the barns at each site. This is particularly noticeable at IN3B, where Rooms 5 and 7 both have average daily emission values that are nearly half of those at Rooms 6 and 8. Figure D-7 shows an extreme value in the H_2S emissions at IN3B room 6.

Table C-4 presents the summary statistics for daily average PM_{10}, $PM_{2.5}$, and TSP emissions at each grow-finish site. As shown in Table C-4, the daily average PM emissions values for the grow-finish sites and their barns were highly variable. Rooms 5 and 6 at site IN3B have higher emission values than the other two barns 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 grams per day, which contributed to an overall negative $PM_{2.5}$ emissions value for the site. The time series plots of PM_{10} (Figure D-8) show the same cyclical nature to the emissions that the plots for NH_3 and H_2S showed. $PM_{2.5}$ (Figure D-9) and TSP (Figure D-10), however, do not clearly show the same trends, largely because of the shorter sampling periods.

7.1.3 Open sources

Table C-5 presents the summary statistics for daily average NH_3 and H_2S emissions by open source site. Open sources at swine AFOs (i.e., lagoons and basins) are not sources of PM emissions, and were not monitored for PM emissions during NAEMS.

NH_3 emissions varied greatly across the open-source sites. For lagoons, NH_3 emissions were highest in OK for both the sow lagoons and the grow-finish lagoons, with OK4A NH_3 emissions approximately two times higher than at NC4A, and OK3A NH_3 emissions approximately three times higher than at NC3A. NH_3 emissions at the basin site (IA3A) were considerably higher than lagoon emissions, with the average NH_3 emission twice as high as the lagoon site with the highest emissions. Figure D-11 reiterates that OK4A is consistently higher than all the other sites.

The summary statistics in Table C-6 show that there are negative H_2S emission values at all the sites except OK4A. As with NH_3 emissions, H_2S emissions are considerably higher at the OK sites (Figure D-12); at least five times higher than the other lagoon sites. In contrast to the NH_3 emissions, H_2S emissions are lower at the basin than the lagoons, with emissions at the basin at least an order of magnitude lower than H_2S emissions from the lagoon sites.

7.2 Environmental and Production Parameters

7.2.1 Breeding and Gestation

Table C-7 presents the summary statistics for environmental and production parameters for the breeding and gestation farms. The average inventory counts for the farrowing rooms were in a narrow range, from 200 to 286 head. There is high variability between the sites, as IA4B and NC4B have periods when the head count drops to zero. However, the inventory at OK4B remains fairly stable, at between 263 and 310. (There are only three instances of inventory levels falling to 118, which was the minimum for the barn.) This difference in inventory variation is apparent in Figure D-13, which 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.

Figure D-13 also shows the inventory trends at the gestation barns. Again, the OK4B barn has less variability than the other site. Barn 1 at NC4B also shows little variability over the study period. Barn 2, however, has a cyclical pattern similar to the farrowing rooms. The inventory levels at the IA4B barns varied throughout the year, but not as frequently as the farrowing rooms. The average number of animals housed was similar between the sites, with NC4B on the low end at an average of 900 head.

Animal weight at the farrowing rooms does not vary much between sites, with each farm raising 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 when sows were housed in the farrowing rooms. Figure D-14 shows that, like the inventory levels, animal weight shows a cyclical pattern. Unlike the inventory levels, weight steadily increases with the animal’s age, until they are removed. The cycle then repeats, starting with the younger animals at the minimum weight.

Combining the inventory with weight to obtain a total live animal weight provides a better proxy for manure volume, as the animal weight and inventory determines the volume of manure generated. For the farrowing rooms, Figure D-15 shows a cyclical pattern similar to the weight trends, with live animal weight increasing until the room is emptied. For the gestation barns, the higher weight at IA4B leads to a higher live animal weight than OK4B, despite similar inventory values.

The exhaust temperatures from the farrowing rooms were very similar, with the average temperature ranging from 24.0°C at OK4B to 25.5°C at NC4B. The variability in exhaust temperature is small, 1.42°C to 2.21°C. This 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 D-16 does show a seasonal trend in exhaust temperatures, with peaks in summer and lows in winter. IA4B has 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 the sows, which is consistent with the fact that they are not as susceptible to cold as the piglets.

The ranges of ambient temperatures and their variation, shown in Figure D-17, are indicative of their varying geographic locations. The minimum average temperature of 8.72°C occurred at IA4B, and the maximum average temperature of 19.4°C occurred at NC4B. The coastal North Carolina farm is not subject to as many snowstorms or sub-freezing weather as compared to the OK and IA farms. In fact, NC4B did not drop below 0°C for the entire study period, unlike the IA4B and OK4B.

Average relative humidity values for the building exhaust are similar across the sites. Figure D-18 shows a seasonal pattern, with peak values in the summer and the lowest values occurring in winter for both the farrowing rooms and gestation barns. IA4B exhibits a secondary peak in the January/February timeframe, with a second low in the late spring. This is possibly due to differences in the ventilation schemes at this site, as the winter months used manually adjusted ceiling inlets. The average ambient relative humidity is similar across sites, with Figure D-19 showing high variability across the entire monitoring period, with no particular seasonal pattern.

The farrowing rooms had lower airflow rates than the gestation barns, but had a similar seasonal pattern of peaks in summer and lows in winter (see Figure D-20). The seasonal pattern reflects the ventilation design efforts to maintain a consistent temperature inside the barns.

7.2.2 Finishing Operations

Table C-8 presents the summary statistics for environmental and production parameters for the finishing farms. The barns at IN3B had higher inventory and live animal weight than the barns at NC3B. The animal weights at the NC3B barns were slightly higher than the IN3B barns, with mean barns values ranging from 63.02 kg at IN3B (Room 7) to 75.15 kg at NC3B (Barn 2).

The inventory trends differed between the two sites, likely due to differences in 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 (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. This creates the stepped pattern seen on the IN3B inventory plots (Figure D-21), when 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 decreases in number of animals for the bulk of the cycle, owing to irregular losses 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 pig are shipped, as seen in Figure D-21, in the halving of the population near the end of the cycle. Both barns are run in sync for efficiency.

The trends in weight gain among the farms shown in Figure D-22 are similar, with a steady increase in weight from the initial placement (values of 0 kg in Figure D-22 indicate that the barn or room was empty). Site NC3B begins with a slightly larger piglet and raises the pigs to a slightly higher finishing weight.

The trends in live animal weight (Figure D-23) reflect the differences in loading practices at site IN3B, as there is slight drop in the live animal weight early in the cycle as piglets are redistributed across the barns. Again, IN3B had a slightly higher inventory, resulting in a higher live animal weight than at NC3B. As expected, NC4B had the lowest weight, inventory, and live animal weight.

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 during both winters of the monitoring period, while the ambient temperature at site

NC3B was below 0°C for only a few days. Overall, exhaust temperatures generally remained between 25°C and 30°C, with a few exceptions. The exhaust temperatures followed a similar trend as the ambient temperatures, with the peaks during the summer and lower values in the winter. The average exhaust temperature at NC3B was slightly higher than IN3B, largely due to several readings that were less than 10°C in early 2009, when the barns were empty for an extended time.

Both ambient relative humidity and exhaust relative humidity were approximately 3% higher at NC3B than IN3B. Both sites had comparable variability, with the exhaust relative humidity showing a slight seasonal trend in Figure D-24. The ambient relative humidity shows even less seasonal trend in Figure D-25.

7.2.3 Open Sources

Table C-9 shows the summary statistics for environmental and production parameters for the open source farms. 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 Figures D-26 and D-27 demonstrates the intermittent nature of the measurements at the open source sites, the figure still shows a seasonal trend in the temperatures.

The wind speed (Figure D-28 and D-29) statistics are similar for the North Carolina and Indiana sites, with the OK3A and OK4A sites standing out with higher average speeds of 4.89 ms^{-1} and 5.75 ms^{-1}, respectively. The IN4A average of 3.96 ms^{-1} approaches the average values seen at the Oklahoma sites; however, the North Carolina average wind speeds are at least half of the speeds seen at OK and with less variability.

In addition to the ambient meteorological parameters, pH (Figures D-30 and D-31), lagoon temperature (Figures D-32 and D-33), and oxidation reduction potential (Figures D-34 and D-53), were collected continuously via probes set in the lagoon at a depth of 0.3 meter. These measurements are summarized in Table C-15. For the continuous samples, the highest pH reading was at IN4A (7.90), followed by OK3A (7.84), NC3A (7.75), NC4A (7.73), and finally OK4A (7.59). The average continuous pH values are comparable to the average pH values obtained from the biomaterial samples. The exception is the Oklahoma sites, which both had an average value greater than 8, which was above the averages from the continuous reading. The continuous method collected some readings that exceeded a pH of 8, suggesting that the few biomaterial samples collected at the Oklahoma sites were collected during a peak pH period. As mentioned, at higher pH values, the amount of NH_3 available in the manure increases, thus, increasing the probability of NH_3 emissions. Also, at higher pH values, the amount of H_2S available in the manure decreases pH, thus, decreasing the potential for H_2S emissions. These continuous measurements of pH should be reviewed further during EEM development.

The average lagoon temperature (Figure D-32) was highest at IN4A (20.57°C) and NC4A (20.42°C). The average lagoon temperatures decreased from there, with the remaining sites averaging below 20°C.

The oxidation reduction potential was determined for each lagoon. The oxidation reduction potential provides an indication of how much oxygen is available in the water. Higher oxidation reduction potential can indicate the potential for less H_2S and NH_3 emissions, as the available oxygen can convert these compounds to fewer volatile compounds by oxidation, and thereby reduce the emissions. Of the NAEMS sites, IN4A has the highest oxidation reduction potential (-204.81) with all other sites falling between -475.00 and -494.3. IN4A is the only deep pit system, which might be the cause of the difference in oxidation reduction potential.

7.3 Manure Parameters

7.3.1 Breeding and Gestation Operations

Manure sampling at the breeding and gestation sites under NAEMS included full-depth manure profiles (loadout sampling) and surface manure samples. The summary statistics for all surface samples of manure nitrogen content, pH, manure ammonia content, and manure solids content are provided in Table C-10. Samples were collected on varying schedules at each site. Nitrogen content in surface manure was only recorded for barns IA4B G1 and IA4B G2.

Loadout manure was sampled to determine TKN, TAN, manure solids content, and manure sulfur content. Table C-11 summarizes these values. Ammonia content and pH were only recorded for loadout samples at IA4B F9 and NC4B B1, B2, and B3. Sulfur content was only recorded for IA4B F9, G1, and NC4B B1, B2, and B3.

EPA performed extensive analysis to determine if trends existed in NH_3 content, pH, solids, or nitrogen over time, or if these parameters correlated with emissions. However, the inconsistency in the analyses conducted on samples between the sites constrained trend analysis . For example, only one site, IA4B, reported TKN content in surface samples. Therefore, comparisons across sites could not be made and site-specific data could not be included in the EEMs. The frequency of collection also differed, as some sites collected samples on multiple days, while others processed a single sample. Overall, EPA could not find strong temporal trends or relationships that would lead to incorporating these limited data into the EEMs. While such data could not be included in these EEMs, these parameters should be considered in future work.

The parameters, particularly the TKN and TAN content, provide useful information on the amount of nitrogen excreted, which informs how much nitrogen can be emitted from barns. The available data have some utility in a simple mass balance but would have to be supplemented with default values for some nitrogen sources, such as feed and water.

In addition to the previously mentioned summary tables in Appendix C, EPA has provided the time series and scatter plots in Appendix D (Figure D-33). Section 8 discusses the relationship of TAN and TKN with emissions.

7.3.2 Finishing Operations

Sampling at site IN3B, which used deep pit manure management, included full-depth manure profiles (loadout sampling) and surface manure samples. Table C-12 provides the summary statistics for all surface samples of manure TKN, pH, TAN, manure solids content, and manure ash content. During NAEMS, samples were collected approximately every four months at each site; however, ammonia content and pH samples were not recorded for loadout samples at site IN3B.

For the finishing sites with pull-plug recharge (i.e., NC3B), the pit liquid was sampled to determine TAN, pH, manure ammonia content, manure solids content, and TKN. Table C-13 summarizes these values. Pit liquid sampling was more frequent than loadout sampling. While percent solids and pH were similar across both sites and all barns, N and NH_3 content were consistently lower at the NC3B pull plug recharge site.

EPA performed an extensive analysis to determine if there were trends in NH_3 content, pH, solids, or nitrogen over time, or if any of these parameters were correlated with emissions. There were more data than for the breeding and gestation sites, but they did not yield strong relationships (though the literature may indicate otherwise). The data available would have some utility in a simple mass balance but would have to be supplemented with default values for some nitrogen sources, such as feed and water. Overall, EPA could not find strong temporal trends or relationships that would prompt incorporating these limited data into the EEMs. Appendix C contains summary tables and figures of this analysis. Section 8 discusses the relationship of TAN and TKN with emissions.

7.3.3 Open Sources

NAEMS collected limited biomaterial samples from lagoons. Table C-14 shows what data are available from lagoon samples at each site, with a visual representation of the values in Figure D-37. The table notes that the IN4A, OK3A, and OK4A had one to five samples collected for each parameter. The North Carolina sites (NC3A and NC4A) collected 20 samples, but, unlike the other sites, did not process these samples for solids or TAN. The table also notes that no biomaterial samples were collected at IN4A. Due to the limited data available for manure solids and ammonia concentrations, EPA did not investigate these parameters further.

The average percent TKN is comparable across sites, ranging from an average of 0.29 (NC4A) to 0.57 (OK3A). The breeding and gestation sites (4B) show comparable percent TKN levels, as do the finishing site (3B) lagoons. The plot (Figure D-37) suggests a seasonal trend to the TKN level, which again reinforces that ambient temperature and lagoon temperature could affect TKN levels in the lagoon, and overall nitrogen emissions from the lagoon.

The percent sulfur values across sites are comparable, except for NC4A, which is approximately two times higher than the other sites. This is easily seen in Figure D-37, as the line for NC4A is consistently above all other sites, except for one reading close to the end of the monitoring period. (There is no indication of what may have caused this difference in measurements.) USDA NRCS collected the biomaterial samples, as they were required to analyze wastewater used to irrigate nearby fields. The final reports did not provide additional notes on the samples, which might have explained the decrease in sulfur content.

While the data frequency allowed for some comparisons across sites, the data did not yield consistent relationships (though the literature may indicate otherwise). The data available would have some utility in a simple mass balance but would have to be supplemented with default values for some nitrogen sources, such as feed and water.

8.0 VARIABLES FOR CONSIDERATION

Based on the analysis described in Section 7.0, EPA identified the key environmental and manure parameters that potentially affect emissions from swine barns and open sources. Parameters of particular interest to barn emissions included inventory, live animal weight, 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, exhaust relative humidity and ambient relative humidity were identified as potential parameters for the EEM dataset. For open sources, EPA explored wind speed, lagoon temperature, ambient temperature, relative humidity, pH, and oxidation reduction potential.

The next step of EEM development was to look at the selected variables compared to emissions trends. The exploratory data analysis was conducted to confirm that these variables were selected based on the following criteria: (1) data analysis in this study and in the literature suggested that these variables had a major 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 almost all days of monitored emissions, so that no extra time would be needed to include these parameters in the dataset. This issue particularly applies to using manure moisture and manure TAN concentration. Due to the limited number of samples, development of an appropriate method to produce daily values for these variables was needed.

To further explore the trends between these variables and emissions, and determine whether the parameter should be included in developing an EEM, EPA prepared scatter plots of emissions versus the process, environmental, and manure parameters and conducted least squares regression analysis (Appendix E) to assess the influence of each variable on emissions. For the regressions, EPA classified the linear relationships based on the ranges in Table 8-1

Table 8-1: Relationship classification based on R^2 values

Range of R^2	Relationship strength
$R^2 = 0$	none
$0 < R^2 \leq 0.2$	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

8.1 NH_3 Confinement Sources

8.1.1 Breeding and Gestation Environmental and Activity Parameters

Figures E-1 through E-9 present the scatter plots for NH_3 emissions from breeding and gestation sites versus animal inventory, live animal weight, exhaust temperature, air temperature, exhaust relative humidity, ambient relative humidity, and airflow, respectively. Table 8-2 presents the R^2 values for each parameter, sorted from highest to lowest, and the corresponding scatter plot figure.

Table 8-2. Linear regression summary of NH_3 emissions from breeding and gestation sites – environmental and activity parameters.

Operation	Parameter	Slope	R^2	Figure
Farrowing	Live animal weight	Positive	0.2125	E-1
	Ambient relative humidity	Negative	0.1759	E-4
	Ventilation rate	Positive	0.1682	E-3
	Animal inventory	Positive	0.127	E-1
	Cycle day	Positive	0.0413	E-2
	Ambient temperature	Positive	0.0308	E-4
	Exhaust relative humidity	Positive	0.0088	E-3
	Exhaust temperature	Negative	0.0008	E-3
Gestation	Live animal weight	Positive	0.2442	E-5
	Ventilation rate	Positive	0.0873	E-6
	Animal inventory	Positive	0.0391	E-5
	Exhaust relative humidity	Positive	0.0163	E-6
	Ambient relative humidity	Positive	0.0164	E-8
	Ambient temperature	Positive	0.0081	E-8
	Exhaust temperature	Negative	0.0041	E-6

As noted in Section 7.0, EPA observed distinct differences in the animals and management of the different barn types, which led to different trends in the environmental parameters. Therefore, EPA developed separate EEMs for the farrowing and gestation barn types at the sites.

For farrowing rooms, the relationship between NH_3 emissions and live animal weight is positive and is the strongest linear relationship of all the environmental parameters, although it is a modest relationship with an R^2 of 0.2125. The relationship between NH_3 emissions and inventory was also positive but resulted in a weaker R^2 value (0.127). For gestation barns, the relationship between NH_3 emissions and live animal weight is stronger (R^2 = 0.2442) than the relationship between NH_3 emissions to inventory (R^2 = 0.0391). EPA anticipated a positive relationship with NH_3 emissions for these parameters because both inventory and live animal weight are proportional to the volume of manure produced and, therefore, the potential amount of NH_3 emissions produced. The very weak relationship between gestation barn NH_3 emissions and inventory might be due to the relatively constant number of sows housed within the barn compared to the highly variable emissions from the site. Cycle day showed a very weak positive relationship with NH_3 emissions, but stronger than inventory.

Of the exhaust-related parameters, the ventilation rate has the strongest relationship to NH_3 emission in farrowing rooms, with an R^2 value of 0.1682. Similarly, the gestation barn ventilation rate had a positive relationship with NH_3 emissions (R^2 = 0.0873), one of the strongest relationships evaluated. Exhaust temperature (R^2 = 0.0041) displayed a very weak relationship. However, exhaust relative humidity (R^2 = 0.0164) was the second strongest relationship for gestation barns. On its surface, the very weak relationship of exhaust temperature with emissions seems anomalous, given the published literature (noted in Section 7.0) that emissions should increase with increases in temperature. However, the temperature, especially in the farrowing room, varies within a relatively small range; there is limited variability in temperature compared to the emission rates. For the gestation barns, site NC4B appears to be masking a positive linear relationship with exhaust temperature. Figure E-7 shows separate linear regressions of exhaust temperature and NH_3 emissions for each site. Sites IA4B and OK4B show positive relationships with R^2 values of 0.3357 and 0.2512, respectively. However, NC4B has an R^2 value of 0.0007, basically no linear relationship. This R^2 value and graph suggest that the relationship for NC4A is not linear, but a possibly quadratic form.

Ambient temperature in farrowing rooms showed a very weak positive relation with NH_3 emission (R^2 = 0.0308), while ambient relative humidity demonstrated a weak negative relationship (R^2 = 0.1759). For gestation barns, the relationship between NH_3 emissions and ambient temperature was a very weak, slightly positive (R^2 = 0.0081), as was ambient relative humidity (R^2 = 0.0164). As with the exhaust parameters, the very weak relationships between temperature and emissions in the gestation barns seem to be the result of a non-linear relationship between NH_3 emissions and ambient temperature, particularly at NC4B (Figure E-9). IA4B and OK4B are both characterized by a positive linear relationship between NH_3 emissions and ambient temperature.

Based on this analysis and the analysis in Section 7.0, EPA selected live animal weight, inventory, ambient temperature, and exhaust temperature as parameters for EEM development for the farrowing and gestation barns.

8.1.2 Finishing Environmental and Activity Parameters

Figures E-10 through E-16 show the influence of inventory, live animal weight, exhaust temperature, air temperature, exhaust relative humidity, ambient relative humidity, and ventilation rate on NH_3 emissions at the two finishing sites. Table 8-3 presents the R^2 values for each parameter, sorted from highest to lowest, and the corresponding scatter plot figures, which appear in Appendix E.

Table 8-3. Linear regression summary of NH_3 emissions from finishing sites – environmental and activity parameters.

Parameter	Slope	R^2	Figure
Live animal weight	Positive	0.485	E-11
Ventilation rate	Positive	0.174	E-16
Animal inventory	Positive	0.052	E-10
Exhaust temperature	Positive	0.031	E-12
Exhaust relative humidity	Negative	0.009	E-14
Ambient relative humidity	Positive	0.002	E-15
Ambient temperature	Negative	0.002	E-13

The regression analysis indicated that live animal weight had a modest positive relationship with NH_3 emissions. EPA expected this correlation because live animal weight is a proxy for the amount of manure produced. Ventilation rate had a weak positive relationship with NH_3 emissions. This analysis suggests that production variables, particularly live animal weight, may have the largest influence on NH_3 emissions. Although not supported by the linear regression analysis, the information that EPA obtained from the literature suggests that ambient temperature should have a stronger correlation with emissions. Consequently, EPA considered the impact of temperature on emissions and conducted a rigorous statistical evaluation to identify explanatory factors for the emissions trend when viewed in conjunction with other parameters.

8.1.3 Breeding and Gestation Manure Parameters

To evaluate the influence of manure TAN concentration, TKN concentration, moisture content, and pH on NH_3 emissions, EPA used the average daily NH_3 emissions value for the day of the manure sample collection in the linear regression analysis. To facilitate identification of the potential influence of manure characteristics, particularly across different sites, EPA normalized the NH_3 emissions by live animal weight (i.e., [NH_3 emissions]/(inventory x average live animal weight)). Figures E-17 through E-19 show the influence of manure parameters on NH_3 emissions at the breeding and gestation sites. Table 8-4 presents the R^2 values for each parameter and the corresponding scatter plot figure.

Table 8-4. Linear regression summary of NH_3 emissions from breeding and gestation sites – manure parameters.

Parameter	Slope	R^2	Figure
pH (surface)	Positive	0.0072	E-19
TAN (surface)	Positive	0.0013	E-17
TKN (surface)	[a]		E-18

[a] EPA did not have sufficient TKN measurement data for surface manure samples from NAEMS to conduct a linear regression analysis.

The regression analysis identified very weak relationships between NH_3 emissions and the TAN in the surface samples, which suggests that NH_3 emissions are more strongly influenced by other factors at breeding and gestation barns. NAEMS analyzed only two surface samples for TKN concentration; therefore, EPA did not conduct a linear regression analysis for this small sample size. Also, the regression analysis identified weak relationships between NH_3 emissions and the pH values of surface samples.

The linear regression analysis conducted in this study suggests that NH_3 emissions from breeding and gestation barns are relatively constant with respect to the TAN, TKN, and pH of the manure. Additional analysis that could be done include exploring the relationship between different temporal averages of NH_3 emissions (e.g., weekly) and manure characteristics, which may yield more of a relationship. Based on the limited relationships identified by the regression analysis and limited number of sample values available, EPA did not include manure parameters in the EEM dataset.

8.1.4 Grow-Finish Manure Parameters

Figures E-20 through E-23 show the influence of manure parameters on NH_3 emissions at the grow-finishing sites. Table 8-5 presents the R^2 values for each parameter and the corresponding scatter plot figure. As with the breeding and gestation manure parameters, EPA normalized the average daily NH_3 emission for the corresponding day of the manure sample collection by the live animal weight to account for the difference in the volume of manure generated between the sites.

The regression analysis identified a very weak positive relationship between NH_3 emissions and TAN from all samples, a weak positive relationship in the surface samples, and a negligible negative relationship for the pit liquid samples. For TKN, the regression analysis found a weak positive relationship for all samples; weak positive relationships for the surface samples; and a weak negative relationship with the TKN in pit liquid samples and NH_3 emissions. For pH, the regression analysis identified a modest positive relationship with NH_3 emissions for all manure samples, a moderate positive relationship for the surface samples, and a weak positive relationship for pit liquid samples (NAEMS did not provide pH measurements for the loadout samples).

Table 8-5. Linear regression summary of NH_3 emissions from finishing sites – manure parameters.

Parameter	Slope	R^2	Figure
pH (surface)	Positive	0.5766	E-23
pH (all)	Positive	0.3995	E-23
TAN (all)	Positive	0.3228	E-20
TAN (surface)	Positive	0.292	E-20
pH (pit liquid)	Positive	0.1677	E-23
TKN (all)	Positive	0.1247	E-21
TKN (pit liquid)	Negative	0.1237	E-21
TKN (surface)	Positive	0.0849	E-21
TAN (pit liquid)	Negative	0.0295	E-20
Moisture content (surface)	Positive	0.0193	E-22

[a] NAEMS did not provide pH measurements for loadout manure samples.

The linear regression analysis conducted in this study suggests that NH_3 emissions from breeding and gestation barns generally have weak positive relationships with respect to TAN, TKN, moisture content, and pH of the manure. Based on the limited number of sample values available, EPA has elected to omit the manure parameters from the EEM dataset.

8.2 NH_3 Open Source Sites

Based on the process differences enumerated in the literature reviewed (Section 4.2), EPA decided to separate the lagoons from the basin for EEM analysis. The difference in management practices and animals between the both farm types suggests different relationships between the possible predictive parameters and the emissions, which is supported by literature.

8.2.1 Environmental and Activity Parameters

Figures E-24 through E-27 present the influence of air temperature, barometric pressure, relative humidity, and wind speed on NH_3 emissions at the five sites with lagoons. Figure E-28 presents the scatter plot for the basin data. Table 8-6 presents the R^2 values for each parameter and the corresponding scatter plot figure.

Table 8-6. Linear regression summary of NH_3 emissions from open source sites – environmental and activity parameters.

Source	Parameter	Slope	R^2	Figure
Lagoons	Ambient temperature	Positive	0.649	E-24
	Ambient pressure	Negative	0.2229	E-25
	Wind speed	Positive	0.1027	E-27
	Relative humidity	Negative	0.0349	E-26
Basin	Ambient temperature	Positive	0.6882	E-28
	Wind speed	Negative	0.2149	E-28
	Ambient pressure	Negative	0.1151	E-28
	Relative humidity	Flat	0.0001	E-28

The regressions analysis for lagoons identified a moderately strong positive relationship between NH_3 emissions and ambient temperature; weak negative relationships for ambient pressure and relative humidity; and a weak positive relationship for wind speed. EPA anticipated a stronger relationship between wind speed and NH_3 emissions. Ultimately, EPA included ambient temperature and wind speed in the EEM development dataset for lagoons. For the basin site, the regression analysis indicated a moderate positive relationship between NH_3 emissions and ambient temperature, while ambient pressure and wind speed displayed weak negative relationships with NH_3 emissions. Relative humidity showed no relationship with NH_3 emissions. Ultimately, EPA included ambient temperature and wind speed in EEM development for basins.

8.2.2 Manure Parameters

Figures E-29 through E-31 present the influence of temperature, oxidation reduction potential, and pH on NH_3 emissions at the five lagoon sites (NAEMS did not collect measurements for these parameters from basins). Table 8-7 presents the R^2 values for each parameter and the corresponding scatter plot figure.

Table 8-7. Linear regression summary of NH_3 emissions from open source sites – manure parameters.

Parameter	Slope	R^2	Figure
Lagoon temperature	Positive	0.5184	E-29
pH	Negative	0.0398	E-31
Oxidation reduction potential	Negative	0.0051	E-30

The regression analysis identified a moderate positive relationship between NH_3 emissions and lagoon temperature, while pH and oxidation reduction potential showed weak negative relationships with NH_3 emissions. Based on these results, EPA included lagoon temperature and pH in the EEM development dataset.

8.3 H_2S Confinement

8.3.1 Breeding and Gestation Environmental and Activity Parameters

Figures E-32 through E-45 present the scatter plots for H_2S emissions from breeding and gestation sites versus animal inventory, live animal weight, exhaust temperature, air temperature, exhaust relative humidity, ambient relative humidity, and airflow, respectively. Tables 8-8 and 8-9 present the R^2 values for each parameter and the corresponding scatter plot figure for farrowing and gestation sites, respectively.

Table 8-8. Linear regression summary of H_2S emissions from farrowing sites – environmental and activity parameters.

Parameter	Site	Slope	R^2	Figure
Animal inventory	OK4B	Negative	0.2418	E-32
	IA4B	Negative	0.0472	
	NC4B	Positive	0.0399	
	All	Negative	0.0216	
Live animal weight	OK4B	Positive	0.5834	E-33
	NC4B	Positive	0.1221	
	All	Flat	0.0002	
	IA4B	Flat	205E-7	
Cycle Day	OK4B	Positive	0.7798	E-34
	NC4B	Positive	0.4319	
	All	Positive	0.3028	
	IA4B	Positive	0.1248	
Exhaust temperature	IA4B	Positive	0.0919	E-35
	All	Positive	0.0337	
	OK4B	Negative	0.0051	
	NC4B	Flat	0.0001	
Exhaust relative humidity	IA4B	Positive	0.1913	E-36
	OK4B	Negative	0.0872	
	All	Positive	0.0273	
	NC4B	Positive	0.0087	
Ambient relative humidity	OK4B	Negative	0.0064	E-37
	NC4B	Positive	0.0038	
	IA4B	Positive	0.0013	
	All	Positive	0.0003	
Ventilation rate	IA4B	Positive	0.1941	E-38
	OK4B	Negative	0.0525	
	NC4B	Positive	0.0511	
	All	Positive	0.0215	
Ambient temperature	IA4B	Positive	0.1971	E-39
	OK4B	Negative	0.1313	
	All	Positive	0.0542	
	NC4B	Positive	0.0025	

Table 8-9. Linear regression summary of H_2S emissions from gestation sites – environmental and activity parameters.

Parameter	Site	Slope	R^2	Figure
Animal inventory	IA4B	Negative	0.0301	E-40
	NC4B	Positive	0.0185	
	OK4B	Positive	0.0153	
	All	Positive	0.0137	
Live animal weight	All	Positive	0.2803	E-41
	IA4B	Negative	0.0301	
	NC4B	Positive	0.0185	
	OK4B	Positive	0.0153	
Exhaust temperature	IA4B	Positive	0.1677	E-42
	All	Negative	0.0662	
	OK4B	Positive	0.0012	
	NC4B	Positive	0.0003	
Exhaust relative humidity	All	Positive	0.0078	E-43
	IA4B	Negative	0.0041	
	NC4B	Negative	0.0019	
	OK4B	Negative	0.0017	
Ventilation rate	IA4B	Positive	0.1405	E-44
	All	Positive	0.0274	
	NC4B	Positive	0.0051	
	OK4B	Positive	0.0014	
Ambient relative humidity	IA4B	Negative	0.0475	E-45
	All	Positive	0.0284	
	NC4B	Positive	0.0046	
	OK4B	Negative	0.0035	
Ambient temperature	IA4B	Positive	0.2287	E-46
	NC4B	Positive	0.0117	
	OK4B	Positive	0.0049	
	All	Negative	0.0037	

Overall, the relationships between the environmental parameters and H_2S emissions were weaker than observed for NH_3 emissions. Farrowing rooms had a weak negative relationship with inventory for all sites, with NC4B the only site that indicated the expected positive relationship (although the relationship was very weak). The regression analysis for gestation barns also showed similarly weak, but positive, relationship with inventory.

Across all the sites, the farrowing room had a weak positive relationship with cycle day. The individual site R^2 values were higher for NC4B and OK4B in particular. IA4B had a weak relationship, but still positive like the other sites and overall trends. The regression analysis showed little relationship between live animal weight and H_2S emissions from farrowing rooms, based on the combined site data. The lack of a relationship between live animal weight and H_2S emissions when using the combined dataset appears to be due to the cluster of high emission values at site IA4B, which results in an R^2 of 205E-7 for this site and masks any relationship when using the combined dataset. For gestation barns, the relationship between H_2S emissions and live animal weight is stronger than for farrowing rooms and the analysis indicates a positive relationship, as expected, because live animal weight is proportional to the volume of manure produced and, therefore, the amount of H_2S emissions produced. The low R^2 values for the relationships between inventory and live animal weight and the gestation barn H_2S emissions might be due to the relatively constant number of sows housed within the barn compared to the highly variable emissions measured at the site.

The overall relationship between exhaust temperature and H_2S emission in farrowing rooms and gestation barns is weak and positive. The individual site R^2 values were higher than the combined dataset at site IA4B. Site NC4B and OK4B showed less of a relationship for both farrowing room and gestation barns, as R^2 values dropped below 0.001 for both confinement types. As noted with NH_3, the temperature range, especially in the farrowing room, is confined to a relatively small range, with little variability, which leads to a negligible relationship between H_2S emissions. Similar to exhaust temperature, exhaust relative humidity for the farrowing room and gestation barns showed a negligible relationship, even when examined on a site by site basis.

The regression analysis identified weak relationships between H_2S emissions and ambient temperature and ventilation rate for farrowing rooms and gestation barns; however, site IA4B stands out from the other two sites with slightly larger R^2 values for these parameters. The scatter plot for the farrowing room at IA4B suggests a nonlinear form, which may account for the low R^2 value. Ambient relative humidity for farrowing rooms and gestation barns also showed very little relationship with H_2S emissions.

Given the limited relationships demonstrated in the analysis, EPA drew on the literature to select ambient temperature, exhaust temperature, live animal weight, and inventory for the EEM development dataset. These parameters are also consistent with those selected for NH_3, which provides consistency in the EEM development process.

8.3.2 Finishing Environmental and Activity Parameters

Figures E-47 through E-53 present the influence of inventory, live animal weight, exhaust temperature, air temperature, exhaust relative humidity, ambient relative humidity, and airflow on emissions at the two finishing sites, respectively. Table 8-10 presents the R^2 values for each parameter and the corresponding scatter plot figure for the grow-finishing sites.

Table 8-10. Linear regression summary of H2S emissions from finishing sites – environmental and activity parameters.

Parameter	Slope	R^2	Figure
Live animal weight	Positive	0.1342	E-48
Ventilation rate	Positive	0.0351	E-53
Ambient temperature	Negative	0.0171	E-50
Exhaust relative humidity	Negative	0.0133	E-51
Animal inventory	Positive	0.0127	E-47
Ambient relative humidity	Positive	0.0086	E-52
Exhaust temperature	Flat	0.0003	E-48

As with NH_3 emissions from finishing operations, the regression analysis identified live animal weight as having the strongest relationship to H_2S emissions with a slight positive slope. Ventilation rate had the second strongest relationship with H_2S emissions.

8.3.3 Breeding and Gestation Manure Parameters

Figure E-54 shows the scatter plot of daily H_2S emissions and the percent sulfur content of manure from the breeding and gestation barns. Overall, the percent sulfur content showed a weak negative relationship for the combined dataset. For site NC4B, the regression analysis shows a similar weak negative relationship. EPA did not conduct a regression analysis of manure sulfur content for sites IA4B and OK4B due to limited data. NAEMS collected two sulfur content samples for IA4B, and no samples for OK4B.

As with the NH_3 manure samples, additional analysis exploring the relationship between different temporal averages of H_2S emissions (e.g., weekly) and manure characteristics may yield more of a relationship and should be considered in any future analysis. Based on the limited relationship seen and limited number of sample values available, EPA determined it was too limited to provide insight that could be applied to all sites in the EEM process.

8.3.4 Finishing Manure Parameters

NAEMS did not analyze manure samples for sulfur content at the grow-finish sites. Therefore, EPA could not assess the relationship between H_2S emissions and manure sulfur content at the grow-finish sites.

8.4 H_2S Open Source Sites

Based on the difference in emissions levels (Section 7.1.3) and process variations that lead to these differences, as established in literature (Section 4.2), EPA decided to separate the lagoons from the basin for EEM analysis. The large difference in emissions generated between the source types suggests different relationships between the possible predictive parameters and the emissions.

8.4.1 Environmental and Activity Parameters

Figures E-55 through E-58 present the influence of air temperature, relative humidity, and wind speed on lagoon emissions at the five sites. Figure E-58 presents the influence of the environmental parameters on basin emissions. Table 8-11 presents the R^2 values for each parameter and the corresponding scatter plot figures for lagoons and the basin.

Table 8-11. Linear regression summary of H_2S emissions from open source sites – environmental and activity parameters.

Operation	Parameter	Slope	R^2	Figure
Lagoons	Wind speed	Positive	0.2485	E-57
	Ambient relative humidity	Negative	0.1661	E-56
	Ambient temperature	Flat	24E-6	E-55
Basin	Ambient temperature	Positive	0.2782	E-58
	Wind speed	Negative	0.0648	
	Ambient relative humidity	Positive	0.0003	

For lagoons, the regression analysis determined that wind speed had the strongest relationship with H_2S emissions. The strength of the relationship with relative humidity (0.1661) was comparable but suggested a negative relationship with H_2S emissions. The relationship with relative humidity is considerably higher than for ambient temperature (24E-6), which suggests less of a relationship than expected. However, EPA retained ambient temperature for consideration based on the literature (Section 4.2) and for consistency with NH_3 EEM development. EPA also included wind speed in the EEM development dataset.

For the basin site, the regression analysis found that air temperature had the strongest relationship with H_2S emissions. Barometric pressure and wind speed had weak negative relationships with H_2S emissions, and relative humidity showed no relationship with H_2S emissions. Consistent with the NH_3 findings and the lagoon source findings, EPA included ambient temperature and wind speed in EEM development dataset.

8.4.2 Manure Parameters

Figures E-59 through E-61 present the influence of lagoon temperature, oxidation reduction potential, and pH on H_2S emissions at the five lagoon sites. NAEMS did not collect manure parameter data from the basin site. Table 8-12 presents the R^2 values for each parameter and the corresponding scatter plot figures for lagoons and the basin.

Table 8-12. Linear regression summary of H_2S emissions from open source sites –manure parameters.

Parameter	Slope	R^2	Figure
Oxidation reduction potential	Negative	0.0643	E-60
pH	Negative	0.0372	E-61
Lagoon temperature	Negative	0.006	E-59

The regression analysis found weak negative relationships between H_2S emissions and oxidation reduction potential, pH, and lagoon temperature. However, EPA included lagoon temperature and pH in EEM development dataset to maintain consistency with the NH_3 model development.

8.5 PM Confinement Sites

In selecting the environmental and activity parameter variables for developing the EEMs for PM from confinement operations, EPA considered the strengths of the parameter relationships across all PM species. For selecting the manure parameter variables, EPA assessed the relationship to PM_{10} only, since PM_{10} represented approximately 80% of the collected particulate matter data, as noted in Section 2. The limited amount of TSP and $PM_{2.5}$ did not span all meteorological conditions and therefore limited the conclusions that could be drawn about the strength of relationships. However, the literature review (Section 4.3) indicated similar emission processes are responsible for the emission of TSP, PM_{10}, and $PM_{2.5}$. Therefore, the PM_{10} data analysis would be applicable to TSP and $PM_{2.5}$. The limited data for TSP and $PM_{2.5}$ were used to confirm this, to the extent possible.

8.5.1 Breeding and Gestation Environmental and Activity Parameters

Table 8-13 presents the R^2 values from the regression analysis, sorted from highest to lowest, and the corresponding scatter plot figure for each PM species for the following environmental and activity parameters: inventory, live animal weight, exhaust temperature, air temperature, exhaust relative humidity, ambient relative humidity, and ventilation rate.

For PM_{10}, the regression analysis found that cycle day had the strongest relationship to PM_{10} emissions, followed by live animal weight. Live animal weight values had a lower R^2 value than NH_3 and H_2S. EPA expected this correlation because live animal weight is a surrogate for the volume of manure generated. Exhaust relative humidity had the second highest R^2 with a weak negative relationship with PM_{10} emissions. The R^2 value for live animal weight was higher than for the temperature variables (0.0019 for air temperature and 0.0436 for exhaust temperature), ambient relative humidity (0.058), airflow (0.0347) and inventory (0.0541). Of note is the increase in the R^2 values associated with humidity variables.

Table 8-13. Linear regression summary of PM emissions from breeding and gestation sites – environmental and activity parameters.

PM Size	Operation	Parameter	Slope	R^2	Figure
PM_{10}	Farrowing	Cycle day	Positive	0.2934	E-65
		Live animal weight	Positive	0.0975	E-63
		Ambient relative humidity	Negative	0.058	E-68
		Animal inventory	Positive	0.0541	E-62
		Exhaust relative humidity	Negative	0.0376	E-66
		Ventilation rate	Positive	0.0347	E-69
		Exhaust temperature	Negative	0.0127	E-65
		Ambient temperature	Positive	0.0019	E-67
	Gestation	Live animal weight	Positive	0.1216	E-63
		Exhaust relative humidity	Negative	0.0822	E-66
		Exhaust temperature	Negative	0.0436	E-65
		Animal inventory	Positive	0.0403	E-62
		Ambient relative humidity	Negative	0.0299	E-68
		Ambient temperature	Negative	0.004	E-67
		Ventilation rate	Flat	0.0003	E-69
$PM_{2.5}$	Farrowing	Cycle day	Positive	0.2934	E-72
		Ventilation rate	Positive	0.2576	E-77
		Live animal weight	Positive	0.1065	E-71
		Exhaust temperature	Positive	0.0764	E-73
		Animal inventory	Positive	0.0467	E-70
		Exhaust relative humidity	Negative	0.0343	E-74
		Ambient relative humidity	Negative	0.0129	E-76
		Ambient temperature	Positive	0.0006	E-75
	Gestation	Exhaust temperature	Negative	0.0556	E-73
		Live animal weight	Positive	0.0321	E-71
		Exhaust relative humidity	Positive	0.0289	E-74
		Ambient temperature	Negative	0.0189	E-75
		Ambient relative humidity	Positive	0.0131	E-76
		Ventilation rate	Negative	0.0038	E-77
		Animal inventory	Flat	0.0005	E-70
TSP	Farrowing	Cycle day	Positive	0.3541	E-80
		Exhaust relative humidity	Negative	0.1968	E-82
		Ambient relative humidity	Negative	0.1916	E-84
		Exhaust temperature	Negative	0.0708	E-81
		Live animal weight	Positive	0.0663	E-79
		Animal inventory	Positive	0.0179	E-78
		Ambient temperature	Negative	0.0155	E-83
		Ventilation rate	Flat	174E-7	E-85
	Gestation	Exhaust relative humidity	Negative	0.2726	E-82
		Ventilation rate	Negative	0.1738	E-85
		Exhaust temperature	Negative	0.1656	E-81
		Live animal weight	Positive	0.1432	E-79
		Ambient temperature	Negative	0.1206	E-83
		Animal inventory	Positive	0.0493	E-78
		Ambient relative humidity	Negative	0.0182	E-84

For $PM_{2.5}$, the regression analysis identified that cycle day had the strongest relationship to $PM_{2.5}$ emissions for the farrowing rooms, followed by ventilation rate and live animal weight. For the gestation barns, exhaust temperature had the strongest relationship, followed by live animal weight. The regression analysis did not find strong relationships between $PM_{2.5}$ emissions and the inventory, temperature, or humidity variables for either the farrowing rooms or gestation barns.

For TSP, the cycle day had the highest R^2 value for the farrowing rooms (0.3541). Cycle day was followed by both humidity parameters, which had weak negative relationships with TSP. For the gestation barns, exhaust relative humidity had the highest R^2 value (0.2726) across all the parameters examined. In the gestation barns, the R^2 value for exhaust relative humidity was higher than temperature variables (0.1206 for air temperature and 0.1656 for exhaust temperature), ventilation rate (0.1738), inventory (0.0452), and live animal weight (0.183). For the farrowing rooms ambient relative humidity had the second highest R^2 value (0.1916), with a weak negative relationship with TSP emissions. The remaining parameters did not have strong relationships with TSP emissions.

Based on the literature review (Section 4.3) and the strength of the relationship seen across the three species of PM, particularly for PM_{10}. EPA opted to test models that included various combinations of inventory, live animal weight, ambient temperature, and ambient relative humidity.

8.5.2 Finishing Environmental and Activity Parameters

Table 8-14 presents the R^2 values from the regression analysis, sorted from highest to lowest, and the corresponding scatter plot figure for each PM species for the following environmental and activity parameters: inventory, live animal weight, exhaust temperature, air temperature, exhaust relative humidity, ambient relative humidity, and ventilation rate.

For PM_{10}, the R^2 values for live animal weight (0.2192) were the highest of the parameters and indicate a slight positive relationship between PM_{10} emissions and live animal weight. It is substantially lower R^2 value than was seen with NH_3, but higher than with H_2S. The correlation is not unexpected as live animal weight is a suitable surrogate for the volume of manure that would be generated. The R^2 value for live animal weight was higher than for the temperature variables (0.004 for air temperature and 0.0126 for exhaust temperature), relative humidity (0.0697 for ambient relative humidity and 0.0919 for exhaust relative humidity), and inventory (0.027). Airflow had the second highest R^2 value at 0.1124, with a weak positive relationship with PM_{10} emissions. Of note is the increase in the R^2 values associated with the humidity variables.

Table 8-14. Linear regression summary of PM emissions from finishing sites – environmental and activity parameters.

PM Size Cut	Parameter	Slope	R^2	Figure
PM_{10}	Live animal weight	Positive	0.2192	E-87
	Ventilation rate	Positive	0.1128	E-92
	Exhaust relative humidity	Negative	0.0919	E-90
	Ambient relative humidity	Negative	0.0697	E-91
	Animal inventory	Positive	0.0271	E-86
	Exhaust temperature	Positive	0.0126	E-85
	Ambient temperature	Positive	0.004	E-89
$PM_{2.5}$	Live animal weight	Positive	0.2247	E-94
	Animal inventory	Negative	0.0808	E-93
	Exhaust relative humidity	Positive	0.0635	E-97
	Ventilation rate	Positive	0.0181	E-99
	Ambient relative humidity	Positive	0.0157	E-98
	Exhaust temperature	Negative	0.0132	E-95
	Ambient temperature	Negative	0.0034	E-96
TSP	Animal inventory	Positive	0.4593	E-100
	Exhaust relative humidity	Negative	0.3867	E-103
	Live animal weight	Positive	0.1825	E-101
	Ambient relative humidity	Negative	0.1154	E-105
	Ventilation rate	Positive	0.0494	E-106
	Ambient temperature	Negative	0.0234	E-104
	Exhaust temperature	Negative	0.0135	E-102

For $PM_{2.5}$, live animal weight again had the highest R^2 (0.2247) across all the parameters examined. The R^2 value for live animal weight was higher than for the temperature variables (0.0034 for air temperature and 0.0132 for exhaust temperature), relative humidity (0.0157 for ambient relative humidity and 0.0635 for exhaust relative humidity), airflow (0.0181), and inventory (0.081). Exhaust relative humidity had the second highest R^2 value, with a weak negative relationship with $PM_{2.5}$ emissions. Looking at the separate farm plots, there is a difference between the two farms in their $PM_{2.5}$ trends. This is possibly due to the negative emission values at IN3B. These negative values occur under conditions of high inventory and low weight (e.g., early in the cycle), while there are high ambient and exhaust temperatures as well as high airflow rates.

For TSP, inventory had the highest R^2 (0.459) across all the parameters examined. The r2 value for live animal weight was higher than for the temperature variables (0.0234 for air temperature and 0.0135 for exhaust temperature), relative humidity (0.1154 for ambient relative humidity and 0.3867 for exhaust relative humidity), airflow (0.0452), and live animal weight (0.183). Exhaust relative humidity had the second highest R^2 value, with a weak negative relationship with TSP emissions.

Based on the literature review (Section 4.3) and the strength of the relationship seen across the three species of PM, particularly for PM_{10}, EPA opted to test models that included various combinations of inventory, live animal weight, ambient temperature, and ambient relative humidity.

8.5.3 Manure Parameters

EPA conducted regression analyses to determine the extent of a relationship between PM_{10} emissions and the solids content of the manure samples from breeding-gestation and the finishing operations. Table 8-15 presents the R^2 values from the regressions and the corresponding figure for each operation.

Table 8-15. Linear regression summary of PM emissions – manure parameters.

Operation	Sample	Slope	R^2	Figure
Breeding and gestation	Loadout	Negative	0.0898	E-107
	Surface	Negative	0.0483	
Finishing	Loadout	Positive	0.5915	E-108
	Surface	Positive	0.4399	
	Pit liquid	Negative	0.0011	

For the breeding and gestation sites, the loadout and surface samples showed a weak negative relationship. Intuitively, a higher solids content should correspond to a lower moisture content, which should contribute to higher particulate emissions. One loadout sample with high emissions and a low solids content is apparently an outlier that is driving the negative relationship. Similarly, in the surface samples, a few samples with low solids content, but with high emissions seem to be driving the trend. Additional analysis exploring the relationship between different temporal averages of PM_{10} emissions (e.g., weekly) and manure characteristics may yield a more robust relationship. Because of the limited relationship seen and the limited number of sample values available, EPA decided to omit the solids content data from the particulate matter EEM dataset.

Overall, the samples for the finishing sites showed a weak positive relationship across all sample types. However, when separating the data based on sample type, loadout samples and surface samples showed a moderate positive relationship between solids content and PM_{10} emissions. The pit liquid showed virtually no relationship. Unfortunately, the limited number of sample values available limits how the data could be used during EEM development. That is, including them in the EEM development dataset would limit the number of complete observations available. Additionally, this type of manure analysis is not regularly conducted at farms and would require sampling by the producer. For these reasons, EPA did not include the manure solids content in the EEM development dataset for PM.

9.0 DEVELOPMENT AND SELECTION OF MODELS FOR DAILY EMISSIONS

9.1 Model Development Process for Daily Emissions

EPA developed a linear mixed effects model (SAS version 9.4, Proc Mixed, SAS®) to estimate average daily emissions at swine operations by determining the effect of predictor variables on pollutant emissions. An advantage of using mixed models over standard linear models is that they allow for correlated errors, meaning that the mixed models can account for correlation among successive measurements. In this study, EPA accounted for correlation among successive measurements from each barn using a repeated variance spatial power covariance structure [Proc mixed SAS option: repeated day /subject=house type=sp(pow) day]. This covariance structure can be used when time intervals are not evenly spaced, which was a common occurrence in the NAEMS dataset due to missing data.

For modeling, all emissions were natural log transformed. To help with the log transformation, a constant (C) was added to the emission values of some EEMs (i.e., the same constant value was applied to all emission values within an individual EEM) before log transformation to make all emissions values positive and/or not close to zero. This constant was subtracted from predicted emissions after back-transformation (see section 9.3). To avoid having several orders of magnitude difference between predictor variables, which can cause model convergence, units for live animal weight and inventory were changed to Mg and thousands, respectively. EPA′s objective was to develop multiple models to predict average emissions in kg per day or grams per day, based on different combinations of the predictor variables (e.g., inventory, live animal weight, ambient temperature, and exhaust temperature) and then to evaluate the models based on their performance and how easily a producer could obtain measurements of the predictor values. When setting the combinations of the predictor variables to include, EPA often performed a pairwise correlation analysis to screen for predictor variables that might have a strong relationship to one another or could be linearly predicted from another variable. For example, correlation analysis found that live animal weight and inventory were highly correlated, which was expected because live animal weight is a function of inventory and average weight. Including related predictor variables in a multivariate regression can cause the estimates of the coefficient to change erratically in response to small changes in the data (e.g., when outliers are removed, or during model validation testing). Having related parameters as predictor variables does not affect how well the model can predict observations but can cloud the importance of any individual predictor. For this reason, strongly correlated parameters, such as live animal weight and inventory, were generally not included in the same model (except in some testing instances). Parameters with moderate correlations were used simultaneously in models because their interaction could be indicative of management practices. For example, the interaction of ambient temperature (an ambient parameter) and exhaust temperature (a barn parameter) could be informative of barn management practices.

For the particulate matter species (i.e., TSP, PM_{10}, and $PM_{2.5}$), EEM development started with the PM_{10} analysis, because, as noted in Section 2, PM_{10} measurements were the majority of particulate matter measurements taken over the course of the study. The PM_{10} dataset covered a broader set of meteorological and barn conditions. EPA considered how to ensure the more limited TSP and $PM_{2.5}$ datasets were still consistent with a broad range of conditions. For TSP, the literature review (Section 4.3) indicated similar emission processes responsible for the emission of both TSP and PM_{10}. Therefore, the parameters that influence PM_{10} should be similar to those that influence TSP, and a model that performs well for PM_{10} should also perform well for TSP. Therefore, the results for the PM_{10} analysis were considered when selecting a TSP model, giving preference to a model similar to one for PM_{10}, if all other parameters were equal.

Similarly, literature indicated that the processes for primary $PM_{2.5}$ in the barns would be similar to those for PM_{10}. $PM_{2.5}$ could be complicated by consideration of secondary formation via chemical reactions. However, literature indicates that the formation of secondary $PM_{2.5}$ within the barns is probably minimal. EPA decided to consider the results for the PM_{10} analysis when selecting a $PM_{2.5}$ model, with preference given to models that included the same parameters, if evaluation statistics did not suggest otherwise.

EPA regressed the included predictor variables against natural log transformed average daily emissions, developed separate regressions for all combinations of the parameters, and eliminated from further consideration combinations that included insignificant predictors (p-value < 0.05).

9.2 Model Fit Statistics

EPA assessed the fit of each model by preparing the residual diagnostic plots and used the following statistics to evaluate the predictiveness and effectiveness of the fitted models: Negative Twice the Likelihood (-2LogL), Akaike Information Criterion (AIC), Adjusted Akaike Information Criterion (AICc) for number of predictors, and Schwarz Bayesian Information Criterion (BIC).

Like the p-values, EPA calculated the values for -2LogL, AIC, AICc, and BIC from the "likelihood function" of an EEM, which quantifies the probabilities that different sets of parameter values will reproduce the emissions in NAEMS data. "Fitting the EEM" refers to finding the parameter estimates that maximize the likelihood function, or, finding the values of the parameters that account for the most variability in NAEMS data. Minimizing the function that is equal to -2LogL is mathematically equivalent to maximizing the likelihood, and the required computations take less time to perform. When comparing the values of -2LogL for two different EEMs, the model with the lower -2LogL value provides better fit to the data.

The equations below define the formulas for AIC, AICc, and BIC, where *d* is the number of model parameters and *n* is the sample size:

$$AIC = -2LogL + 2d \qquad \textit{Equation 1}$$

$$AICc = -2LogL + 2d\left(\frac{n}{n-d-1}\right) \qquad \textit{Equation 2}$$

$$BIC = -2LogL + \ln(n)\, d \qquad \textit{Equation 3}$$

All three criteria are functions of -2LogL, with an added term that penalizes inefficient models and models that achieve overfitting by adding more parameters. The equation for AIC is the simplest approach; the added penalty is twice the number of parameters used in the model (2*d*). The AICc and BIC statistics refine this approach by considering the overall sample size with respect to the number of parameters used in the model. AICc is generally considered the better statistic for small sample sizes. For all of these criteria, lower values indicate better performance of the model being evaluated relative to other models. EPA focused on AICc to compare, rank, and select models that best explained the variation in NAEMS data, while penalizing candidate models that included greater numbers of predictors (Christensen et al., 2014).

9.3 Model Evaluation Statistics

EPA evaluated agreement between log-transformed observed emissions and model-predicted emissions using the following equation for log-transformed normalized mean error (LNME):

$$LNME = \frac{\sum |Y_p - Y_{lo}|}{\sum Y_o} \times 100\% \qquad \text{Equation 4}$$

Where:

Y_{lo} is the log transformed observed (or measured) emissions.
Y_p is the model predicted (log transformed) emissions.
Y_o is the observed (or measured) emission.

EPA assessed the agreement between the observed and predicted (back transformed from log) emissions for mean error (ME) and normalized mean error (NME) (defined below), which researchers have previously used in the evaluation of atmospheric and emission models (Walker et al., 2014; Rumsey and Aneja, 2014).

$$ME = \frac{\sum |Y_{bp} - Y_o|}{n} \qquad \textit{Equation 5}$$

$$NME = \frac{\sum |Y_{bp} - Y_o|}{\sum Y_o} \times 100\% \qquad \textit{Equation 6}$$

where Y_o is the observed (or measured) emission, n is the number of measurements, and Y_{bp} is the back transformed model-predicted log emission, using the following equation:

$$Y_{bp} = e^{\widehat{(y_p)}} * \left(\frac{\sum e^{e_i}}{n}\right) - C \qquad \textit{Equation 7}$$

Where:

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

The variable e_i includes an adjustment for bias associated with the log back-transformation (Newman, 1993). All EEMs expressed emissions as log transformed values. For back-transformed model-predicted emissions, Equation 5 should be used after the EEM calculations. The values of e_i and C for each EEM developed are provided in Section 12, along with an example calculation.

EPA assessed the agreement between the observed and predicted (back transformed from log) emissions for mean bias (MB) and normalized mean bias (NMB) using the following equations:

$$MB = \frac{\sum (Y_{bp} - Y_o)}{n} \qquad \text{Equation 8}$$

$$NMB = \frac{\sum (Y_{bp} - Y_o)}{\sum Y_o} \times 100\% \qquad \text{Equation 9}$$

To further evaluate the model fit, EPA developed scatter plots of the observed emissions versus the EEM predicted emissions. The plots include the one-to-one (1:1) line. Points that fall on the 1:1 line were predicted perfectly by the EEM. Points above the line indicates over predictions by the EEM (positive bias) and those below were under predicted by the model (negative bias). Plots for all the model ae included in Appendix F.

9.4 Daily Emissions Estimation Method Results and Discussion

9.4.1 Breeding and Gestation Operations

The exploratory data analysis suggested that EPA should consider ambient temperature, exhaust temperature, inventory, and live animal weight in the development of the EEMs for the breeding and gestation barns. As noted in the emissions trends section (Section 7.0) and the exploratory data analysis (Section 8.0) 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 emission 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 emission levels and trends (see Section 7.0) 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.

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 emission 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.

9.4.1.1 NH_3 Model Results and Evaluation

Table 9-1 and Table 9-2 present the parameters, estimates, and fit and evaluation statistics for the farrowing barn NH_3 models. Scatter plots of the observed emissions versus the EEM predicted values are in Figure F-1. EPA developed six different models with different combinations of the four predictor variables—ambient temperature, exhaust temperature, inventory, and live animal weight. Models 1, 2, 5, and 6 had coefficients that were not significant ($p > 0.05$); those coefficients are in boldface in Table 9-1. For models 3 and 4, EPA found a significant positive correlation between NH_3 emissions and live animal weight, meaning that as inventory or live animal weight increase, so do NH_3 emissions (see Table 9-2). EPA expected this positive relationship because live animal weight 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 9-2 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 live animal weight, 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:

$$Farrowing, ln(NH_3) = 0.6888 + 0.0020 * cycleday + 0.0006 * Amb_T + 0.0084 * LAW \quad \text{Equation 10}$$

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

Table 9-1. Parameters and estimates for the Farrowing barn NH_3 models tested.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	0.619374	0.04527	<.0001
	Cycleday	0.002028	0.00084	0.017
	AmbT	0.00017	0.00035	**0.6266**
	ExhT	0.003027	0.00175	**0.084**
	LAW	0.00805	0.00187	<.0001
2	Intercept	0.634065	0.04378	<.0001
	Cycleday	0.002188	0.00069	0.0018
	AmbT	0.00006	0.00035	**0.8659**
	ExhT	0.003527	0.00173	0.0422
	Inv	0.03089	0.04146	**0.4566**
3	Intercept	0.607334	0.02146	<.0001
	Cycleday	0.001882	0.00056	0.0011
	ExhT	0.003658	0.00073	<.0001
	LAW	0.007369	0.00169	<.0001
4	Intercept	0.68875	0.01775	<.0001
	Cycleday	0.001961	0.0008	0.0157
	AmbT	0.000581	0.00029	0.0449
	LAW	0.008405	0.00154	<.0001
5	Intercept	0.627724	0.02043	<.0001
	Cycleday	0.002053	0.0005	<.0001
	ExhT	0.003771	0.00069	<.0001
	Inv	0.028189	0.03115	**0.3658**
6	Intercept	0.713155	0.01572	<.0001
	Cycleday	0.002087	0.0007	0.0035
	AmbT	0.00054	0.00029	**0.0596**
	Inv	0.049431	0.03829	**0.1972**

Table 9-2. Fit and evaluation statistics for the Farrowing barn NH_3 models tested.

Model	2LogL	AIC	AICc	BIC	Corr.	LNME[a] (%)	NME[b] (%)	ME[b] (kg day^{-1})	MB[b] (kg day^{-1})	NMB[b] (%)
1	-5975	-5953	-5953	-5926	0.429	9.305	57.162	0.174	-0.0009	-0.303
2	-5948	-5926	-5926	-5899	0.227	10.195	59.898	0.182	-0.0002	-0.078
3	-6698	-6678	-6678	-6653	0.412	9.215	60.058	0.175	-0.0009	-0.291
4	-6010	-5990	-5990	-5965	0.503	9.086	55.927	0.169	-0.0012	-0.392
5	-6673	-6653	-6653	-6628	0.215	9.971	62.692	0.182	-0.0002	-0.073
6	-5973	-5953	-5953	-5928	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 live animal weight. EPA also tested two versions of these models, one that did not distinguish between the type of manure pit used in the barn (“no pit model”; Tables 9-3 and 9-4, Figure F-9) and one that did (“pit model”; Tables 9-5 and 9-6, Figure F-10).

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 (live animal weight and inventory) correlated positively with NH_3 emissions, as well as with the temperature variables (Table9-3).

Table 9-4 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 statistics and model evaluation statistics. Therefore, when selecting the model for further analysis, EPA considered the potential ease of use and concluded that ambient temperature and would be potentially easier to obtain than exhaust temperature. Therefore, EPA selected model 4 for further analysis. Model 4 is as follows:

$$Gestation\ Barn, No\ Pit: ln(y_p) = 0.7844 + 0.0056 * Amb_T\ + 0.0073 * LAW \qquad Equation\ 11$$

Where:

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

Table 9-3. Parameters and estimates for the no pit Gestation barn NH_3 models tested.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	-0.124019	0.14725	**0.4013**
	AmbT	0.003627	0.00112	0.0012
	ExhT	0.012324	0.00365	0.0007
	LAW	0.009382	0.00052	<.0001
2	Intercept	-0.571962	0.21034	0.0078
	AmbT	0.003585	0.00108	0.0009
	ExhT	0.012258	0.00346	0.0004
	Inv	2.256826	0.1715	<.0001
3	Intercept	-0.380329	0.1093	0.0007
	ExhT	0.024796	0.00174	<.0001
	LAW	0.009566	0.00042	<.0001
4	Intercept	0.154785	0.11861	**0.1972**
	AmbT	0.006855	0.00055	<.0001
	LAW	0.009122	0.00051	<.0001
5	Intercept	-0.887715	0.15215	<.0001
	ExhT	0.02473	0.00165	<.0001
	Inv	2.343046	0.1268	<.0001
6	Intercept	-0.266956	0.19692	**0.1811**
	AmbT	0.00678	0.00052	<.0001
	Inv	2.18221	0.16987	<.0001

Table 9-4. Fit and evaluation statistics for the no pit Gestation barn NH_3 models tested.

Model	-2LogL	AIC	AICc	BIC	Corr.	LNME[a] (%)	NME[b] (%)	ME[b] (kg day^{-1})	MB[b] (kg day^{-1})	NMB[b] (%)
1	-2851	-2819	-2819	-2823	0.738	12.528	36.917	4.783	-0.655	-5.056
2	-2825	-2793	-2793	-2796	0.383	16.686	54.764	7.096	0.369	2.846
3	-3006	-2976	-2976	-2979	0.747	12.755	36.748	4.653	-0.655	-5.169
4	-2841	-2811	-2811	-2815	0.739	12.461	36.699	4.755	-0.652	-5.033
5	-2980	-2950	-2950	-2953	0.395	17.12	55.258	6.996	0.386	3.052
6	-2816	-2786	-2785	-2789	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 9-5). As with the other NH_3 models, the parameters have a significant positive relationship with NH_3 emissions, which is consistent with literature.

Table 9-6 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:

$$Gestation\ Barn, Shallow\ Pit: ln(y_p) = 0.3075 + 0.0118 * Amb_T + 0.0079 * LAW \quad \text{Equation 12}$$

$$Gestation\ Barn, Deep\ Pit: ln(y_p) = 0.8348 + 0.0118 * Amb_T + 0.0079 * LAW \quad \text{Equation 13}$$

Where:

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

Amb_T = ambient temperature in ^oC.

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

Table 9-5. Parameters and estimates for the pit Gestation barn NH_3 models tested.

Model	Parameter	Estimate	Standard Error	p-value
1	Deep	0.820119	0.2827	0.0045
	Shallow	0.290714	0.23005	**0.2084**
	AmbT	0.011567	0.00157	<.0001
	ExhT	0.000783	0.00489	**0.8726**
	LAW	0.007912	0.001	<.0001
2	Deep	0.837378	0.28892	0.0045
	Shallow	-0.156823	0.29033	**0.59**
	AmbT	0.011558	0.00157	<.0001
	ExhT	0.000673	0.00489	**0.8905**
	Inv	1.95569	0.25514	<.0001
3	Deep	0.160772	0.24154	**0.507**
	Shallow	-0.447705	0.18902	0.0193
	ExhT	0.037453	0.00257	<.0001
	LAW	0.008436	0.00087	<.0001
4	Deep	0.834777	0.26817	0.0025
	Shallow	0.30747	0.20558	**0.1382**
	AmbT	0.011778	0.00085	<.0001
	LAW	0.007899	0.001	<.0001
5	Deep	0.145302	0.24822	**0.5594**
	Shallow	-0.95979	0.24429	0.0001
	ExhT	0.03733	0.00258	<.0001
	Inv	2.117453	0.22432	<.0001
6	Deep	0.850101	0.27458	0.0026
	Shallow	-0.141677	0.26961	**0.6004**
	AmbT	0.011739	0.00085	<.0001
	Inv	1.952928	0.25467	<.0001

Table 9-6. Fit and evaluation statistics for the pit Gestation barn NH_3 models tested.

Model	2LogL	AIC	AICc	BIC	Corr.	LNME[a] (%)	NME[b] (%)	ME[b] (kg day^{-1})	MB[b] (kg day^{-1})	NMB[b] (%)
1	-2009	-1995	-1995	-1996	0.779	11.615	31.179	4.040	-0.361	-2.787
2	-2007	-1993	-1992	-1994	0.776	11.713	31.257	4.050	-0.373	-2.877
3	-2046	-2034	-2034	-2035	0.796	11.458	30.499	3.862	-0.306	-2.415
4	-2009	-1997	-1997	-1998	0.779	11.622	31.205	4.043	-0.361	-2.786
5	-2044	-2032	-2032	-2033	0.794	11.521	30.563	3.870	-0.314	-2.482
6	-2007	-1995	-1994	-1996	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.

9.4.1.2 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 live animal weight. All models, except model 7, had at least one coefficient that was insignificant ($p > 0.05$); these are in boldface in Table 9-7. Model 7 included only live animal weight and cycle day as parameters, both of which correlated positively with NH_3 emissions.

Table 9-8 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. Scatter plots of the observed emissions versus the EEM predicted values are in Figure F-2.

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:

$$Farrowing\ room,\ ln(H_2S) = 2.1423 + 0.1298 * cycleday + 0.0614 * LAW \qquad \text{Equation 14}$$

Where:

$ln(H_2S)$ = 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 9-7. Parameters and estimates for the farrowing barn H_2S models developed.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	1.696616	0.4	<.0001
	cycleday	0.128162	0.00595	<.0001
	AmbT	0.002557	0.0033	0.4392
	ExhT	0.009579	0.01667	0.5657
	LAW	0.091992	0.01932	<.0001
2	Intercept	1.998359	0.40565	<.0001
	cycleday	0.12883	0.00574	<.0001
	AmbT	0.001747	0.0033	0.5971
	ExhT	0.016646	0.01666	0.3179
	Inv	0.181305	0.39501	0.6463
3	Intercept	1.599675	0.33031	<.0001
	cycleday	0.128651	0.00561	<.0001
	ExhT	0.018381	0.01242	0.1393
	LAW	0.080834	0.0186	<.0001
4	Intercept	2.030664	0.13947	<.0001
	cycleday	0.128944	0.0059	<.0001
	AmbT	0.003998	0.00256	0.1184
	LAW	0.0684	0.01688	<.0001
5	Intercept	1.923371	0.33545	<.0001
	cycleday	0.129496	0.00554	<.0001
	ExhT	0.021562	0.01243	0.0831
	Inv	0.123177	0.38741	0.7506
6	Intercept	2.393581	0.13808	<.0001
	cycleday	0.128682	0.00575	<.0001
	AmbT	0.003897	0.00255	0.1264
	Inv	0.089971	0.3678	0.8068
7	Intercept	2.142329	0.12728	<.0001
	cycleday	0.129797	0.00562	<.0001
	LAW	0.061406	0.01641	0.0002

Table 9-8. 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	1346	1368	1369	1396	0.592	20.071	70.091	72.624	19.724	19.036
2	1372	1394	1394	1421	0.613	19.663	69.993	72.644	19.193	18.492
3	1473	1493	1494	1519	0.602	19.626	68.944	72.316	18.900	18.019
4	1386	1406	1406	1430	0.600	19.946	69.932	72.382	19.485	18.826
5	1496	1516	1516	1541	0.622	19.264	69.283	72.779	18.945	18.035
6	1406	1426	1426	1451	0.612	19.712	70.892	73.497	20.170	19.455
7	1516	1534	1534	1556	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 live animal weight. Again, EPA tested two sets of models, one that did not distinguish between the type of pit ("no pit model"; Table 9-9, Figure F-11) and one that did ("pit model"; Table 9-11, Figure F-12).

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 9-9). Table 9-10 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:

$$Gestation\ Barns, No\ Pit: ln(H_2S) = 2.0773 + 0.0035 * Amb_T + 0.0199 * LAW \qquad \text{Equation 15}$$

Where:

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

Table 9-9. 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	<.0001
	AmbT	0.006591	0.00213	0.002
	ExhT	-0.01153	0.00705	0.1021
	LAW	0.01961	0.00055	<.0001
2	Intercept	1.049288	0.22272	<.0001
	AmbT	0.006192	0.00209	0.003
	ExhT	-0.01059	0.00688	0.1236
	Inv	5.007765	0.14404	<.0001
3	Intercept	2.079784	0.14511	<.0001
	ExhT	0.007943	0.00315	0.0119
	LAW	0.019339	0.0005	<.0001
4	Intercept	2.077258	0.12093	<.0001
	AmbT	0.003547	0.00098	0.0003
	LAW	0.019862	0.00053	<.0001
5	Intercept	0.803968	0.17442	<.0001
	ExhT	0.007805	0.0031	0.012
	Inv	4.955695	0.1336	<.0001
6	Intercept	0.788813	0.16547	<.0001
	AmbT	0.003397	0.00097	0.0005
	Inv	5.070146	0.14418	<.0001

Table 9-10. 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	1241	1273	1273	1270	0.851	8.682	68.727	1580.5	-520.1	-22.62
2	1265	1297	1297	1293	0.467	13.124	123.96	2850.6	389.82	16.95
3	1556	1586	1586	1583	0.847	9.004	69.458	1523.2	-518.7	-23.65
4	1244	1274	1274	1271	0.848	8.792	69.332	1594.4	-514.8	-22.39
5	1575	1605	1605	1602	0.471	13.201	124.38	2727.6	343.1	15.65
6	1267	1297	1297	1293	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 9-11). As with the NH_3 models, the parameters had significant positive correlations with H_2S emissions.

Table 9-12 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:

$$Gestation\ Barn,\ \ Shallow\ Pit: ln(H_2S) = 2.1305 + 0.0038 * Amb_T\ + 0.0196 * LAW \qquad \text{Equation 16}$$

$$Gestation\ Barn,\ \ Deep\ Pit: ln(H_2S) = 3.1785 + 0.0038 * Amb_T\ + 0.0196 * LAW \qquad \text{Equation 17}$$

Where:

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

Table 9-11. 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	<.0001
	Shallow	2.320599	0.20474	<.0001
	AmbT	0.006075	0.00218	0.0053
	ExhT	-0.00839	0.00728	0.2491
	LAW	0.019413	0.00056	<.0001
2	Deep	3.16381	0.21225	<.0001
	Shallow	1.015716	0.23834	<.0001
	AmbT	0.005911	0.00218	0.0069
	ExhT	-0.00832	0.0073	0.254
	Inv	4.996525	0.14574	<.0001
3	Deep	3.163799	0.1596	<.0001
	Shallow	2.094309	0.14531	<.0001
	ExhT	0.009296	0.00319	0.0037
	LAW	0.01913	0.00051	<.0001
4	Deep	3.171852	0.1471	<.0001
	Shallow	2.130472	0.12289	<.0001
	AmbT	0.003844	0.00098	0.0001
	LAW	0.019592	0.00054	<.0001
5	Deep	2.975309	0.16444	<.0001
	Shallow	0.797081	0.17776	<.0001
	ExhT	0.008994	0.0032	0.0051
	Inv	4.938084	0.13301	<.0001
6	Deep	2.990124	0.15311	<.0001
	Shallow	0.813576	0.16124	<.0001
	AmbT	0.003696	0.00099	0.0002
	Inv	5.043545	0.14044	<.0001

Table 9-12. 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	1197	1231	1231	1227	0.913	6.079	50.904	1170.6	-241.9	-10.52
2	1208	1242	1242	1238	0.911	6.134	51.24	1178.4	-245.6	-10.68
3	1509	1541	1542	1538	0.912	6.258	50.252	1102	-233.6	-10.65
4	1198	1230	1230	1227	0.913	6.078	50.681	1165.5	-241.1	-10.49
5	1517	1549	1550	1546	0.91	6.302	50.592	1109.4	-238	-10.85
6	1209	1241	1241	1237	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.

9.4.1.3 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 live animal weight. Models 4 and 7 each had at least one coefficient that was insignificant ($p > 0.05$); these are in boldface in Table 9-13. Overall, ambient relative humidity and exhaust relative humidity had a negative correlation with PM_{10} concentration. This was expected, as the literature review (Section 4) 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 9-15 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 the 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:

$$Farrowing\ room, ln(\mathrm{PM}_{10}) = 2.490 + 0.0558 * cycleday\ + 0.1063 * LAW - 0.0034\ Amb_{RH} \quad \text{Equation 18}$$

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 live animal weight). 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 tested (see Table 9-16, Figures F-13 and F-14). Table 9-17 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:

$$Gestation\ barns, ln(PM_{10}) = 5.1868 - 0.0078 * Amb_{RH} + 0.0055 * LAW \qquad \text{Equation 19}$$

Where:

ln(PM10) = the natural log transformed predicted PM_{10} emissions in grams per day (g day^{-1}).
LAW = live animal weight in thousands of kilograms (Mg).
AmbRH = average daily relative humidity (percent).

Table 9-13. Parameters and estimates for the farrowing barn PM_{10} models

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	2.31939	0.08016	<.0001
	cycleday	0.05454	0.00362	<.0001
	LAW	0.09776	0.01175	<.0001
2	Intercept	2.489915	0.09914	<.0001
	cycleday	0.055625	0.00366	<.0001
	LAW	0.106263	0.01302	<.0001
	AmbRH	-0.00344	0.00066	<.0001
3	Intercept	2.631802	0.10743	<.0001
	cycleday	0.059459	0.0037	<.0001
	AmbT	-0.00756	0.00192	<.0001
	LAW	0.106851	0.01316	<.0001
	AmbRH	-0.00407	0.0007	<.0001
4	Intercept	3.062805	0.11999	<.0001
	cycleday	0.059061	0.00367	<.0001
	AmbT	-0.00132	0.00189	**0.4868**
	LAW	0.100043	0.01303	<.0001
	Exh_RH	-0.01287	0.00135	<.0001
5	Intercept	3.103209	0.11574	<.0001
	cycleday	0.059367	0.00367	<.0001
	LAW	0.088094	0.01244	<.0001
	Exh_RH	-0.01285	0.00126	<.0001
6	Intercept	2.584906	0.10593	<.0001
	cycleday	0.061876	0.00389	<.0001
	AmbT	-0.00697	0.00193	0.0003
	Inv	2.347235	0.2836	<.0001
	AmbRH	-0.00415	0.0007	<.0001
7	Intercept	3.005011	0.12027	<.0001
	cycleday	0.061125	0.00384	<.0001
	AmbT	-0.00061	0.0019	**0.7489**
	Inv	2.291581	0.28682	<.0001
	Exh_RH	-0.0132	0.00135	<.0001
8	Intercept	3.52795	0.26291	<.0001
	cycleday	0.058797	0.00368	<.0001
	ExhT	-0.04199	0.00953	<.0001
	LAW	0.102848	0.01333	<.0001
	AmbRH	-0.00361	0.00065	<.0001
9	Intercept	3.672323	0.24689	<.0001
	cycleday	0.060507	0.00363	<.0001
	ExhT	-0.02458	0.00924	0.008
	LAW	0.08629	0.01269	<.0001
	Exh_RH	-0.0123	0.00126	<.0001
10	Intercept	3.459979	0.26643	<.0001
	cycleday	0.061093	0.00386	<.0001
	ExhT	-0.04036	0.00962	<.0001
	Inv	2.252306	0.2923	<.0001
	AmbRH	-0.00368	0.00065	<.0001
11	Intercept	3.534881	0.24964	<.0001
	cycleday	0.062781	0.00376	<.0001
	ExhT	-0.02262	0.00927	0.0148
	Inv	2.144946	0.28392	<.0001
	Exh_RH	-0.01253	0.00126	<.0001

Table 9-14. 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 9-15. Parameters and estimates for the gestation barn PM_{10} models.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	4.746812	0.18103	<.0001
	LAW	0.005227	0.00077	<.0001
2	Intercept	5.186761	0.17987	<.0001
	LAW	0.005472	0.00076	<.0001
	AmbRH	-0.00766	0.00053	<.0001
3	Intercept	5.197462	0.19044	<.0001
	AmbT	0.001332	0.00143	**0.3515**
	LAW	0.005432	0.00077	<.0001
	AmbRH	-0.00794	0.00056	<.0001
4	Intercept	6.009517	0.16609	<.0001
	AmbT	0.006093	0.00134	<.0001
	LAW	0.005005	0.00064	<.0001
	ExhRH	-0.02175	0.00094	<.0001
5	Intercept	6.222609	0.15542	<.0001
	LAW	0.004471	0.00061	<.0001
	ExhRH	-0.02213	0.00096	<.0001
6	Intercept	5.513233	0.32609	<.0001
	AmbT	0.001056	0.00143	**0.4592**
	Inv	0.835821	0.28124	0.0048
	AmbRH	-0.00785	0.00057	<.0001
7	Intercept	5.935606	0.28506	<.0001
	AmbT	0.005531	0.00134	<.0001
	Inv	1.109027	0.24632	<.0001
	ExhRH	-0.02162	0.00096	<.0001
8	Intercept	5.562154	0.22881	<.0001
	ExhT	-0.01149	0.00423	0.0068
	LAW	0.004915	0.00077	<.0001
	AmbRH	-0.00791	0.00054	<.0001
9	Intercept	6.240271	0.20282	<.0001
	ExhT	-0.00055	0.00407	**0.8919**
	LAW	0.004443	0.00064	<.0001
	ExhRH	-0.02213	0.00096	<.0001
10	Intercept	5.794705	0.30808	<.0001
	ExhT	-0.01587	0.00406	0.0001
	Inv	0.8952	0.26107	0.0012
	AmbRH	-0.00783	0.00055	<.0001
11	Intercept	6.145041	0.28393	<.0001
	ExhT	-0.0057	0.0039	**0.1444**
	Inv	1.127905	0.2377	<.0001
	ExhRH	-0.02209	0.00097	<.0001

Table 9-16. 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.

9.4.1.4 $PM_{2.5}$ Model Results and Evaluation

As noted in Section 9.1, 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 live animal weight—were tested. All the models except model 1 had at least one coefficient that was insignificant ($p > 0.05$); these are in boldface in Table 9-17. 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 emission could be due to the additional chemical pathways for $PM_{2.5}$ development, and the effects of the emission of other pollutants on secondary formation, or an artifact of the limited dataset. More $PM_{2.5}$ emission measurements, taken in concert with ambient and barn parameters, would help identify additional parameters to characterize this relationship.

Table 9-18 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:

$$Farrowing\ Room, ln(PM_{2.5}) = -1.2146 + 0.0759 * cycleday\ + 0.2564 * LAW \qquad \text{Equation 20}$$

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 tested 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 live animal weight as a parameter, was the only model with no insignificant parameters (Table 9-19). The models showed the same relationships between the predictive parameters as in the farrowing rooms.

Table 9-20 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:

$$Gestation\ Barn, ln(PM_{2.5}) = 4.88715 + 0.0007 * LAW \qquad \text{Equation 21}$$

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 9-17. Parameters and estimates for the farrowing barn $PM_{2.5}$ models.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	-1.21456	0.19779	<.0001
	cycleday	0.075902	0.00225	<.0001
	LAW	0.256357	0.03492	<.0001
2	Intercept	-1.22295	0.20482	<.0001
	cycleday	0.075309	0.00212	<.0001
	LAW	0.254803	0.03335	<.0001
	AmbRH	0.000573	0.00294	**0.8465**
3	Intercept	-0.96654	0.29083	0.0015
	cycleday	0.065442	0.0091	<.0001
	AmbT	-0.01808	0.01225	**0.1524**
	LAW	0.242206	0.05058	<.0001
	AmbRH	0.001018	0.00159	**0.5268**
4	Intercept	-0.10714	0.53486	**0.8423**
	cycleday	0.072982	0.00857	<.0001
	AmbT	-0.01472	0.00893	**0.1074**
	LAW	0.211476	0.04989	0.0001
	ExhRH	-0.01609	0.00784	0.0475
5	Intercept	-0.57278	0.47918	**0.2381**
	cycleday	0.077513	0.00748	<.0001
	LAW	0.249139	0.06454	0.0009
	ExhRH	-0.01397	0.00775	**0.0822**
6	Intercept	-1.24104	0.27014	<.0001
	cycleday	0.087952	0.00353	<.0001
	AmbT	-0.01262	0.00751	0.1
	Inv	4.939231	0.7756	<.0001
	AmbRH	0.001565	0.00224	**0.4913**
7	Intercept	-0.68262	0.34997	**0.0607**
	cycleday	0.093276	0.0079	<.0001
	AmbT	-0.00831	0.00905	**0.3637**
	Inv	4.70608	0.85298	<.0001
	ExhRH	-0.01089	0.0049	0.0347
8	Intercept	-5.44691	1.24162	<.0001
	cycleday	0.066785	0.02129	0.006
	ExhT	0.179198	0.05016	0.0009
	LAW	0.166968	0.01505	<.0001
	AmbRH	0.003391	0.00639	**0.5997**
9	Intercept	-4.07391	1.18021	0.001
	cycleday	0.086992	0.0045	<.0001
	ExhT	0.168803	0.04758	0.0007
	LAW	0.155647	0.03003	<.0001
	ExhRH	-0.01415	0.00868	**0.112**
10	Intercept	-5.38343	0.86921	<.0001
	cycleday	0.100078	0.00518	<.0001
	ExhT	0.167264	0.03988	<.0001
	Inv	5.092094	0.82731	<.0001
	AmbRH	0.000251	0.00367	**0.9461**
11	Intercept	-4.61514	0.96869	<.0001
	cycleday	0.101842	0.00367	<.0001
	ExhT	0.162427	0.03734	<.0001
	Inv	4.743317	0.81837	<.0001
	ExhRH	-0.01232	0.00645	**0.0664**

Table 9-18. 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 9-19. Parameters and estimates for the gestation barn $PM_{2.5}$ models.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	4.88715	0.07109	<.0001
	LAW	0.0007	0.00031	0.027
2	Intercept	4.824807	0.08396	<.0001
	LAW	0.000689	0.00031	0.0281
	AmbRH	0.001005	0.00074	0.1745
3	Intercept	4.880687	0.09764	<.0001
	AmbT	-0.00111	0.0011	0.3165
	LAW	0.0006	0.00031	0.0592
	AmbRH	0.000681	0.00079	0.3921
4	Intercept	4.749922	0.11574	<.0001
	AmbT	-0.00129	0.00102	0.2118
	LAW	0.000536	0.00031	0.0884
	ExhRH	0.003155	0.00158	0.0484
5	Intercept	4.712665	0.1142	<.0001
	LAW	0.00064	0.00031	0.0404
	ExhRH	0.00309	0.0016	0.0553
6	Intercept	4.896295	0.17405	<.0001
	AmbT	-0.00152	0.00109	0.168
	Inv	0.10554	0.12992	0.4193
	AmbRH	0.000885	0.00089	0.3194
7	Intercept	4.79353	0.16774	<.0001
	AmbT	-0.00173	0.00103	0.0967
	Inv	0.05847	0.11824	0.6227
	ExhRH	0.003508	0.00161	0.0313
8	Intercept	5.078659	0.14699	<.0001
	ExhT	-0.0063	0.00306	0.0425
	LAW	0.000344	0.00034	0.3117
	AmbRH	0.000265	0.0008	0.7409
9	Intercept	4.923306	0.14416	<.0001
	ExhT	-0.00605	0.00274	0.0306
	LAW	0.000307	0.00033	0.3526
	ExhRH	0.002892	0.00155	0.0644
10	Intercept	5.132446	0.19452	<.0001
	ExhT	-0.0076	0.00274	0.0068
	Inv	0.047445	0.12546	0.7064
	AmbRH	0.000259	0.00089	0.771
11	Intercept	4.969183	0.16959	<.0001
	ExhT	-0.00721	0.00245	0.0044
	Inv	0.036209	0.11101	0.7454
	ExhRH	0.003035	0.00156	0.0545

Table 9-20. 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.

9.4.1.5 TSP Model Results and Evaluation

As noted in Section 9.1, the analysis for TSP tested 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 9-21. 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 9-22 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 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:

$$Farrowing\ room, ln(TSP) = 2.8589 + 0.0706 * cycleday\ + 0.1473 * LAW\ - 0.0049\ Amb_{RH} \quad \text{Equation 22}$$

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 tested, and most models had at least one coefficient that was insignificant. The exceptions were models 1, 2, and 5 (see Table 9-23). 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 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 9-24 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:

$$Gestation\ Barn, ln(TSP) = 5.53397 + 0.0080 * Amb_{RH} + 0.0066 * LAW \qquad \text{Equation 23}$$

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 9-21. Parameters and estimates for the farrowing barn TSP models.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	2.510049	0.44876	<.0001
	cycleday	0.075409	0.01396	<.0001
	LAW	0.147389	0.07907	**0.0679**
2	Intercept	2.858928	0.47281	<.0001
	cycleday	0.070551	0.01348	<.0001
	LAW	0.147305	0.07879	**0.0679**
	AmbRH	-0.00491	0.00263	**0.0644**
3	Intercept	2.801817	0.53016	<.0001
	cycleday	0.070724	0.01347	<.0001
	AmbT	0.001602	0.0066	**0.8086**
	LAW	0.152652	0.08146	**0.0663**
	AmbRH	-0.0049	0.00264	**0.0654**
4	Intercept	3.621464	0.56437	<.0001
	cycleday	0.069119	0.01319	<.0001
	AmbT	0.009349	0.00686	**0.1758**
	LAW	0.124026	0.0784	**0.1201**
	ExhRH	-0.01866	0.00497	0.0003
5	Intercept	3.56584	0.52094	<.0001
	cycleday	0.074342	0.01373	<.0001
	LAW	0.117031	0.07536	**0.1271**
	ExhRH	-0.01586	0.00485	0.0014
6	Intercept	3.136307	0.38035	<.0001
	cycleday	0.080618	0.01299	<.0001
	AmbT	-0.00014	0.00638	**0.9821**
	Inv	1.823107	0.92016	0.0497
	AmbRH	-0.0047	0.00264	**0.0771**
7	Intercept	3.946555	0.43644	<.0001
	cycleday	0.076822	0.01279	<.0001
	AmbT	0.007496	0.00661	**0.2603**
	Inv	1.31966	0.92362	**0.1558**
	ExhRH	-0.01857	0.00501	0.0003
8	Intercept	3.341498	0.98955	0.001
	cycleday	0.070461	0.01342	<.0001
	ExhT	-0.01684	0.03054	**0.5824**
	LAW	0.136466	0.08079	**0.0971**
	AmbRH	-0.0049	0.00263	**0.065**
9	Intercept	3.261496	0.97183	0.0011
	cycleday	0.074396	0.01371	<.0001
	ExhT	0.01196	0.03205	**0.7096**
	LAW	0.123135	0.077	**0.116**
	ExhRH	-0.01638	0.00502	0.0014
10	Intercept	3.64785	0.87406	<.0001
	cycleday	0.079772	0.01283	<.0001
	ExhT	-0.01918	0.03003	**0.5242**
	Inv	1.716278	0.92608	**0.0661**
	AmbRH	-0.00469	0.00262	**0.0762**
11	Intercept	3.575734	0.85828	<.0001
	cycleday	0.082153	0.0127	<.0001
	ExhT	0.010094	0.03162	**0.7501**
	Inv	1.525284	0.86906	**0.0821**
	ExhRH	-0.01665	0.00503	0.0012

Table 9-22. 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 9-23. Parameters and estimates for the gestation barn TSP models.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	5.047799	0.50254	<.0001
	LAW	0.006649	0.00206	0.0048
2	Intercept	5.533966	0.56243	<.0001
	LAW	0.006601	0.0023	0.012
	AmbRH	-0.008	0.00126	<.0001
3	Intercept	5.718378	0.61185	<.0001
	AmbT	-0.003629	0.00358	**0.3121**
	LAW	0.006107	0.00242	0.0228
	AmbRH	-0.008349	0.00129	<.0001
4	Intercept	6.587825	0.50241	<.0001
	AmbT	0.001207	0.00295	**0.6835**
	LAW	0.005874	0.00189	0.0071
	ExhRH	-0.02364	0.00236	<.0001
5	Intercept	6.500666	0.42744	<.0001
	LAW	0.006073	0.00166	0.0021
	ExhRH	-0.022781	0.00222	<.0001
6	Intercept	6.375716	0.8023	<.0001
	AmbT	-0.005564	0.00341	**0.1041**
	Inv	0.7009	0.74125	**0.36**
	AmbRH	-0.008471	0.0013	<.0001
7	Intercept	7.043938	0.69332	<.0001
	AmbT	-0.000342	0.00247	**0.89**
	Inv	0.813449	0.63836	**0.2241**
	ExhRH	-0.023564	0.0024	<.0001
8	Intercept	6.336514	0.69604	<.0001
	ExhT	-0.019719	0.00831	0.0189
	LAW	0.005016	0.0025	**0.0607**
	AmbRH	-0.008459	0.00126	<.0001
9	Intercept	6.863691	0.54038	<.0001
	ExhT	-0.009764	0.00659	**0.141**
	LAW	0.005357	0.00186	0.0094
	ExhRH	-0.022867	0.00224	<.0001
10	Intercept	7.09542	0.64832	<.0001
	ExhT	-0.027513	0.00711	0.0002
	Inv	0.515996	0.65632	**0.444**
	AmbRH	-0.008555	0.00127	<.0001
11	Intercept	7.443337	0.46078	<.0001
	ExhT	-0.017032	0.00268	<.0001
	Inv	0.722282	0.49451	**0.1627**
	ExhRH	-0.022716	0.00226	<.0001

Table 9-24. 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.

9.4.2 Finishing Operations

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 live animal weight 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 relative humidity, inventory and live animal weight in the development of the models.

9.4.2.1 NH_3 Model Results and Evaluation

EPA developed six different models using a combination of four predictor variables—ambient temperature, exhaust temperature, inventory, and live animal weight. 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 9-25. The model fit statistics (-2 log Likelihood, AIC, AICc, and BIC) and the model evaluation statistics (ME, NME, MB, NMB) are provided in Table 9-26. Models 1, 3, and 4, which all contained live animal weight, and either the ambient temperature or exhaust temperature, had the lowest model fit values. The exhaust temperature and live animal weight 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 much different from the other models. Scatter plots of the observed emissions versus the EEM predicted values are in Figure F-19.

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 live animal weight would be potentially easier to obtain than exhaust temperature. Model 4 is as follows:

$$ln(\mathrm{NH_3}) = 1.2363 + 0.00895 * Amb_T + 0.0089 * LAW \qquad \text{Equation 24}$$

Where:

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

Table 9-27 and Table 9-28 provides the model fit statistics and the model evaluation statistics for the six “pit” models. Scatter plots of the observed emissions versus the EEM predicted values are in Figure F-20. Overall, the “pit” model rankings were similar to the “no pit” versions, with the models that contained live animal weight 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 live animal weight would be potentially easier to obtain and therefore selected model 4 for further analysis. Model 4 is as follows:

$$Shallow\ Pit: ln(y_p) = 1.1422 + 0.0091 * Amb_T + 0.0085 * LAW \qquad \text{Equation 25}$$

$$Deep\ Pit: ln(y_p) = 1.3424 + 0.0091 * Amb_T + 0.0085 * LAW \qquad \text{Equation 26}$$

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 in ^oC.
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 9-25. 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	<.0001
	Ambient Temp	0.004347	0.00132	*0.0010*
	ExhsT	0.013342	0.00314	<.0001
	LAW	0.008451	0.00052	<.0001
2	Intercept	1.267617	0.07386	<.0001
	Ambient Temp	0.004228	0.00137	*0.0020*
	ExhsT	0.015666	0.00328	<.0001
	Inv	0.177549	0.04043	<.0001
3	Intercept	0.913240	0.05235	<.0001
	ExhsT	0.021452	0.00185	<.0001
	LAW	0.008360	0.00051	<.0001
4	Intercept	1.236262	0.03916	<.0001
	Ambient Temp	0.008953	0.00081	<.0001
	LAW	0.008939	0.00051	<.0001
5	Intercept	1.171164	0.06556	<.0001
	ExhsT	0.023489	0.00195	<.0001
	Inv	0.154185	0.03880	<.0001
6	Intercept	1.492383	0.05647	<.0001
	Ambient Temp	0.009613	0.00084	<.0001
	Inv	0.235848	0.03939	<.0001

Table 9-26. 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	-2883	-2847	-2847	-2848	0.681	13.232	27.129	1.654	0.013	0.206
2	-2755	-2719	-2719	-2720	0.238	17.861	36.314	2.214	0.029	0.470
3	-2968	-2934	-2934	-2935	0.693	13.309	27.009	1.632	-0.008	-0.129
4	-2866	-2832	-2832	-2833	0.674	13.338	27.435	1.673	0.027	0.439
5	-2831	-2797	-2797	-2798	0.304	17.949	36.344	2.196	0.000	0.008
6	-2734	-2700	-2700	-2701	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 9-27. 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	<.0001
	Shallow	0.920418	0.06548	<.0001
	Ambient Temp	0.004275	0.00132	0.0012
	ExhsT	0.013952	0.00313	<.0001
	LAW	0.008080	0.00052	<.0001
2	Deep	1.415308	0.08386	<.0001
	Shallow	1.151833	0.07895	<.0001
	Ambient Temp	0.003980	0.00137	0.0037
	ExhsT	0.016534	0.00329	<.0001
	Inv	0.144983	0.04258	0.0007
3	Deep	1.007922	0.05438	<.0001
	Shallow	0.809468	0.05609	<.0001
	ExhsT	0.021950	0.00185	<.0001
	LAW	0.007990	0.00050	<.0001
4	Deep	1.342386	0.04249	<.0001
	Shallow	1.142239	0.04362	<.0001
	Ambient Temp	0.009077	0.00081	<.0001
	LAW	0.008545	0.00051	<.0001
5	Deep	1.327761	0.07679	<.0001
	Shallow	1.062030	0.07049	<.0001
	ExhsT	0.023880	0.00195	<.0001
	Inv	0.122264	0.04096	0.0029
6	Deep	1.644386	0.07165	<.0001
	Shallow	1.398875	0.06257	<.0001
	Ambient Temp	0.009662	0.00084	<.0001
	Inv	0.208959	0.04138	<.0001

Table 9-28. 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	-2903	-2865	-2865	-2866	0.719	12.231	25.503	1.555	0.037	0.606
2	-2767	-2729	-2729	-2730	0.402	16.584	33.264	2.028	0.019	0.315
3	-2988	-2952	-2952	-2953	0.731	12.297	25.373	1.533	0.018	0.294
4	-2885	-2849	-2848	-2850	0.712	12.346	25.799	1.573	0.049	0.798
5	-2844	-2808	-2808	-2809	0.450	16.592	33.105	2	-0.008	-0.131
6	-2744	-2708	-2708	-2709	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.

9.4.2.2 H_2S Model Results and Evaluation

EPA developed six different models based on the four identified predictor variables—ambient temperature, exhaust temperature, inventory, and live animal weight. For all models, live animal weight and inventory have a significant ($p < 0.05$) positive correlation with H_2S emissions. This was expected based on the literature 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 4.1, but is consistent with the linear regressions of H_2S emissions from finishing sites reported in Section 8.3.2. Across the models, exhaust temperature shows both a positive and negative relationship with emissions.

For the "no pit" version of the models (Table 9-29, Figure F-21), 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 9-30 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, 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 statistics 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:

$$ln(H_2S) = 4.0820 - 0.0066 * Amb_T + 0.0172 * LAW \quad \text{Equation 27}$$

Where:

$ln(H_2S)$ = the natural log transformed predicted H_2S emissions in grams per day ($g\ day^{-1}$).
Amb_T = ambient temperature in ^oC.
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 9-31 and 9-32, Figure F-22). The two models that contained ambient temperature variables and inventory or live animal weight (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:

$$Shallow\ Pit: ln(H_2S) = 4.1905 - 0.0055 * Amb_T + 0.0133 * LAW \quad \text{Equation 28}$$

$$Deep\ Pit: ln(H_2S) = 4.9916 + 0.0055 * Amb_T + 0.0133 * LAW \quad \text{Equation 29}$$

Where:

$ln(H_2S)$ = the natural log transformed predicted H_2S emissions in grams per day (g day^{-1}).
Amb_T = ambient temperature in ^oC.
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 9-29. Parameters and estimates for the no pit H2S finishing models developed.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	3.828226	0.15457	<.0001
	Ambient Temp	-0.010738	0.00256	<.0001
	Exhaust Temp	0.014873	0.00716	0.0380
	LAW	0.016662	0.00153	<.0001
2	Intercept	4.352401	0.15505	<.0001
	Ambient Temp	-0.010445	0.00264	<.0001
	Exhaust Temp	0.012584	0.00750	**0.0936**
	Inv	0.479303	0.07728	<.0001
3	Intercept	4.114478	0.13359	<.0001
	Exhaust Temp	-0.007280	0.00442	**0.0997**
	LAW	0.017307	0.00153	<.0001
4	Intercept	4.081979	0.09500	<.0001
	Ambient Temp	-0.006592	0.00161	<.0001
	LAW	0.017163	0.00151	<.0001
5	Intercept	4.637743	0.13164	<.0001
	Exhaust Temp	-0.009723	0.00454	0.0324
	Inv	0.538907	0.07433	<.0001
6	Intercept	4.559343	0.09387	<.0001
	Ambient Temp	-0.006960	0.00163	<.0001
	Inv	0.519982	0.07361	<.0001

Table 9-30. 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	3110	3146	3146	3145	0.377	17.443	83.944	294.42	15.792	4.503
2	3174	3210	3210	3209	0.225	18.090	89.751	314.79	1.876	0.535
3	3207	3241	3241	3240	0.369	17.658	84.291	294.15	15.140	4.339
4	3114	3148	3148	3147	0.371	17.483	84.295	295.66	17.283	4.927
5	3270	3304	3304	3303	0.188	18.326	90.851	317.04	4.912	1.408
6	3177	3211	3211	3210	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 9-31. 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	<.0001
	Shallow	4.076802	0.20572	<.0001
	Ambient Temp	-0.007641	0.00330	0.0205
	Exhaust Temp	0.006977	0.00859	**0.4169**
	LAW	0.013027	0.00176	<.0001
2	Deep	5.194357	0.20687	<.0001
	Shallow	4.361626	0.21300	<.0001
	Ambient Temp	-0.007357	0.00335	0.0284
	Exhaust Temp	0.005595	0.00883	**0.5262**
	Inv	0.507381	0.10628	<.0001
3	Deep	5.055498	0.18008	<.0001
	Shallow	4.226298	0.18395	<.0001
	Exhaust Temp	-0.007016	0.00514	**0.1728**
	LAW	0.013636	0.00174	<.0001
4	Deep	4.991579	0.15159	<.0001
	Shallow	4.190492	0.15138	<.0001
	Ambient Temp	-0.005539	0.00202	0.0062
	LAW	0.013317	0.00173	<.0001
5	Deep	5.369327	0.18585	<.0001
	Shallow	4.513433	0.19158	<.0001
	Exhaust Temp	-0.007894	0.00521	**0.1299**
	Inv	0.536013	0.10299	<.0001
6	Deep	5.277375	0.16029	<.0001
	Shallow	4.450293	0.16093	<.0001
	Ambient Temp	-0.005676	0.00203	0.0052
	Inv	0.527087	0.10200	<.0001

Table 9-32. 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.

9.4.2.3 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 live animal weight in the development of the PM_{10} models. EPA tested 13 models, each with a different combination of the six predictor variables (Figures F-23 and F-24). For all models, as expected, live animal weight and inventory again had significant positive correlations with emissions (Table 9-33). 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 9-33 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 9-34 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:

$$ln(PM_{10}) = 5.5039 - 0.0094 * Amb_{RH} + 0.0104 * LAW \qquad \textit{Equation 30}$$

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 9-33. Parameters and estimates for the PM_{10} finishing models developed.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	4.827106	0.03924	<.0001
	LAW	0.011002	0.00067	<.0001
2	Intercept	5.503943	0.04999	<.0001
	LAW	0.010447	0.00066	<.0001
	Ambient RH	-0.009403	0.00044	<.0001
3	Intercept	5.559664	0.05575	<.0001
	Ambient Temp	-0.002254	0.00122	**0.0656**
	LAW	0.010372	0.00068	<.0001
	Ambient RH	-0.009606	0.00046	<.0001
4	Intercept	6.212768	0.06174	<.0001
	Ambient Temp	-0.001257	0.00112	**0.2623**
	LAW	0.009975	0.00063	<.0001
	Exhaust RH	-0.021830	0.00074	<.0001
5	Intercept	6.196228	0.05891	<.0001
	LAW	0.010083	0.00062	<.0001
	Exhaust RH	-0.021951	0.00073	<.0001
6	Intercept	5.601306	0.07235	<.0001
	Ambient Temp	-0.003847	0.00127	0.0025
	Inv	0.611182	0.06029	<.0001
	Ambient RH	-0.009735	0.00046	<.0001
7	Intercept	6.345648	0.07928	<.0001
	Ambient Temp	-0.003070	0.00117	0.0090
	Inv	0.501598	0.05839	<.0001
	Exhaust RH	-0.021901	0.00074	<.0001
8	Intercept	5.677437	0.07953	<.0001
	Exhaust Temp	-0.007965	0.00279	0.0044
	LAW	0.010555	0.00068	<.0001
	Ambient RH	-0.009319	0.00044	<.0001
9	Intercept	6.406988	0.08168	<.0001
	Exhaust Temp	-0.009524	0.00254	0.0002
	LAW	0.010212	0.00065	<.0001
	Exhaust RH	-0.021880	0.00073	<.0001
10	Intercept	5.736529	0.09043	<.0001
	Exhaust Temp	-0.011636	0.00289	<.0001
	Inv	0.673236	0.05806	<.0001
	Ambient RH	-0.009382	0.00043	<.0001
11	Intercept	6.544987	0.09438	<.0001
	Exhaust Temp	-0.013957	0.00264	<.0001
	Inv	0.607481	0.05467	<.0001
	Exhaust RH	-0.022011	0.00073	<.0001

Table 9-34. 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.

9.4.2.4 $PM_{2.5}$ 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 live animal weight(Figures F-25 and F-26). Table 9-35 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 9-36 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:

$$ln(PM_{2.5}) = 2.4954 - 0.0023 * Amb_{RH} + 0.01095 * LAW \qquad \text{Equation 31}$$

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 9-35. Parameters and estimates for the six $PM_{2.5}$ finishing models developed.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	2.302348	0.11809	<.0001
	LAW	0.011715	0.00236	0.0001
2	Intercept	2.495430	0.19623	<.0001
	LAW	0.010950	0.00334	0.0041
	Ambient RH	-0.002279	0.00086	0.0089
3	Intercept	2.537710	0.19484	<.0001
	Ambient Temp	0.009621	0.00485	**0.0514**
	LAW	0.008145	0.00432	**0.0697**
	Ambient RH	-0.003306	0.00102	0.0017
4	Intercept	2.288922	0.12719	<.0001
	LAW	0.009030	0.00405	0.0338
	Ambient Temp	0.007974	0.00484	**0.1041**
5	Intercept	2.663306	0.21940	<.0001
	Ambient Temp	0.010045	0.00452	0.0296
	LAW	0.009193	0.00382	0.0225
	Exhaust RH	-0.006906	0.00200	0.0008
6	Intercept	2.622421	0.18732	<.0001
	LAW	0.011931	0.00267	0.0004
	Exhaust RH	-0.005534	0.00156	0.0006
7	Intercept	3.005931	0.51392	<.0001
	Ambient Temp	0.012476	0.00222	<.0001
	Inventory	0.002496	0.71390	**0.9972**
	Ambient RH	-0.004533	0.00083	<.0001
8	Intercept	3.342486	0.63180	<.0001
	Ambient Temp	0.011141	0.00257	<.0001
	Inventory	-0.000151	0.91844	**0.9999**
	Exhaust RH	-0.009457	0.00078	<.0001
9	Intercept	3.425887	0.56136	<.0001
	Inventory	-0.068691	0.83535	**0.9355**
	Exhaust RH	-0.006851	0.00119	<.0001
10	Intercept	2.166443	0.26835	<.0001
	Exhaust Temp	0.026396	0.02002	**0.1941**
	LAW	0.009100	0.00556	**0.1142**
	Exhaust RH	-0.006921	0.00229	0.0031
11	Intercept	2.340817	0.45361	<.0001
	Exhaust Temp	0.034826	0.00664	<.0001
	Inventory	-0.092030	0.62158	**0.8838**
	Ambient RH	-0.003798	0.00077	<.0001
12	Intercept	2.683586	0.58096	<.0001
	Exhaust Temp	0.033497	0.01025	0.0017
	Inventory	-0.094859	0.78141	**0.9045**
	Exhaust RH	-0.008958	0.00110	<.0001
13	Intercept	3.425856	0.50153	<.0001
	Inventory	-0.068685	0.66384	**0.9190**
	Exhaust RH	-0.006851	0.00205	0.0011

Table 9-36. Fit and evaluation statistics for the six $PM_{2.5}$ 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.

9.4.2.5 TSP Models Results and Evaluation

For TSP, EPA tested the same 13 models as were tested for PM_{10} (Table 9-37, 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 9-38 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:

$$ln(TSP) = 6.266 - 0.0088 * Amb_{RH} + 0.0118 * LAW \quad \text{Equation 32}$$

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 9-37. Parameters and estimates for the six TSP finishing models developed.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	5.815769	0.18411	<.0001
	LAW	0.009746	0.00262	0.0005
2	Intercept	6.266140	0.23119	<.0001
	LAW	0.011813	0.00296	0.0007
	Ambient RH	-0.008831	0.00185	<.0001
3	Intercept	6.559145	0.27572	<.0001
	Ambient Temp	-0.009011	0.00442	0.0430
	LAW	0.010805	0.00357	0.0059
	Ambient RH	-0.009409	0.00203	<.0001
4	Intercept	6.039034	0.20592	<.0001
	LAW	0.009656	0.00273	0.0010
	Ambient Temp	-0.012453	0.00421	0.0035
5	Intercept	7.245363	0.22578	<.0001
	Ambient Temp	-0.008719	0.00366	0.0184
	LAW	0.010740	0.00200	<.0001
	Exhaust RH	-0.023151	0.00305	<.0001
6	Intercept	7.136576	0.21238	<.0001
	LAW	0.010837	0.00188	<.0001
	Exhaust RH	-0.023971	0.00300	<.0001
7	Intercept	6.399395	0.33301	<.0001
	Ambient Temp	-0.011020	0.00415	0.0086
	Inv	0.791571	0.28704	0.0074
	Ambient RH	-0.006994	0.00209	0.0010
8	Intercept	7.180636	0.34955	<.0001
	Ambient Temp	-0.009588	0.00394	0.0157
	Inv	0.613911	0.27245	0.0273
	Exhaust RH	-0.019279	0.00317	<.0001
9	Intercept	6.799693	0.40577	<.0001
	Inv	1.028981	0.27200	0.0006
	Exhaust RH	-0.020994	0.00403	<.0001
10	Intercept	8.191352	0.35972	<.0001
	Exhaust Temp	-0.033454	0.01041	0.0016
	LAW	0.010413	0.00231	0.0003
	Exhaust RH	-0.027139	0.00342	<.0001
11	Intercept	6.850755	0.40872	<.0001
	Exhaust Temp	-0.030522	0.01080	0.0051
	Inv	0.842748	0.27876	0.0035
	Ambient RH	-0.006462	0.00195	0.0011
12	Intercept	7.673387	0.58625	<.0001
	Exhaust Temp	-0.027327	0.01192	0.0232
	Inv	0.851755	0.31108	0.0090
	Exhaust RH	-0.022106	0.00421	<.0001
13	Intercept	6.799693	0.40577	<.0001
	Inv	1.028981	0.27200	0.0006
	Exhaust RH	-0.020994	0.00403	<.0001

Table 9-38. Fit and evaluation statistics for the six 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.

9.5 Open Source

The exploratory data analysis suggested that EPA should consider ambient temperature, lagoon temperature, wind speed, pH, and live animal weight 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.

9.5.1 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 9-39). The only exceptions were pH in models 8 and 11. These positive relationships are consistent with the typical trends reported in literature.

Table 9-40 provides the model fit statistics (-2 log Likelihood, AIC, AICc, BIC) and the model evaluation statistics (ME, NME, MB, 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:

$$Breeding\ Gestation\ Lagoon, ln(NH_3) = 0.5821 + 0.0557 * Amb_T\ + 0.0914 * ws \qquad \text{Equation 33}$$

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 in ^{o}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 tested the same 12 models developed for the breeding and gestation lagoons (Table 9-41, 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 9-41). The only exception was pH in model 11. These positive relationships are consistent with the typical trends reported in literature.

Table 9-42 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:

$$Grow\ Finish\ Lagoon, ln(NH_3) = -0.6801 + 0.0854 * Amb_T\ + 0.1319 * ws \qquad \text{Equation 34}$$

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 in °C.
ws = average daily wind speed in meters per second (m/s) at a height of 2.5 meters.

For the basin, EPA tested 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 9-43 and Figures F-33). Two of the three models had insignificant parameters, highlighted in bold in Table 9-43. 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 9-44). 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:

$$Basin, ln(NH_3) = 1.5049 + 0.01171 * Amb_T \quad \text{Equation 35}$$

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 in °C.

Table 9-39. Parameters and estimates for the swine breeding and gestation open source NH_3 models developed.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	0.875636	0.18288	0.0001
	Air Temp	0.023209	0.0073	0.0021
	Lagoon Temp	0.031408	0.01196	0.0115
2	Intercept	1.344128	0.11277	<.0001
	Air Temp	0.029756	0.00492	<.0001
3	Intercept	0.771804	0.19814	0.0009
	Lagoon Temp	0.057949	0.00946	<.0001
4	Intercept	0.556905	0.16137	0.0023
	Air Temp	0.012147	0.00565	0.0346
	Lagoon Temp	0.045369	0.00987	<.0001
	WS	0.062766	0.00781	<.0001
5	Intercept	0.582053	0.07702	<.0001
	Air Temp	0.055673	0.00268	<.0001
	WS	0.091428	0.01123	<.0001
6	Intercept	0.486491	0.16366	0.0072
	Lagoon Temp	0.059394	0.00766	<.0001
	WS	0.066408	0.00778	<.0001
7	Intercept	1.335634	1.97264	**0.5006**
	Air Temp	0.0646	0.01385	<.0001
	Lagoon Temp	-0.018755	0.01441	**0.1974**
	pH	-0.022843	0.24719	**0.9266**
8	Intercept	1.965956	2.47673	**0.4301**
	Air Temp	0.027168	0.00701	0.0002
	pH	-0.074201	0.31181	**0.8126**
9	Intercept	0.265574	2.55621	**0.9176**
	Lagoon Temp	0.052431	0.0123	0.0004
	pH	0.073016	0.31363	**0.8166**
10	Intercept	-0.860651	1.95067	**0.6604**
	Air Temp	0.010235	0.00606	**0.097**
	Lagoon Temp	0.045602	0.01183	0.0005
	WS	0.05794	0.00855	<.0001
	pH	0.181902	0.23885	**0.4488**
11	Intercept	1.492571	1.38919	**0.2863**
	Air Temp	0.055412	0.00409	<.0001
	WS	0.108678	0.01318	<.0001
	pH	-0.128854	0.17588	**0.4662**
12	Intercept	-0.759231	1.9849	**0.7032**
	Lagoon Temp	0.056318	0.01014	<.0001
	WS	0.060473	0.00861	<.0001
	pH	0.164322	0.24292	**0.501**

Table 9-40. Fit and evaluation statistics for the swine breeding and gestation open source 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 9-41. Parameters and estimates for the swine growing and finishing open source NH_3 models developed.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	-0.566633	0.2496	**0.0593**
	AirTemp	0.023119	0.01253	0.0717
	LagnTemp	0.087319	0.01867	<.0001
2	Intercept	-0.049884	0.67955	**0.942**
	AirTemp	0.038719	0.01238	0.0027
3	Intercept	-0.603991	0.24051	0.0407
	LagnTemp	0.112214	0.01316	<.0001
4	Intercept	-1.128417	0.1993	<.0001
	AirTemp	0.016087	0.01227	**0.1974**
	LagnTemp	0.09329	0.01491	<.0001
	WS	0.13032	0.03173	0.0002
5	Intercept	-0.680078	0.24813	0.0169
	AirTemp	0.085372	0.01423	0.0033
	WS	0.131932	0.05442	0.02
6	Intercept	-1.171433	0.18552	<.0001
	LagnTemp	0.109863	0.00817	<.0001
	WS	0.138518	0.03068	<.0001
7	Intercept	-5.963413	3.94171	**0.1557**
	AirTemp	0.021854	0.01447	**0.1385**
	LagnTemp	0.125063	0.02234	<.0001
	pH	0.638838	0.48002	**0.2076**
8	Intercept	-0.836278	11.0659	**0.9412**
	AirTemp	0.045035	0.01714	0.0113
	pH	0.096251	1.41519	**0.9471**
9	Intercept	-6.654716	3.89618	**0.1143**
	LagnTemp	0.150671	0.01457	<.0001
	pH	0.718096	0.47492	**0.1574**
10	Intercept	-7.928994	2.74523	0.0095
	AirTemp	0.00609	0.01416	**0.6696**
	LagnTemp	0.13598	0.01904	<.0001
	WS	0.157811	0.03288	<.0001
	pH	0.80741	0.33239	0.0256
11	Intercept	6.210049	5.48066	**0.2827**
	AirTemp	0.019652	0.01157	0.0963
	WS	0.076797	0.03599	0.0393
	pH	-0.758828	0.70323	**0.3056**
12	Intercept	-8.252853	2.65417	0.0068
	LagnTemp	0.143149	0.00982	<.0001
	WS	0.162008	0.03126	<.0001
	pH	0.843797	0.3231	0.019

Table 9-42. Fit and evaluation statistics for the swine growing and finishing open source 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.

Table 9-43. Parameters and estimates for the swine basin open source NH_3 models developed.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	1.504932	0.18455	<.0001
	AmbT	0.075879	0.01171	<.0001
2	Intercept	1.901887	0.31764	<.0001
	AmbT	0.071725	0.0109	<.0001
	ws	-0.079949	0.05457	**0.1512**
3	Intercept	2.774765	0.36936	<.0001
	ws	-0.070246	0.05977	**0.2484**

Table 9-44. Fit and evaluation statistics for the swine basin open source 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.

9.5.2 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 9-45, 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 9-46 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:

$$Breeding \ \& \ Gestation \ Lagoons, ln(H_2S) = 4.6796 + 0.11516 * ws \qquad \text{Equation 36}$$

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 tested the same 13 models as were tested for the breeding and gestation lagoons (Figures F-36 and F-37). Table 9-47 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, ambient temperature, lagoon temperature, and wind speed relationships were consistent with the typical trends seen in literature.

Table 9-48 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:

$$Grow - Finish\ Lagoons, ln(H_2S) = 3.6948 + 0.2790 * ws \quad \text{Equation 37}$$

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.

For the basin, EPA tested three models that used combinations of ambient temperature and wind speed, as NAEMS did not collect temperature or pH measurements of the basin liquid (figure F-38). All three models had insignificant parameters, highlighted in bold in Table 9-49. The models produced comparable model fit statistics and evaluation statistics (Table 9-50). EPA selected model 1 because it was consistent with the NH_3 model selected, which did have significant coefficients. Model 1 is as follows:

$$Basin, ln(H_2S) = 0.4689 + 0.0270 * Amb_T \quad \text{Equation 38}$$

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 in ^oC.

Table 9-45. Parameters and estimates for the H_2S swine gestation lagoon models.

Model	Parameter	Estimate	Standard Error	p-value
1	Intercept	6.478992	0.3387	<.0001
	AirTemp	0.119184	0.02631	<.0001
	LagnTemp	-0.173902	0.03106	<.0001
2	Intercept	6.428343	0.23161	<.0001
	AirTemp	-0.02363	0.0111	0.0379
3	Intercept	6.196805	0.44893	<.0001
	LagnTemp	-0.050033	0.02127	0.0315
4	Intercept	5.022463	0.36237	<.0001
	AirTemp	0.094013	0.03212	0.0065
	LagnTemp	-0.111776	0.03607	0.0035
	WS	0.168391	0.04212	0.0004
5	Intercept	6.52387	0.31046	<.0001
	AirTemp	-0.024557	0.01148	0.0377
	WS	-0.006003	0.03223	0.853
6	Intercept	5.410901	0.43287	<.0001
	LagnTemp	-0.03885	0.01718	0.0362
	WS	0.129965	0.03991	0.0017
7	Intercept	10.448431	6.025	0.0951
	AirTemp	0.070218	0.02918	0.0221
	LagnTemp	-0.169165	0.03307	<.0001
	pH	-0.401988	0.76214	0.6023
8	Intercept	-1.986147	6.45492	0.7604
	AirTemp	-0.007457	0.0233	0.751
	pH	0.959146	0.83502	0.2595
9	Intercept	5.691389	6.28786	0.3721
	LagnTemp	-0.097135	0.0202	0.0014
	pH	0.188021	0.79272	0.814
10	Intercept	9.548496	6.33186	0.1478
	AirTemp	0.075029	0.03012	0.018
	LagnTemp	-0.167581	0.03433	<.0001
	WS	0.022008	0.03533	0.5395
	pH	-0.312304	0.79045	0.697
11	Intercept	-1.061752	6.97035	0.8799
	AirTemp	-0.00625	0.02337	0.7908
	WS	-0.0109	0.03269	0.7416
	pH	0.843677	0.89476	0.3528
12	Intercept	5.355561	6.73864	0.4328
	LagnTemp	-0.09578	0.02179	0.001
	WS	0.005886	0.03421	0.8648
	pH	0.224932	0.83865	0.7903
13	Intercept	4.833256	0.25025	<.0001
	WS	0.099772	0.04391	0.0253

Table 9-46. 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 9-47. 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
	Air Temp	0.083699	0.03236	0.0141
	Lagoon Temp	0.041352	0.06788	**0.5489**
2	Intercept	3.735991	0.60044	<.0001
	Air Temp	0.084295	0.02491	0.0014
3	Intercept	2.54563	1.16909	0.0553
	Lagoon Temp	0.131182	0.06277	**0.061**
4	Intercept	1.458511	0.92977	**0.1337**
	Air Temp	0.049379	0.03397	**0.1581**
	Lagoon Temp	0.078182	0.05821	**0.1918**
	WS	0.263928	0.09545	0.008
5	Intercept	3.166201	0.54568	<.0001
	Air Temp	0.052501	0.02584	0.0481
	WS	0.221709	0.08295	0.0099
6	Intercept	1.261412	0.87337	**0.1675**
	Lagoon Temp	0.12634	0.04316	0.0126
	WS	0.303785	0.08537	0.0009
7	Intercept	22.901945	4.09576	<.0001
	Air Temp	0.116961	0.02952	0.0004
	Lagoon Temp	0.055851	0.0407	**0.1784**
	pH	-2.574006	0.50141	<.0001
8	Intercept	25.573479	3.83417	<.0001
	Air Temp	0.150334	0.01514	<.0001
	pH	-2.869505	0.47948	<.0001
9	Intercept	18.670458	4.80653	0.0015
	Lagoon Temp	0.193279	0.02407	<.0001
	pH	-2.080679	0.59078	0.0031
10	Intercept	24.000677	4.08593	<.0001
	Air Temp	0.092797	0.02822	0.0033
	Lagoon Temp	0.043962	0.03778	**0.2534**
	WS	0.26001	0.09257	0.0071
	pH	-2.831053	0.50683	<.0001
11	Intercept	26.266885	3.81109	<.0001
	Air Temp	0.115684	0.01854	<.0001
	WS	0.279819	0.09384	0.0045
	pH	-3.09202	0.48223	<.0001
12	Intercept	21.446313	4.66658	0.0003
	Lagoon Temp	0.139203	0.02672	<.0001
	WS	0.342479	0.09143	0.0005
	pH	-2.575565	0.58147	0.0004
13	Intercept	3.694758	0.49199	<.0001
	WS	0.279011	0.0731	0.0004

Table 9-48. 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.

Table 9-49. 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**
	Air Temp	0.026991	0.01578	**0.103**
2	Intercept	0.362633	0.32848	**0.2876**
	Air Temp	0.023929	0.01637	**0.1619**
	ws	0.029956	0.04085	**0.4702**
3	Intercept	0.573781	0.34208	**0.1262**
	ws	0.050215	0.03903	**0.2115**

Table 9-50. 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.

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

10.1 Breeding and Gestation Models

10.1.1 NH_3 Model Evaluation

For the farrowing rooms, the model coefficients from the jackknife approach were comparable across the withheld sets (Table 10-1). Table 10-1 shows the variation in coefficients and standard errors for the selected model 4 and each of the jackknife models. The plots in Figure 10-1 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 live animal weight, 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 10-2, Figure 10-2), as well as for the "pit" model set (Table 10-3, Figure 10-3). 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 live animal weight, while site OK4BB2 falls outside for ambient temperature. Comparing the average values to the selected model, the maximum percent differences for parameter estimates across the "no pit" models were 30%, 40%, and 10% for intercept, ambient temperature and live animal weight, 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 live animal weight, respectively. The largest percent 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 10-1. Model coefficients developed using the jackknife approach for NH_3 emissions from farrowing barns.

	Parameters and Estimates				Fit and Evaluation Statistics					
Site Out	Parameter	Estimate	Standard Error	p-value	LNME (%)	NME (%)	ME (kg day^{-1})	MB (kg day^{-1})	NMB (%)	Corr.
None	Intercept	0.68875	0.01775	<.0001	9.086	55.927	0.169	-0.00119	-0.39215	0.498
	cycleday	0.001961	0.0008	0.0157						
	AmbT	0.000581	0.00029	0.0449						
	LAW	0.008405	0.00154	<.0001						
IA4BF	Intercept	0.784435	0.01932	<.0001	9.295	54.942	0.184	-0.00044	-0.13226	0.331
	cycleday	0.003193	0.00056	<.0001						
	AmbT	0.000101	0.0002	0.6032						
	LAW	0.005396	0.00276	0.0509						
NC4BF	Intercept	0.791997	0.04058	<.0001	8.898	45.099	0.1697	-0.00044	-0.11624	0.402
	cycleday	0.004576	0.00161	0.0049						
	AmbT	0.000276	0.00022	0.2136						
	LAW	0.009463	0.00137	<.0001						
OK4BF	Intercept	0.678472	0.0123	<.0001	4.949	47.966	0.092	-0.00075	-0.38973	0.5
	cycleday	0.001467	0.00056	0.0105						
	AmbT	0.001227	0.00024	<.0001						
	LAW	0.009068	0.00144	<.0001						

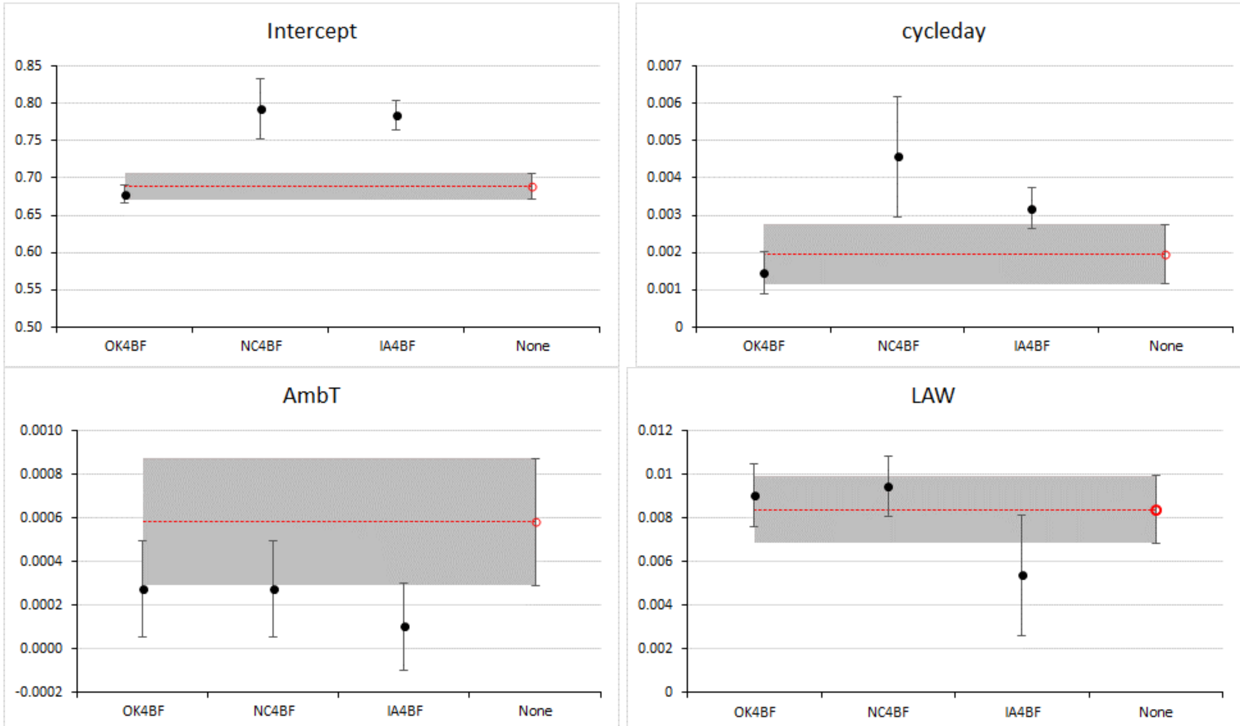

Figure 10-1. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected NH_3 farrowing model coefficient ("None," gray band for ± SE) for each model parameter.

Table 10-2. Model coefficients developed using the jackknife approach for NH_3 emissions from gestation barns, no pit model.

	Parameters and Estimates				Fit and Evaluation Statistics					
Site Out	Parameter	Estimate	Standard Error	p-value	LNME (%)	NME (%)	ME (kg day^{-1})	MB (kg day^{-1})	NMB (%)	Corr.
None	Intercept	0.1548	0.1186	0.1972	12.461	36.699	4.755	-0.652	-5.033	0.546
	AmbT	0.0069	0.0006	<.0001						
	LAW	0.0091	0.0005	<.0001						
IA4BB1	Intercept	0.1850	0.1017	0.0741	10.499	23.485	2.480	-0.155	-1.467	0.774
	AmbT	0.0058	0.0006	<.0001						
	LAW	0.0091	0.0004	<.0001						
IA4BB2	Intercept	0.1834	0.1209	0.1354	11.930	36.821	4.392	-0.708	-5.935	0.540
	AmbT	0.0071	0.0006	<.0001						
	LAW	0.0090	0.0005	<.0001						
NC4BB1	Intercept	0.4524	0.1390	0.0028	11.784	38.524	5.503	-0.638	-4.467	0.502
	AmbT	0.0067	0.0006	<.0001						
	LAW	0.0079	0.0006	<.0001						
NC4BB2	Intercept	-0.0657	0.1341	0.6273	11.691	37.576	5.336	-0.648	-4.565	0.511
	AmbT	0.0065	0.0006	<.0001						
	LAW	0.0101	0.0006	<.0001						
OK4BB1	Intercept	0.1254	0.1237	0.3146	14.286	40.398	5.474	-0.854	-6.303	0.562
	AmbT	0.0065	0.0007	<.0001						
	LAW	0.0093	0.0005	<.0001						
OK4BB2	Intercept	0.0697	0.1306	0.5957	14.699	40.699	5.452	-0.914	-6.822	0.581
	AmbT	0.0097	0.0007	<.0001						
	LAW	0.0092	0.0006	<.0001						

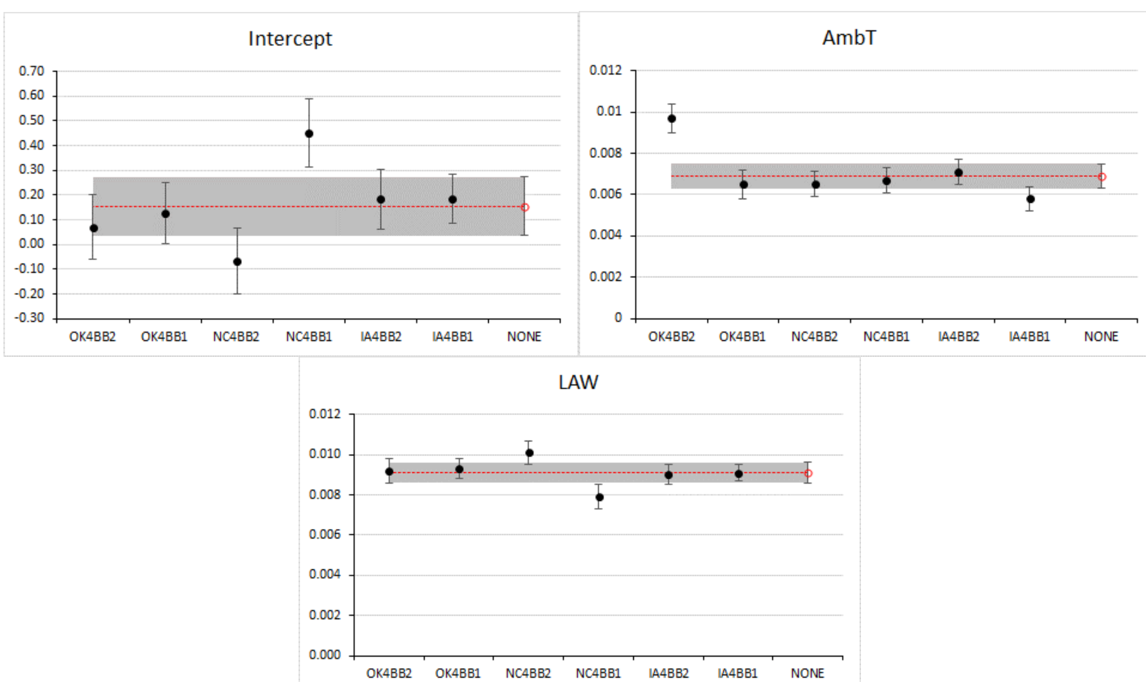

Figure 10-2. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected NH_3 gestation "no pit" model coefficient ("None," gray band for ± SE) for each model parameter.

Table 10-3. Model coefficients developed using the jackknife approach for NH_3 emissions from gestation barns, pit model.

	Parameters and Estimates				Fit and Evaluation Statistics					
Site Out	Parameter	Estimate	Standard Error	p-value	LNME (%)	NME (%)	ME (kg day^{-1})	MB (kg day^{-1})	NMB (%)	Corr.
None	Deep	0.834777	0.26817	0.0025	11.622	31.205	4.043	-0.361	-2.7861	0.653
	Shallow	0.30747	0.20558	0.1382						
	AmbT	0.011778	0.00085	<.0001						
	LAW	0.007899	0.001	<.0001						
IA4BB1	Deep	0.357293	0.18567	0.057	10.278	22.109	2.335	-0.021	-0.1996	0.807
	Shallow	0.168421	0.13529	0.2158						
	AmbT	0.008475	0.00087	<.0001						
	LAW	0.008873	0.00065	<.0001						
IA4BB2	Deep	0.721361	0.226	0.002	11.126	29.146	3.477	-0.405	-3.3943	0.762
	Shallow	0.001492	0.17789	0.9933						
	AmbT	0.013103	0.00092	<.0001						
	LAW	0.009311	0.00086	<.0001						
NC4BB1	Deep	1.331542	0.34521	0.0003	10.575	31.011	4.43	-0.493	-3.4496	0.633
	Shallow	0.762074	0.2798	0.0082						
	AmbT	0.010919	0.00084	<.0001						
	LAW	0.006047	0.00129	<.0001						
NC4BB2	Deep	0.794288	0.34624	0.0245	10.919	31.725	4.505	-0.446	-3.1441	0.621
	Shallow	0.270919	0.28157	0.339						
	AmbT	0.01065	0.00085	<.0001						
	LAW	0.008105	0.0013	<.0001						
OK4BB1	Deep	0.88397	0.34063	0.0113	13.577	35.233	4.774	-0.419	-3.0893	0.661
	Shallow	0.31036	0.24715	0.213						
	AmbT	0.013658	0.00107	<.0001						
	LAW	0.007643	0.00128	<.0001						
OK4BB2	Deep	0.993592	0.33709	0.0042	13.343	34.723	4.651	-0.459	-3.4235	0.671
	Shallow	0.369208	0.24456	0.1352						
	AmbT	0.014208	0.00104	<.0001						
	LAW	0.007204	0.00126	<.0001						

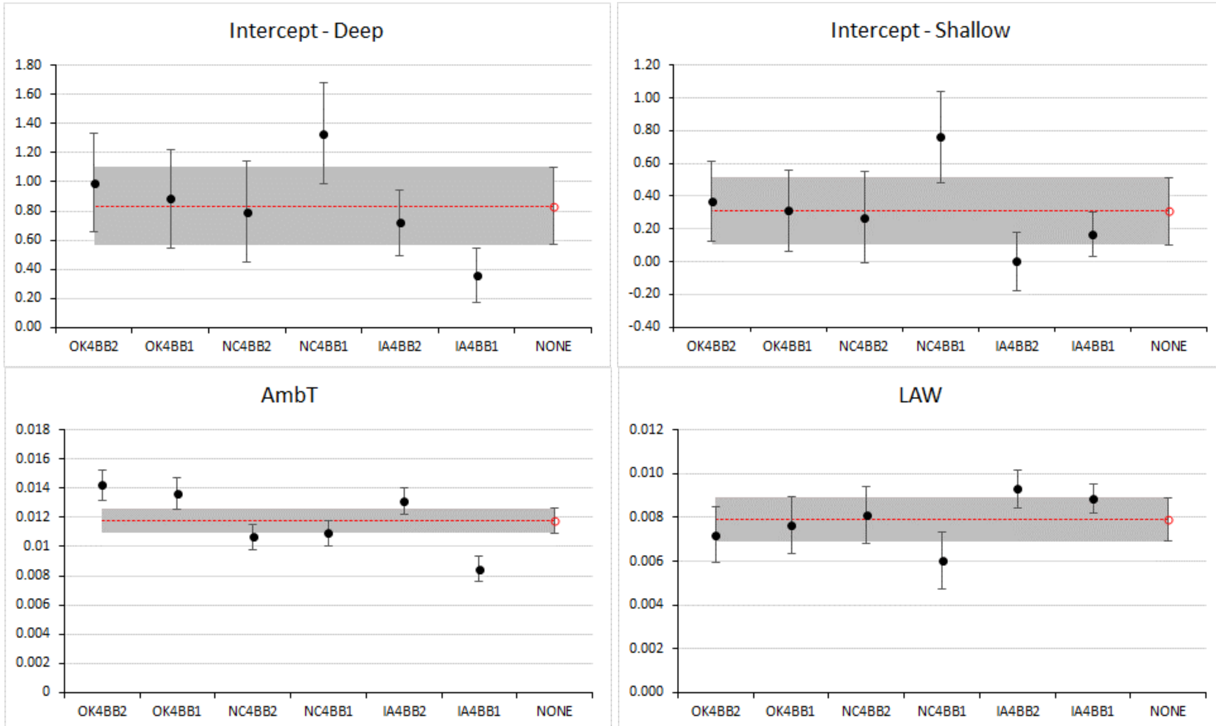

Figure 10-3. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected NH_3 gestation "pit" model coefficient ("None," gray band for ± SE) for each model parameter.

10.1.2 H_2S Model Evaluation

For the farrowing rooms, the coefficients for the jackknife models were fairly consistent across the withheld sets (Table 10-4). Figure 10-4 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 live animal weight, 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 10-5 and Figure 10-5) and "pit" (Table 10-6 and Figure 10-6) 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 live animal weight, respectively.

For the pit model, coefficients differed by 21%, 23%, 64%, and 8% for the deep model intercept, shallow model intercept, ambient temperature, and live animal weight, 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 10-4. Model coefficients developed using the jackknife approach for H_2S emissions from farrowing barns.

Site Out	Parameters and Estimates				Fit and Evaluation Statistics					
	Parameter	Estimate	Standard Error	p-value	LNME (%)	NME (%)	ME (g day-1)	MB (g day-1)	NMB (%)	Corr.
None	Intercept	2.142329	0.12728	<.0001	19.73	70.283	73.785	20.322	19.357	0.521
	cycleday	0.129797	0.00562	<.0001						
	LAW	0.061406	0.01641	0.0002						
IA4BF	Intercept	1.98399	0.19918	<.0001	13.545	62.794	74.321	34.576	29.213	0.642
	cycleday	0.141673	0.00612	<.0001						
	LAW	0.071958	0.03561	0.0438						
NC4BF	Intercept	2.142329	0.12728	<.0001	22.472	70.131	63.162	9.889	10.980	0.523
	cycleday	0.129797	0.00562	<.0001						
	LAW	0.061406	0.01641	0.0002						
OK4BF	Intercept	2.650861	0.15832	<.0001	23.343	76.795	81.23	9.789	9.255	0.45
	cycleday	0.102079	0.00788	<.0001						
	LAW	0.063076	0.01794	0.0005						

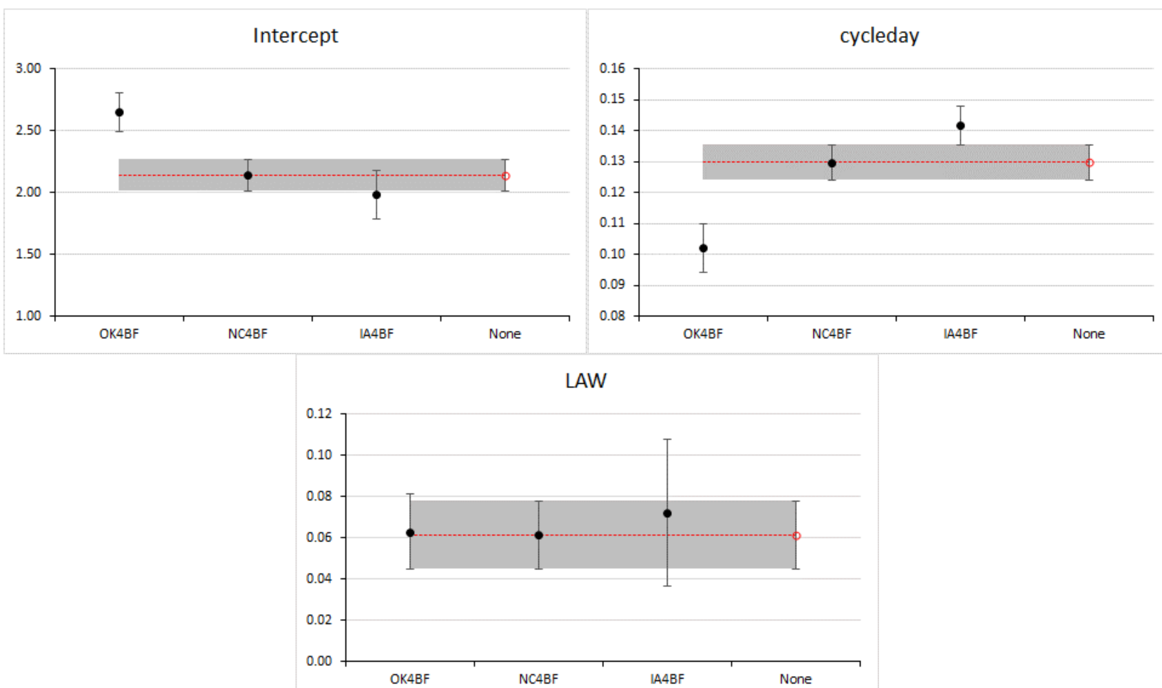

Figure 10-4. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected $H^{2}S$ farrowing model coefficient ("None," gray band for ± SE) for each model parameter.

Table 10-5. Model coefficients developed using the jackknife approach for H_2S emissions from gestation sites, with no pit.

	Parameters and Estimates				Fit and Evaluation Statistics					
Site Out	Parameter	Estimate	Standard Error	p-value	LNME[a] (%)	NME[b] (%)	ME[b] (kg day^{-1})	MB[b] (kg day^{-1})	NMB[b] (%)	Corr.
None	Intercept	2.0773	0.1209	<.0001	8.792	69.332	1594.40	-514.8	-22.387	0.573
	AmbT	0.0035	0.0010	0.0003						
	LAW	0.0199	0.0005	<.0001						
IA4BB1	Intercept	2.1231	0.1183	<.0001	6.667	51.874	733.33	-298.1	-21.089	0.735
	AmbT	0.0019	0.0010	0.0623						
	LAW	0.0198	0.0005	<.0001						
IA4BB2	Intercept	2.0702	0.1219	<.0001	8.346	79.777	1386.20	-438.1	-25.213	0.548
	AmbT	0.0043	0.0010	<.0001						
	LAW	0.0198	0.0005	<.0001						
NC4BB1	Intercept	1.9357	0.1415	<.0001	8.568	69.715	1869.00	-491.4	-18.329	0.542
	AmbT	0.0036	0.0010	0.0003						
	LAW	0.0205	0.0006	<.0001						
NC4BB2	Intercept	2.3780	0.1888	<.0001	8.778	71.326	1951.70	-482.9	-17.649	0.536
	AmbT	0.0033	0.0010	0.0009						
	LAW	0.0186	0.0008	<.0001						
OK4BB1	Intercept	2.0518	0.1262	<.0001	10.219	66.319	1775.10	-651.5	-24.340	0.587
	AmbT	0.0032	0.0012	0.0106						
	LAW	0.0200	0.0006	<.0001						
OK4BB2	Intercept	2.0303	0.1300	<.0001	10.401	66.966	1772.50	-656.7	-24.812	0.594
	AmbT	0.0058	0.0013	<.0001						
	LAW	0.0199	0.0006	<.0001						

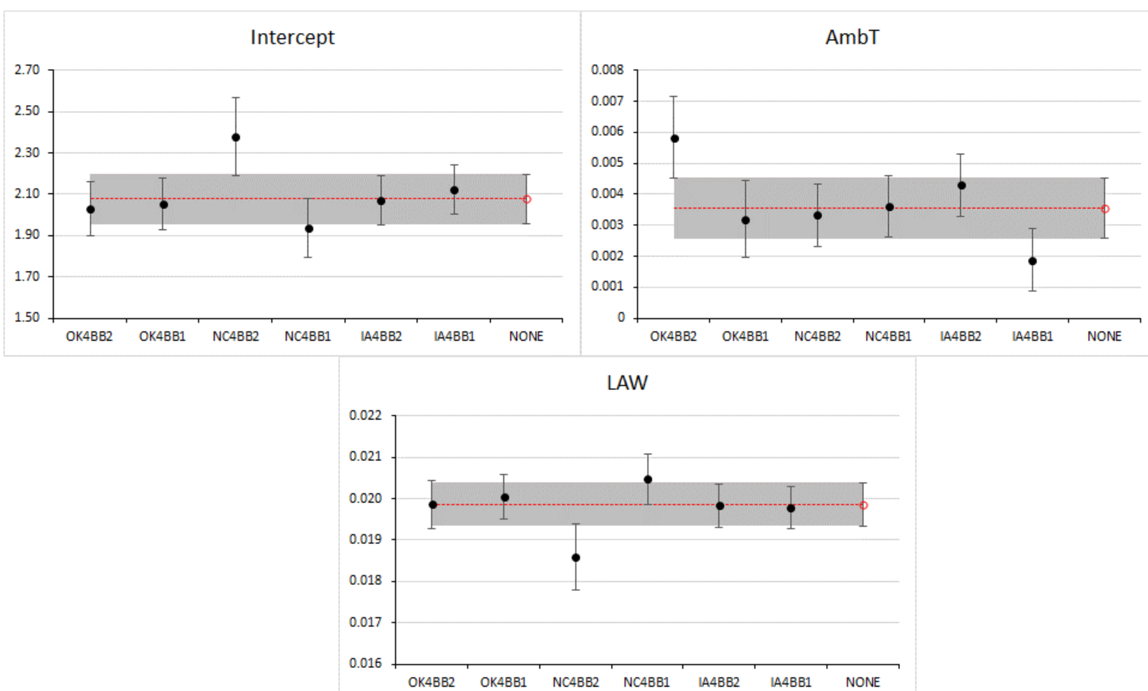

Figure 10-5. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected H_2S gestation "no pit" model coefficient ("None," gray band for ± SE) for each model parameter.

Table 10-6. Model coefficients developed using the jackknife approach for H_2S emissions from gestation sites, with pit.

Site Out	Parameters and Estimates				Fit and Evaluation Statistics					
	Parameter	Estimate	Standard Error	p-value	LNME (%)	NME (%)	ME (g day^{-1})	MB (g day^{-1})	NMB (%)	Corr.
None	Deep	3.171852	0.1471	<.0001	6.078	50.681	1165.5	-241.1	-10.485	0.666
	Shallow	2.130472	0.12289	<.0001						
	AmbT	0.003844	0.00098	0.0001						
	LAW	0.019592	0.00054	<.0001						
IA4BB1	Deep	3.110121	0.15481	<.0001	5.538	38.483	544.03	36.985	2.616	0.791
	Shallow	2.153327	0.12341	<.0001						
	AmbT	0.002188	0.001	0.0295						
	LAW	0.019606	0.00054	<.0001						
IA4BB2	Deep	3.851503	0.10637	<.0001	5.674	44.325	770.2	-46.66	-2.685	0.814
	Shallow	2.069741	0.12368	<.0001						
	AmbT	0.004546	0.00102	<.0001						
	LAW	0.019814	0.00054	<.0001						
NC4BB1	Deep	3.031241	0.16843	<.0001	5.565	50.892	1364.4	-276.5	-10.314	0.639
	Shallow	2.011579	0.1451	<.0001						
	AmbT	0.003921	0.00099	<.0001						
	LAW	0.020098	0.00063	<.0001						
NC4BB2	Deep	3.617535	0.21637	<.0001	5.415	49.723	1360.6	-295.1	-10.787	0.649
	Shallow	2.508618	0.19514	<.0001						
	AmbT	0.003652	0.00099	0.0003						
	LAW	0.017988	0.00084	<.0001						
OK4BB1	Deep	3.134284	0.16218	<.0001	6.896	53.649	1436	-237.7	-8.881	0.651
	Shallow	2.10801	0.12746	<.0001						
	AmbT	0.003664	0.00124	0.0032						
	LAW	0.019735	0.00056	<.0001						
OK4BB2	Deep	3.174794	0.16916	<.0001	6.883	52.622	1392.9	-248.8	-9.398	0.663
	Shallow	2.097823	0.1319	<.0001						
	AmbT	0.006314	0.00131	<.0001						
	LAW	0.019485	0.0006	<.0001						

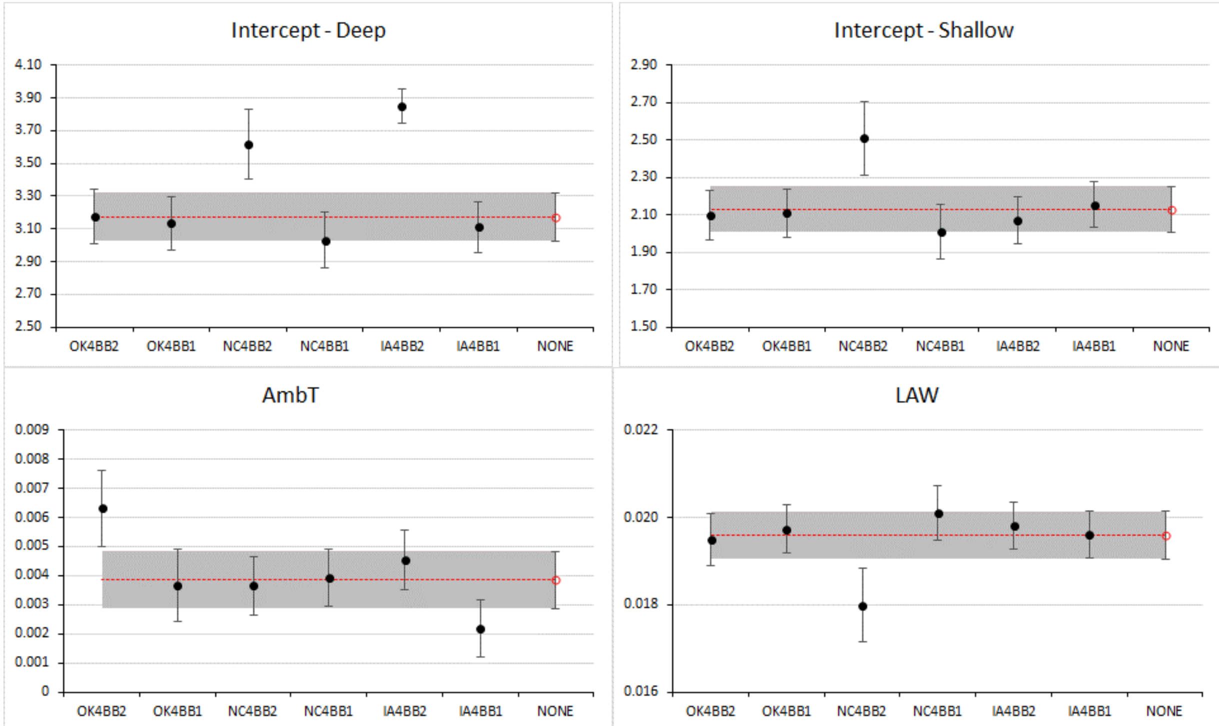

Figure 10-6. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected H_2S gestation "pit" model coefficient ("None," gray band for ± SE) for each model parameter.

10.1.3 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 10-7). Figure 10-7 shows the variation in coefficients and standard errors for the selected model and each of the jackknife models. The plots in Figure 10-7 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, live animal weight, 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, Table 10-8 presents the results of the "minus-one" jackknife approach. Figure 10-8 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 live animal weight. Comparing the withheld models to the selected model, the maximum percentage differences for parameter estimates were 10%, 37%, and 9% for intercept, ambient temperature and live animal weight, respectively.

Table 10-7. Model coefficients developed using the jackknife approach for PM_{10} emissions from farrowing barns.

	Parameters and Estimates				Fit and Evaluation Statistics					
Site Out	**Parameter**	**Estimate**	**Standard Error**	**p-value**	**LNME (%)**	**NME (%)**	**ME (g day-1)**	**MB (g day-1)**	**NMB (%)**	**Corr.**
None	Intercept	2.489915	0.09914	<.0001	9.813	39.112	13.585	0.834	2.400	0.596
	cycleday	0.055625	0.00366	<.0001						
	LAW	0.106263	0.01302	<.0001						
	AmbRH	-0.003436	0.00066	<.0001						
IA4BF	Intercept	2.526142	0.15529	<.0001	7.551	31.397	12.171	0.664	1.713	0.734
	cycleday	0.068382	0.00424	<.0001						
	LAW	0.085696	0.02531	0.0011						
	AmbRH	-0.002824	0.00072	0.0001						
NC4BF	Intercept	2.274249	0.12651	<.0001	10.914	43.422	16.071	2.925	7.903	0.544
	cycleday	0.069256	0.00429	<.0001						
	LAW	0.126377	0.01783	<.0001						
	AmbRH	-0.003002	0.00089	0.0008						
OK4BF	Intercept	2.700754	0.11819	<.0001	10.199	38.91	10.79	0.578	2.085	0.478
	cycleday	0.039055	0.00458	<.0001						
	LAW	0.075749	0.01415	<.0001						
	AmbRH	-0.003791	0.00082	<.0001						

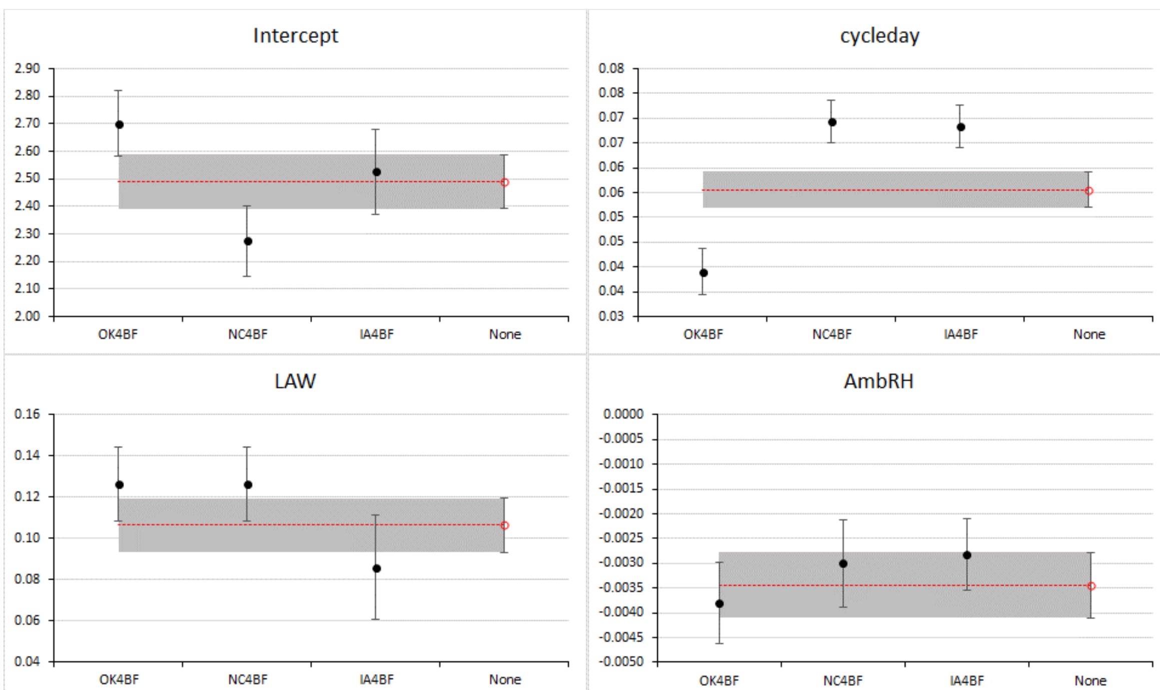

Figure 10-7. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected PM_{10} farrowing model coefficient ("None," gray band for ± SE) for each model parameter.

Table 10-8. Model coefficients developed using the jackknife approach for PM_{10} emissions from gestation sites.

Site Out	Parameters and Estimates				Fit and Evaluation Statistics					
	Parameter	Estimate	Standard Error	p-value	LNME (%)	NME (%)	ME (g day^{-1})	MB (g day^{-1})	NMB (%)	Corr.
None	Intercept	5.186761	0.17987	<.0001	2.167	39.471	17.033	-0.012	-0.028	0.201
	LAW	0.005472	0.00076	<.0001						
	AmbRH	-0.007661	0.00053	<.0001						
IA4BB1	Intercept	5.140164	0.19635	<.0001	2.335	43.415	18.252	-0.019	-0.044	0.189
	LAW	0.005613	0.00084	<.0001						
	AmbRH	-0.007407	0.00058	<.0001						
IA4BB2	Intercept	5.290841	0.20881	<.0001	1.945	36.679	15.027	-0.007	-0.017	0.132
	LAW	0.004953	0.0009	<.0001						
	AmbRH	-0.007869	0.00055	<.0001						
NC4BB1	Intercept	5.683417	0.26176	<.0001	2.299	41.154	18.320	-0.007	-0.016	0.151
	LAW	0.003426	0.00109	0.0035						
	AmbRH	-0.007389	0.00058	<.0001						
NC4BB2	Intercept	5.035882	0.18558	<.0001	2.338	42.093	18.313	-0.012	-0.028	0.229
	LAW	0.006124	0.00078	<.0001						
	AmbRH	-0.007867	0.00057	<.0001						
OK4BB1	Intercept	5.248244	0.18492	<.0001	1.920	33.104	15.659	-0.017	-0.037	0.263
	LAW	0.005539	0.00077	<.0001						
	AmbRH	-0.008026	0.00062	<.0001						
OK4BB2	Intercept	5.209886	0.18475	<.0001	2.043	38.978	15.856	-0.006	-0.015	0.221
	LAW	0.004424	0.00078	<.0001						
	AmbRH	-0.007	0.00064	<.0001						

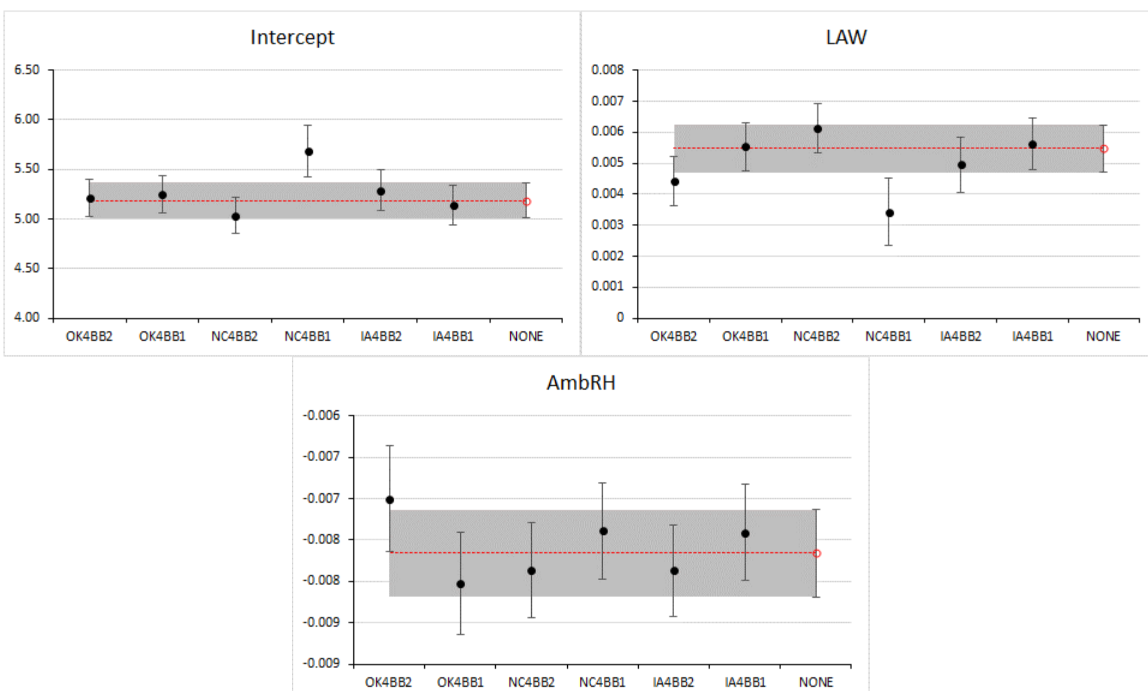

Figure 10-8. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected PM_{10} gestation model coefficient ("None," gray band for ± SE) for each model parameter.

10.1.4 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 10-9). The plots in Figure 10-9 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 live animal weight. 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 live animal weight, 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 10-10 presents the results of the "minus-one" jackknife approach. The plots (Figure10-10) 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 live animal weight, 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 10-9. Model coefficients developed using the jackknife approach for PM$_{2.5}$ emissions from farrowing barns.

Site Out	Parameters and Estimates				Fit and Evaluation Statistics					
	Parameter	Estimate	Standard Error	p-value	LNME (%)	NME (%)	ME (g day^{-1})	MB (g day^{-1})	NMB (%)	Corr.
None	Intercept	-1.21456	0.19779	<.0001	58.639	53.647	1.900	0.364	10.266	0.548
	cycleday	0.075902	0.00225	<.0001						
	LAW	0.256357	0.03492	<.0001						
IA4BF	Intercept	-2.128576	0.36318	0.0027	18.786	18.716	0.691	0.053	1.429	0.948
	cycleday	0.068876	0.00542	<.0001						
	LAW	0.421707	0.06499	0.0017						
NC4BF	Intercept	-0.951649	0.22029	<.0001	66.67	64.214	2.596	0.55	13.615	0.504
	cycleday	0.077615	0.0023	<.0001						
	LAW	0.212175	0.0392	<.0001						
OK4BF	Intercept	-1.385241	0.16117	<.0001	57.594	60.33	1.86	0.416	13.481	0.19
	cycleday	0.074381	0.00859	<.0001						
	LAW	0.230567	0.02857	<.0001						

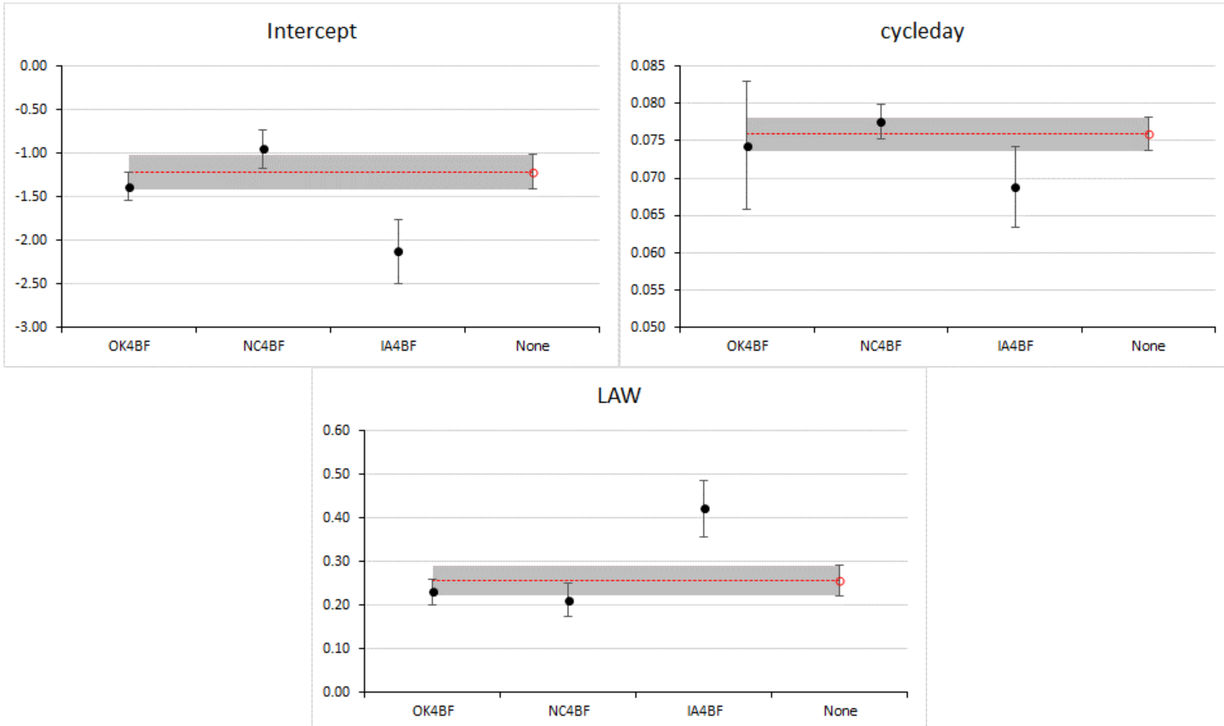

Figure 10-9. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected $PM_{2.5}$ farrowing model coefficient ("None," gray band for ± SE) for each model parameter.

Table 10-10. Model coefficients developed using the jackknife approach for $PM_{2.5}$ emissions from gestation barns.

Site Out	Parameters and Estimates				Fit and Evaluation Statistics					
	Parameter	Estimate	Standard Error	p-value	LNME (%)	NME (%)	ME (g day^{-1})	MB (g day^{-1})	NMB (%)	Corr.
None	Intercept	4.88715	0.07109	<.0001	2.167	39.471	17.033	-0.012	-0.0283	0.201
	LAW	0.0007	0.00031	0.027						
IA4BB1	Intercept	4.900209	0.07571	<.0001	2.335	43.415	18.252	-0.019	-0.0440	0.189
	LAW	0.000623	0.00034	0.0712						
IA4BB2	Intercept	4.935704	0.06516	<.0001	1.945	36.679	15.027	-0.007	-0.0167	0.132
	LAW	0.00045	0.0003	0.1353						
NC4BB1	Intercept	4.905205	0.09643	<.0001	2.299	41.154	18.32	-0.007	-0.0156	0.151
	LAW	0.000629	0.0004	0.126						
NC4BB2	Intercept	4.809812	0.09443	<.0001	2.338	42.093	18.313	-0.012	-0.0282	0.229
	LAW	0.001008	0.0004	0.0138						
OK4BB1	Intercept	4.890792	0.06903	<.0001	1.92	33.104	15.659	-0.017	-0.0368	0.263
	LAW	0.000809	0.0003	0.0099						
OK4BB2	Intercept	4.878499	0.07977	<.0001	2.043	38.978	15.856	-0.006	-0.0147	0.221
	LAW	0.000679	0.00035	0.0574						

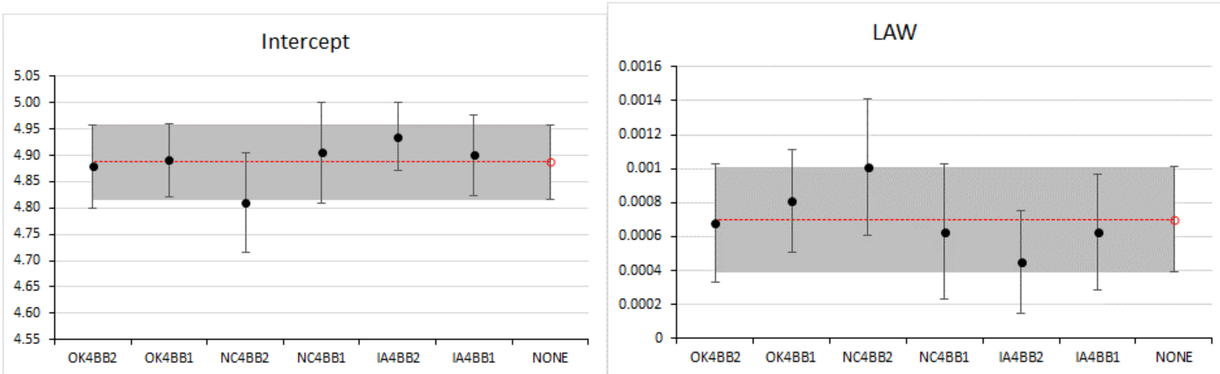

Figure 10-10. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected $PM_{2.5}$ gestation model coefficient ("None," gray band for ± SE) for each model parameter.

10.1.5 TSP Model Evaluation

For the farrowing rooms, the model coefficients from the jackknife approach were all significant and comparable across the withheld sets (Table 10-11). The plots in Figure 10-11 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 live animal weight. 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, live animal weight, 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 10-12 presents the results of the jackknife approach. The plots (Figure 10-12) show 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, live animal weight, 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 10-11. Model coefficients developed using the jackknife approach for TSP emissions from farrowing barns.

Site Out	Parameters and Estimates				Fit and Evaluation Statistics					
	Parameter	Estimate	Standard Error	p-value	LNME[a] (%)	NME (%)	ME (kg day^{-1})	MB (kg day^{-1})	NMB (%)	Corr.
None	Intercept	2.858928	0.47281	<.0001	10.953	41.732	40.709	1.883	1.930	0.618
	cycleday	0.070551	0.01348	<.0001						
	LAW	0.147305	0.07879	0.0679						
	AmbRH	-0.004908	0.00263	0.0644						
IA4BF	Intercept	1.740335	0.6517	0.0105	8.823	32.868	37.179	6.706	5.929	0.811
	cycleday	0.077898	0.0139	<.0001						
	LAW	0.356794	0.10285	0.0014						
	AmbRH	-0.004685	0.00301	0.1236						
NC4BF	Intercept	3.186904	0.64065	<.0001	10.192	41.883	40.973	3.472	3.549	0.62
	cycleday	0.085413	0.01804	<.0001						
	LAW	0.043285	0.1202	0.7205						
	AmbRH	-0.002136	0.00264	0.4208						
OK4BF	Intercept	3.294123	0.51839	<.0001	11.831	43.321	34.273	0.894	1.130	0.532
	cycleday	0.059449	0.01675	0.0016						
	LAW	0.081324	0.08216	0.3306						
	AmbRH	-0.00668	0.00468	0.1583						

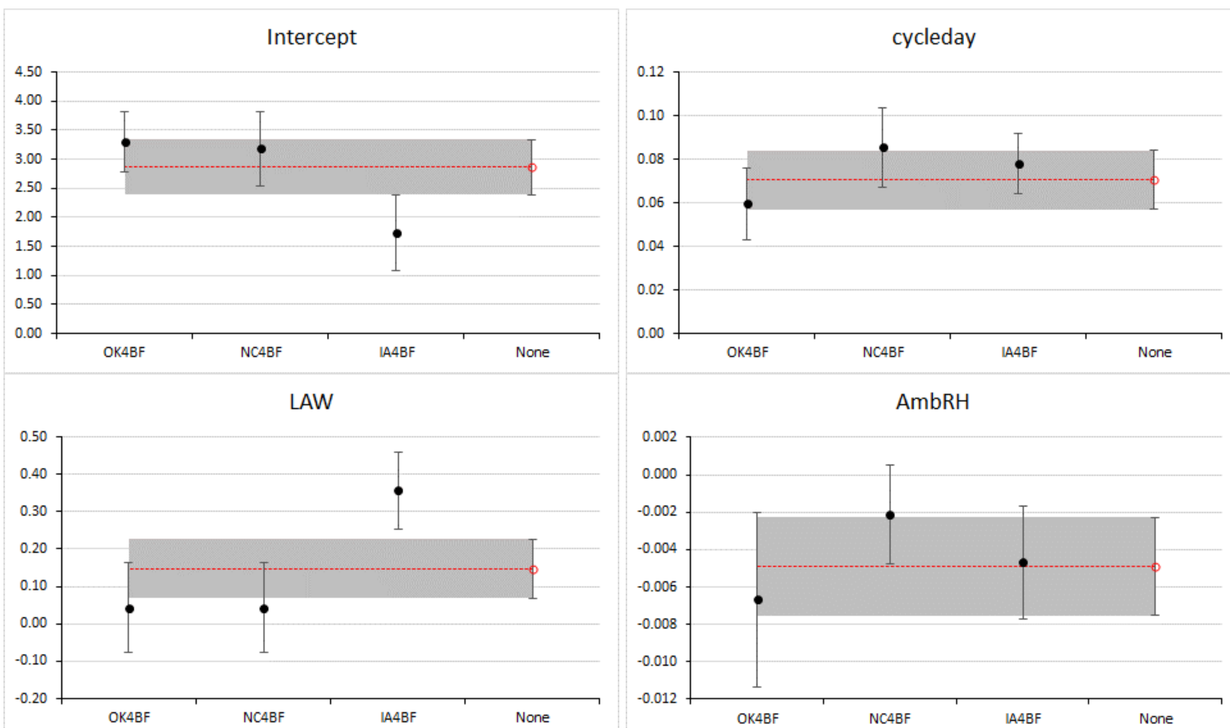

Figure 10-11. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected TSP farrowing model coefficient (“None,” gray band for ± SE) for each model parameter.

Table 10-12. Model coefficients developed using the jackknife approach for TSP emissions from gestation barns.

	Parameters and Estimates				Fit and Evaluation Statistics					
Site Out	Parameter	Estimate	Standard Error	p-value	LNME (%)	NME (%)	ME (g day^{-1})	MB (g day^{-1})	NMB (%)	Corr.
None	Intercept	5.533966	0.56243	<.0001						
	LAW	0.006601	0.0023	0.012	7.147	39.887	281.19	9.735	1.381	0.399
	AmbRH	-0.008	0.00126	<.0001						
IA4BB1	Intercept	5.498281	0.70079	<.0001						
	LAW	0.006729	0.00306	0.0449	6.695	38.083	267.26	11.2	1.596	0.434
	AmbRH	-0.007809	0.0013	<.0001						
IA4BB2	Intercept	5.959879	0.56781	<.0001						
	LAW	0.004523	0.00231	0.0727	7.216	39.657	255.65	2.54	0.394	0.373
	AmbRH	-0.008112	0.00129	<.0001						
NC4BB1	Intercept	5.766295	0.63247	<.0001						
	LAW	0.005532	0.00258	0.0712	6.918	39.513	292.4	5.315	0.718	0.315
	AmbRH	-0.007425	0.00127	<.0001						
NC4BB2	Intercept	5.096022	0.57473	<.0001						
	LAW	0.00827	0.00235	0.0041	7.044	39.328	284.86	6.745	0.931	0.409
	AmbRH	-0.007702	0.0013	<.0001						
OK4BB1	Intercept	5.657414	0.55129	<.0001						
	LAW	0.006356	0.00221	0.0116	7.193	38.896	286.84	5.434	0.737	0.452
	AmbRH	-0.007913	0.00167	<.0001						
OK4BB2	Intercept	5.595466	0.59389	<.0001						
	LAW	0.006677	0.00239	0.0149	7.76	43.236	294.98	15.978	2.342	0.401
	AmbRH	-0.009585	0.00154	<.0001						

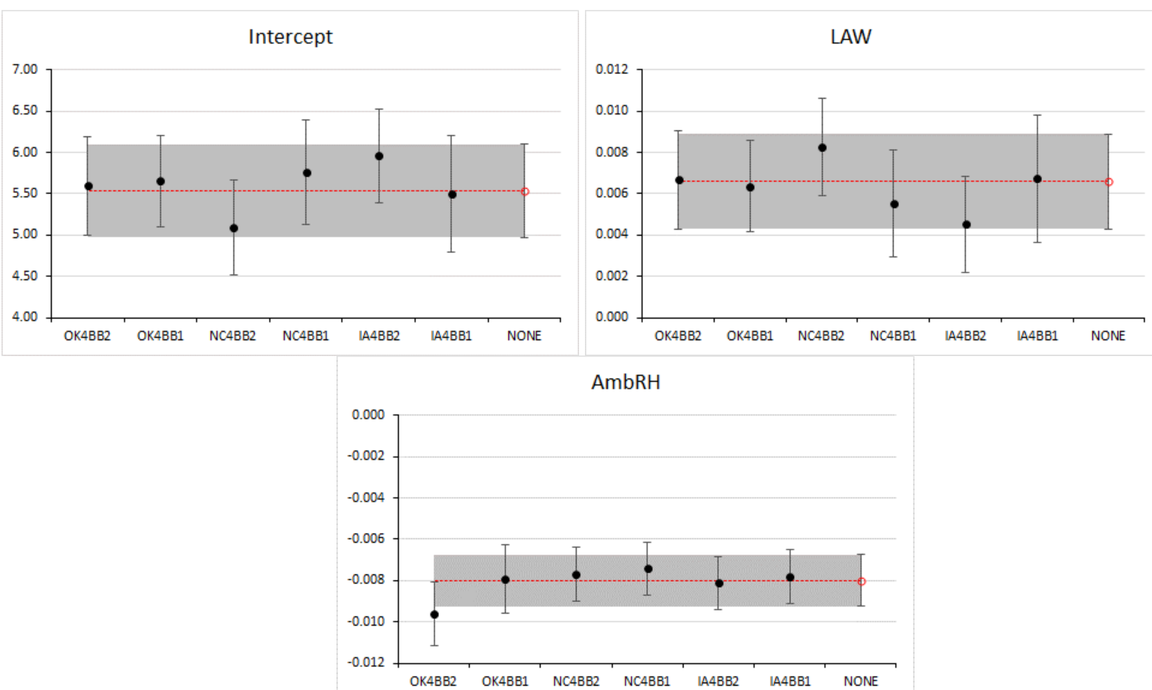

Figure 10-12. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected TSP gestation model coefficient (“None,” gray band for ± SE) for each model parameter.

10.2 Finishing Operation Models

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 live animal weight 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 live animal weight in the development of the models.

10.2.1 NH_3 Model Evaluation

The model coefficients developed for the “no pit” (Table 10-13) and “pit” (Table 10-14) model sets using the jackknife approach were comparable. Figure 10-13 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 live animal weight, respectively. For the deep pit model, coefficients differed by 5.5%, 24.4%, and 6.1% for intercept, ambient temperature, and live animal weight, respectively. Results for the shallow pit model were similar: 4.8%, 24.4%, and 5.2% for intercept, ambient temperature, and live animal weight, respectively. EPA identified the 24.4% difference for each model set with the IN3BR5-withheld 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 10-13. Model coefficients developed using the jackknife approach for NH_3 emissions from Grow-Finish sites, no pit.

Site Out	Parameters and Estimates				Fit and Evaluation Statistics					
	Parameter	Estimate	Standard Error	p-value	LNME (%)	NME (%)	ME (kg day^{-1})	MB (kg day^{-1})	NMB (%)	Corr.
None	Intercept	1.236262	0.03916	<.0001	13.338	27.435	1.673	0.027	0.439	0.661
	Ambient Temp	0.008953	0.00081	<.0001						
	LAW	0.008939	0.00051	<.0001						
IN3BR5	Intercept	1.159515	0.04028	<.0001	13.370	27.375	1.615	0.009	0.149	0.686
	Ambient Temp	0.011134	0.00086	<.0001						
	LAW	0.009210	0.00054	<.0001						
IN3BR6	Intercept	1.205131	0.04076	<.0001	13.516	27.961	1.641	0.017	0.283	0.643
	Ambient Temp	0.008839	0.00085	<.0001						
	LAW	0.008823	0.00054	<.0001						
IN3BR7	Intercept	1.279189	0.04393	<.0001	13.715	28.179	1.697	0.007	0.122	0.629
	Ambient Temp	0.008970	0.00084	<.0001						
	LAW	0.008414	0.00058	<.0001						
IN3BR8	Intercept	1.218012	0.04373	<.0001	13.778	28.367	1.704	0.025	0.422	0.636
	Ambient Temp	0.010143	0.00085	<.0001						
	LAW	0.008719	0.00058	<.0001						
NC3BB1	Intercept	1.244118	0.04194	<.0001	12.532	26.149	1.644	0.073	1.163	0.682
	Ambient Temp	0.007587	0.00088	<.0001						
	LAW	0.009461	0.00055	<.0001						
NC3BB2	Intercept	1.265149	0.04267	<.0001	13.073	26.818	1.697	0.044	0.702	0.677
	Ambient Temp	0.007875	0.00092	<.0001						
	LAW	0.009192	0.00055	<.0001						
NC3BB3	Intercept	1.308254	0.04299	<.0001	13.010	26.639	1.684	0.011	0.172	0.674
	Ambient Temp	0.007772	0.00091	<.0001						
	LAW	0.008520	0.00055	<.0001						

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

Table 10-14. Model coefficients developed using the jackknife approach for NH_3 emissions from Grow-Finish sites.

Site Removed	Parameters and Estimates				Fit and Evaluation Statistics					
	Parameter	Estimate	Standard Error	p-value	LNME (%)	NME (%)	ME (kg day^{-1})	MB (kg day^{-1})	NMB (%)	Corr.
None	Deep	1.342386	0.04249	<.0001	12.346	25.799	1.573	0.049	0.798	0.696
	Shallow	1.142239	0.04362	<.0001						
	Ambient Temp	0.009077	0.00081	<.0001						
	LAW	0.008545	0.00051	<.0001						
IN3BR5	Deep	1.268263	0.04527	<.0001	12.533	25.892	1.527	0.034	0.581	0.712
	Shallow	1.087888	0.04289	<.0001						
	Ambient Temp	0.011289	0.00086	<.0001						
	LAW	0.008858	0.00054	<.0001						
IN3BR6	Deep	1.301069	0.04798	<.0001	12.905	26.982	1.583	0.023	0.397	0.667
	Shallow	1.150047	0.04535	<.0001						
	Ambient Temp	0.008912	0.00085	<.0001						
	LAW	0.008442	0.00056	<.0001						
IN3BR7	Deep	1.400621	0.04613	<.0001	12.325	25.860	1.557	0.034	0.562	0.682
	Shallow	1.163358	0.04533	<.0001						
	Ambient Temp	0.009068	0.00084	<.0001						
	LAW	0.008101	0.00056	<.0001						
IN3BR8	Deep	1.384624	0.04800	<.0001	12.476	26.094	1.567	0.054	0.899	0.684
	Shallow	1.136793	0.04572	<.0001						
	Ambient Temp	0.010155	0.00085	<.0001						
	LAW	0.008252	0.00057	<.0001						
NC3BB1	Deep	1.326421	0.04361	<.0001	11.641	24.657	1.550	0.095	1.512	0.716
	Shallow	1.133037	0.04857	<.0001						
	Ambient Temp	0.007736	0.00088	<.0001						
	LAW	0.009070	0.00054	<.0001						
NC3BB2	Deep	1.335902	0.04440	<.0001	12.257	25.646	1.623	0.067	1.058	0.702
	Shallow	1.152681	0.05139	<.0001						
	Ambient Temp	0.008016	0.00092	<.0001						
	LAW	0.008872	0.00055	<.0001						
NC3BB3	Deep	1.380227	0.04424	<.0001	12.037	25.025	1.582	0.037	0.578	0.705
	Shallow	1.180283	0.05007	<.0001						
	Ambient Temp	0.007897	0.00090	<.0001						
	LAW	0.008250	0.00054	<.0001						

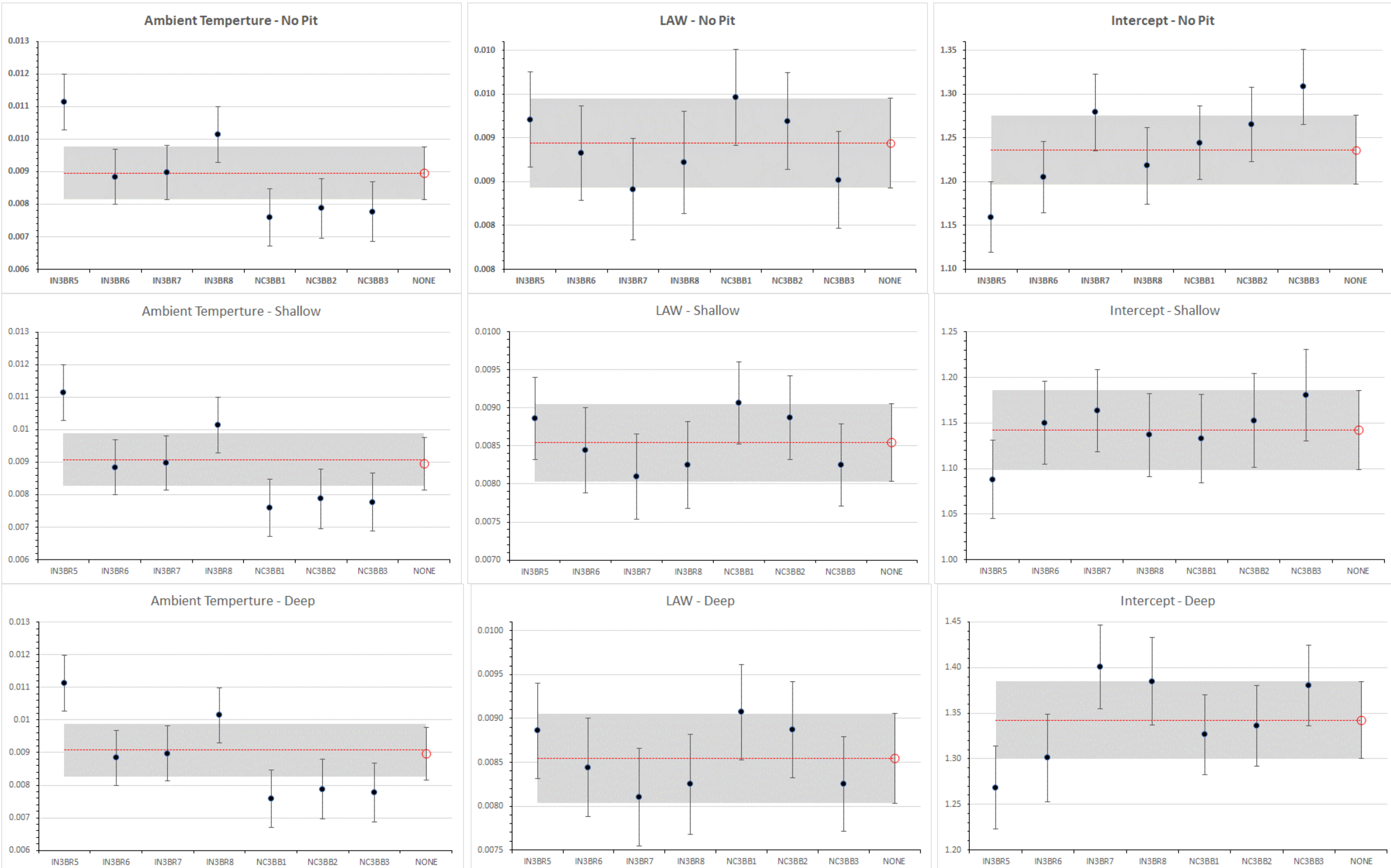

Figure 10-13. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected NH_3 Grow-Finish model coefficient ("None," gray band for ± SE) for each model parameter. Plots are for the ambient temperature (left column), and live animal weight (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.

10.2.2 H_2S Model Evaluation

EPA developed the jackknife model coefficients by removing one barn/room from the dataset and re-running the model. Tables 10-15 and 10-16 show the results for the “no pit” and “pit” model sets, respectively. Figure 10-14 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 live animal weight, respectively. For the deep pit model, coefficients differed by 2.5%, 46.7% and 8.5% for the intercept, ambient temperature, and live animal weight, respectively. EPA identified similar results for the shallow pit model: 1.6%, 46.7%, and 8.5% for the intercept, ambient temperature and live animal weight, 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 grow. 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 10-15. Model coefficients developed using the jackknife approach for H_2S emissions from Grow-Finish sites, no pits.

Site Out	Parameters and Estimates				Fit and Evaluation Statistics					
	Parameter	Estimate	Standard Error	p-value	LNME (%)	NME (%)	ME (g day^{-1})	MB (g day^{-1})	NMB (%)	Corr.
None	Intercept	4.081979	0.09500	<.0001	17.483	84.295	295.66	17.283	4.927	0.384
	Ambient Temp	-0.006592	0.00161	<.0001						
	LAW	0.017163	0.00151	<.0001						
IN3BR5	Intercept	4.091295	0.10141	<.0001	17.227	82.090	280.39	9.454	2.768	0.413
	Ambient Temp	-0.007782	0.00193	<.0001						
	LAW	0.017289	0.00165	<.0001						
IN3BR6	Intercept	4.058112	0.10045	<.0001	16.490	83.607	258.10	17.010	5.51	0.382
	Ambient Temp	-0.008481	0.00183	<.0001						
	LAW	0.018223	0.00162	<.0001						
IN3BR7	Intercept	4.051440	0.09861	<.0001	16.986	81.873	280.31	13.208	3.858	0.413
	Ambient Temp	-0.005896	0.00169	0.0005						
	LAW	0.017365	0.00160	<.0001						
IN3BR8	Intercept	3.983525	0.09837	<.0001	17.034	84.137	257.99	14.075	4.59	0.376
	Ambient Temp	-0.003048	0.00182	**0.0948**						
	LAW	0.017642	0.00158	<.0001						
NC3BB1	Intercept	4.181300	0.10874	<.0001	17.875	84.646	329.79	23.598	6.057	0.364
	Ambient Temp	-0.006764	0.00166	<.0001						
	LAW	0.016476	0.00169	<.0001						
NC3BB2	Intercept	4.117450	0.10952	<.0001	18.355	85.228	328.52	22.167	5.751	0.368
	Ambient Temp	-0.006868	0.00166	<.0001						
	LAW	0.016516	0.00168	<.0001						
NC3BB3	Intercept	4.113334	0.10710	<.0001	18.289	85.889	330.34	22.018	5.725	0.366
	Ambient Temp	-0.007277	0.00167	<.0001						
	LAW	0.016486	0.00166	<.0001						

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

Table 10-16. Model coefficients developed using the jackknife approach for H_2S emissions from Grow-Finish sites, deep and shallow pits.

Site Out	Parameters and Estimates				Fit and Evaluation Statistics					
	Parameter	Estimate	Standard Error	p-value	LNME (%)	NME (%)	ME (g day^{-1})	MB (g day^{-1})	NMB (%)	Corr.
None	Deep	4.991579	0.15159	<.0001	16.247	76.412	268.00	3.241	0.924	0.469
	Shallow	4.190492	0.15138	<.0001						
	Ambient Temp	-0.005539	0.00202	0.0062						
	LAW	0.013317	0.00173	<.0001						
IN3BR5	Deep	5.079570	0.16063	<.0001	15.663	72.420	247.36	-0.820	-0.24	0.515
	Shallow	4.214277	0.14627	<.0001						
	Ambient Temp	-0.006483	0.00234	0.0057						
	LAW	0.013275	0.00184	<.0001						
IN3BR6	Deep	4.878786	0.16019	<.0001	15.899	77.493	239.23	5.368	1.739	0.46
	Shallow	4.159743	0.14659	<.0001						
	Ambient Temp	-0.006517	0.00228	0.0042						
	LAW	0.014453	0.00183	<.0001						
IN3BR7	Deep	5.116008	0.15622	<.0001	15.350	72.071	246.75	2.553	0.746	0.516
	Shallow	4.190931	0.14172	<.0001						
	Ambient Temp	-0.004186	0.00218	**0.0555**						
	LAW	0.012858	0.00181	<.0001						
IN3BR8	Deep	4.807978	0.16395	<.0001	16.295	77.335	237.14	-0.540	-0.176	0.457
	Shallow	4.122399	0.15098	<.0001						
	Ambient Temp	-0.002952	0.00228	**0.1956**						
	LAW	0.013816	0.00187	<.0001						
NC3BB1	Deep	4.982270	0.17095	<.0001	16.618	77.963	303.75	10.534	2.704	0.435
	Shallow	4.221809	0.19706	<.0001						
	Ambient Temp	-0.005709	0.00204	0.0052						
	LAW	0.013452	0.00194	<.0001						
NC3BB2	Deep	5.022033	0.16888	<.0001	16.910	78.055	300.87	6.635	1.721	0.444
	Shallow	4.189982	0.19648	<.0001						
	Ambient Temp	-0.006173	0.00205	0.0026						
	LAW	0.012906	0.00189	<.0001						
NC3BB3	Deep	5.038359	0.16491	<.0001	16.751	78.111	300.42	3.904	1.015	0.444
	Shallow	4.216006	0.19177	<.0001						
	Ambient Temp	-0.006697	0.00210	0.0014						
	LAW	0.012768	0.00186	<.0001						

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

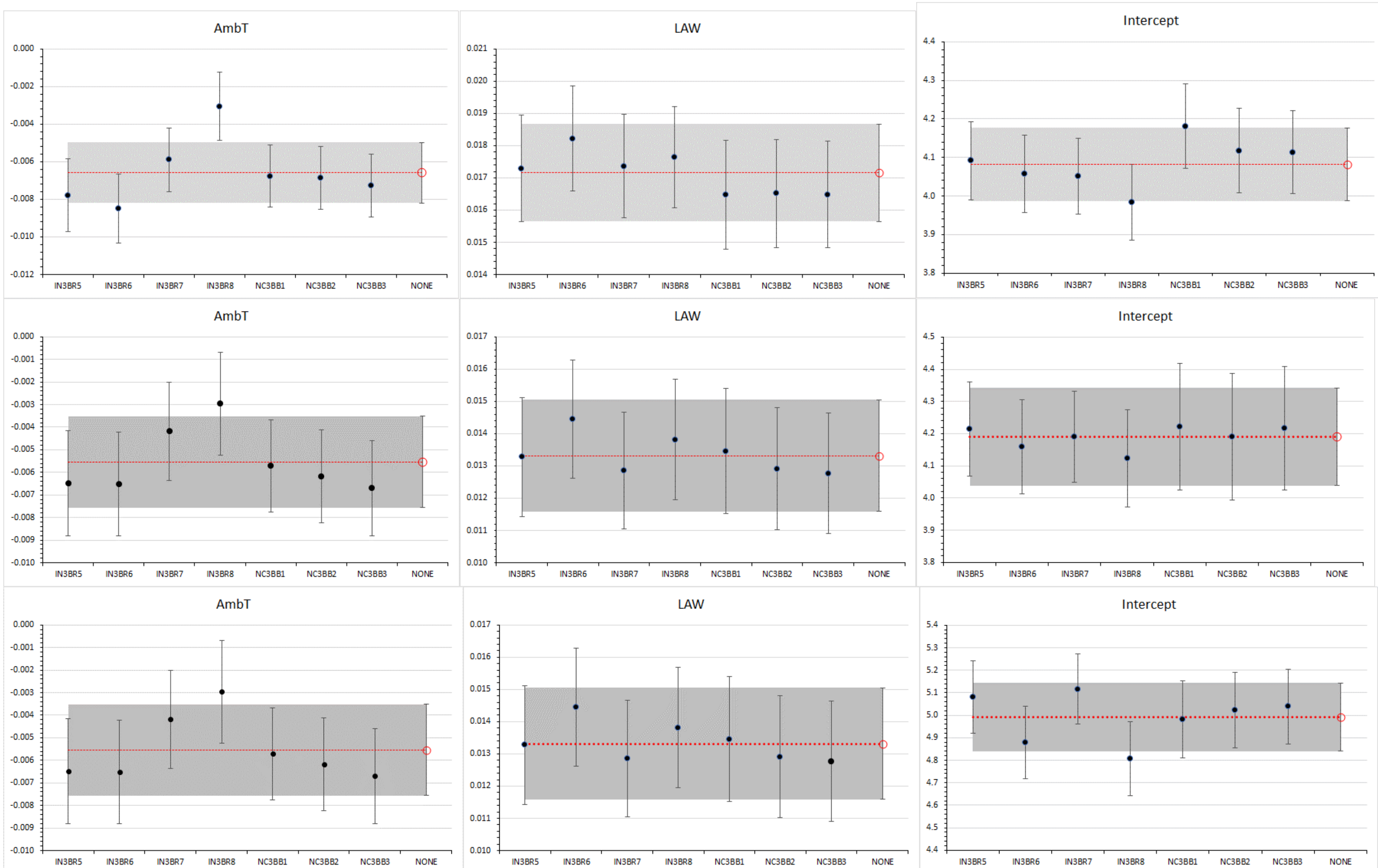

Figure 10-14. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected H_2S Grow-Finish model coefficient ("None," gray band for ± SE) for each model parameter. Plots are for the ambient temperature (left column), and live animal weight (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.

10.2.3 PM_{10} Model Evaluation

The model coefficients developed using the jackknife approach were comparable (Table 10-17). Figure 10-15 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 live animal weight, 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 10-17. Model coefficients developed using the jackknife approach for PM_{10} emissions from Grow-Finish sites.

Site Out	Parameters and Estimates				Fit and Evaluation Statistics					
	Parameter	Estimate	Standard Error	p-value	LNME (%)	NME (%)	ME (kg day^{-1})	MB (kg day^{-1})	NMB (%)	Corr.
None	Intercept	5.503943	0.04999	<.0001	5.126	37.858	70.505	4.299	2.308	0.560
	LAW	0.010447	0.00066	<.0001						
	Ambient RH	-0.009403	0.00044	<.0001						
IN3BR5	Intercept	5.526831	0.05124	<.0001	5.229	38.870	70.954	4.109	2.251	0.546
	LAW	0.010664	0.00068	<.0001						
	Ambient RH	-0.009915	0.00046	<.0001						
IN3BR6	Intercept	5.498268	0.05156	<.0001	5.082	37.792	68.485	3.790	2.091	0.573
	LAW	0.010654	0.00069	<.0001						
	Ambient RH	-0.009537	0.00045	<.0001						
IN3BR7	Intercept	5.511390	0.05231	<.0001	5.014	36.951	68.849	4.538	2.435	0.574
	LAW	0.011075	0.00072	<.0001						
	Ambient RH	-0.009645	0.00045	<.0001						
IN3BR8	Intercept	5.510694	0.04989	<.0001	4.729	35.576	66.230	3.637	1.954	0.601
	LAW	0.010640	0.00064	<.0001						
	Ambient RH	-0.009542	0.00045	<.0001						
NC3BB1	Intercept	5.457815	0.05712	<.0001	5.305	39.238	72.748	5.183	2.796	0.542
	LAW	0.010223	0.00073	<.0001						
	Ambient RH	-0.009031	0.00051	<.0001						
NC3BB2	Intercept	5.450092	0.05567	<.0001	5.212	38.166	72.232	5.473	2.892	0.550
	LAW	0.010414	0.00071	<.0001						
	Ambient RH	-0.008723	0.00050	<.0001						
NC3BB3	Intercept	5.552647	0.05751	<.0001	5.309	38.314	74.010	3.219	1.667	0.540
	LAW	0.009572	0.00072	<.0001						
	Ambient RH	-0.009218	0.00050	<.0001						

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

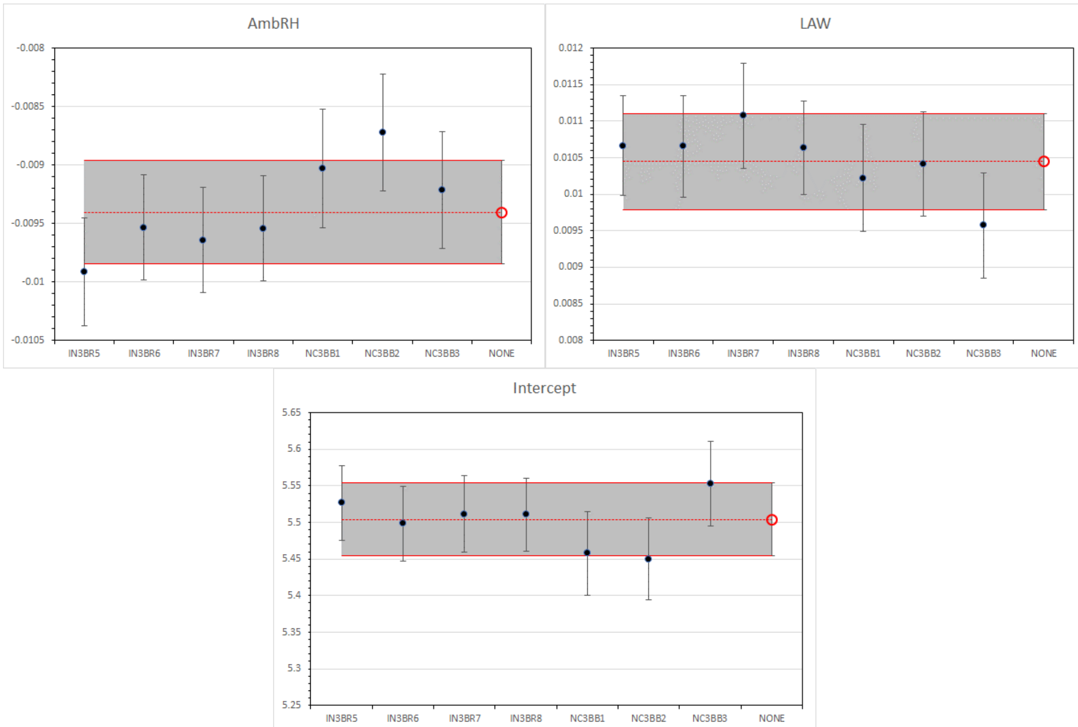

Figure 10-15. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected PM_{10} Grow-Finish model coefficient ("None," gray band for ± SE) for each model parameter.

10.2.4 $PM_{2.5}$ Model Evaluation

The model coefficients developed using the jackknife approach were comparable (see Table 10-18). Figure 10-16 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 live animal weight, 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 10-18. Model coefficients developed using the jackknife approach for $PM_{2.5}$ emissions from Grow-Finish sites.

Site Out	Parameters and Estimates				Fit and Evaluation Statistics					
	Parameter	Estimate	Standard Error	p-value	LNME (%)	NME (%)	ME (kg day^{-1})	MB (kg day^{-1})	NMB (%)	Corr.
None	Intercept	2.495430	0.19623	<.0001	9.852	52.742	6.123	0.442	3.805	0.473
	LAW	0.010950	0.00334	0.0041						
	Ambient RH	-0.002279	0.00086	0.0089						
IN3BR5	Intercept	2.458096	0.09846	<.0001	9.848	51.629	6.187	0.475	3.967	0.43
	LAW	0.011681	0.00134	<.0001						
	Ambient RH	-0.002199	0.00086	0.0117						
IN3BR6	Intercept	2.505692	0.11620	<.0001	9.343	50.917	6.031	0.374	3.156	0.472
	LAW	0.010972	0.00172	<.0001						
	Ambient RH	-0.002429	0.00091	0.0085						
IN3BR7	Intercept	2.482571	0.19437	<.0001	9.460	50.172	6.106	0.529	4.348	0.478
	LAW	0.011272	0.00328	0.0030						
	Ambient RH	-0.002300	0.00092	0.0134						
IN3BR8	Intercept	2.484291	0.18428	<.0001	8.752	45.319	5.744	0.329	2.596	0.533
	LAW	0.011254	0.00308	0.0018						
	Ambient RH	-0.002320	0.00092	0.0133						
NC3BB1	Intercept	2.467530	0.14746	<.0001	9.560	56.578	4.990	0.641	7.272	0.499
	LAW	0.010743	0.00217	0.0001						
	Ambient RH	-0.001791	0.00106	0.0952						
NC3BB2	Intercept	2.502909	0.21884	<.0001	11.114	60.194	6.781	0.448	3.976	0.478
	LAW	0.010815	0.00377	0.0122						
	Ambient RH	-0.002400	0.00068	0.0007						
NC3BB3	Intercept	2.540677	1.17482	0.0438	11.950	55.149	6.671	0.018	0.146	0.475
	LAW	0.008480	0.01858	0.6637						
	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.

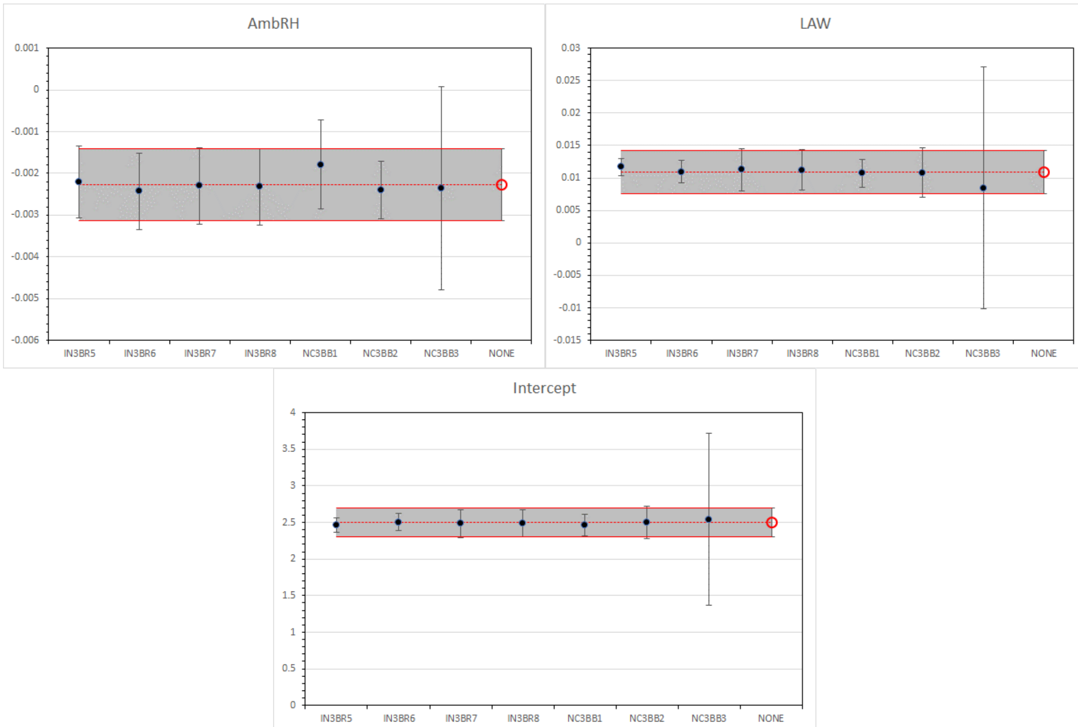

Figure 10-16. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected $PM_{2.5}$ Grow-Finish model coefficient ("None," gray band for ± SE) for each model parameter.

10.2.5 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 10-19). Figure 10-17 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 live animal weight, 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 10-19. Model coefficients developed using the jackknife approach for TSP emissions from Grow-Finish sites.

Site Out	Parameters and Estimates				Fit and Evaluation Statistics					
	Parameter	Estimate	Standard Error	p-value	LNME (%)	NME (%)	ME (kg day^{-1})	MB (kg day^{-1})	NMB (%)	Corr.
None	Intercept	6.266140	0.23119	<.0001	5.932	34.590	240.34	3.083	0.444	0.565
	Ambient Temp	0.011813	0.00296	0.0007						
	LAW	-0.008831	0.00185	<.0001						
IN3BR5	Intercept	6.321492	0.22403	<.0001	6.244	36.717	246.74	-2.826	-0.421	0.517
	Ambient Temp	0.010197	0.00298	0.0008						
	LAW	-0.009144	0.00182	<.0001						
IN3BR6	Intercept	6.204000	0.23819	<.0001	5.844	35.367	230.00	4.806	0.739	0.554
	Ambient Temp	0.012636	0.00324	0.0010						
	LAW	-0.009863	0.00187	<.0001						
IN3BR7	Intercept	6.060494	0.24017	<.0001	5.609	31.941	206.84	-3.085	-0.476	0.669
	Ambient Temp	0.013710	0.00322	0.0006						
	LAW	-0.008590	0.00191	<.0001						
IN3BR8	Intercept	6.142430	0.24171	<.0001	5.762	33.551	221.41	1.617	0.245	0.600
	Ambient Temp	0.012712	0.00327	0.0011						
	LAW	-0.008868	0.00186	<.0001						
NC3BB1	Intercept	7.174425	0.34089	<.0001	7.118	36.539	280.47	-15.72	-2.048	0.595
	Ambient Temp	0.003708	0.00400	0.3671						
	LAW	-0.008333	0.00279	0.0035						
NC3BB2	Intercept	7.120128	0.26170	<.0001	7.412	37.958	288.12	-14.08	-1.854	0.580
	Ambient Temp	0.003323	0.00299	0.2827						
	LAW	-0.007071	0.00253	0.0061						
NC3BB3	Intercept	7.178959	0.12129	<.0001	7.838	38.100	275.80	-17.45	-2.410	0.632
	Ambient Temp	0.003742	0.00117	0.0053						
	LAW	-0.008464	0.00161	<.0001						

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

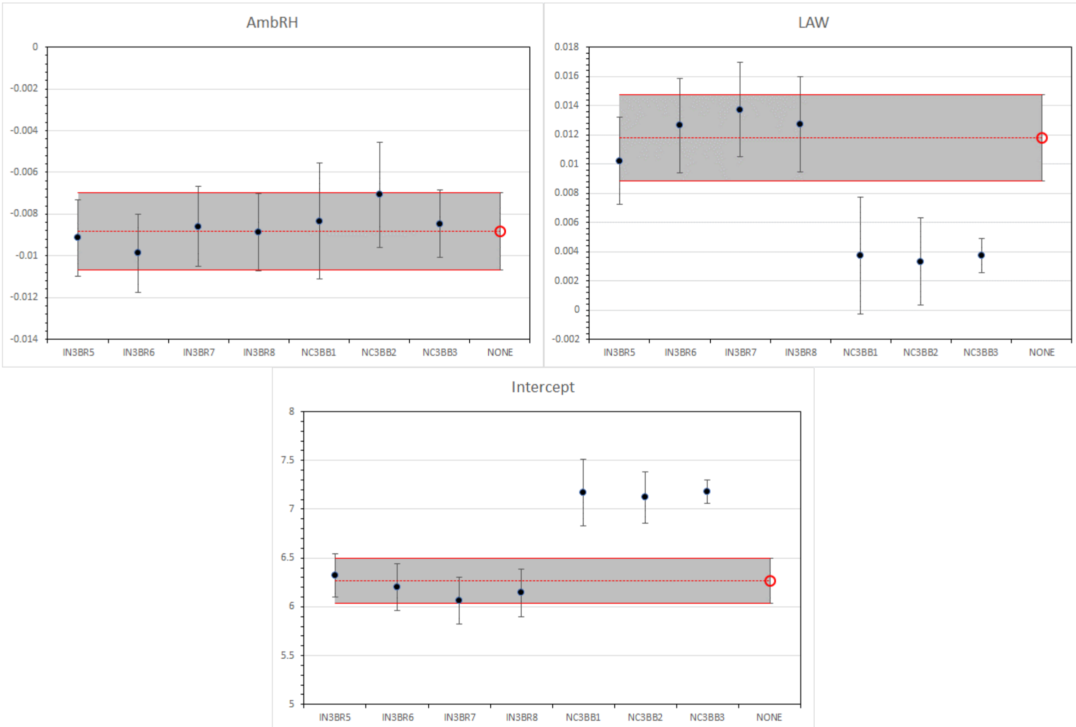

Figure 10-17. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected TSP Grow-Finish model coefficient (“None,” gray band for ± SE) for each model parameter.

10.3 Open Source Models

The exploratory data analysis suggested that EPA should consider ambient temperature, lagoon temperature, wind speed, pH, and live animal weight 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.

10.3.1 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 10-20). The plots in Figure 10-18 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 10-21 presents the results of the jackknife approach. The plots (Figure 10-19) 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 percent difference for parameters estimates were 200%, 70%, and 129% for intercept, ambient temperature, and wind speed, respectively. Across the all models, the difference in NME and NMB percentages in comparison to the selected model were moderate, with NME values differing by less than of 21.74% and NMB less than 0.006%.

For the basin model, EPA did not complete jackknife analysis 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. Future EPA effort will look into obtaining additional data that would allow for further model testing and evaluation and an improved EEM.

Table 10-20. Model coefficients developed using the jackknife approach for NH_3 emissions from Breeding - Gestation farm lagoons.

Site Out	Parameters and Estimates				Fit and Evaluation Statistics					
	Parameter	Estimate	Standard Error	p-value	LNME (%)	NME (%)	ME (kg day^{-1})	MB (kg day^{-1})	NMB (%)	Corr.
None	Intercept	0.582053	0.07702	<.0001	10.626	23.847	1.434	-0.001	-0.009	0.896
	AirTemp	0.055673	0.00268	<.0001						
	WS	0.091428	0.01123	<.0001						
NC4A	Intercept	0.810115	0.08773	<.0001	8.632	19.497	1.392	0.059	0.821	0.919
	AirTemp	0.056123	0.0026	<.0001						
	WS	0.06094	0.01223	<.0001						
OK4A	Intercept	0.890644	0.15759	<.0001	11.313	25.309	0.881	-0.031	-0.887	0.88
	AirTemp	0.047354	0.00512	<.0001						
	WS	-0.029071	0.03857	0.456						

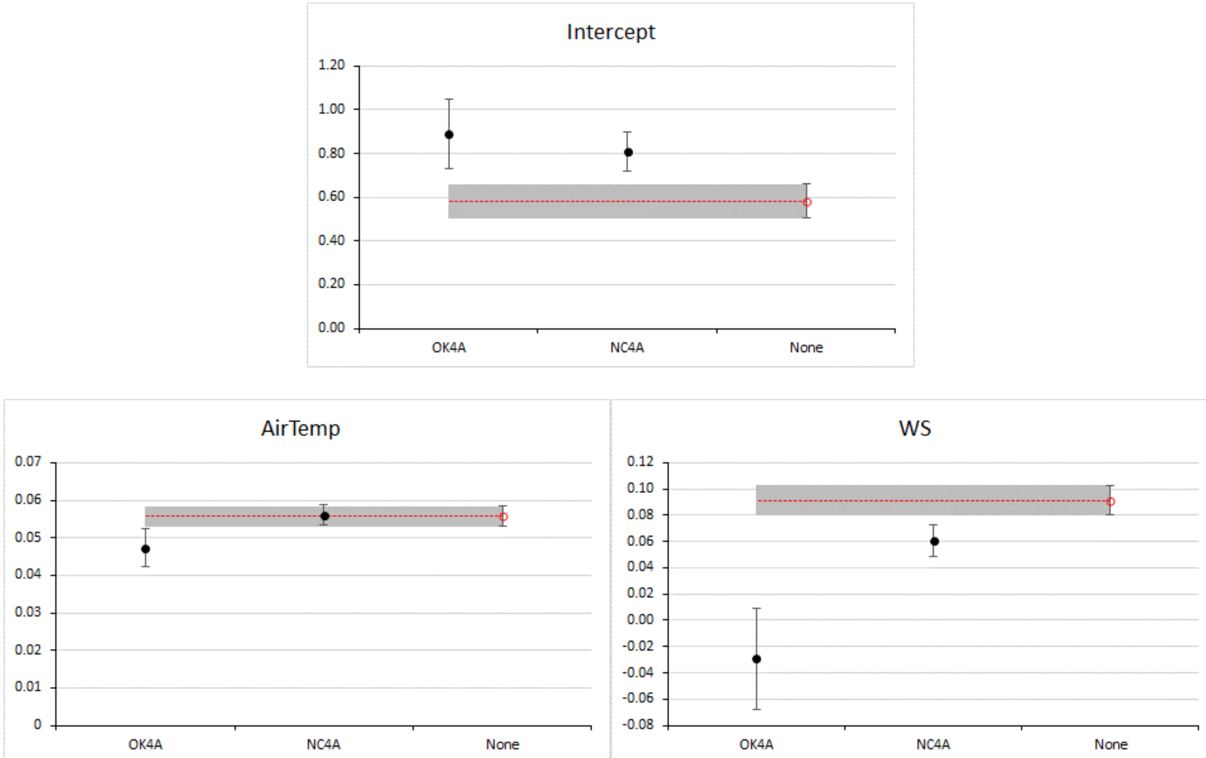

Figure 10-18. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected NH_3 Grow-Finish lagoon model coefficient ("None," gray band for ± SE) for each model parameter.

Table 10-21. Model coefficients developed using the jackknife approach for NH_3 emissions from Grow-finish farms.

Site Out	Parameters and Estimates				Fit and Evaluation Statistics					
	Parameter	Estimate	Standard Error	p-value	LNME (%)	NME (%)	ME (kg day^{-1})	MB (kg day^{-1})	NMB (%)	Corr.
None	Intercept	-0.680078	0.24813	0.0169	34.087	28.822	1.223	-0.208	-4.913	0.895
	AirTemp	0.085372	0.01423	0.0033						
	WS	0.131932	0.05442	0.02						
NC3A	Intercept	0.680268	0.37354	0.1155	56.959	50.559	2.642	-0.665	-12.73	0.889
	AirTemp	0.025556	0.01087	0.0233						
	WS	0.073289	0.03001	0.0192						
OK3A	Intercept	-0.238145	0.32152	0.4684	71.985	27.796	0.497	-0.022	-1.204	0.896
	AirTemp	0.065001	0.01577	0.0006						
	WS	-0.037631	0.11655	0.7507						

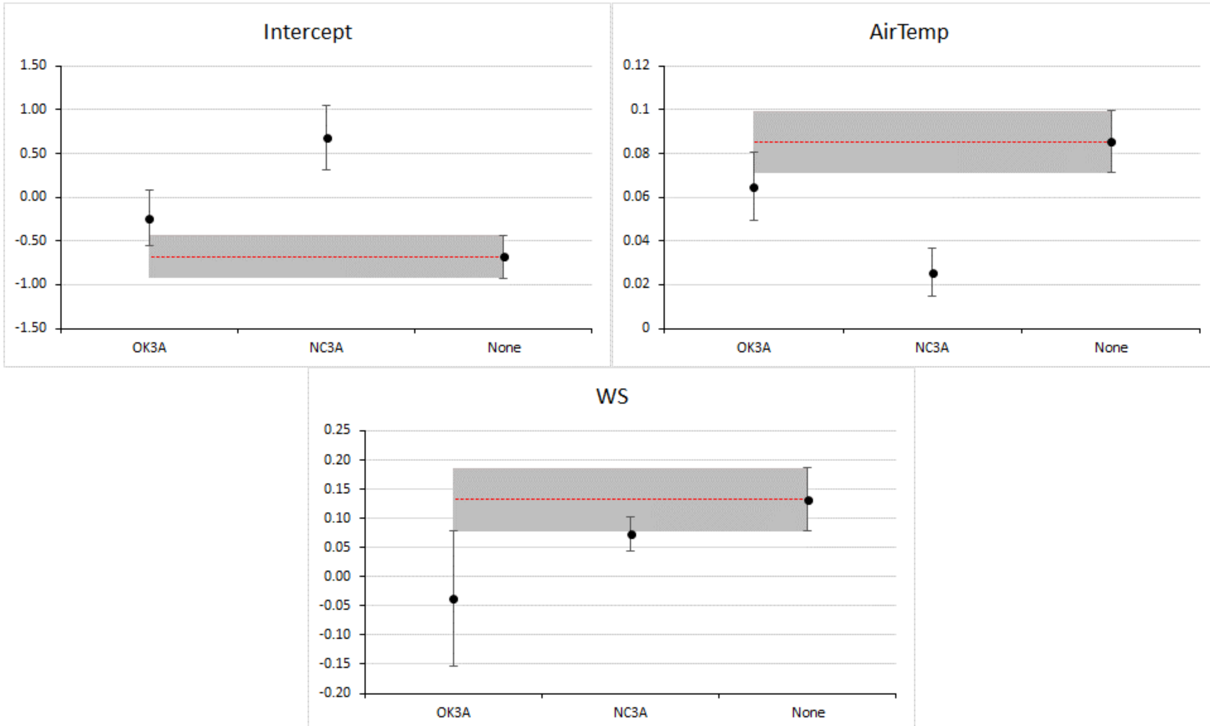

Figure 10-19. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected NH_3 Grow-Finish lagoon model coefficient (“None,” gray band for ± SE) for each model parameter.

10.3.2 H_2S Model Evaluation

For the breeding and gestation lagoons model, Table 10-22 shows the coefficients from the jackknife models. The plots in Figure 10-20 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 percent difference for parameters estimates across the sites were 12% and 105% for intercept and wind speed, respectively. Across the all models, the difference in NME and NMB percentages in comparison to the selected model were moderate, with NME values differing by less than of 59.21% and NMB less than 0.086%.

For the grow-finish lagoon model, Table 10-23 presents the results of the jackknife approach. The plots (Figure 10-21) 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 percent difference for parameters estimates were 54%, and 177% for intercept, and wind speed, respectively. Across the all models, the difference in NME and NMB percentages in comparison to the selected model were moderate, with NME values differing by less than of 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. Future EPA effort will look into obtaining additional data that would allow for further model testing and an improved EEM.

Table 10-22. Model coefficients developed using the jackknife approach for H_2S emissions from Breeding-Gestation Farms.

Site Out	Parameters and Estimates				Fit and Evaluation Statistics					
	Parameter	Estimate	Standard Error	p-value	LNME (%)	NME (%)	ME (g $d^{-1}m^{-2}$)	MB (g $d^{-1}m^{-2}$)	NMB (%)	Corr.
None	Intercept	4.36054	0.2695	<.0001	13.662	117.64	265.37	-24.48	-10.17	0.35
	WS	0.23571	0.052	<.0001						
NC4A	Intercept	4.86592	0.3785	<.0001	16.252	110.69	346.14	-12.27	-3.922	0.267
	WS	-0.0922	0.1297	0.483						
OK4A	Intercept	4.36054	0.2695	<.0001	5.869	176.85	59.61	-1.228	-3.888	0.153
	WS	0.23571	0.052	<.0001						

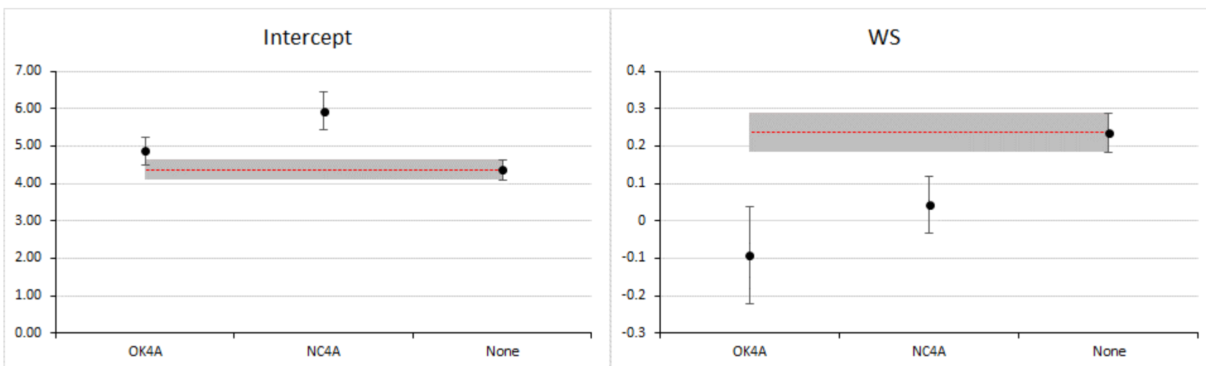

Figure 10-20. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each jackknife model with the selected H_2S Grow-Finish lagoon model coefficient (“None,” gray band for ± SE) for each model parameter.

Table 10-23. Model coefficients developed using the jackknife approach for H_2S emissions from Grow-Finish Farms.

Site Out	Parameters and Estimates				Fit and Evaluation Statistics					
	Parameter	Estimate	Standard Error	p-value	LNME (%)	NME (%)	ME (g $d^{-1}m^{-2}$)	MB (g $d^{-1}m^{-2}$)	NMB (%)	Corr.
None	Intercept	3.694758	0.49199	<.0001	29.034	71.652	280.35	-45.25	-0.116	0.689
	WS	0.279011	0.0731	0.0004						
NC3A	Intercept	4.087401	0.56644	<.0001	24.145	67.549	312.94	-43.7	-0.094	0.662
	WS	0.241888	0.07215	0.0017						
OK3A	Intercept	1.690553	1.06612	0.1493	46.409	160.19	165.33	18.405	0.178	0.024
	WS	0.773746	0.31543	0.0377						

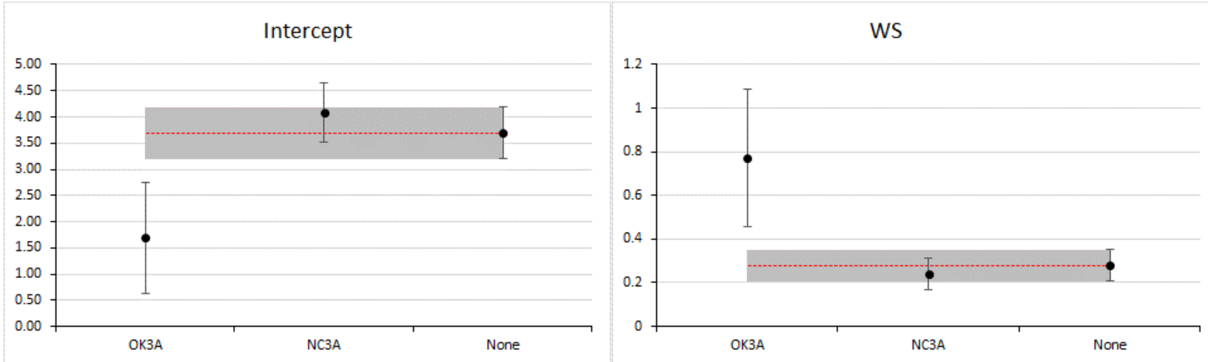

Figure 10-21. Variation in coefficients and standard errors (blue closed circle and ± SE bar) for each the jackknife model with the selected H_2S Grow-Finish lagoon model coefficient ("None," gray band for ± SE) for each model parameter.

11.0 ANNUAL EMISSION ESTIMATES AND MODEL UNCERTIANTY

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 and barn parameters. For an actual emissions estimate, the daily estimates are based on meteorology from a nearby monitors and barn occupancy and weight records for the year from the producer. Since the models were developed with all the available data, producers can specify downtime for cleaning or other reasons with an inventory value of zero. For farms with multiple barns, annual emissions are determined for individual barns and summed across barns to calculate total annual farm-scale emissions.

As noted in Section 9.3, the result will be the transformed values of the emission. To convert to the native emission units (e.g., kg or g), Equation 8 would be applied using the values of e_i and C provided in Table 11-1 for each EEM. Section 12 contains an example of this calculation.

Table 11-1. 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
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 using an approach similar to Monte Carlo analysis. Under this approach, EPA developed the statistical properties of predicted annual emissions by replicating annual sums of daily emissions. EPA ran these simulations for several different intervals of a predictor variable that fell within the observed range. For example, grow-finish barn testing live animal weight ranged from 0 to 130 thousand kg per head. The simulations were then run for live animal weight intervals of 3 thousand kg per head (e.g., 0, 3, 6, 9). Table 11-1 list the predictor variable and the number of intervals used for the annual uncertainty simulations for each model.

Simulations were run 10,000 times for each day for each interval to create an average uncertainty associated with the annual emissions from a single barn. EPA added a random residual to each day of the simulation to replicate the variability that would be seen in a real-world application of the model. For each of the intervals run, EPA calculated standard statistics (i.e., minimum, median, mean, maximum, range) and used these statistics to calculate the uncertainty for a single source, at that interval value, via Equation 39:

$$Single\ source\ uncertainty\ =\ 0.5 \times \left(\frac{Range}{Median\ annual\ emission}\right) \times 100$$ .... Equation 39

EPA then plotted this single barn uncertainty against its associated annual emissions. This plot was then fit with a curve to model annual percent uncertainty for a single source (i.e., barn, house, lagoon, basin). For all uncertainty models, the curve took the form of:

$$Uncertainty\ (\%) = \frac{k}{Annual\ Emissions}$$ Equation 40

Where k is a constant, listed in Table 11-2 and annual emissions are the total annual emission from the daily model.

Table 11-2. Annual Uncertainty Model Details

Animal Type	Source Type	Manure Management System	Pollutant	Simulation variable	Number of Simulations	k
Breeding-gestation	Farrowing Room	Unspecified	H_2S	Cycle day	35	417,629
Breeding-gestation	Farrowing Room	Unspecified	NH_3	Cycle day	35	751
Breeding-gestation	Farrowing Room	Unspecified	PM_{10}	Cycle day	35	69,165
Breeding-gestation	Farrowing Room	Unspecified	$PM_{2.5}$	Cycle day	35	9,808
Breeding-gestation	Farrowing Room	Unspecified	TSP	Cycle day	35	202,354
Breeding-gestation	Gestation Barn	Unspecified	H_2S	Live animal weight	61	12,357,087
Breeding-gestation	Gestation Barn	Unspecified	NH_3	Live animal weight	61	38,497
Breeding-gestation	Gestation Barn	Unspecified	PM_{10}	Live animal weight	61	683,410
Breeding-gestation	Gestation Barn	Unspecified	$PM_{2.5}$	Live animal weight	61	89,832
Breeding-gestation	Gestation Barn	Unspecified	TSP	Live animal weight	61	1,320,487
Breeding-gestation	Lagoon	Unspecified	H_2S	Wind speed	61	1,554,985
Breeding-gestation	Lagoon	Unspecified	NH_3	Ambient Temperature	61	7,541
Grow-Finish	Barn	Deep pit	H_2S	Live animal weight	45	1,520,362
Grow-Finish	Barn	Deep pit	NH_3	Live animal weight	45	7,682
Grow-Finish	Barn	Shallow pit	H_2S	Live animal weight	45	1,515,394
Grow-Finish	Barn	Shallow pit	NH_3	Live animal weight	45	7,649
Grow-Finish	Barn	Unspecified	H_2S	Live animal weight	45	1,588,699
Grow-Finish	Barn	Unspecified	NH_3	Live animal weight	45	7,923
Grow-Finish	Barn	Unspecified	PM_{10}	Live animal weight	45	386,052
Grow-Finish	Barn	Unspecified	$PM_{2.5}$	Live animal weight	45	31,184
Grow-Finish	Barn	Unspecified	TSP	Live animal weight	45	1,138,614
Grow-Finish	Basin	Unspecified	H_2S	Ambient Temperature	61	7,242
Grow-Finish	Basin	Unspecified	NH_3	Ambient Temperature	61	26,296
Grow-Finish	Lagoon	Unspecified	H_2S	Wind speed	61	1,364,889
Grow-Finish	Lagoon	Unspecified	NH_3	Ambient Temperature	61	6,784
Unspecified	Lagoon	Unspecified	H_2S	Wind speed	61	1,575,210
Unspecified	Lagoon	Unspecified	NH_3	Ambient Temperature	61	12,958

Multiplying this percentage by the annual emissions calculated for the source provides the resulting uncertainty in the native emission units (e.g., kg or g), demonstrated in Equation 40.

$$Resulting\ Uncertainty = \frac{Percent\ uncertainty \times Annual\ emissions}{100} \qquad \text{Equation 41}$$

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

$$Total\ farm\ uncertainty = \sqrt{(U_{B1})^2 + \cdots + (U_{Bi})^2 + (U_{L1})^2 + \cdots + \left(U_{Lj}\right)^2} \qquad \text{Equation 42}$$

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 12 provides an example of how the daily, annual, and annual uncertainty calculations are completed.

12.0 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 12.1), the sensitivity of the models to their inputs (Section 12.2), a comparison of the models developed to existing emission factors in literature, and a test of model performance against an independent dataset (Section 12.3).

12.1 Model Application Example

This section demonstrates how the daily EEMs from Section 9 and the annual uncertainty from Section 11 would be used to calculate emissions for a sample farm. Details about the use of the EEMs to demonstrate compliance with Clean Air Act thresholds will be addressed when the EEMs are finalized in a future implementation document. This example is provided to demonstrate how the system of equations is used 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 emission estimation. The NCEI site shows a site 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 25, 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 8, from Section 9.3, and the values for e_i and C provided in Table 11-1. 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 12-1. 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 41 with the value of k from Table 11-1. This results in an annual uncertainty of:

$$Uncertainty\ (\%) = \frac{7649}{2935.80} = 2.61\%$$

This translates to an uncertainty of ± 76.49 kg. Thus, the final annual estimate for this barn is 2,935.80 kg ± 76.49 kg. This calculation would be repeated for any other grow-finish barns on the site. This example assumes there is a second barn, with initial placement of 1,100 pigs. Using the same meteorology, the annual emissions are estimated at 2,360.13 kg ±76.49 kg of NH_3.

Table 12-1. Summary of annual input parameters for Bladen County, NC

Summary Statistic	Ambient Temperature (°C)	Wind Speed (mph; 10m)	Inventory (head)	Average Animal Mass (kg)	Live Animal Weight (kg)
Minimum	-2.22	0.00	0	0.00	0.00
Average	17.86	3.32	1400	62.98	88166.7
Maximum	30.56	15.78	1400	124.93	174900.5

Finally, assume there is a 20,000 m^2 lagoon on the farm. The emissions from the lagoon are calculated from Equation 34:

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

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, while the National Weather Service (NWS) sites archived at NCEI are typically monitored at 10m. Therefore, the difference in measurement heights between NAEMS and NWS requires an adjustment to the wind. The relationship between wind speed and height is well established and can be written as:

$$\frac{V}{V_r} = \left(\frac{Z}{Z_r}\right)^m \qquad \text{Equation 43}$$

Where m is 0.15 for water surfaces (Arya, 1999), 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). This results in

$$V_{2.5m} = \left(\frac{2.5}{10}\right)^{0.15} \times V_{10m} = 0.812252 \times V_{10m} \qquad \text{Equation 44}$$

Using this formula, a 10 m wind speed of 1.3 ms^{-1} would be 1.06 ms^{-1} at 2.5 m. Inserting Equation 45 into Equation 34 yields the following modification:

$$Grow\ Finish\ Lagoon, ln(NH_3) = -0.6801 + 0.0854 \times Amb_T + 0.1319 \times (0.812252 \times ws)$$

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

$$Grow\ Finish\ Lagoon, ln(NH_3) = -0.6801 + 0.0854 \times 20.56 + 0.1319 \times (0.812252 \times 1.3)$$

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

Like with the barn emissions, back transform this result using values from Table 12-1.

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

$$NH_3 = 3.71\ gd^{-1}m^{-2}$$

To get an emission estimate for the whole lagoon, the result is multiplied by the surface area, 20,000 m^2, for a final estimate of 74126.86 g or 74.13 kg. Across the year, the lagoon is estimated to produce 1351.1 gm^{-2}, or 27,021.55 kg of NH_3. To calculate the uncertainty associated with this estimate, use Equation 41 with the value of k from Table 11-1. This results in an annual uncertainty of:

$$Uncertainty\ (\%) = \frac{6784}{1351.1} = 5.02\%$$

This yields an uncertainty of ± 67.85 kg. Thus, the final annual estimate for this lagoon is 27,021.55 kg ± 67.85 kg. This calculation would be repeated for any other lagoons on the site.

To calculate a 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 ± 76.49 kg, NH_3 emissions from barn 2 were 2,360.13 kg ±76.49 kg, and NH_3 emissions from the lagoon were 27,021.55 kg ± 67.85 kg. The annual NH_3emission 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 41:

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

$$Total\ Farm\ Uncertainty = \sqrt{76.49^2 + 76.49^2 + 67.85^2}$$

$$Total\ Farm\ Uncertainty = 127.69$$

The final annual NH_3 estimate for the farm is 32,317.47 ± 127.69 kg.

12.2 Model Sensitivity Testing

In the previous example we calculated NH_3 emissions for a farm with two barns of varying size. The first barn had an initial placement of 1,400 pigs at an initial weight of 14kg. 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

$$\ln(NH_3) = 1.1422+0.0091*(20.56) +0.0085*(15400 /1000)$$

$$\ln(NH_3) = 1.4602$$

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

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 emission results, EPA calculated the emissions for the same farm in two distinctly different climate regions. The first was the farm from the previous example (Section 12.1) 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 12-2.

Table 12-2. Summary of annual input parameters for Crosby, ND

Summary Statistic	Ambient Temperature (°C)	Wind Speed (mph; 10m)	Inventory (head)	Average Animal Mass (kg)	Live Animal Weight (kg)
Minimum	-31.62	2.59	0	0.00	0.00
Average	3.10	10.86	1400	62.98	88166.7
Maximum	25.64	24.68	1400	124.93	174900.5

For our test sites, the temperatures from the North Dakota site were always less than the North Carolina site (Figure 12-1). 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. 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. 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 8, despite the higher wind speeds. This suggests that the EEMs are robust enough to account for the climatic differences of the different growing regions.

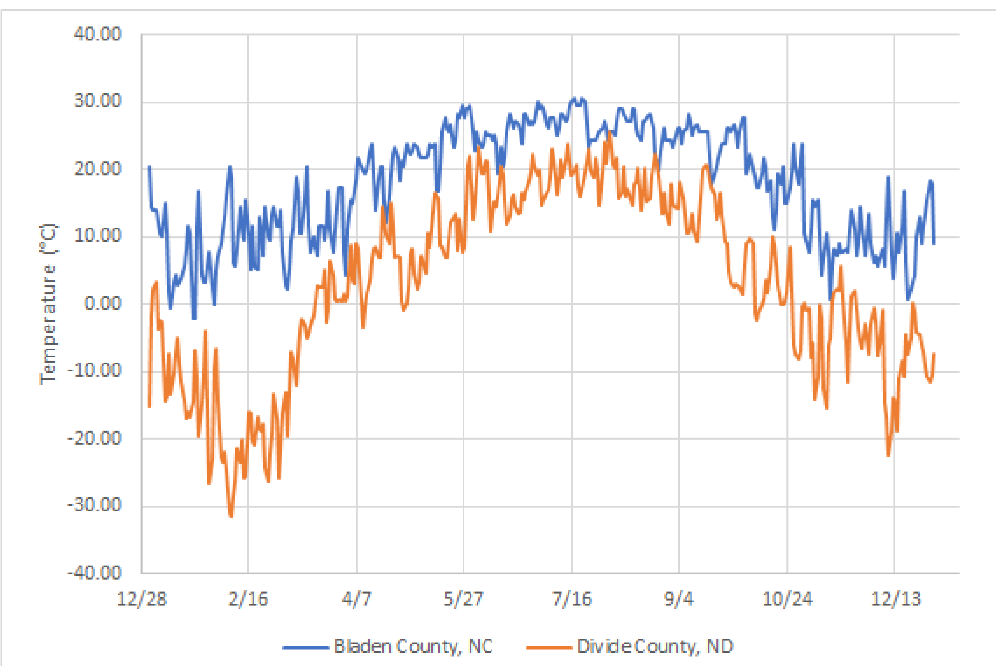

Figure 12-1. Comparison of temperature from test sites.

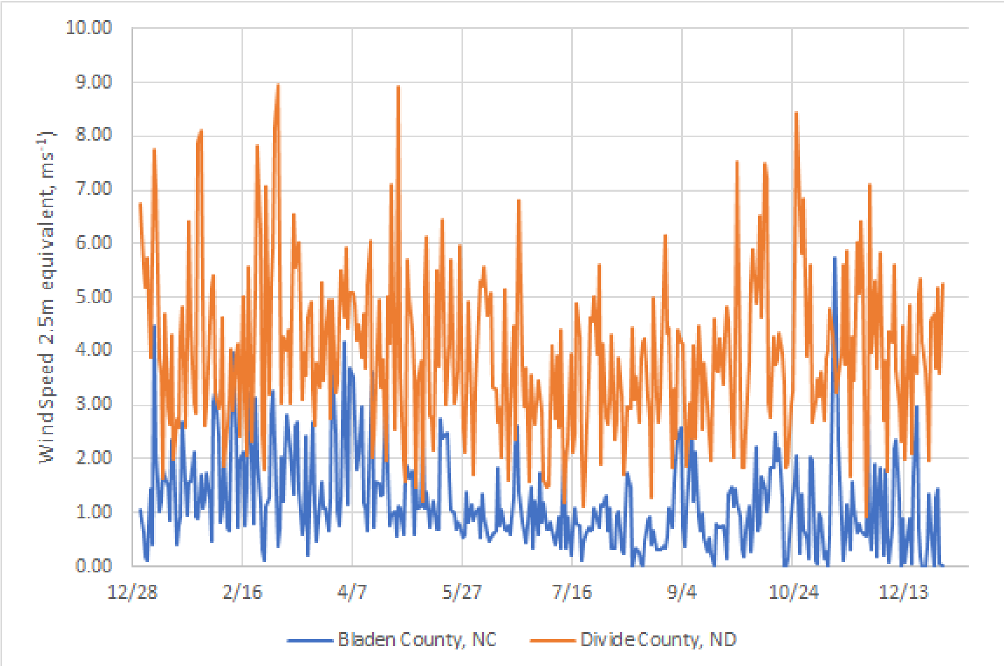

Figure 12-2. Comparison of 2.5 meter equivalent wind speed from test sites.

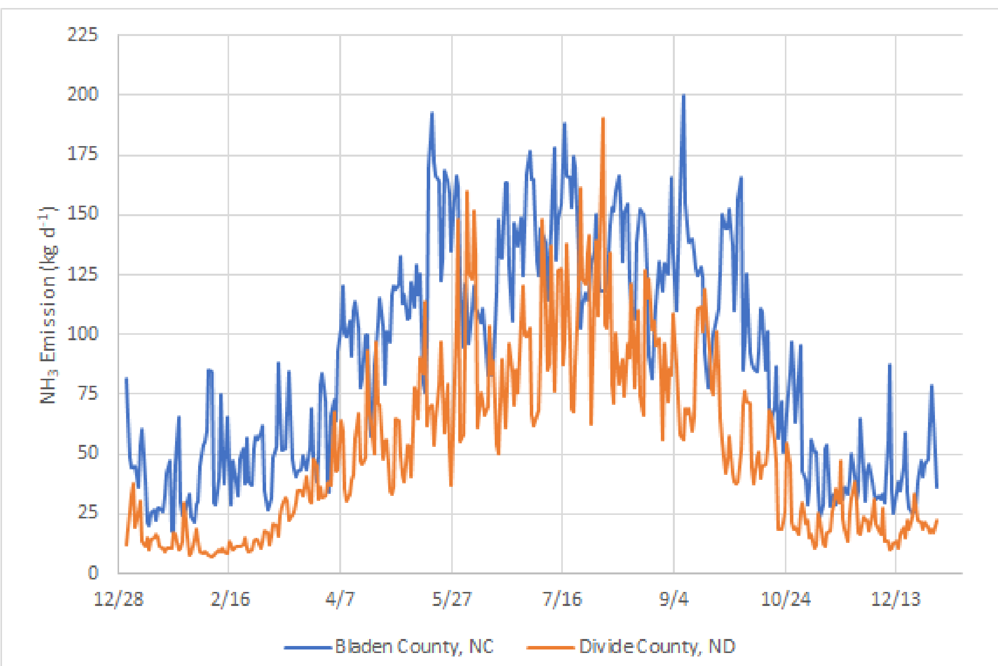

Figure 12-3. Comparison of total NH_3 emissions from test sites.

13.0 SUMMARY AND CONCLUSIONS

Consistent with the Air Compliance Agreement with the AFO industry, EPA has developed emission 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, live animal weight (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 emission 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 particulate matter 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 emission 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 emission models developed here lay the groundwork for developing these more process-related emission 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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Appendix A – Summary of NAEMS Sites

Table A-1. PM Sampling Schedule IA4B

Date, m/d/y		Test duration, d		
Start	**End**	**PM10**	**TSP**	**PM2.5**
9/28/07	1/17/08	111.6		
1/17/08	2/7/08			21.1
2/7/08	4/10/08	62.9		
4/10/08	4/24/08		13.9	
4/24/08	6/12/08	49.1		
6/12/08	6/18/08		6.0	
6/18/08	7/10/08	22.0		
7/10/08	7/23/08			12.9
7/23/08	9/12/08	50.9		
9/12/08	9/18/08		6.0	
9/18/08	11/13/08	56.0		
11/13/08	11/21/08		8.0	
11/21/08	1/29/09	68.0		
1/29/09	2/12/09			13.0
2/12/09	2/19/09		7.4	
2/19/09	4/16/09	57.0		
4/16/09	4/23/09		6.9	
4/23/09	6/18/09	56.1		
6/18/09	6/25/09		7.1	
6/25/09	7/16/09	20.8		
7/16/09	7/30/09			14.2
7/30/09	9/30/09	62.3		
Totals		617	55	61

Table A-2. PM Sampling Schedule IN3B

Time and day, m/d/y		Test duration, d		
Start	Stop	PM_{10}	TSP	$PM_{2.5}$
7/13/07	10/2/07	81.0		
10/2/07	10/10/07		7.9	
10/10/07	12/11/07	62.0		
12/11/07	12/19/07		8.0	
12/19/07	1/10/08	22.0		
1/10/08	1/24/08			13.9
4/23/08	5/7/08		14.0	
5/7/08	6/30/08	53.9		
6/30/08	7/7/08		7.1	
7/7/08	9/22/08	77.2		
9/22/08	10/8/08			16.0
10/8/08	10/17/08	8.7		
10/17/08	10/21/08			4.0
10/21/08	10/28/08		7.1	
10/28/08	12/8/08	40.9		
10/28/08	10/31/08	2.9		
10/31/08	11/3/08			3.0
11/3/08	11/14/08		10.9	
11/14/08	12/8/08	24.0		
12/8/08	12/11/08		3.0	
12/8/08	12/15/08		6.8	
12/15/08	12/18/08			3.0
12/11/08	2/4/09	55.1		
2/4/09	2/12/09			8.1
2/12/09	3/9/09	24.9		
3/9/09	3/11/09			2.0
3/11/09	3/23/09		12.0	
3/23/09	3/27/09			3.9
3/27/09	6/1/09	66.1		
6/1/09	6/4/09		3.0	
6/4/09	7/1/09	26.8		
7/1/09	7/13/09			12.2
7/13/09	7/14/09	0.7		
7/14/09	7/14/09		0.3	
7/14/09	7/20/09			5.9
7/20/09	7/24/09		4.1	

Table A-3. PM Sampling Schedule NC3B

Time and day, m/d/y		Test duration, d		
Start	Stop	PM_{10}	TSP	$PM_{2.5}$
12/4/07	5/31/08	179.5		
5/31/08	6/7/08		6.9	
6/7/08	6/15/08			8.0
6/15/08	10/5/08	112.1		
10/5/08	10/19/08			13.9
10/19/08	2/22/09	126.1		
2/22/09	2/27/09		5.1	
2/27/09	4/4/09	35.8		
4/4/09	4/19/09			15.0
4/19/09	4/25/09	6.0		
4/25/09	5/3/09		7.9	
5/3/09	6/21/09	49.1		
6/21/09	6/27/09		6.0	
6/27/09	7/26/09	28.9		
7/26/09	8/8/09			13.2
8/8/09	8/27/09		19.0	
8/27/09	11/28/09	93.0		
11/28/09	12/2/09			4.0
12/2/09	12/26/09		24.0	
12/26/09	1/1/10	5.5		

Table A-4. PM Sampling Schedule NC4B

Time and day, m/d/y		Test duration, d		
Start	Stop	PM_{10}	TSP	$PM_{2.5}$
12/15/07	1/16/08	32.6		
1/16/08	1/31/08		14.9	
1/31/08	9/29/08	242.1		
9/29/08	10/5/08	5.9**		
9/29/08	10/5/08			5.9*
10/5/08	10/23/08			19.1
10/23/08	1/15/09	97.1		
1/15/09	1/19/09	4.2**		
1/15/09	1/19/09		4.2*	
1/19/09	1/23/09		3.8	
1/23/09	1/27/09		4.0**	
1/23/09	1/27/09	4.0*		
1/27/09	4/7/09	69.8		
4/7/09	4/21/09			14.0
4/21/09	4/28/09		7.0	
4/30/09	6/29/09	61.9		
6/29/09	7/11/09		11.8	
7/11/09	8/5/09	24.9		
8/5/09	8/6/09	1.1*		
8/5/09	8/6/09		1.1**	
8/6/09	8/25/09		19.0	
8/25/09	10/14/09	49.8		
10/14/09	10/27/09		13.0	
10/27/09	12/2/09	36.2		
12/2/09	12/15/09			13.0
	Total	614	70	46

*All except inlet
**Only inlet

Table A-5. PM Sampling Schedule OK4B

Time and Day (m/d/y)		Test Duration (d)		
Start	**Stop**	**PM_{10}**	**TSP**	**$PM_{2.5}$**
7/20/07	8/8/07		19.5	
8/8/07	9/6/07	28.9		
9/6/07	9/11/07	5.2†		
9/6/07	9/11/07			5.0‡
9/11/07	9/28/07			16.8
9/28/07	10/22/07			24.1†
9/28/07	10/22/07	24.1‡		
10/22/07	11/6/07	15.0		
11/6/07	11/13/07		6.9	
11/13/07	1/15/08	62.9		
1/15/08	1/31/08			16.0
1/31/08	2/7/08		6.7	
2/7/08	4/7/08	59.9		
4/7/08	4/14/08		7.0	
4/14/08	6/25/08	71.9		
6/25/08	7/16/08		20.7	
7/16/08	7/24/08	8.0		
7/24/08	8/7/08			14.0
8/7/08	9/12/08	35.8		
9/12/08	9/24/08		11.8	
9/24/08	12/3/08	70.0		
12/3/08	12/12/08		9.0	
12/12/08	2/5/09	54.9		
2/5/09	2/18/09		13.0	
2/18/09	4/8/09	49.0		
4/8/09	4/15/09		6.8	
4/15/09	6/10/09	55.8		
6/10/09	6/18/09		8.0	
6/18/09	7/24/09	35.5		
	Total	576.7	109.3	75.9

†Only B3; ‡All except B3

Appendix B – NAEMS Data Adjustments and Corrections

[To be added.]

Appendix C – Summary Statistics

Table C-1. Summary statistics for NH_3, and H_2S emissions for breeding and gestation confinement sites.

Parameter	Site								
	IA4B (Farrowing)	IA4B (Barn 1)	IA4B (Barn 2)	NC4B (Farrowing)	NC4B (Barn 1)	NC4B (Barn 2)	OK4B (Farrowing)	OK4B (Barn 1)	OK4B (Barn 2)
NH_3 Emissions (kg day^{-1})									
Mean	0.254	31.5	20.4	0.128	5.58	6.80	0.506	10.8	11.2
St. Dev	0.208	25.3	10.3	0.0581	1.82	2.19	0.147	2.14	1.43
N	512	378	432	516	554	578	487	610	579
Median	0.210	22.0	20.5	0.122	5.37	6.79	0.499	10.4	11.1
Min	-0.160	6.14	5.45	-0.108	-0.892	0.149	0.0808	6.88	6.93
Max	1.77	110	60.0	0.363	11.1	12.9	1.04	21.4	17.0
CV(%)	82.0	80.5	50.2	45.4	32.7	32.2	28.9	19.8	12.7
N<0	1	0	0	3	1	0	0	0	0
H_2S Emissions (g day^{-1})									
Mean	91.0	8,590	5,740	132	279	220	103	862	884
St. Dev	170	5,660	3,570	90.4	213	190	81.5	226	203
N	550	391	463	562	592	633	498	619	589
Median	18.2	7,040	5,100	118	217	156	91.7	853	875
Min	0.260	1,900	1,320	1.61	-27.2	-4.56	-1.86	298	451
Max	1,180	27,100	42,500	483	1,370	1,300	352	2,190	1,590
CV(%)	186.7	65.9	62.3	68.6	76.4	86.4	78.9	26.2	23.0
N<0	0	0	0	0	2	1	2	0	0

N = number
N<0 = number less than 0
CV (%) = Coefficient of variation ((St. Dev/mean)*100))

Table C-2. Summary statistics for PM emissions for Swine Breeding and Gestation Confinement Sites.

PM_{10} Emissions (g/d)	IA4BF	IA4BB1	IA4BB2	NC4BF	NC4BB1	NC4BB2	OK4BF	OK4BB1	OK4BB2
PM_{10} (g day^{-1})									
Mean	28.4	466	527	27.8	252	385	46.2	345	493
St. Dev	16.9	225	224	15.0	102	184	26.7	123	152
N	395	359	341	230	379	305	369	494	434
Median	27.3	505	508	25.8	245	378	44.4	329	483
Min	-0.220	-41.3	8.29	3.85	32.1	29.6	-4.56	62.9	93.8
Max	91.5	1,020	1,080	75.4	643	1,110	122	971	1,080
CV(%)	59.4	48.3	42.5	54.0	40.4	47.7	57.7	35.6	30.9
N<0	1	3	0	0	0	0	2	0	0
$PM_{2.5}$ (g day^{-1})									
Mean	3.13	48.3	52.4	2.54	34.6	40.7	6.75	27.7	49.0
St. Dev	2.70	17.3	28.6	1.01	12.5	17.1	5.25	19.9	37.9
N	51	36	39	24	28	25	9	43	42
Median	2.32	46.6	50.6	2.24	38.2	37.1	7.36	28.0	56.6
Min	0.0900	4.93	-5.31	0.962	0.215	23.6	1.44	-27.6	-113
Max	11.6	107	117	4.70	52.1	116	14.8	94.2	146
CV(%)	86.1	35.9	54.5	39.6	36.1	42.0	77.8	71.9	77.3
N<0	0	0	1	0	0	0	0	3	3
TSP (g day^{-1})									
Mean	67.5	728	1070	90.7	445	550	125	630	787
St. Dev	36.4	445	462	60.1	283	267	83.4	277	302
N	45	39	45	33	39	35	58	88	81
Median	60.6	772	1,130	89.9	413	558	100	575	795
Min	15.3	109	318	11.4	55.9	162	18.7	216	256
Max	149	1,600	2,110	193	1,210	1,010	317	1,260	1,550
CV(%)	53.9	61.2	43.3	66.3	63.6	48.5	66.6	44.0	38.3
N<0	0	0	0	0	0	0	0	0	0

N = Number of average daily emissions values.
N<0 = Number of average daily emissions values less than 0.
CV (%) = Coefficient of variation ((St. Dev/mean)*100))

Table C-3. Summary statistics for NH_3, and H_2S emissions for grow-finish confinement sites.

Parameter	Site						
	IN3B (Room 5)	**IN3B (Room 6)**	**IN3B (Room 7)**	**IN3B (Room 8)**	**NC3B (Barn 1)**	**NC3B (Barn 2)**	**NC3B (Barn 3)**
NH_3 Emissions (kg day^{-1})							
Mean	7.50	7.87	6.74	6.93	5.20	4.97	5.00
St. Dev	2.68	2.78	3.31	3.16	2.53	1.94	2.16
N	373	336	331	307	571	561	556
Median	7.30	7.64	7.21	7.23	4.79	4.95	4.93
Min	1.95	0.01	0.00	0.56	0.75	0.83	0.64
Max	18.70	16.00	23.32	25.29	14.90	10.66	11.93
CV (%)	35.72	35.27	49.15	45.54	48.71	39.01	43.18
N<0	0	0	0	0	0	0	0
H_2S Emissions (g day^{-1})							
Mean	417.31	624.11	404.55	689.10	144.64	160.68	164.99
St. Dev	479.06	591.14	504.26	614.63	131.48	138.25	134.58
N	497	446	437	385	555	543	541
Median	189.54	484.14	172.49	435.78	118.21	131.48	143.12
Min	0.93	0.80	-10.52	21.57	-2.22	-11.16	-2.89
Max	2,129.88	5,366.17	2,376.04	2,975.55	712.55	722.54	698.53
CV (%)	114.80	94.72	124.65	89.19	90.91	86.04	81.57
N<0	0	0	3	0	5	2	2

N = Number of average daily emissions values.
N<0 = Number of average daily emissions values less than 0.
CV (%) = Coefficient of variation ((St. Dev/mean)*100))

Table C-4. Summary statistics for PM emissions for grow-finish confinement sites.

Parameter	Site						
	IN3B (Room 5)	IN3B (Room 6)	IN3B (Room 7)	IN3B (Room 8)	NC3B (Barn 1)	NC3B (Barn 2)	NC3B (Barn 3)
PM_{10} (g day^{-1})							
Mean	211.02	223.35	183.05	185.19	189.57	174.25	145.24
St. Dev	114.54	132.45	130.10	171.15	112.23	108.74	83.47
N	301	271	297	210	466	473	342
Median	197.87	199.98	159.04	137.65	174.84	149.23	129.31
Min	14.56	-29.74	-65.12	-10.15	-7.67	-7.01	2.30
Max	614.93	810.05	1179.59	1093.20	645.47	555.41	492.21
CV (%)	54.28	59.30	71.07	92.42	59.20	62.41	57.47
N<0	0	2	16	12	2	3	0
$PM_{2.5}$ (g day^{-1})							
Mean	6.41	4.94	-11.14	3.04	21.46	12.98	8.58
St. Dev	11.90	16.01	41.03	5.40	9.49	5.29	3.70
N	32	31	31	28	59	59	33
Median	3.97	4.68	3.07	0.67	21.82	12.52	7.97
Min	-23.71	-34.63	-166.63	-6.43	6.55	4.20	3.76
Max	29.43	30.68	21.75	16.85	45.56	25.40	17.06
CV (%)	185.71	324.10	-368.32	177.48	44.22	40.73	43.10
N<0	6	8	12	12	0	0	0
TSP (g day^{-1})							
Mean	891.94	1078.95	968.73	1026.63	444.41	473.77	432.12
St. Dev	380.60	269.34	278.38	238.34	195.83	235.61	167.79
N	24	24	34	22	52	52	23
Median	907.27	1024.90	974.83	1061.08	355.95	383.20	391.62
Min	224.57	756.34	436.07	479.42	188.45	202.73	197.42
Max	1,646.60;	1,661.43	1,450.09	1,284.23	978.46	1,158.18	906.48
CV (%)	42.67	24.96	28.74	23.22	44.07	49.73	38.83
N<0	0	0	0	0	0	0	0

N = Number of average daily emissions values.
N<0 = Number of average daily emissions values less than 0.
CV (%) = Coefficient of variation ((St. Dev/mean)*100))

Table C-14-1. Summary statistics for NH_3 and H_2S emissions for open source sites.

Parameter	Site					
	IN4A[a]	NC3A	NC4A	OK3A	OK4A	IA3A
NH_3 Emissions (g $day^{-1}m^{-2}$)						
Mean		1.66	3.48	5.23	7.14	13.66
St. Dev		1.19	2.27	4.30	4.82	11.49
N		21	35	45	79	38
Median		1.40	3.88	4.36	6.91	15.10
Min		1	1	0	0	-1.51
Max		6	9	16	17	38
CV (%)		71.94	65.12	82.24	67.52	84.13
N < 0						
H_2S Emissions (g $day^{-1}m^{-2}$)						
Mean	43.14	89.78	20.69	462	551	1.74
St. Dev	219	194	88.28	495	541	2.24
N	34;	15;	30;	53;	36;	27
Median	2.49	5.50	3.51	379	422	0.90
Min	-82	-5	-96	-2	3	-0.36
Max	1,268	586	467	2,383	2,112	7
CV (%)	508.58	216.38	426.76	107.13	98.21	128.86

[a] NH_3 emissions from IN4A were invalidated due to moisture interference.
N = number
N<0 = number less than 0
CV (%) = Coefficient of variation ((St. Dev/mean)*100))

Table C-14-2. Live animal weight for open source sites (IN4A, NC3A, NC4A, OK3A, and OK4A).

Site	live animal weight (thousands of grams)	Lagoon Surface Area (m^{-2})
IN4A	321,000	13,580
NC3A	491,000	18,987
NC4A	407,500	23,195
OK3A	232,000	22,500
OK4A	639,500	22,488

Table C-7. Summary statistics of environmental and production parameters at swine breeding and gestation barns.

Parameter	Statistic	IA4BF	IA4BB1	IA4BB2	NC4BF	NC4BB1	NC4BB2	OK4BF	OK4BB1	OK4BB2
Inventory (head)	Mean	245	1010	1110	200	902	885	286	1170	1170
	St. Dev	67.7	33.3	33.6	55.8	48.7	8.40	18.3	13.1	13.2
	N	572	474	488	565	627	641	526	655	623
	Median	270	1,020	1,120	219	907	887	286	1,170	1,170
	Min	0.00	909	997	8.00	768	856	118	1,140	1,140
	Max	319	1,080	1,190	347	1,010	896	310	1,200	1,200
Average Animal Weight (kg)	Mean	26.5	249	249	30.0	181	181	21.8	200	200
	St. Dev	10.9	0.00	0.00	36.2	0.00	0.00	2.21	0.00	0.00
	N	568	474	488	565	627	641	526	655	623
	Median	24.9	249	249	21.3	181	181	21.8	200	200
	Min	0.00	249	249	5.35	181	181	18.0	200	200
	Max	205	249	249	181	181	181	30.4	200	200
Live Animal Weight (kg)	Mean	6,330	251,000	275,000	4,340	163,000	160,000	6,200	234,000	234,000
	St. Dev	1,350	8,290	8,360	736	8,820	1,520	426	2,610	2,650
	N	568	474	488	565	627	641	526	655	623
	Median	6,580	254,000	279,000	4,450	164,000	161,000	6,250	234,000	234,000
	Min	0.00	226,000	248,000	660	139,000	155,000	3,590	228,000	228,000
	Max	7,480	269,000	296,000	6,260	183,000	162,000	6,720	240,000	240,000
Barn Temperature (°C)	Mean	25.0	17.2	17.4	25.5	22.9	24.6	24.0	21.8	21.6
	St. Dev	2.21	4.78	5.24	1.47	2.28	2.10	1.42	2.75	3.00
	N	603	490	519	568	624	640	526	655	623
	Median	24.7	17.1	17.2	25.3	23.0	24.3	23.9	21.6	21.5
	Min	16.0	7.30	6.30	22.2	12.8	18.1	20.0	16.1	11.4
	Max	31.8	27.6	27.9	29.2	28.1	31.2	27.6	27.8	27.6
Barn Relative Humidity (%)	Mean	55.6	63.0	59.7	59.9	63.2	60.0	53.1	52.2	55.4
	St. Dev	8.51	7.80	8.36	9.70	9.43	8.12	11.0	9.84	10.4
	N	603	484	498	569	624	628	490	650	613
	Median	54.3	64.5	60.0	59.7	63.1	59.9	50.0	50.6	54.2
	Min	33.9	38.8	33.3	34.4	40.7	39.1	27.4	26.7	28.8
	Max	78.3	83.1	80.8	80.5	83.4	79.5	82.8	76.4	80.2
Airflow (dsm3/s)	Mean	1.14	28.7	35.7	1.71	35.0	25.3	2.70	32.6	34.5
	St. Dev	0.861	18.4	21.5	1.25	23.7	15.7	1.49	17.0	16.9
	N	603	471	494	569	621	629	500	655	623
	Median	0.840	22.2	26.4	1.27	29.6	22.0	2.20	30.3	31.9
	Min	0.180	6.25	8.40	0.218	3.71	3.55	0.631	7.00	7.09
	Max	3.39	68.1	73.4	4.76	90.3	62.6	6.05	62.6	65.1
Ambient Relative Humidity (%)	Mean	71.7			69.4			52.4		
	St. Dev	10.9			12.7			14.8		
	N	642			572			673		
	Median	73.1			69.8			51.5		
	Min	36.4			32.8			12.0		
	Max	91.8			94.6			92.1		
Ambient Temperature (°C)	Mean	8.72			19.4			14.9		
	St. Dev	12.1			6.98			10.2		
	N	642			547			673		
	Median	9.90			20.7			15.7		
	Min	-25.1			1.80			-12.6		
	Max	29.2			32.0			33.2		

Table C-8. Summary statistics of environmental and production parameters at swine finishing barns.

Parameter	Statistic	IN3BR5	IN3BR6	IN3BR7	IN3BR8	NC3BB1	NC3BB2	NC3BB3
Inventory (head)	Mean	1,118	1,111	894	871	702	688	701
	St. Dev	498	460	397	344	170	137	146
	N	592	535	545	483	644	631	622
	Median	1,050	1,060	1,090	1,070	710	732	745
	Min	0	0	0	0	0	0	0
	Max	2,550	2,460	1,190	1,110	860	822	810
Average Animal Weight (kg)	Mean	67.08	66.19	63.02	72.92	71.81	75.15	70.00
	St. Dev	37.60	38.28	39.54	37.85	32.88	33.58	32.90
	N	592	535	545	483	644	631	622
	Median	72	71	65	86	77	81	74
	Min	6	5	0	0	0	0	0
	Max	116	122	119	117	127	130	122
Live Animal Weight (kg)	Mean	62,410	62,003	59,494	63,813	50,296	49,992	48,303
	St. Dev	33,782	33,530	38,200	36,405	21,949	20,457	20,893
	N	592	535	545	483	644	631	622
	Median	59,755	58,851	57,240	67,710	54,547	53,072	49,446
	Min	0	0	0	0	0	0	0
	Max	118,800	115,440	129,800	121,000	92,340	86,016	88,320
Barn Temperature (°C)	Mean	22.44	22.21	21.51	22.00	23.58	23.22	24.27
	St. Dev	3.72	3.68	5.40	4.68	3.41	3.15	3.12
	N	592	535	545	483	639	626	616
	Median	22.50	22.00	22.40	22.40	23.80	23.30	24.40
	Min	4.90	0.90	3.60	4.10	9.00	11.90	9.90
	Max	30.30	30.40	30.30	30.50	31.00	31.80	31.80
Barn Relative Humidity (%)	Mean	57.56	56.85	58.84	56.08	60.33	61.99	63.28
	St. Dev	6.98	7.15	8.07	7.50	7.50	7.04	6.95
	N	562	511	532	473	635	623	600
	Median	57.95	56.90	59.50	56.30	60.40	61.70	62.85
	Min	38.90	39.50	36.50	38.10	43.00	41.80	43.80
	Max	78.30	78.20	83.40	78.90	81.00	78.40	79.60
Airflow (dsm3/s)	Mean	13.97	14.15	15.30	14.91	10.59	12.74	10.08
	St. Dev	11.52	11.74	13.12	12.95	6.50	8.38	6.79
	N	552	501	520	466	640	628	605
	Median	8.08	8.49	9.49	7.33	9.49	11.06	8.51
	Min	1.26	1.80	0.02	0.38	1.07	0.83	1.05
	Max	45.47	46.20	45.80	43.71	29.22	35.34	28.37
Ambient Relative Humidity (%)	Mean	67.51				69.93		
	St. Dev	11.06				11.83		
	N	2,111				1,874		
	Median	67.10				70.70		
	Min	27.20				35.90		
	Max	94.20				96.00		
Ambient Temperature (°C)	Mean	12.49				18.51		
	St. Dev	10.62				7.36		
	N	2,096				1,771		
	Median	14.10				19.50		
	Min	-19.60				-2.20		
	Max	30.80				31.80		

Table C-9. Summary statistics of environmental parameters at swine lagoons.

Parameter	Statistic	IN4A	NC3A	NC4A	OK3A	OK4A	IA3A
Ambient Temperature (°C)	Mean	17.04	11.01	17.27	14.45	15.07	11.54
	St. Dev	8.35	6.07	7.80	9.14	10.16	11.37
	N	79	20	38	84	77	44
	Median	20.54	10.34	19.48	14.32	14.21	17.04
	Min	-6.41	1.02	-4.16	-4.31	-9.9	-9.50
	Max	27.95	28.49	26.57	28.96	31.15	28
Barometric Pressure (kPa)	Mean	98.32	101.02	101.26	90.74	91.07	97.53
	St. Dev	0.39	0.67	0.64	0.68	0.6	0.65
	N	72	17	38	84	66	44
	Median	98.32	101.20	101.42	90.75	91.05	97.38
	Min	97.27	100.07	99.74	88.78	89.38	96
	Max	99.28	102.37	102.84	92.27	92.43	99
Ambient Relative Humidity (%)	Mean	75.54	66.98	71.51	56.4	58.34	71.01
	St. Dev	10.32	20.96	14.53	14.65	17.07	13.49
	N	79	20	38	84	77	44
	Median	77.15	63.77	72.59	55.78	58.49	73.90
	Min	49.18	38.20	35.78	28	21.07	32.26
	Max	93.33	99.29	96.04	93.91	97.91	87.53
Wind speed (ms^{-1})	Mean	3.96	2.12	2.62	4.89	5.75	4.29
	St. Dev	1.52	0.76	0.98	1.66	2.1	1.78
	N	79	18	38	86	76	44
	Median	3.70	2.12	2.47	4.63	5.59	4.08
	Min	1.47	0.91	1.22	2.14	2.58	1.16
	Max	8.18	3.55	5.76	10.04	13.8	7.97

Table C-10. Summary statistics of surface manure characteristics at swine breeding and gestation barns.

Parameter	Statistic	IA4B F9	IA4B G1	IA4B G2	Overall	NC4B B1	NC4B B2	NC4B B3	Overall	OK4B B1	OK4B B2	OK4B B3	Overall
TKN (% wet weight basis)	Mean		0.36	0.32	0.34	-	-	-	-	-	-	-	-
	St. Dev		0	0	0.03								
	N		74	63	182	-	-	-	-	-	-	-	-
	Med		0.36	0.32	0.34								
	Min		0.36	0.32	0.32	-	-	-	-	-	-	-	-
	Max		0.36	0.32	0.36								
pH	Mean	6.7	7.66	7.68	7.23	7.51	7.56	7.09	7.39	7.9	7.82	7.47	7.75
	St. Dev	0.23	0.21	0.14	0.53	0.23	0.28	0.04	0.26	0.23	0.28	0.52	0.38
	N	45	74	63	182	13	11	2	26	156	136	48	340
	Med	6.66	7.74	7.7	7.36	7.51	7.56	7.09	7.51	7.88	7.82	7.4	7.76
	Min	6.32	7.25	7.46	6.32	7.51	7.56	7.09	7.09	7.57	7.39	6.52	6.52
	Max	7	7.81	7.83	7.83	7.51	7.56	7. 09	7.56	8.48	8.45	8.54	8.54
TAN (% wet weight basis)	Mean	0.24	0.24	0.24	0.24	0.17	0.17	0.06	0.13	0.21	0.26	0.12	0.2
	St. Dev	0.09	0.04	0.04	0.07	0.11	0.11	0.02	0.06	0.05	0.08	0.06	0.09
	N	45	74	63	182	13	11	2	26	156	136	48	340
	Med	0.24	0.24	0.24	0.24	0.17	0.17	0.06	0.17	0.21	0.28	0.11	0.2
	Min	0.12	0.2	0.19	0.12	0.17	0.17	0.06	0.06	0.14	0.11	0.07	0.07
	Max	0.36	0.31	0.29	0.36	0.17	0.17	0.06	0.17	0.3	0.37	0.28	0.37
Solids (%)	Mean	1.3	1.48	1.43	1.39	7.04	9.98	0.6	5.87	2.83	4.47	1.97	3.19
	St. Dev	0.37	0.9	0.64	0.62	8.92	10.3	0.26	4.8	1.58	2.32	2.03	2.2
	N	45	74	63	182	13	11	2	0.17	156	136	48	340
	Med	1.24	1.3	1.26	1.27	7.04	9.98	0.6	0	2.33	4.83	1.04	2.39
	Min	0.69	0.8	0.9	0.69	7.04	9.98	0.6	0.6	0.87	1.5	0.76	0.76
	Max	1.95	3.36	2.65	3.36	7.04	9.98	0.6	9.98	5.27	9.1	6.69	9.1

Table C-11. Summary statistics of loadout manure characteristics at swine breeding and gestation barns.

Parameter	Statistic	IA4B F9	IA4B G1	IA4B G2	Overall	NC4B B1	NC4B B2	NC4B B3	Overall	OK4B B1	OK4B B2	OK4B B3	Overall
TKN (%)	Mean	0.44	0.38	0.32	0.38	0.3	0.3	0.1	0.24	0.37	0.49	0.15	0.33
	St. Dev	0.24	0.08	0.01	0.13	0.12	0.12	0.05	0.13	0.02	0.08	0.03	0.16
	N	36	27	42	105	34	34	7	84	36	48	24	108
	Med	0.44	0.38	0.32	0.33	0.31	0.31	0.12	0.22	0.37	0.5	0.14	0.37
	Min	0.27	0.32	0.31	0.27	0.13	0.11	0.03	0.03	0.35	0.42	0.11	0.11
	Max	0.61	0.44	0.33	0.61	0.45	0.45	0.15	0.45	0.38	0.56	0.19	0.56
pH	Mean	7.71	-	-	7.71	7.41	7.41	6.75	7.22	-	-	-	-
	St. Dev	0.33	-	-	0.33	0.1	0.18	0.31	0.35	-	-	-	-
	N	36	-	-	105	34	34	7	84	-	-	-	-
	Med	7.71	-	-	7.71	7.44	7.44	6.68	7.34	-	-	-	-
	Min	7.48	-	-	7.48	7.24	7.14	6.46	6.46	-	-	-	-
	Max	7.94	-	-	7.94	7.51	7.59	7.17	7.59	-	-	-	-
TAN (%)	Mean	0.22	-	-	0.22	0.14	0.14	0.07	0.12	-	-	-	-
	St. Dev	0	-	-	0	0.05	0.06	0.03	0.06	-	-	-	-
	N	36	-	-	105	34	34	7	84	-	-	-	-
	Med	0.22	-	-	0.22	0.15	0.14	0.07	0.13	-	-	-	-
	Min	0.22	-	-	0.22	0.07	0.05	0.03	0.03	-	-	-	-
	Max	0.22	-	-	0.22	0.2	0.23	0.09	0.23	-	-	-	-
Solids (%)	Mean	6.47	2.39	1.41	3.42	11.26	8.89	0.93	7.41	8.29	12.97	2.06	7.72
	St. Dev	7.4	1.06	0.5	4.12	6.96	5.59	0.46	6.64	2.8	3.98	1.19	5.54
	N	36	27	42	105	34	34	7	84	36	48	24	108
	Med	6.47	2.39	1.41	1.7	11.05	8.49	1	5.9	8.63	13.05	1.72	8.26
	Min	1.24	1.64	1.05	1.05	2.07	0.87	0.3	0.3	5.33	8.26	1.05	1.05
	Max	11.7	3.14	1.76	11.7	19.5	16.9	1.41	19.5	10.9	17.5	3.76	17.5
Sulfur (%)	Mean	0.1	0.1	-	0.1	0.11	0.07	0.01	0.06	-	-	-	-
	St. Dev	0.03	0.04	-	0	0.07	0.05	0	0.06	-	-	-	-
	N	36	27	-	105	34	34	7	84	-	-	-	-
	Med	0.1	0.1	-	0.1	0.11	0.06	0.01	0.05	-	-	-	-
	Min	0.1	0.1	-	0.1	0.01	0.01	0.01	0.01	-	-	-	-
	Max	0.1	0.1	-	0.1	0.18	0.15	0.01	0.18	-	-	-	-

Table C-12. Summary statistics of manure characteristics at swine finishing barns (IN3B).

		Surface Manure					Loadout				
Parameter	**Statistic**	**R5**	**R6**	**R7**	**R8**	**Overall**	**R5**	**R6**	**R7**	**R8**	**Overall**
Nitrogen (% wet weight basis)	Mean	0.58	0.52	0.44	0.47	0.5	0.54	0.5	0.44	0.43	0.48
	St. Dev	0.14	0.14	0.12	0.2	0.15	0.08	0.04	0.1	0.07	0.09
	N	7	7	7	7	28	25	25	24	24	98
	Median	0.58	0.48	0.45	0.43	0.46	0.53	0.51	0.47	0.43	0.49
	Min	0.41	0.42	7.27	7.46	0.27	0.40	0.40	0.24	0.30	0.24
	Max	0.82	0.81	8.2	8.2	0.86	0.66	0.53	0.56	0.52	0.66
pH	Mean	7.71	7.68	7.68	0.43	7.69	-	-	-	-	-
	St. Dev	0.2	0.23	0.3	0.86	0.23	-	-	-	-	-
	N	10	9	9	0.27	38	-	-	-	-	-
	Median	7.69	7.69	7.69	0	7.69	-	-	-	-	-
	Min	7.4	7.32	0	7.46	7.27	-	-	-	-	-
	Max	8.14	8.03	0	8.2	8.2	-	-	-	-	-
Ammonia (% wet weight basis)	Mean	0.38	0.35	0.32	0.33	0.35	-	-	-	-	-
	St. Dev	0.06	0.02	0.06	0.07	0.06	-	-	-	-	-
	N	10	9	9	10	38	-	-	-	-	-
	Median	0.36	0.35	0.33	0.34	0.35	-	-	-	-	-
	Min	0.29	0.32	0.22	0.21	0.21	-	-	-	-	-
	Max	0.49	0.39	0.42	0.44	0.49	-	-	-	-	-
Solids (%)	Mean	5.18	5.71	3.7	4.35	4.74	13.85	13.81	13.3	13.55	13.63
	St. Dev	2.42	4.24	2.75	3.32	3.2	7.46	27.46	27.14	28.43	26.43
	N	10	9	9	10	38	25	25	24	24	98
	Median	5.25	4.46	3.09	3.38	3.92	5.19	4.74	4.74	4.68	4.74
	Min	1.76	2.7	1.61	1.6	1.6	2.57	3.42	1.79	2.67	1.79
	Max	10.7	16.7	10.6	13	16.7	87	87.1	85.6	89.3	89.3
Ash (%)	Mean	1.67	1.46	1.12	1.26	1.38	1.37	1.29	1.2	1.14	1.25
	St. Dev	0.85	0.95	0.64	1	0.85	0.35	0.25	0.36	0.3	0.32
	N	10	7	7	7	28	25	25	24	24	98
	Median	1.51	1.18	1.02	0.93	1.14	1.39	1.31	1.38	1.2	1.27
	Min	0.44	0.6	0.43	0.27	0.27	0.85	0.79	0.61	0.72	0.61
	Max	2.77	3.53	2.41	3.4	3.53	1.9	1.69	1.56	1.64	1.9

Table C-13. Summary statistics for pit liquid at swine finishing barns (NC3B)

Parameter	Statistic	NC3B			
		B1	B2	B3	Overall
TKN (% wet weight basis)	Mean	0.15	0.13	0.14	0.14
	St. Dev	0.04	0.03	0.03	0.04
	N	24	25	22	71
	Median	0.14	0.13	0.14	0.14
	Min	0.08	0.08	0.08	0.08
	Max	0.23	0.18	0.17	0.23
pH	Mean	7.46	7.49	7.56	7.5
	St. Dev	0.18	0.21	0.20	0.20
	N	21	23	20	64
	Median	7.44	7.47	7.56	7.48
	Min	7.22	7.18	7.24	7.18
	Max	7.88	7.89	8.06	8.06
TAN (% wet weight basis)	Mean	0.15	0.13	0.14	0.14
	St. Dev	0.04	0.03	0.03	0.04
	N	24	25	22	71
	Median	0.14	0.13	0.14	0.14
	Min	0.08	0.08	0.08	0.08
	Max	0.23	0.18	0.17	0.23
Solids (%)	Mean	2.59	1.95	1.99	2.18
	St. Dev	1.28	0.71	0.69	0.97
	N	24	25	22	71
	Median	2.40	1.70	2.10	2.20
	Min	0.6	0.87	0.9	0.6
	Max	7.00	3.60	3.40	7.00

Table C-14. Summary statistics of open source manure characteristics at swine farms.

Parameter	Statistic	IA3A	IN4A	NC3A	NC4A	OK3A	OK4A
pH	Average	7.32	-	7.60	7.50	8.17	8.28
	St dev	0.30	-	0.32	0.15	0.24	-
	N	5	-	20	22	3	1
	Min	6.91	-	6.80	7.22	7.9	-
	med	7.44	-	7.70	7.50	8.26	-
	max	7.62	-	7.94	7.79	8.36	-
Nitrogen	Average	0.43	-	0.42	0.29	0.57	0.44
	St dev	0.05	-	0.15	0.05	0.11	-
	N	4	-	20	22	3	1
	min	0.37	-	0.17	0.20	0.46	-
	med	0.44	-	0.40	0.30	0.57	-
	max	0.48	-	0.68	0.39	0.68	-
Solids	Average	2.71	-	-	-	0.46	0.2
	St dev	1.46	-	-	-	0.08	-
	N	5	-	-	-	3	1
	min	1.33	-	-	-	0.4	-
	med	1.82	-	-	-	0.43	-
	max	4.37	-	-	-	0.55	-
Ammonia	Average	0.31	-	-	-	0.50	0.33
	St dev	0.04	-	-	-	0.05	-
	N	5	-	-	-	3	1
	min	0.24	-	-	-	0.45	-
	med	0.3	-	-	-	0.49	-
	max	0.36	-	-	-	0.55	-
Sulfur	Average	0.03	-	0.04	0.07	0.03	0.03
	St dev	0	-	0.01	0.02	0.01	-
	N	2	-	20	22	3	1
	min	0.03	-	0.03	0.01	0.02	-
	med	0.03	-	0.04	0.07	0.03	-
	max	0.03	-	0.05	0.09	0.03	-

Table C-15. Summary statistics of continuously collected open source manure parameters at swine farms.

Parameter	Statistic	IN4A	NC3A	NC4A	OK3A	OK4A
Lagoon Temperature (°C)	Mean	20.57	15.31	20.42	16.91	18.19
	St. Dev	6.85	4.61	6.91	7.29	7.92
	N	69	18	37	71	58
	Median	23.56	14.36	22.39	18.58	18.08
	Min	2.92	8.95	4.54	3.17	3.38
	Max	27.81	30.17	27.41	27.19	28.81
Oxidation Reduction Potential (mV)	Mean	-204.81	-475.00	-483.75	-494.3	-491.6
	St. Dev	176.96	80.40	67.68	55.67	43.02
	N	68	18	37	71	57
	Median	-66.12	-497.23	-507.96	-510.4	-504.47
	Min	-483.35	-546.83	-553.14	-560.2	-545.3
	Max	-36.70	-228.56	-281.33	-262.5	-329.95
pH	Mean	7.90	7.75	7.73	7.84	7.59
	St. Dev	0.12	0.31	0.08	0.24	0.5
	N	38	19	32	62	44
	Median	7.88	7.63	7.73	7.89	7.78
	Min	7.69	7.43	7.62	7.42	6.56
	Max	8.19	8.36	7.91	8.12	8.33

Appendix D – Time Series Plots

List of Figures

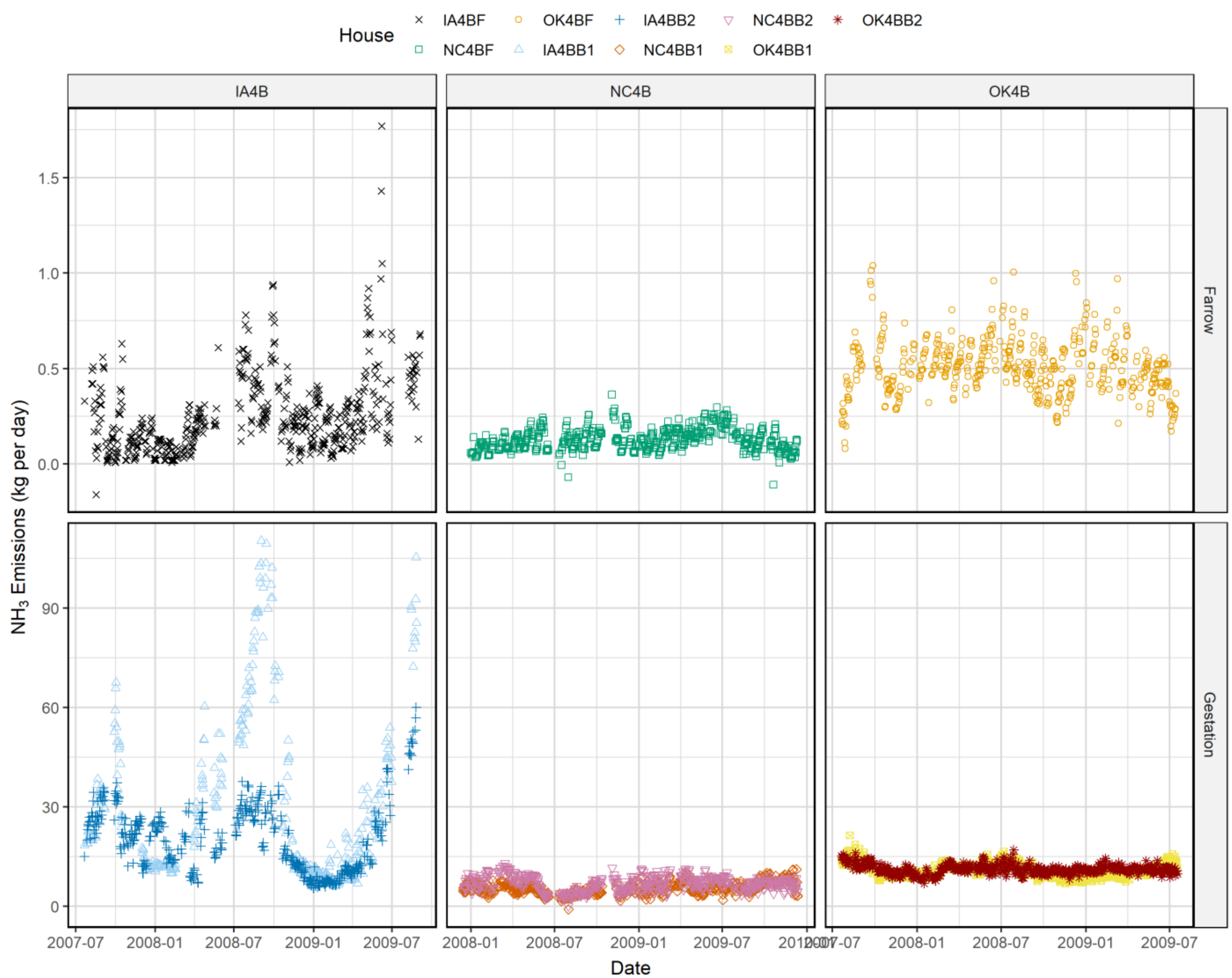


Figure D-1. NAEMS Breeding and Gestation confinement site NH_3 emissions, by site, by farrowing room (top row) and gestation barn (bottom row).

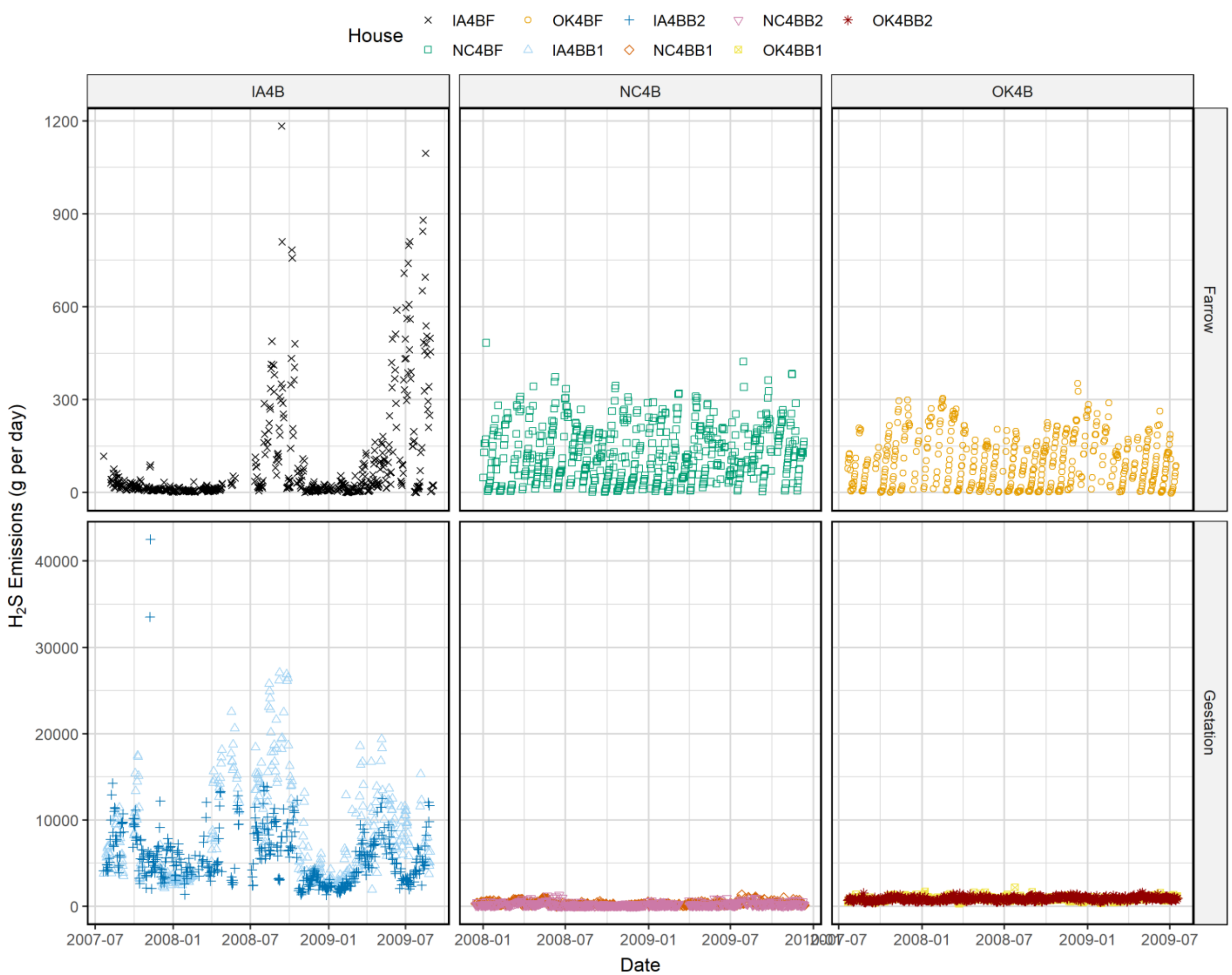


Figure D-2. NAEMS Breeding and Gestation confinement site H_2S emissions, by site.

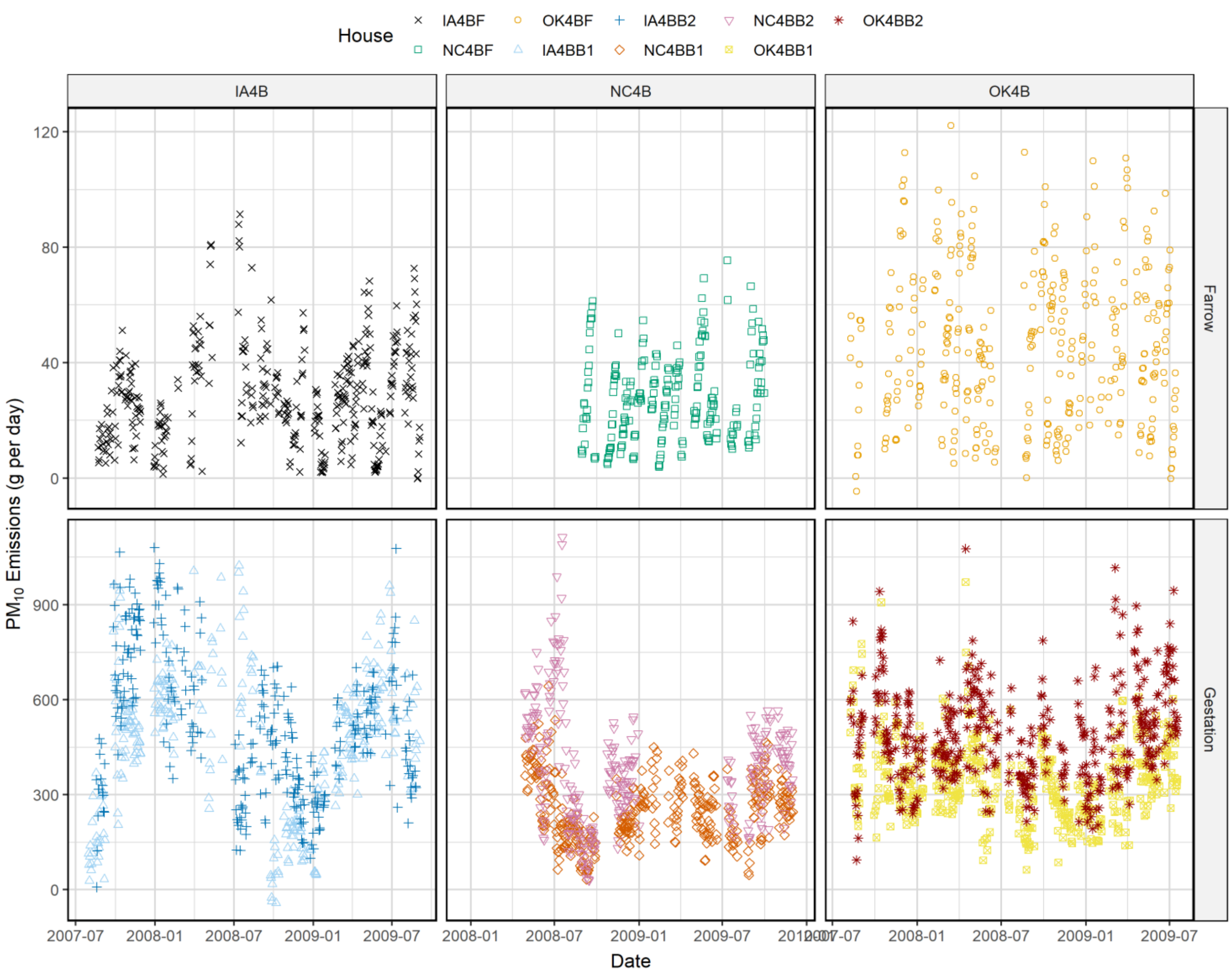


Figure D-3. NAEMS Breeding and Gestation confinement site PM_{10} emissions, by site.

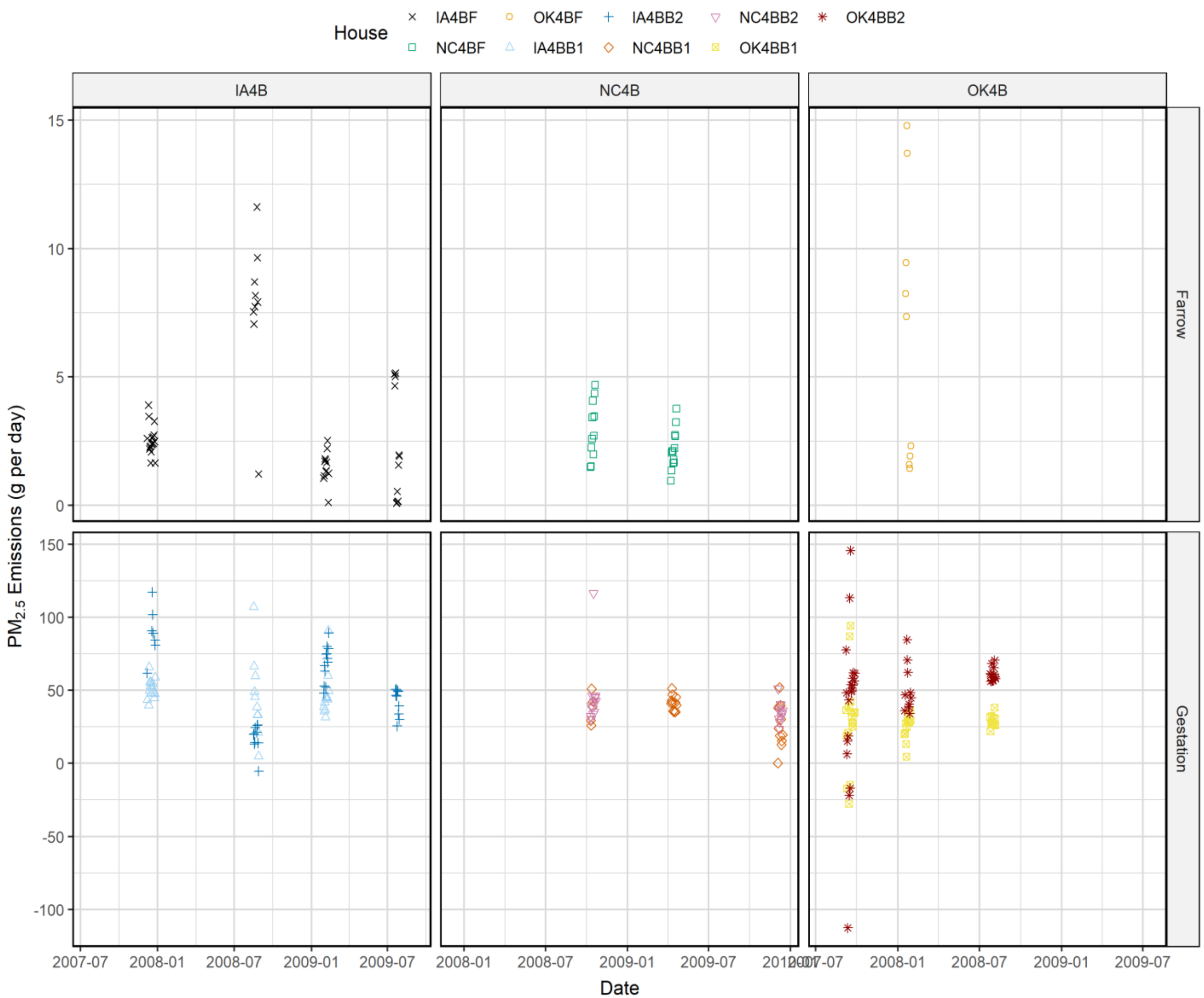


Figure D-4. NAEMS Breeding and Gestation confinement site $PM_{2.5}$ emissions, by site.

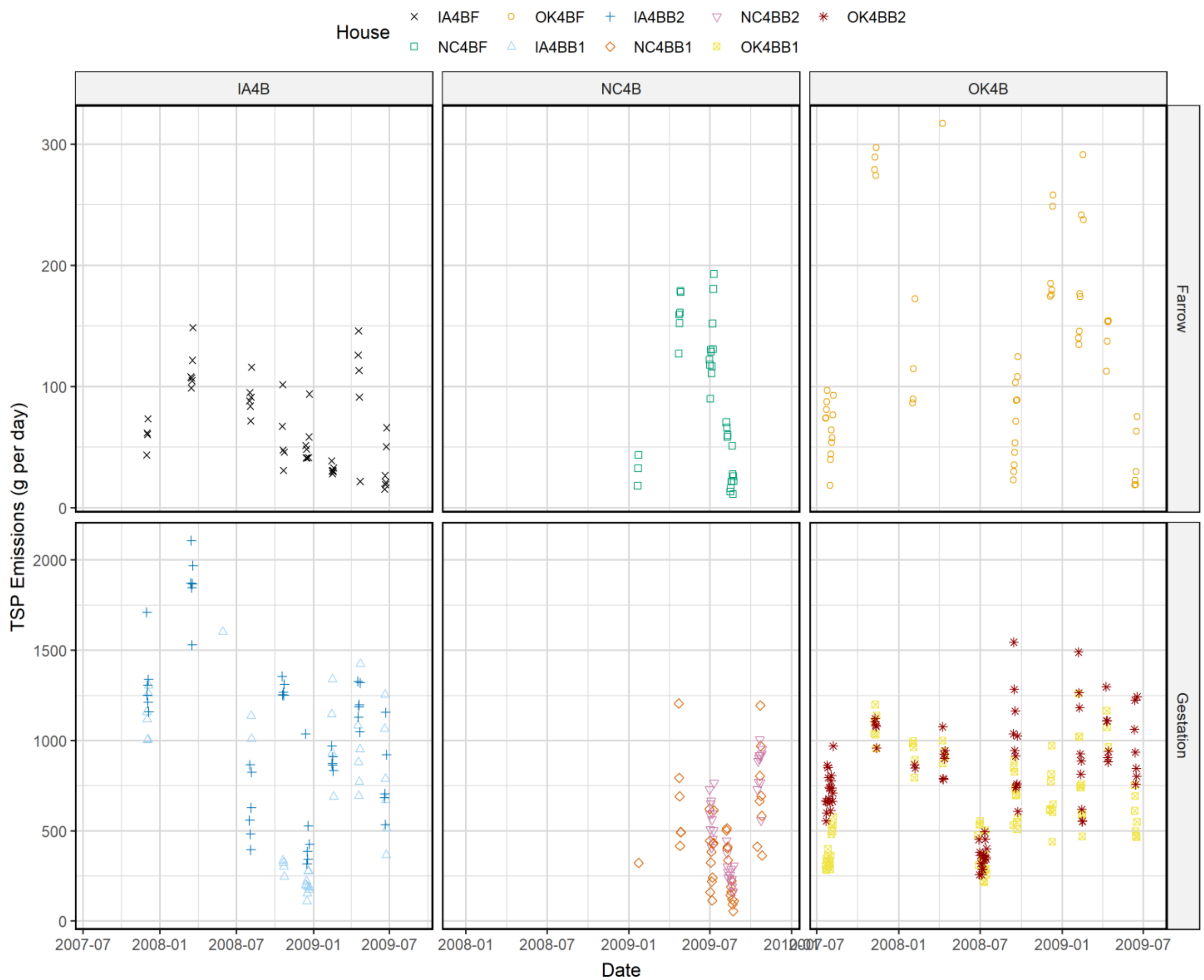
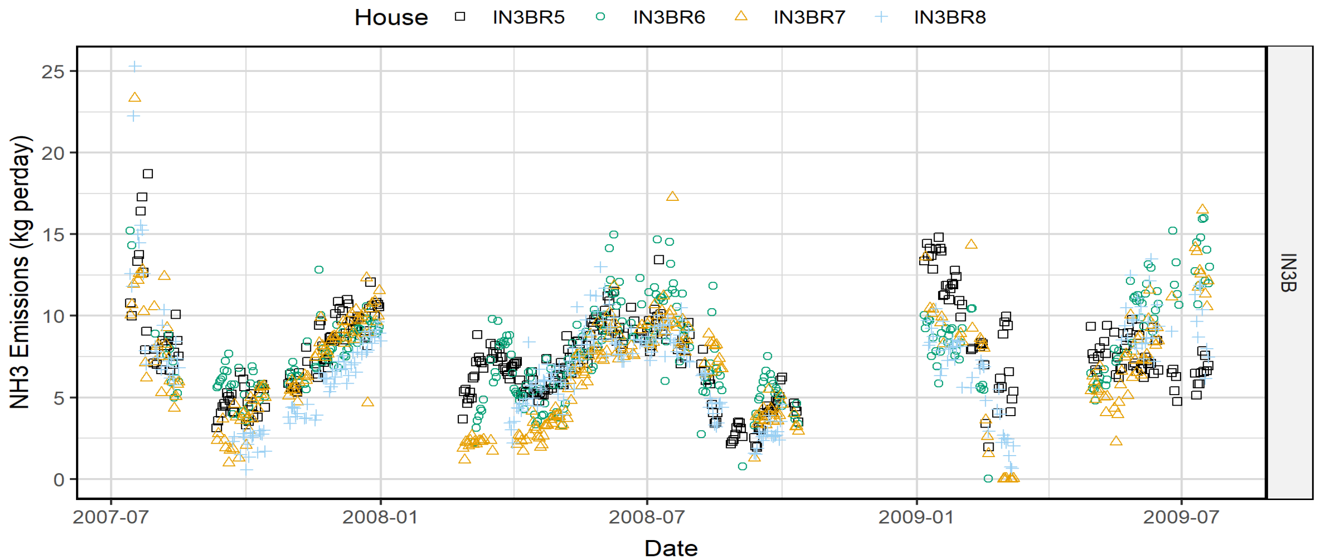


Figure D-5. NAEMS Breeding and Gestation confinement site TSP emissions, by site.



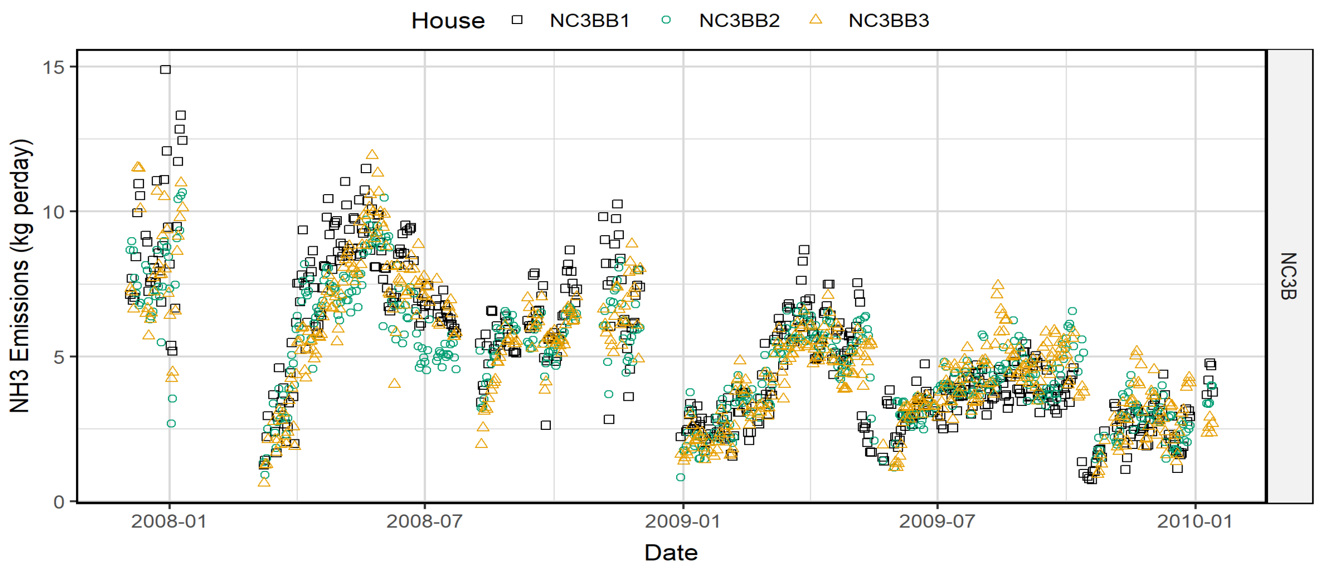


Figure D-6. NAEMS Grow-finish confinement site NH_3 emissions, by site.

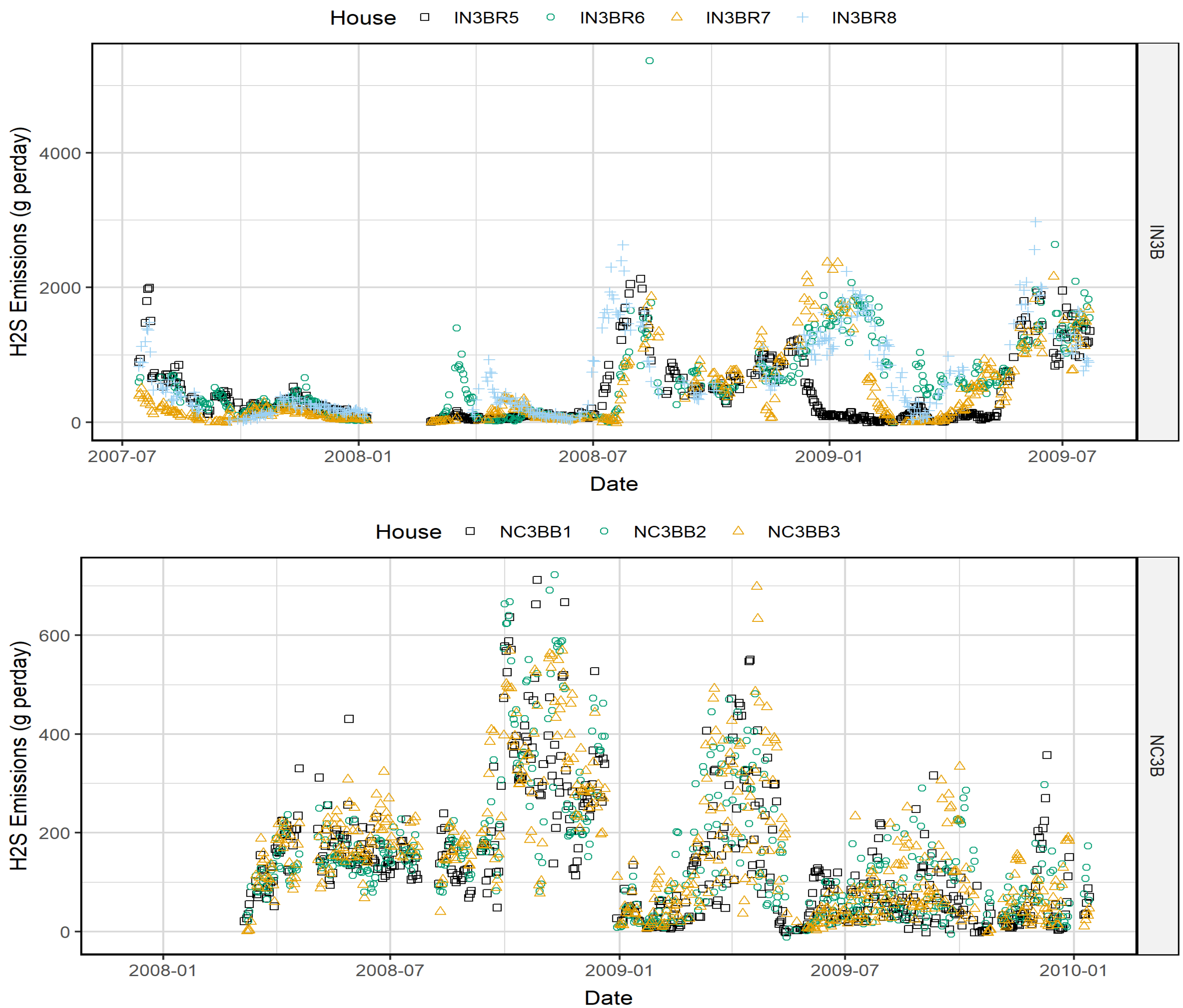


Figure D-7. NAEMS Grow-finish confinement site H_2S emissions, by site.

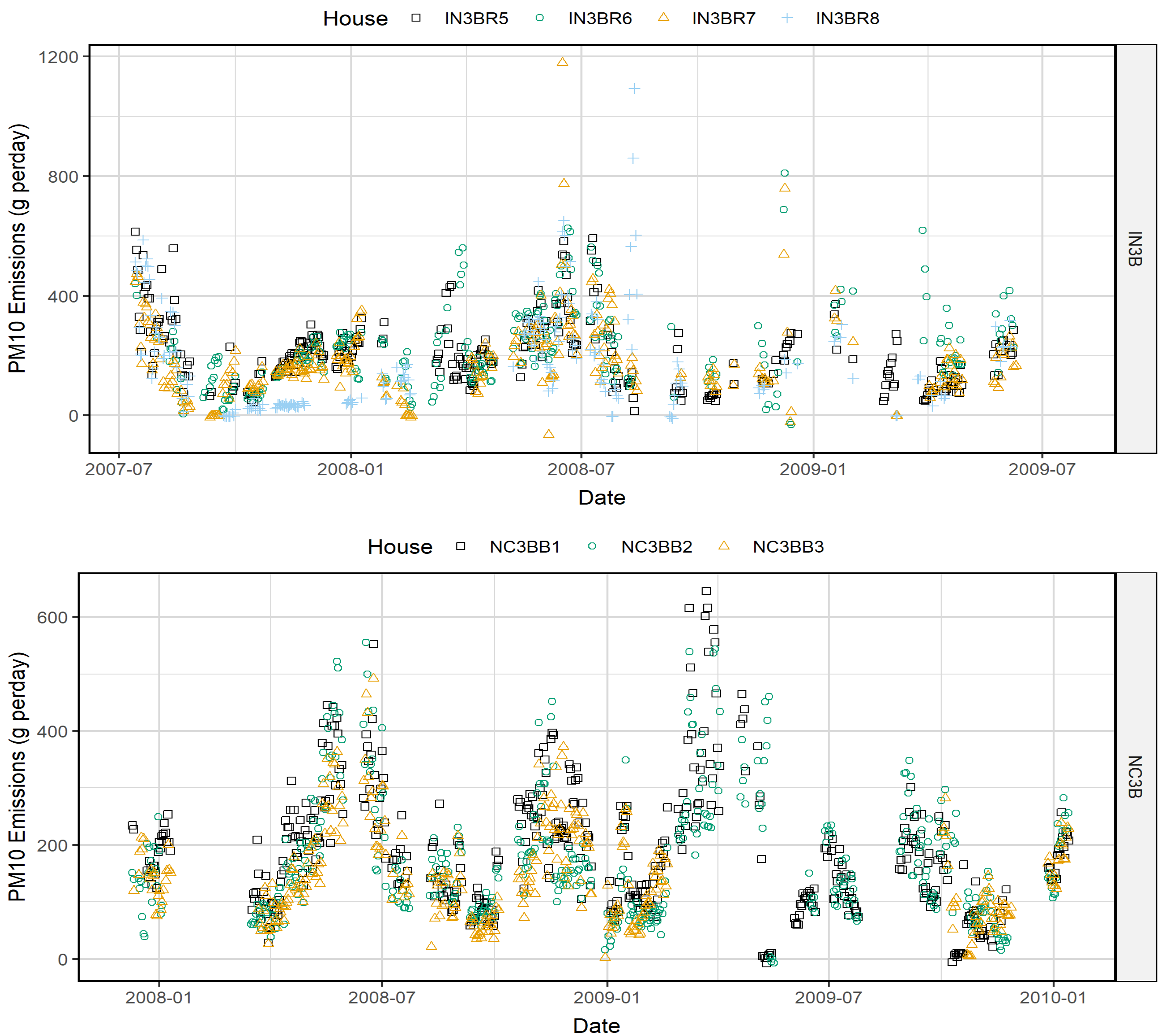


Figure D-8. NAEMS Grow-finish confinement site PM_{10} emissions, by site.

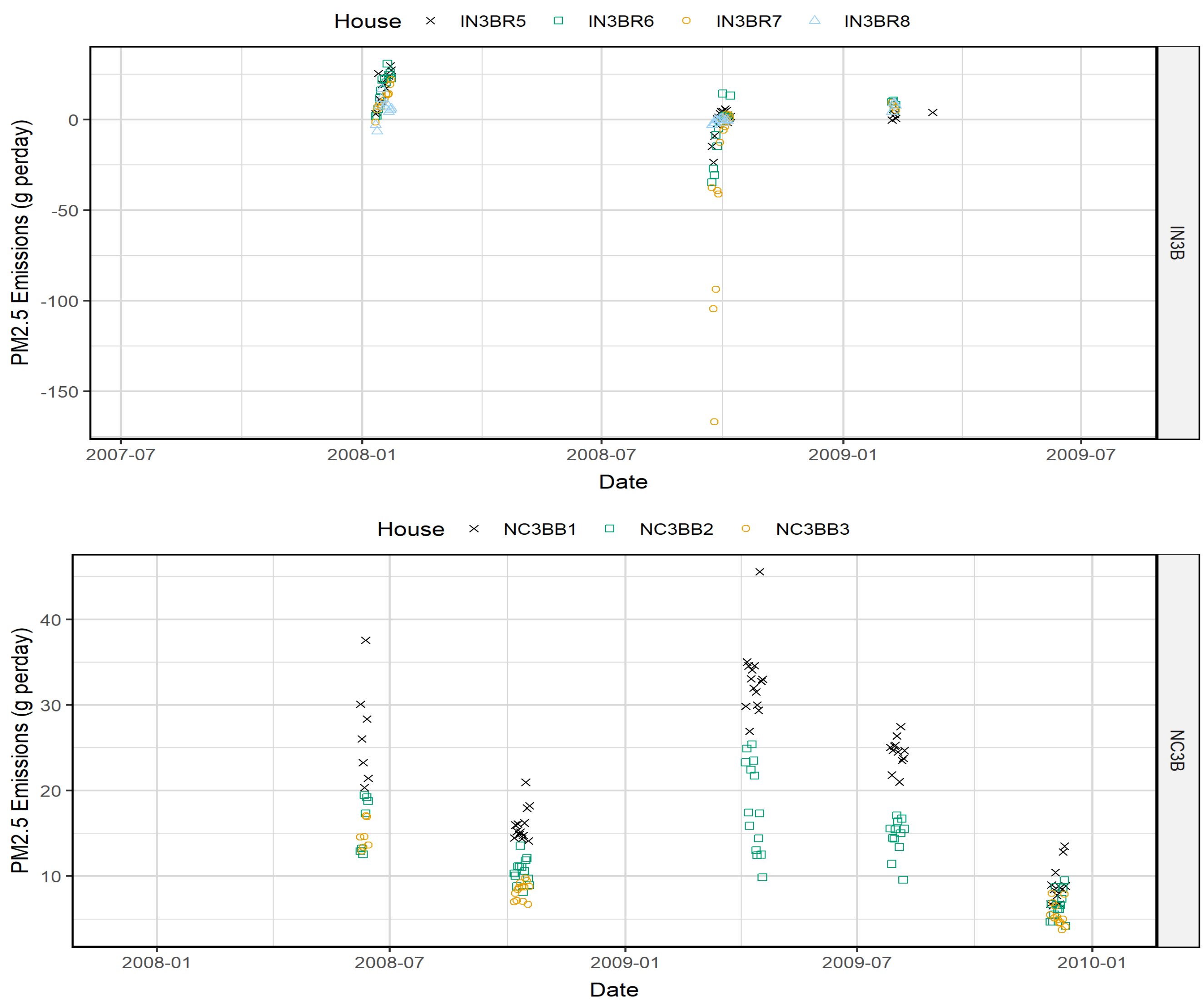


Figure D-9. NAEMS Grow-finish confinement site $PM_{2.5}$ emissions, by site.

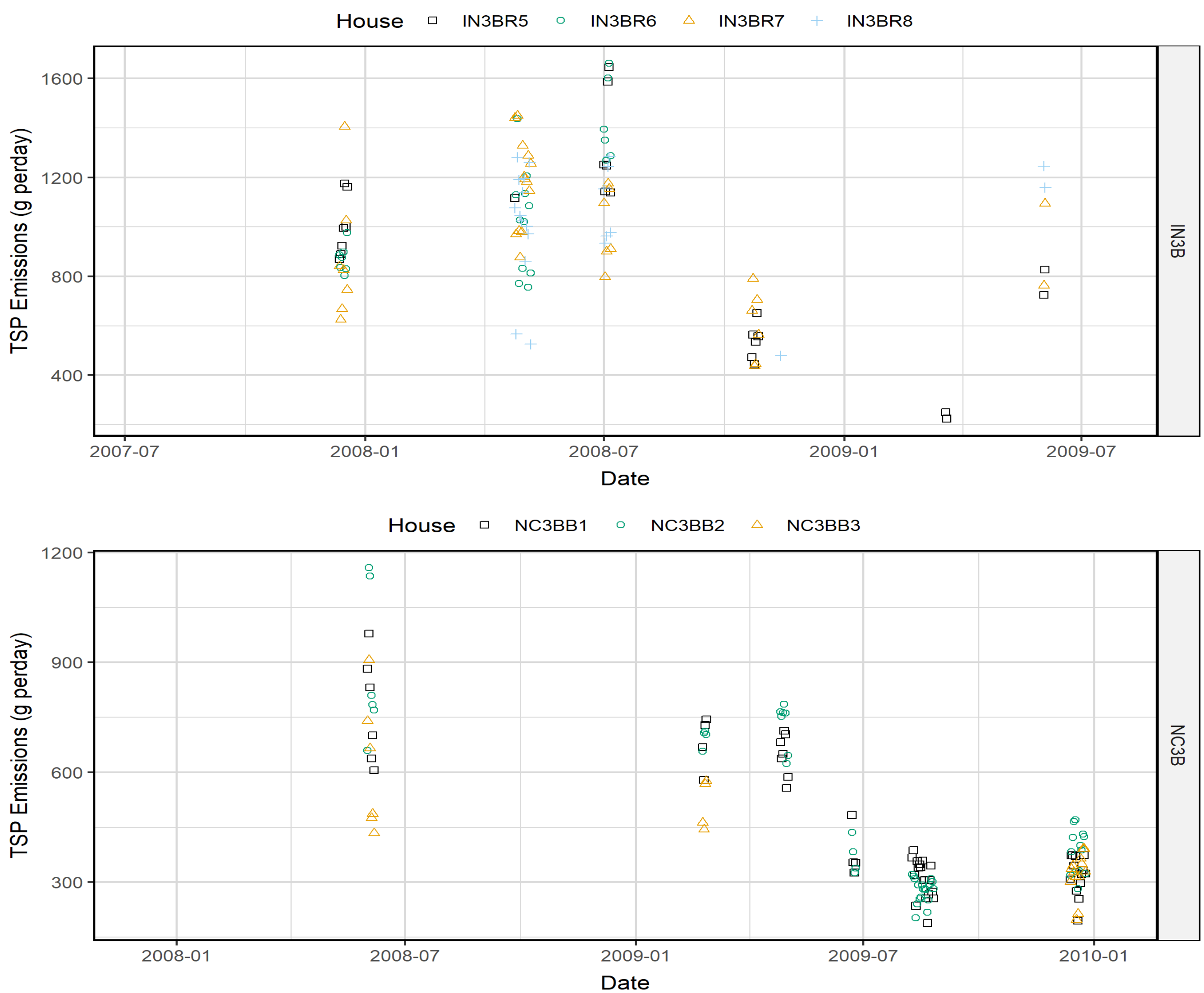


Figure D-10. NAEMS Grow-finish confinement site TSP emissions, by site.

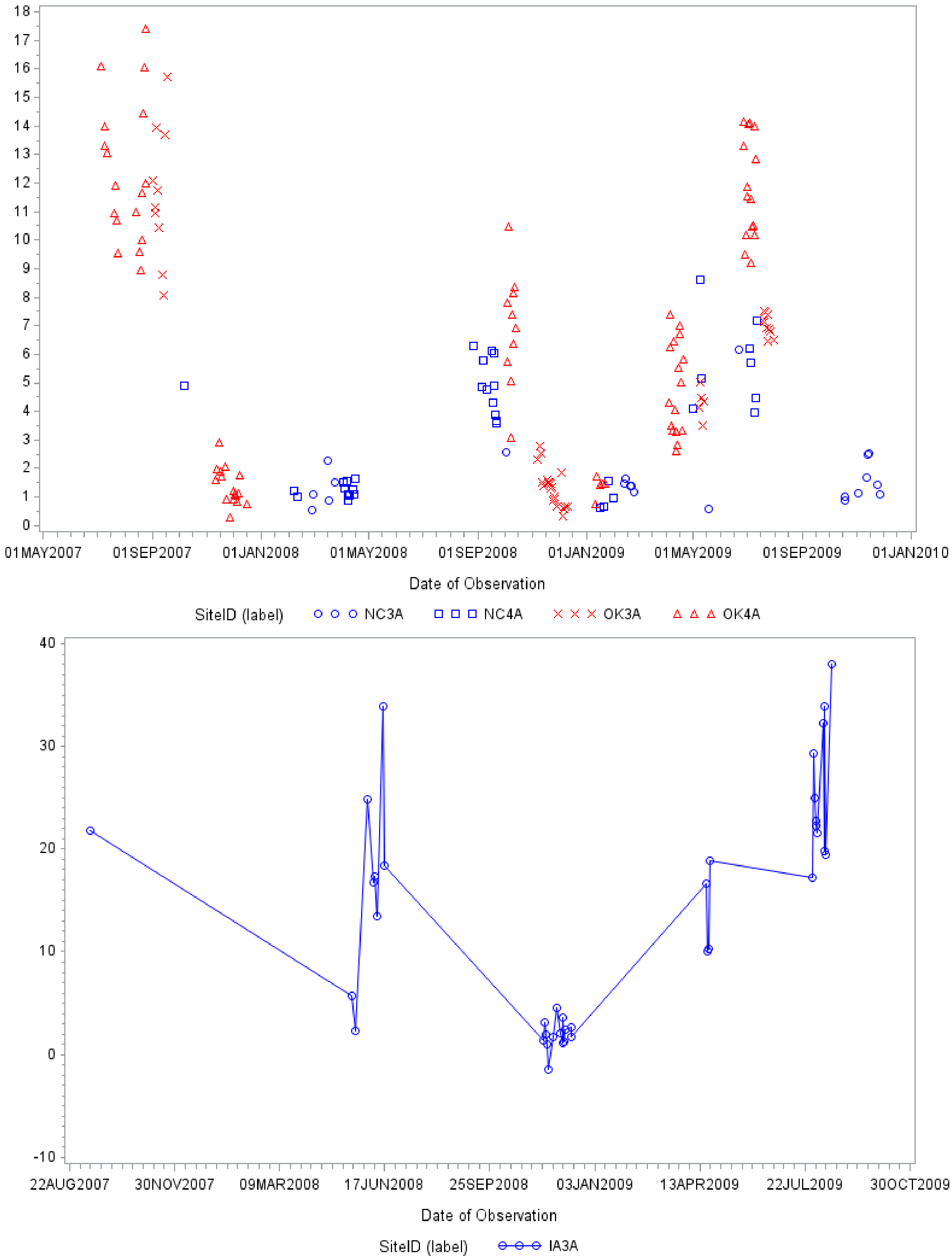


Figure D-11. NAEMS open source NH_3 emissions, by site. Lagoons presented on the top, basins on the bottom.

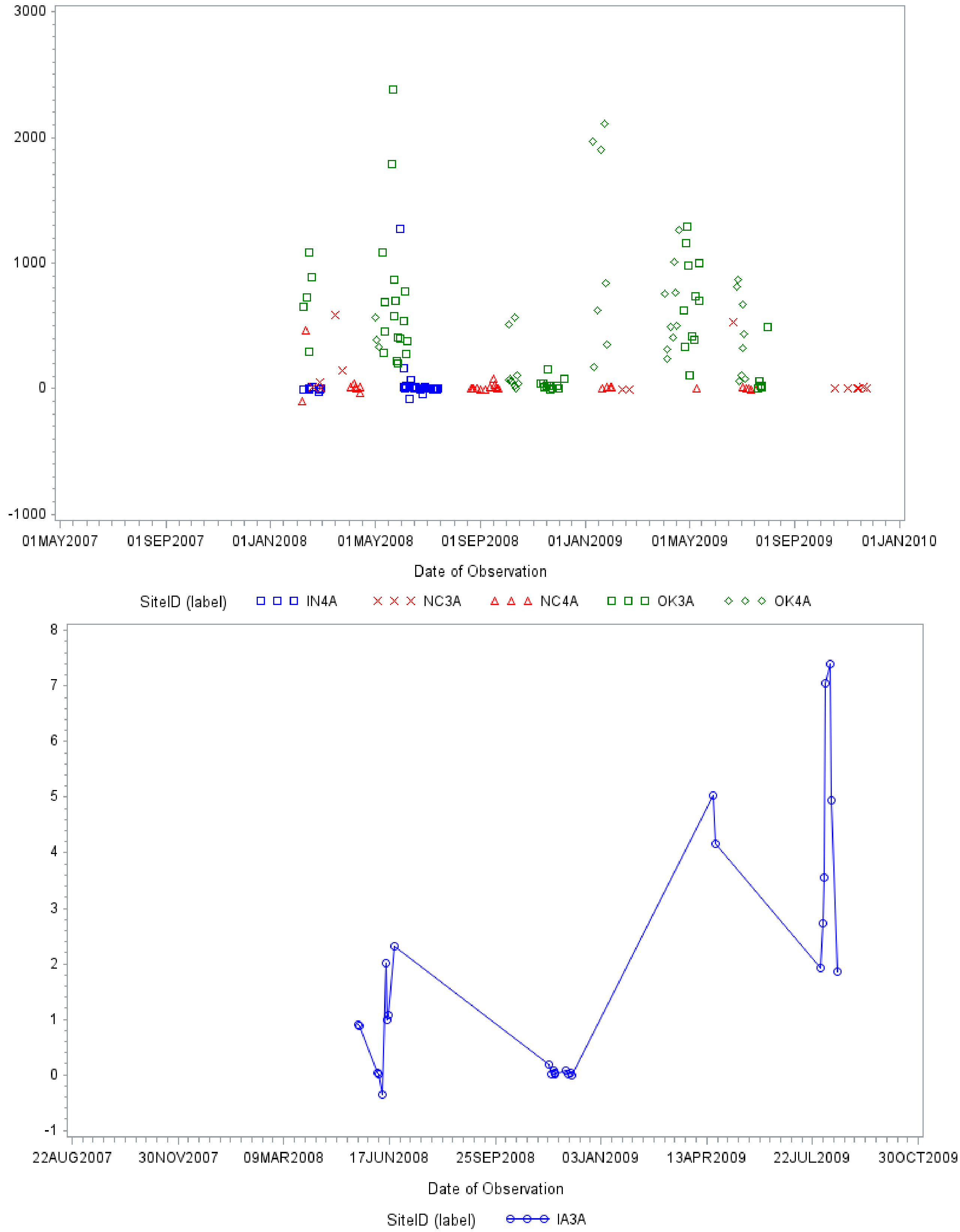


Figure D-12. NAEMS open source site H_2S emissions, by site. Lagoons presented on the top, basins on the bottom.

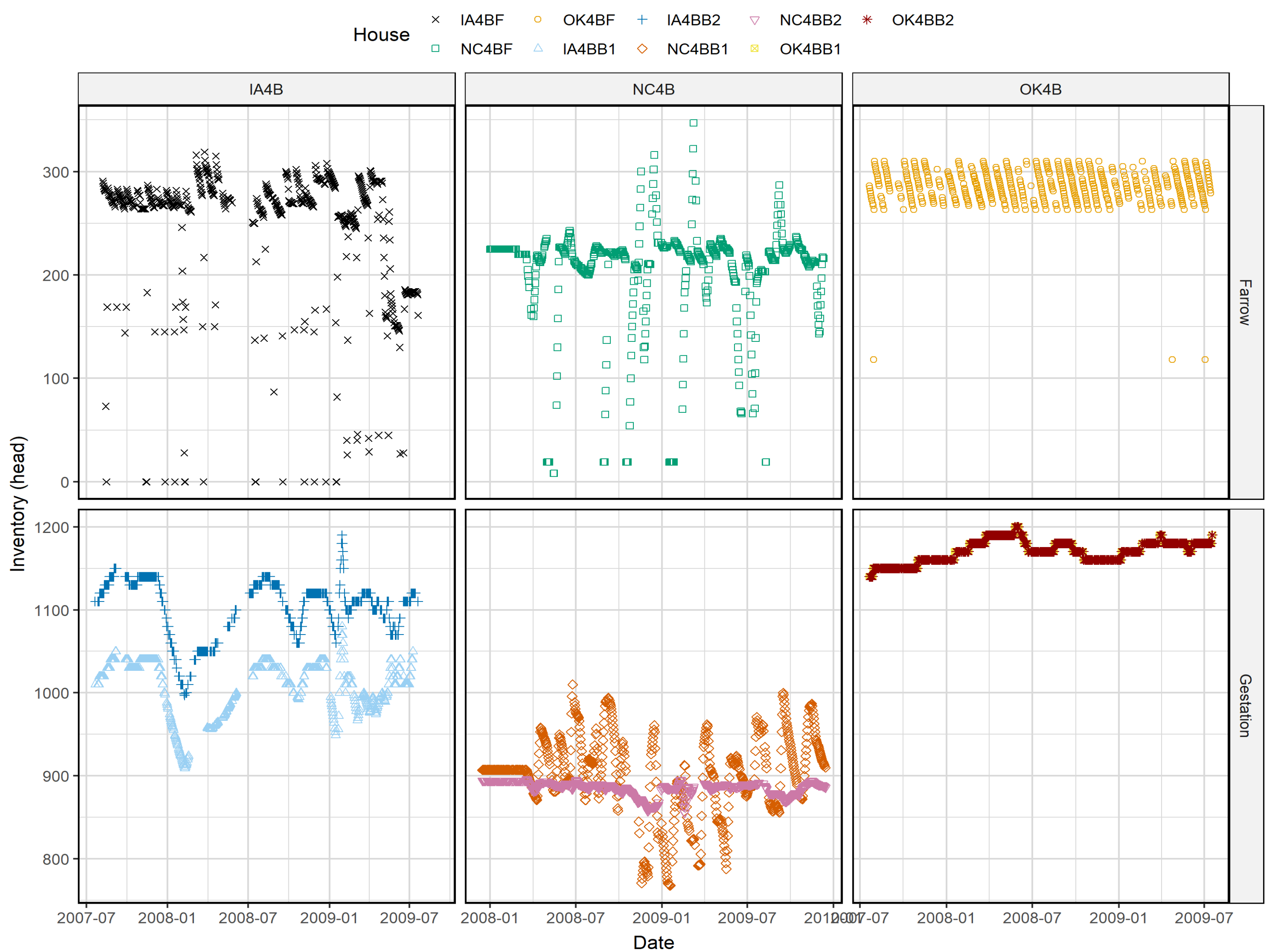


Figure D-13. Swine farrowing (top row) and gestation (bottom row) house inventory trends during the NAEMS monitoring period.

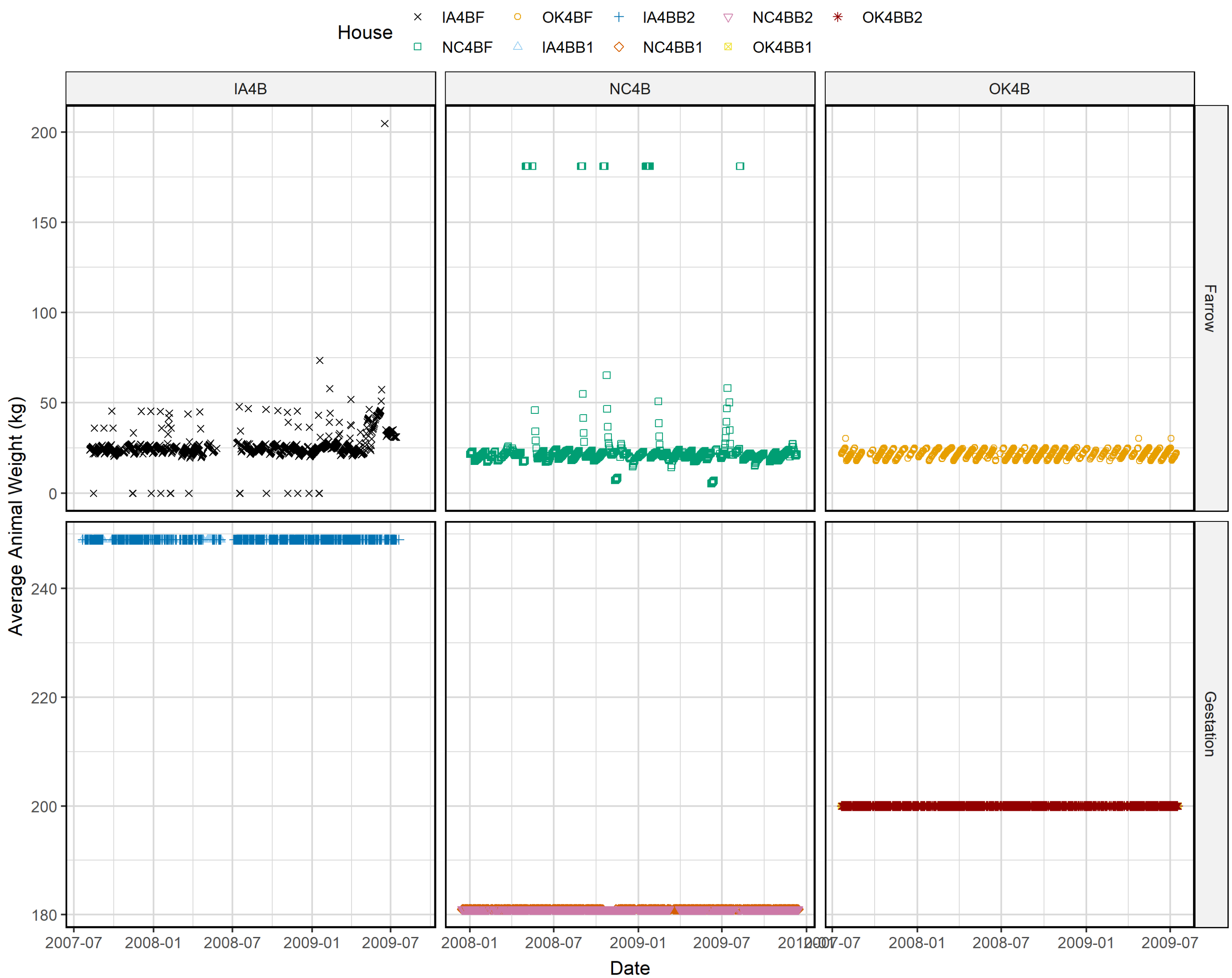


Figure D-14. Swine farrowing (top row) and gestation (bottom row) house weight trends during the NAEMS monitoring period.

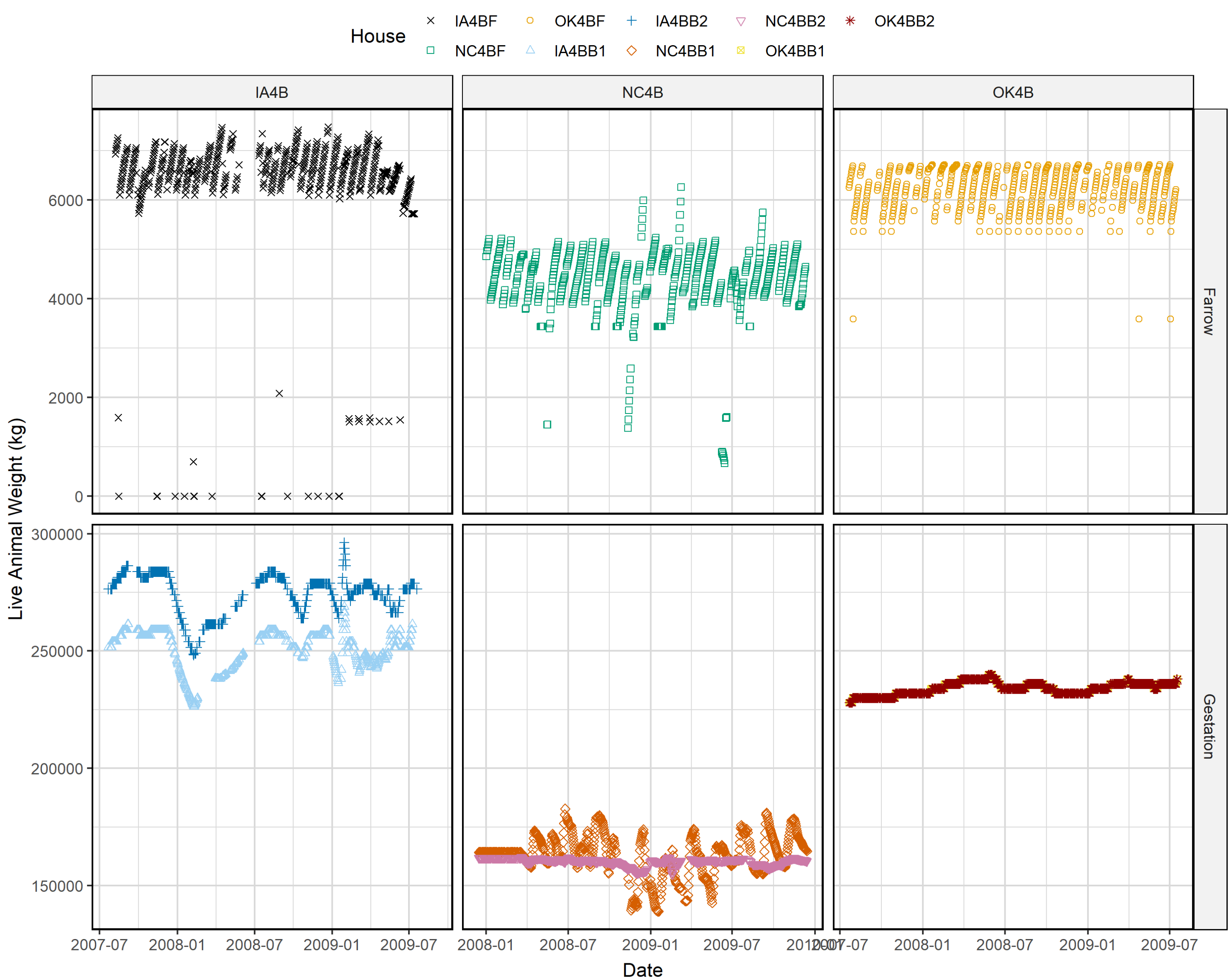


Figure D-15. Swine farrowing (top row) and gestation (bottom row) house LAW during the NAEMS monitoring period.

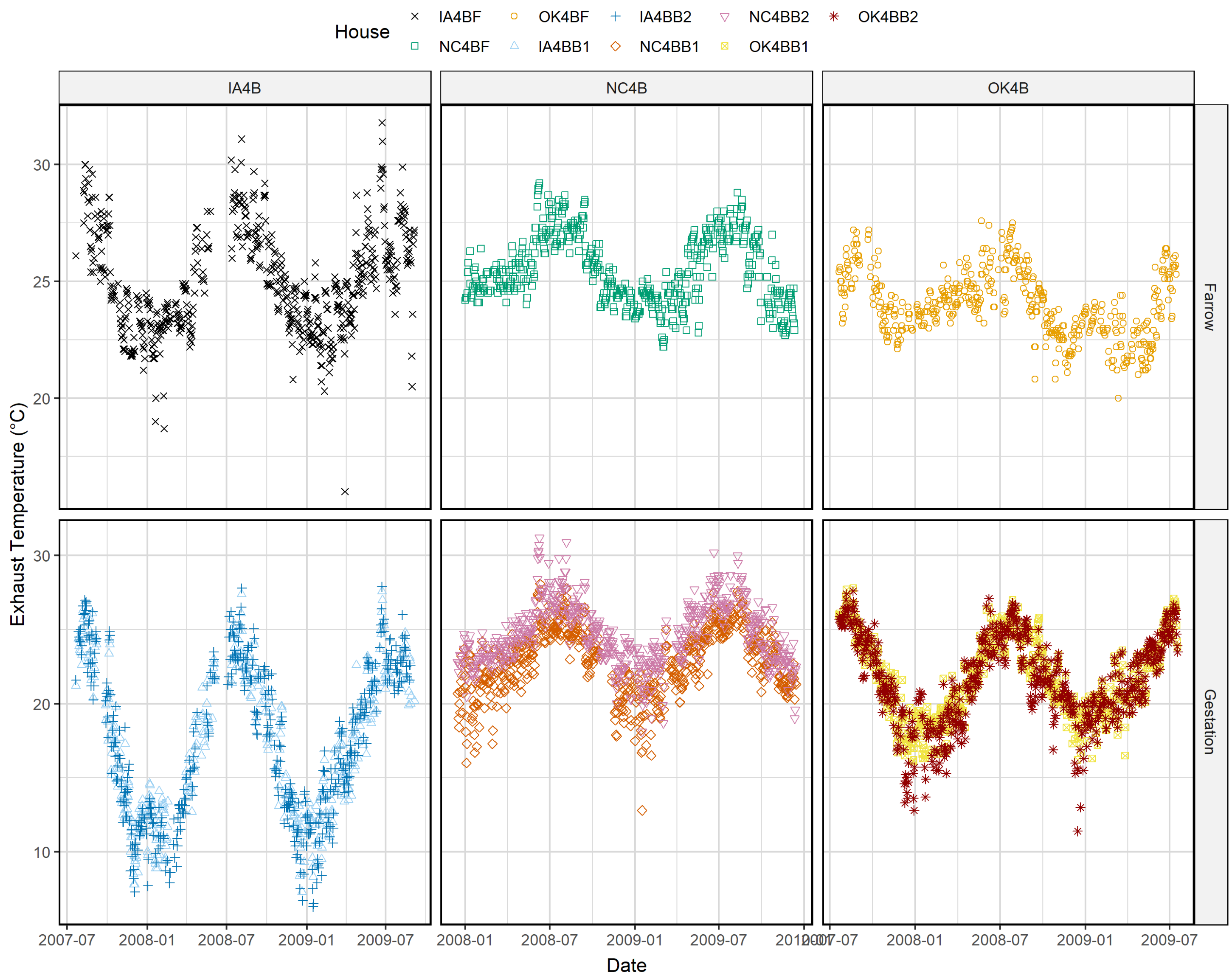


Figure D-16. Swine farrowing (top row) and gestation (bottom row) house exhaust temperature trends during the NAEMS monitoring period.

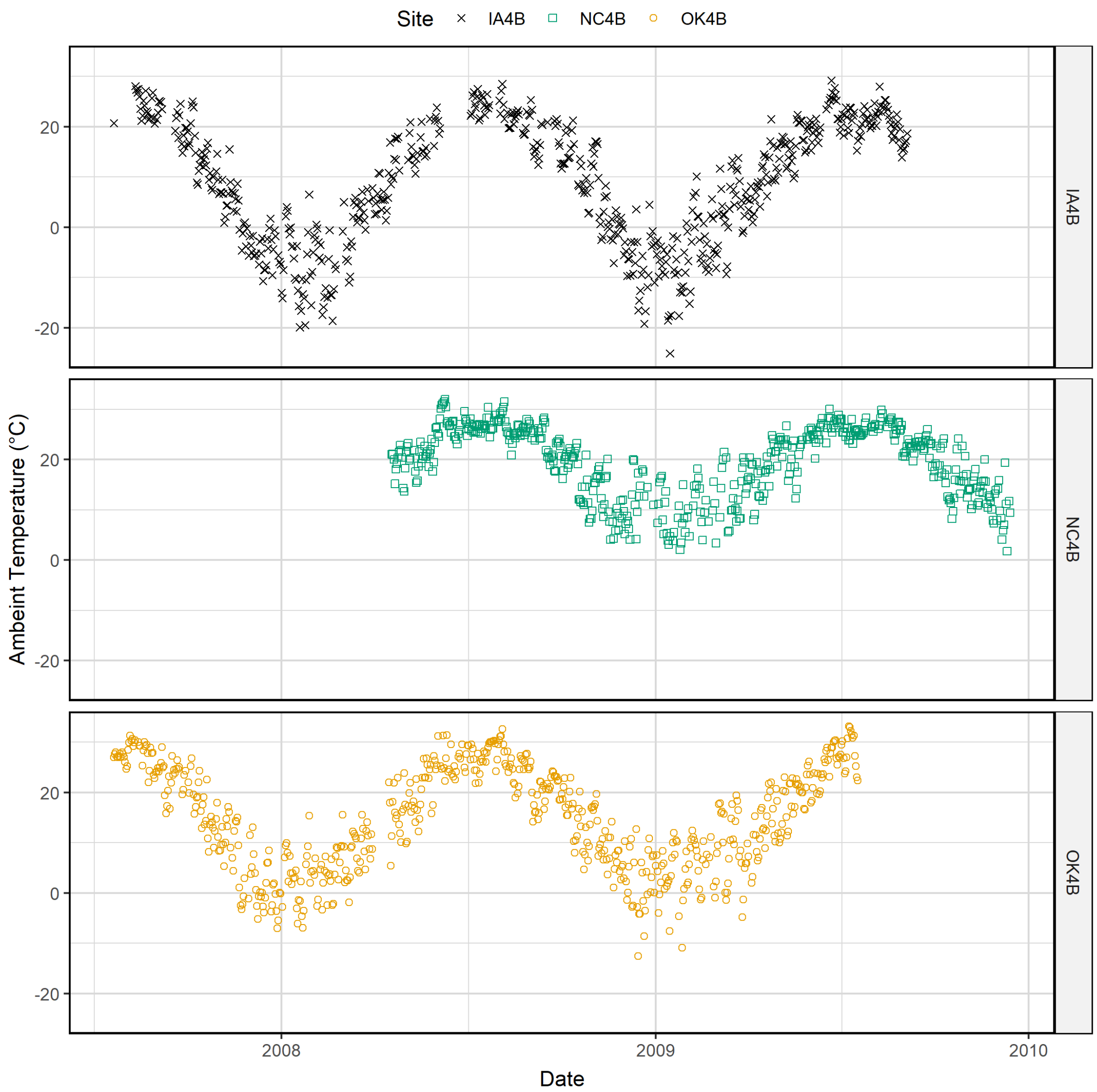


Figure D-17. Swine farrowing (top row) and gestation (bottom row) house ambient temperature trends during the NAEMS monitoring period.

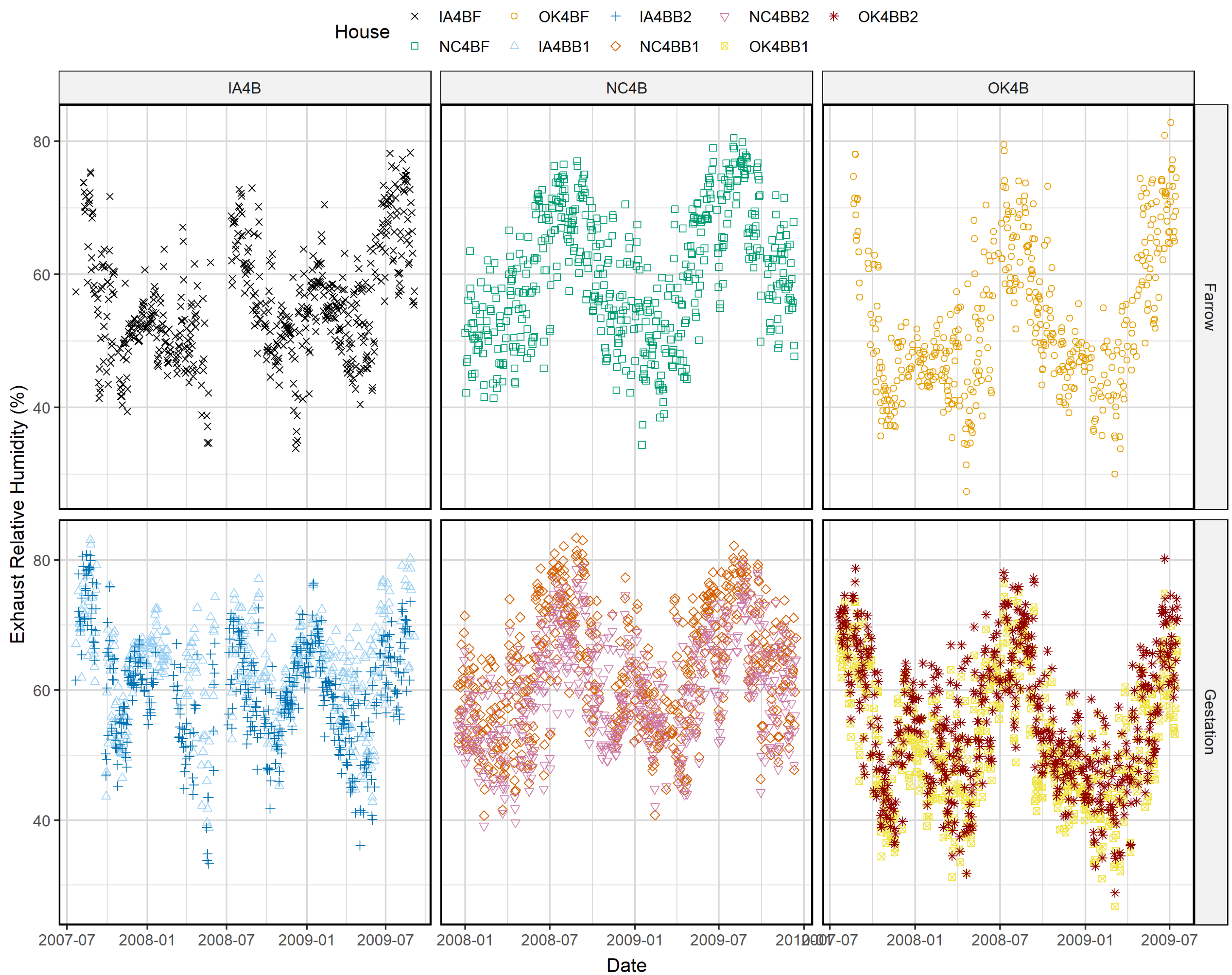


Figure D-18. Swine farrowing (top row) and gestation (bottom row) house exhaust relative humidity during the NAEMS monitoring period.

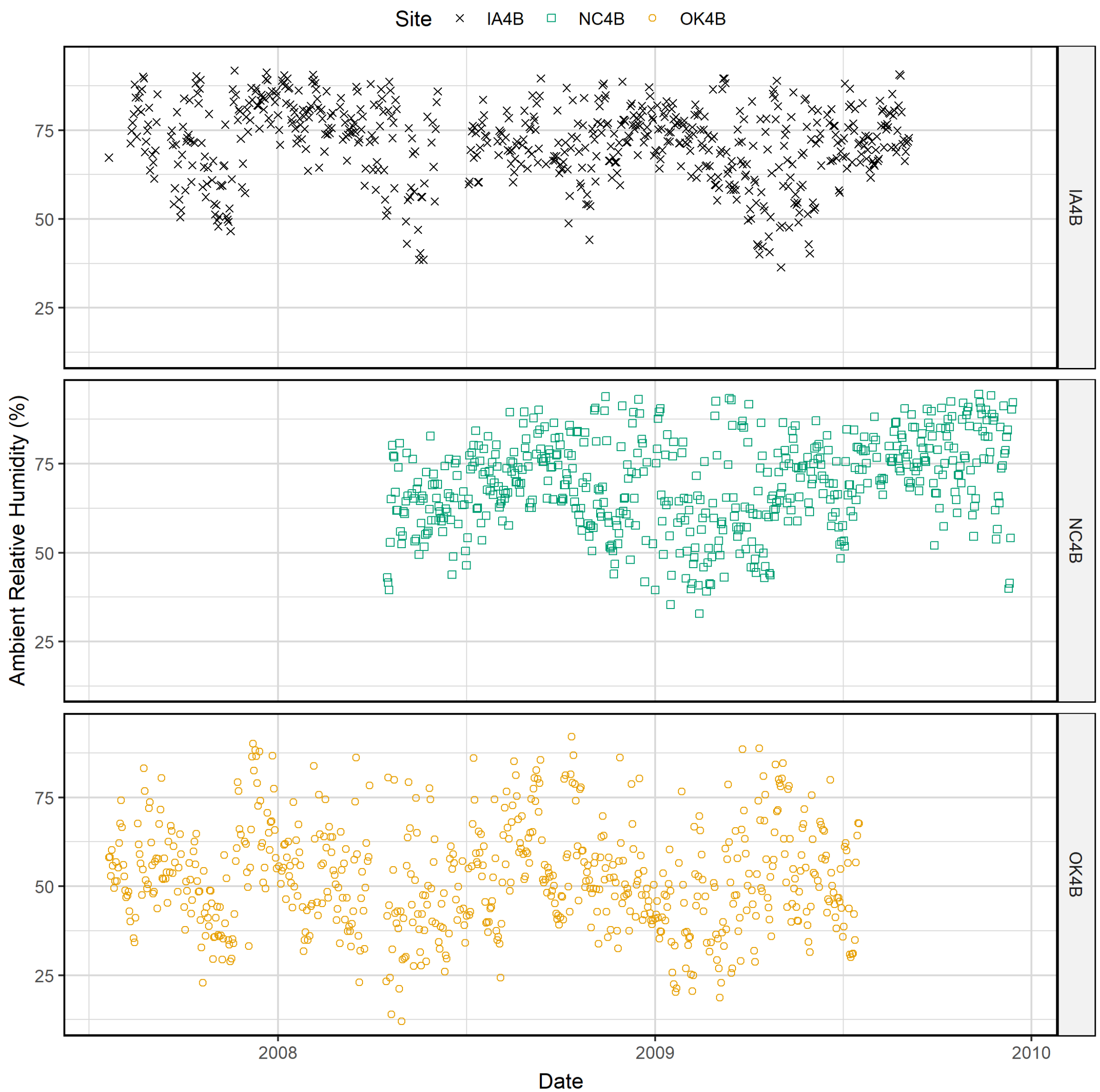


Figure D-19. Swine farrowing (top row) and gestation (bottom row) house ambient relative humidity during the NAEMS monitoring period.

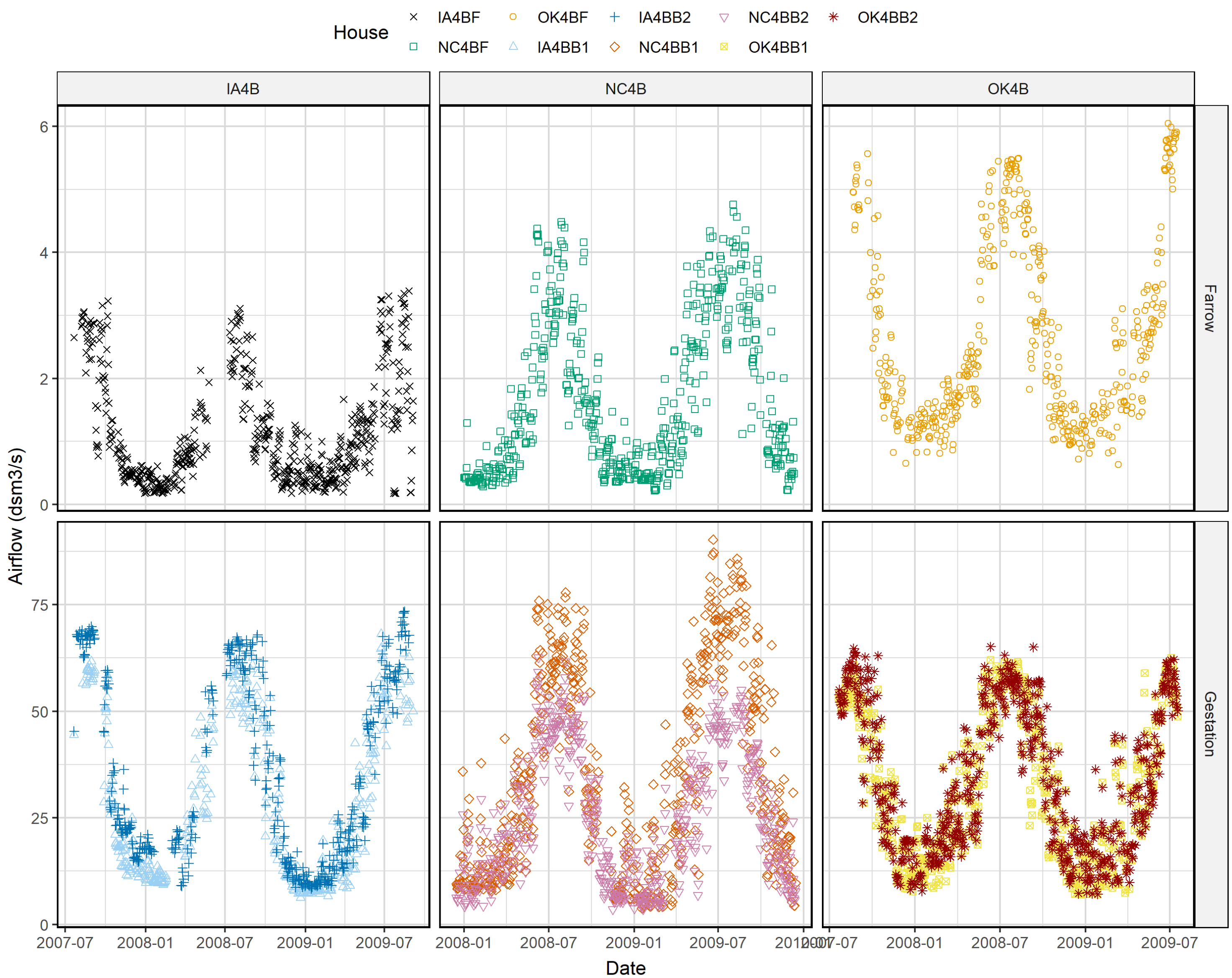


Figure D-20. Swine farrowing (top row) and gestation (bottom row) house ventilation rate trends during the NAEMS monitoring period.

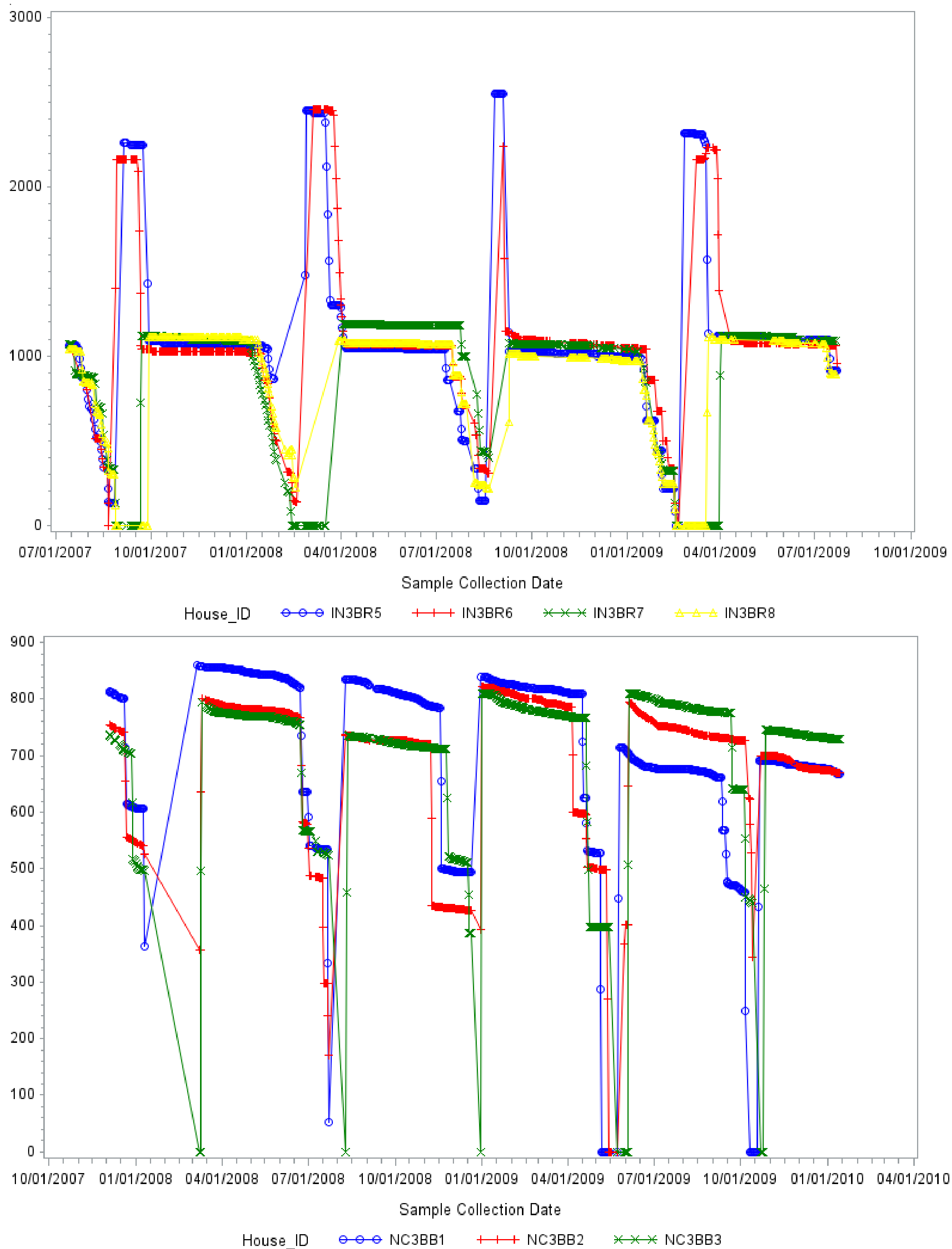


Figure D-21. Swine grow-finish house inventory trends during the NAEMS monitoring period at the two sites.

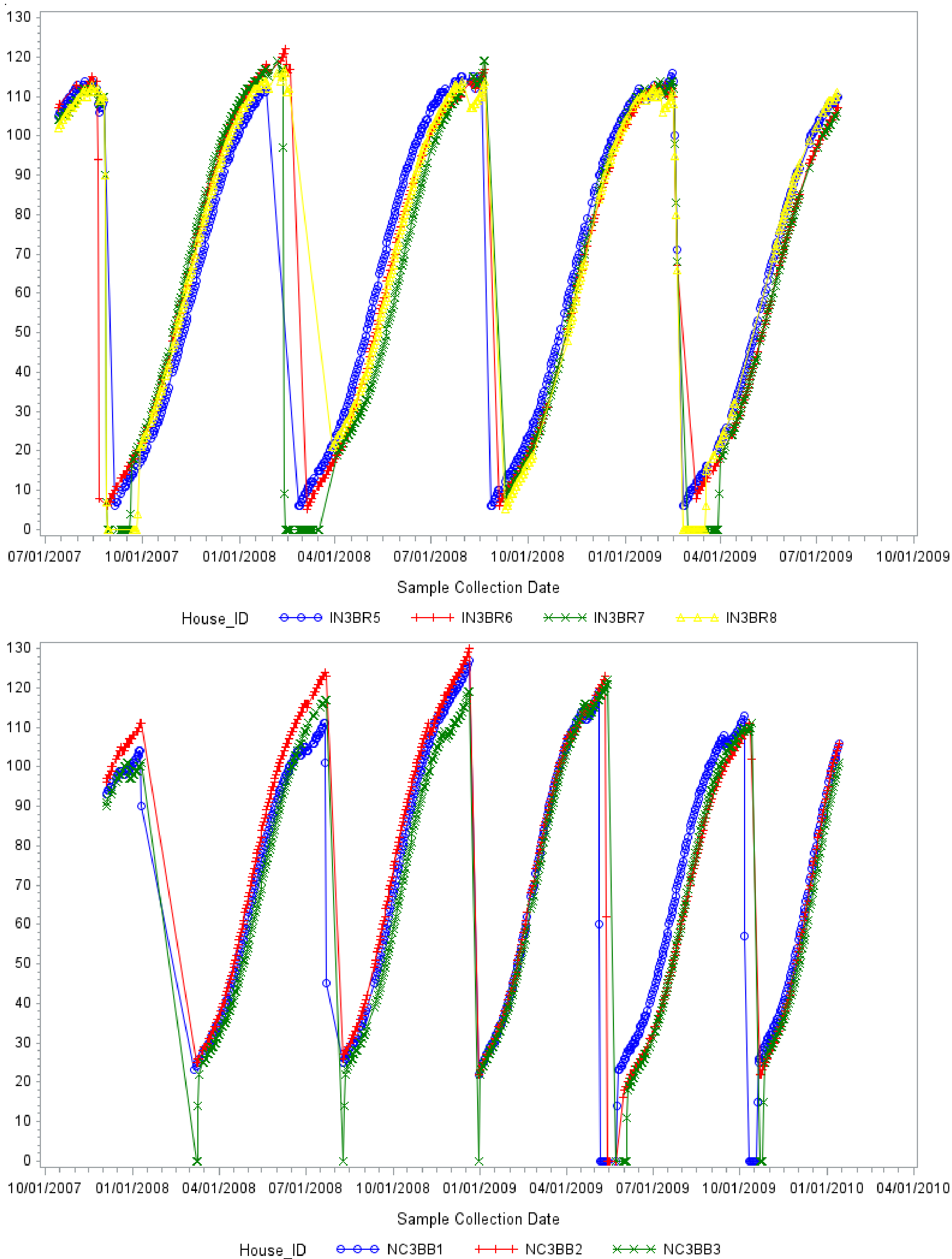
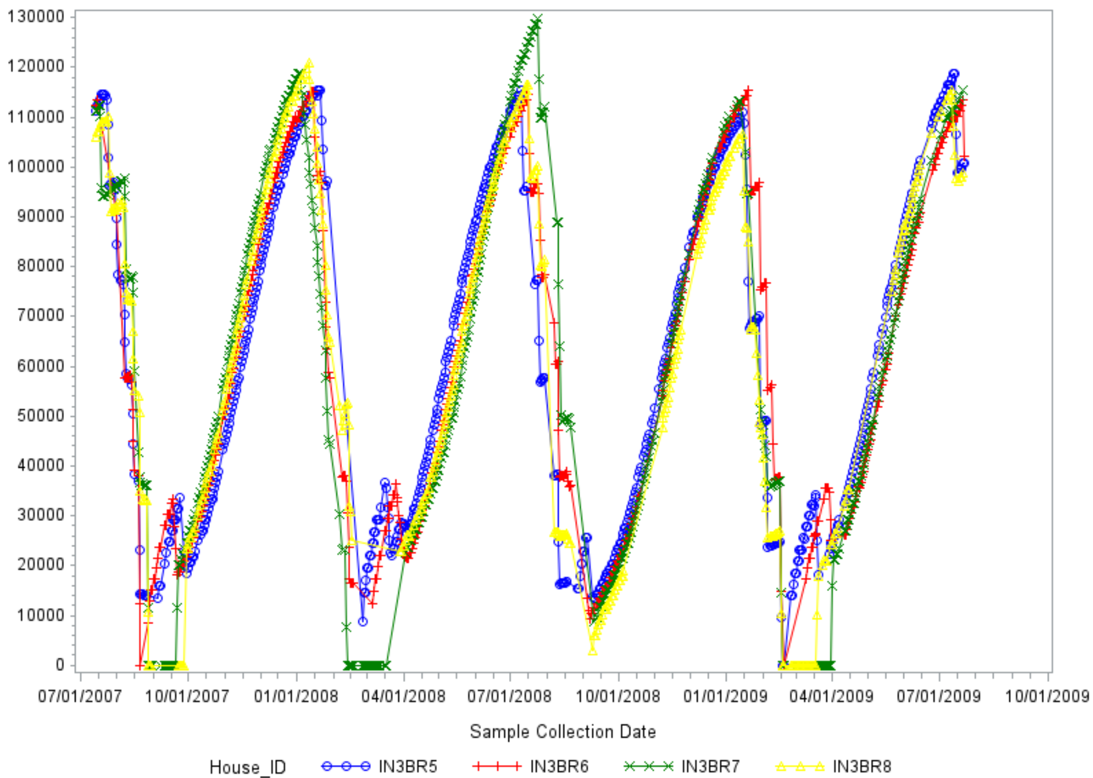


Figure D-22. Swine grow-finish house weight trends during the NAEMS monitoring period at the two sites.



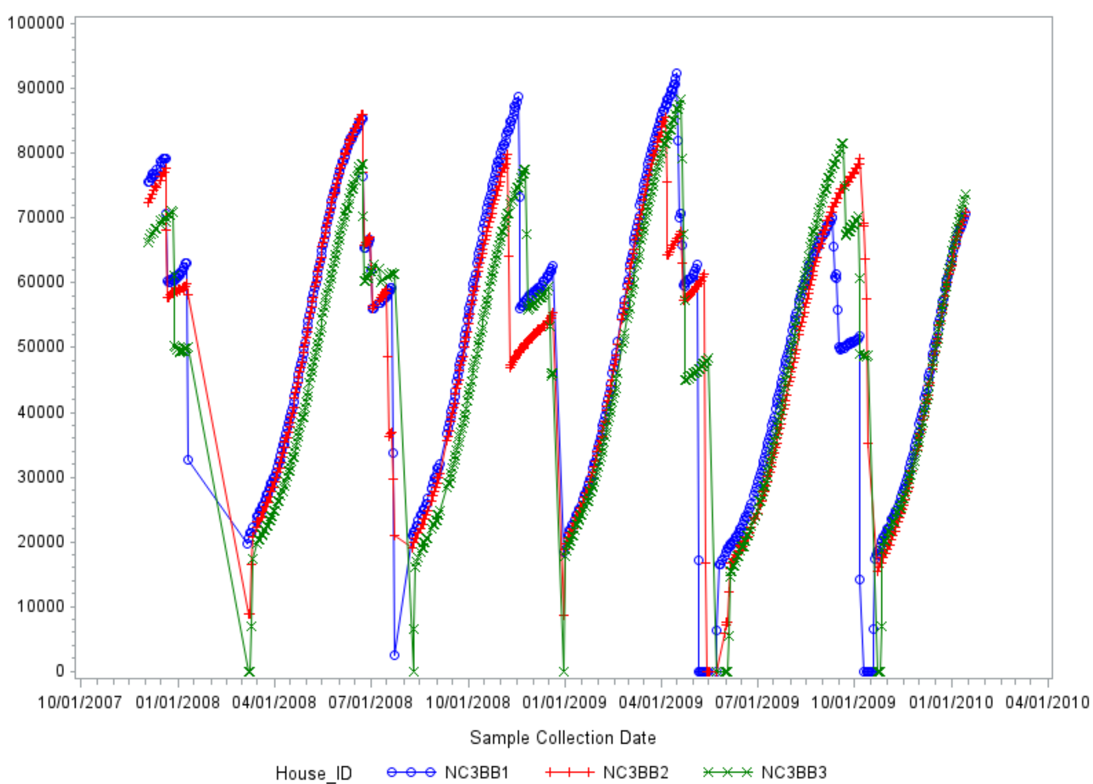


Figure D-23. Swine grow-finish house LAW during the NAEMS monitoring period at the two sites.

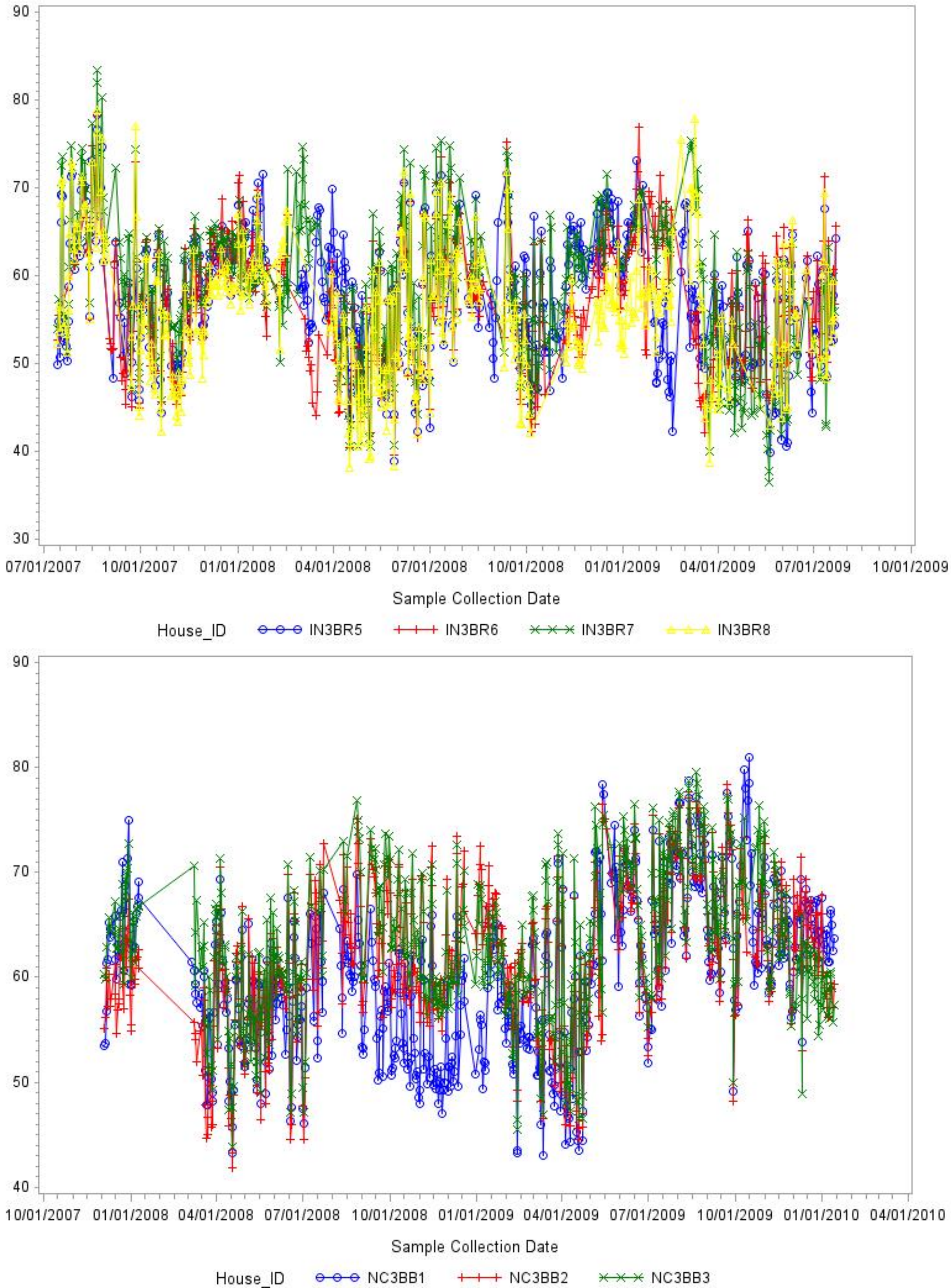


Figure D-24. Swine grow-finish house exhaust relative humidity during the NAEMS monitoring period at the two sites

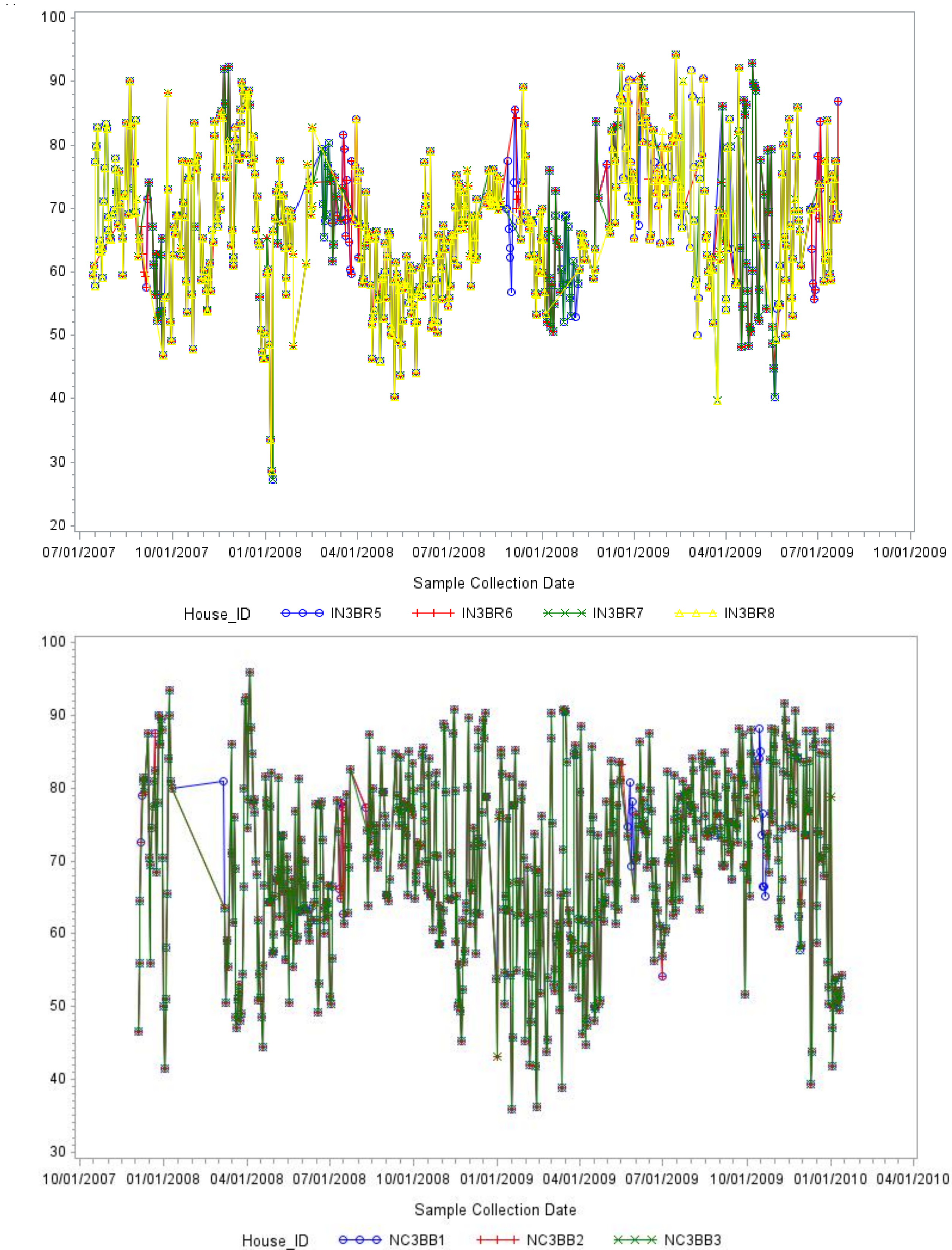


Figure D-25. Swine grow-finish house ambient relative humidity during the NAEMS monitoring period at the two sites.

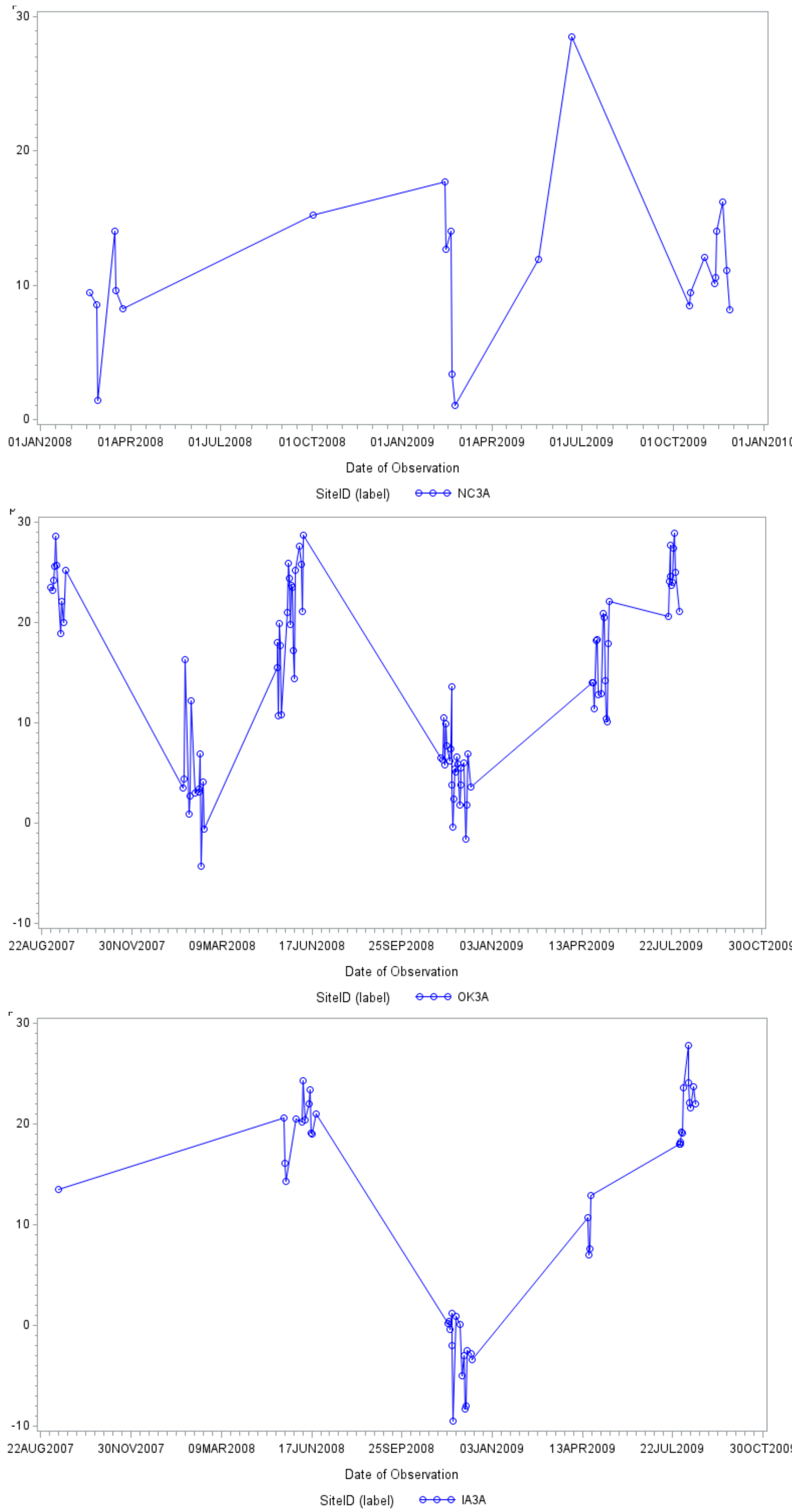


Figure D-26. Temperature trends at swine breeding/gestation open source sites during the NAEMS monitoring period. NC4A (top), OK4A (middle), IA3A (bottom).

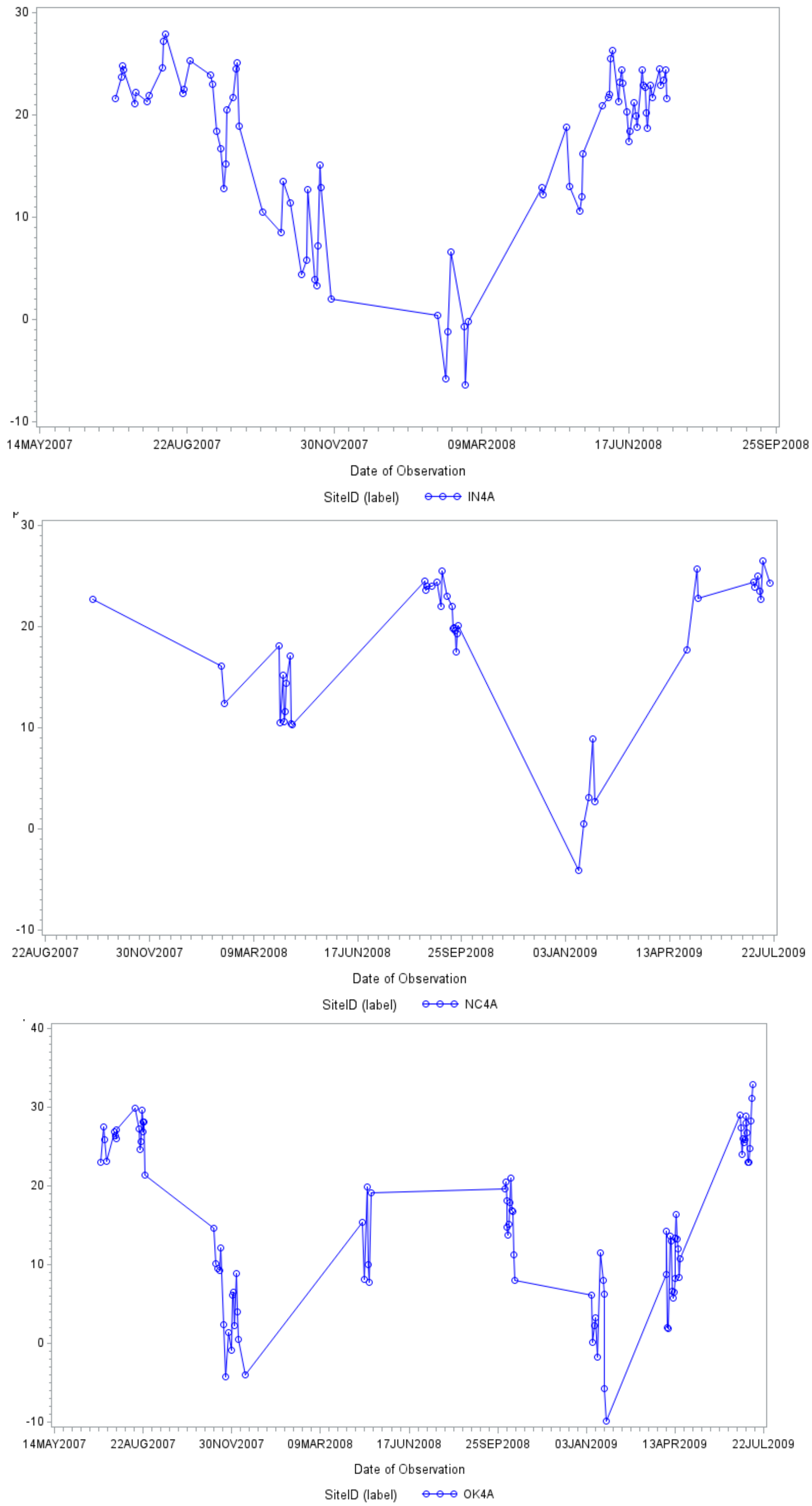


Figure D-27. Temperature trends at swine grow-finish open source sites during the NAEMS monitoring period. IN4A (top), NC4A (middle), and OK4A (bottom).

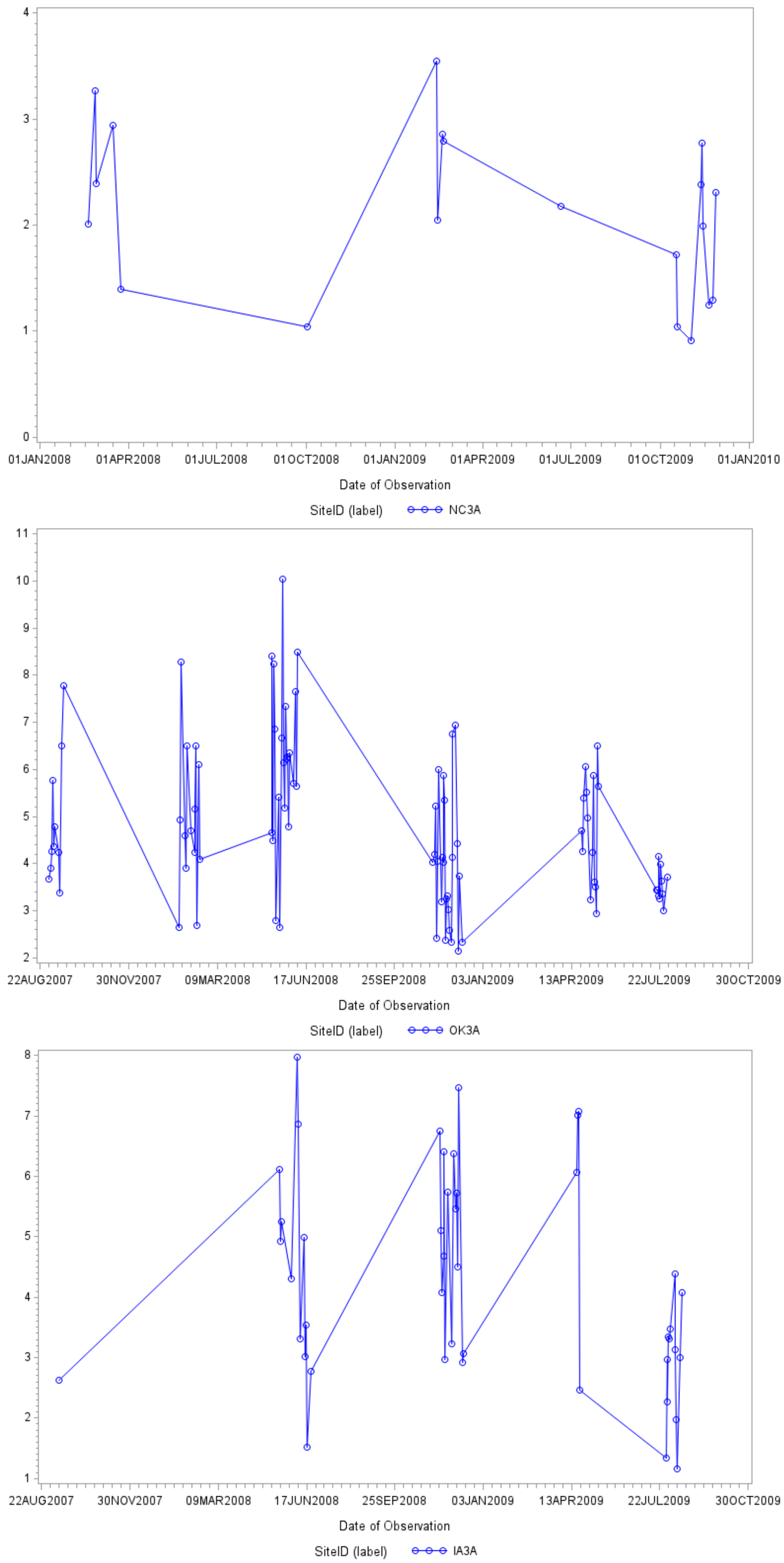
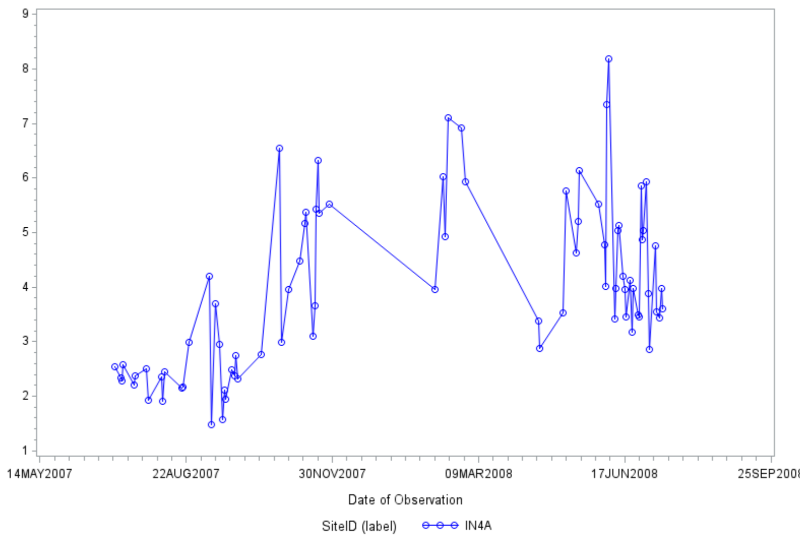
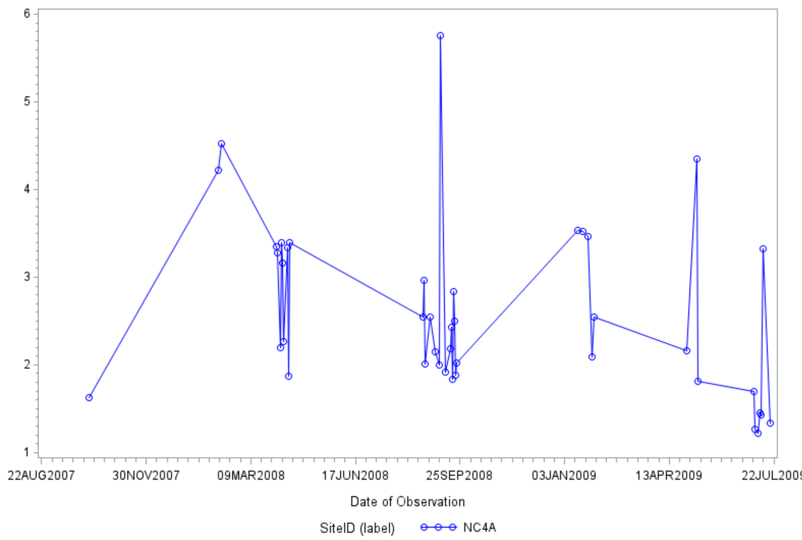


Figure D-28. Wind speed trends at swine breeding/gestation open source sites during the NAEMS monitoring period. NC4A (top), OK4A (middle), IA3A (bottom).





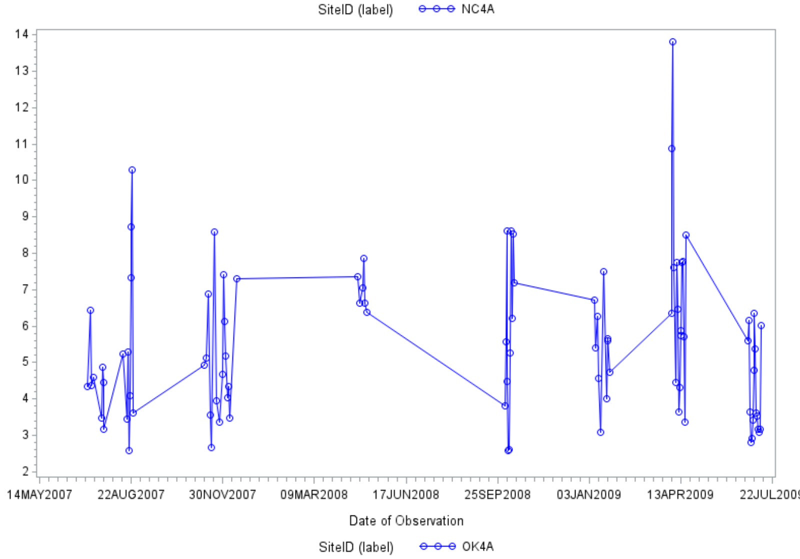
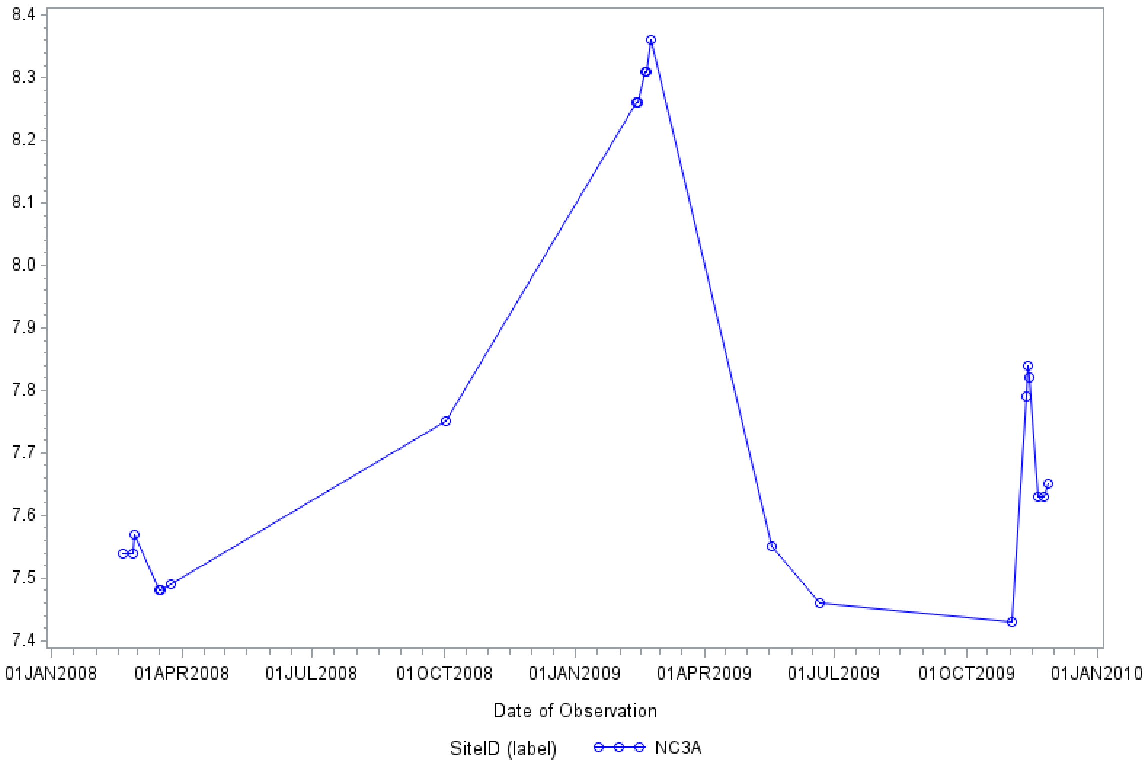


Figure D-29. Wind speed trends at swine grow-finish open source sites during the NAEMS monitoring period. IN4A (top), NC4A (middle), and OK4A (bottom).



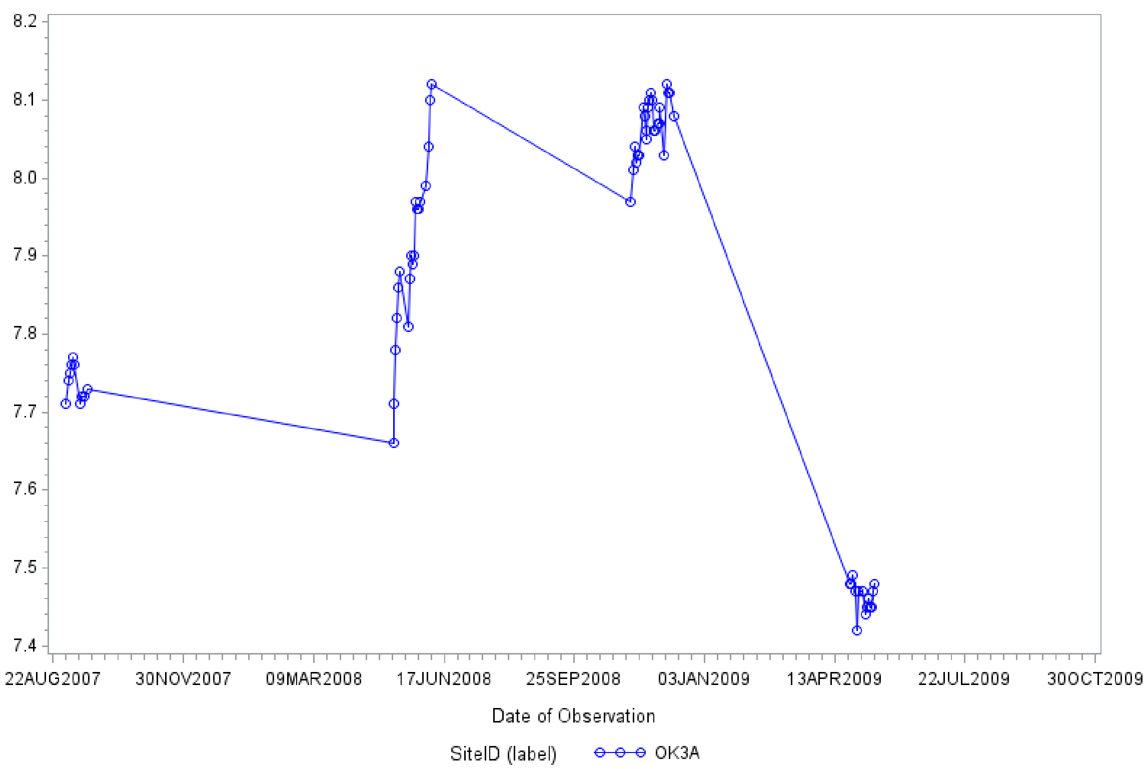


Figure D-30. Trends in pH at swine breeding/gestation open source sites. NC4A (top) and OK4A (bottom).

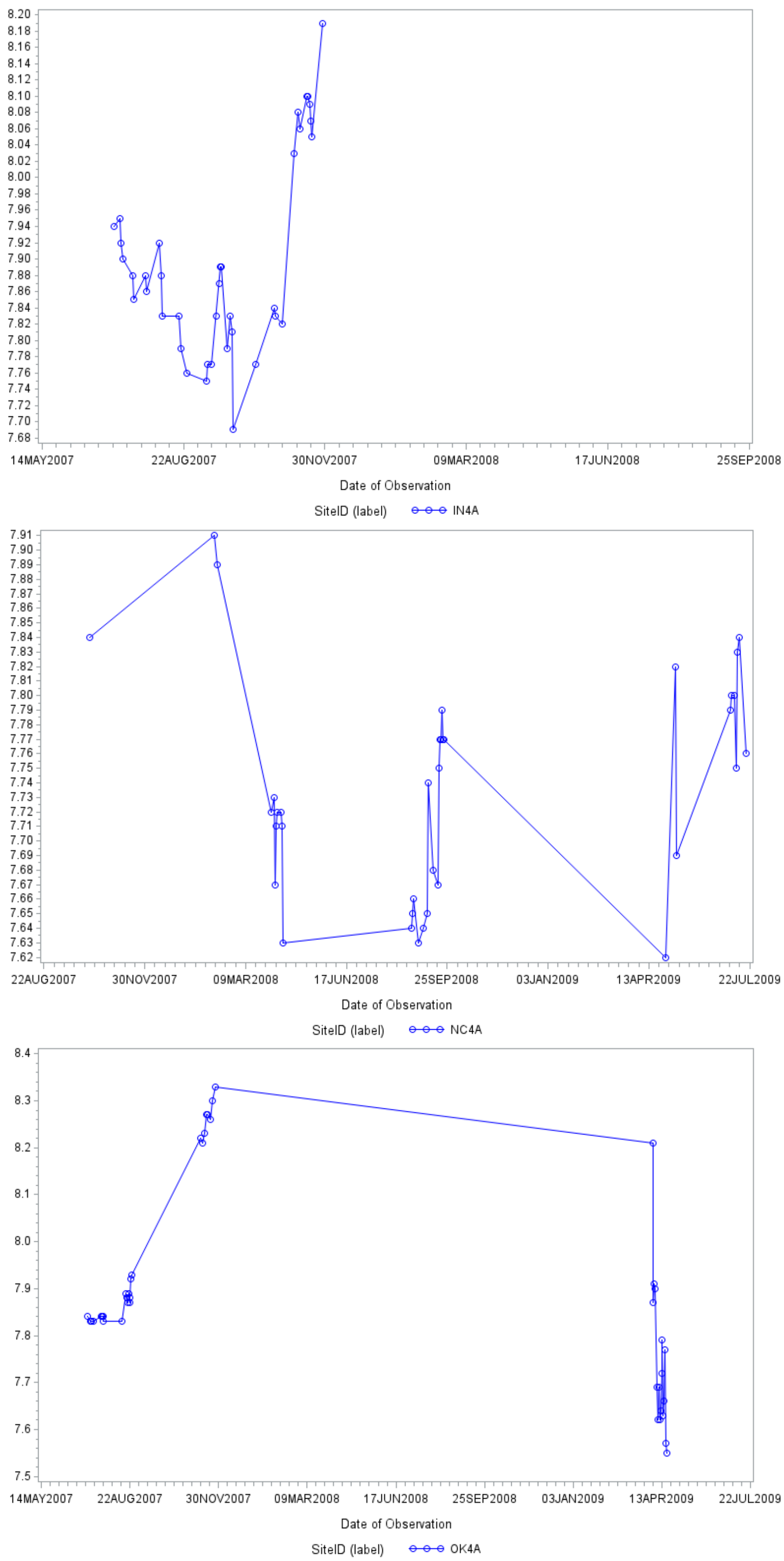


Figure D-31. Trends in pH at swine grow-finish open source sites. IN4A (top), NC4A (middle), and OK4A (bottom).

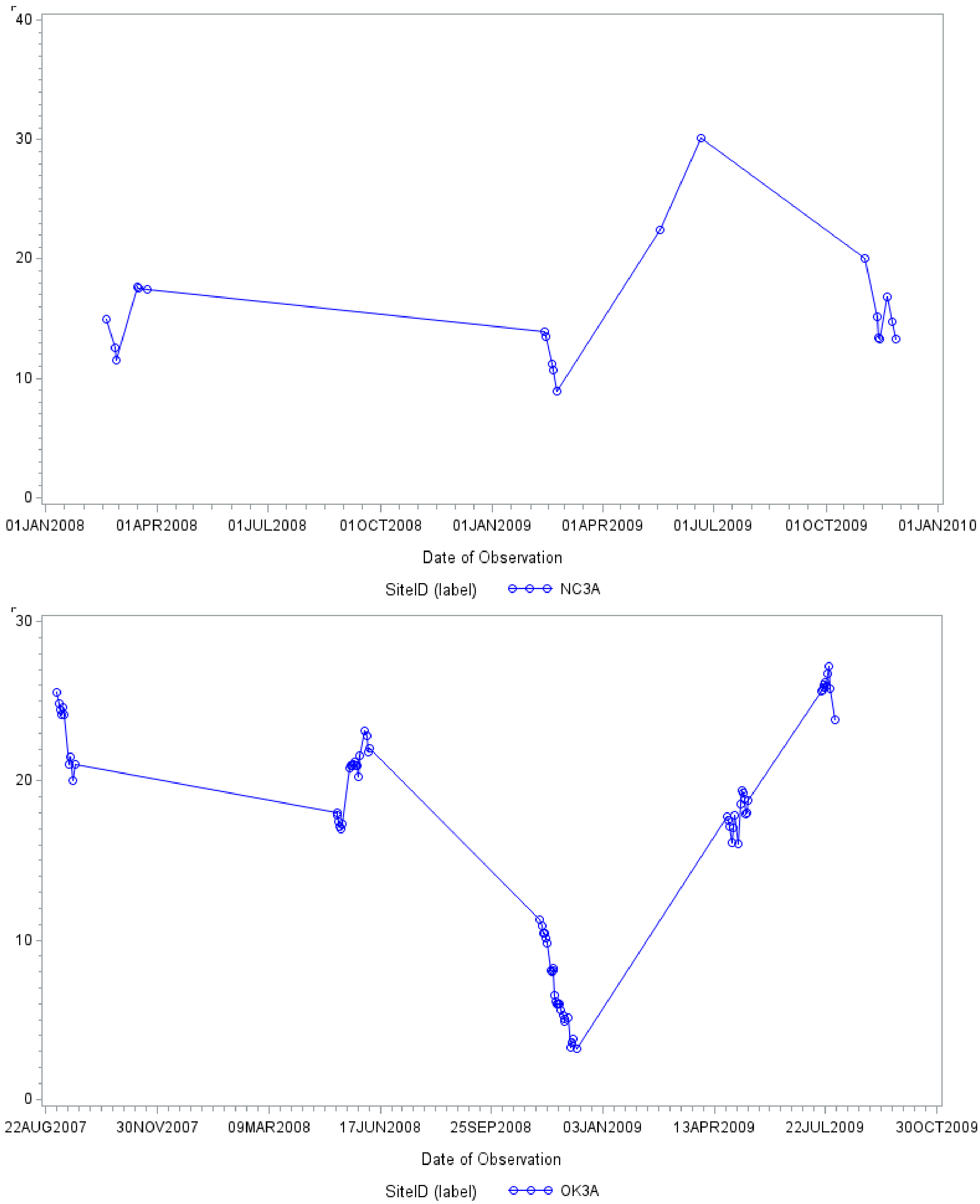


Figure D-32. Lagoon temperature trends at swine breeding/gestation open source sites. NC4A (top) and OK4A (bottom).

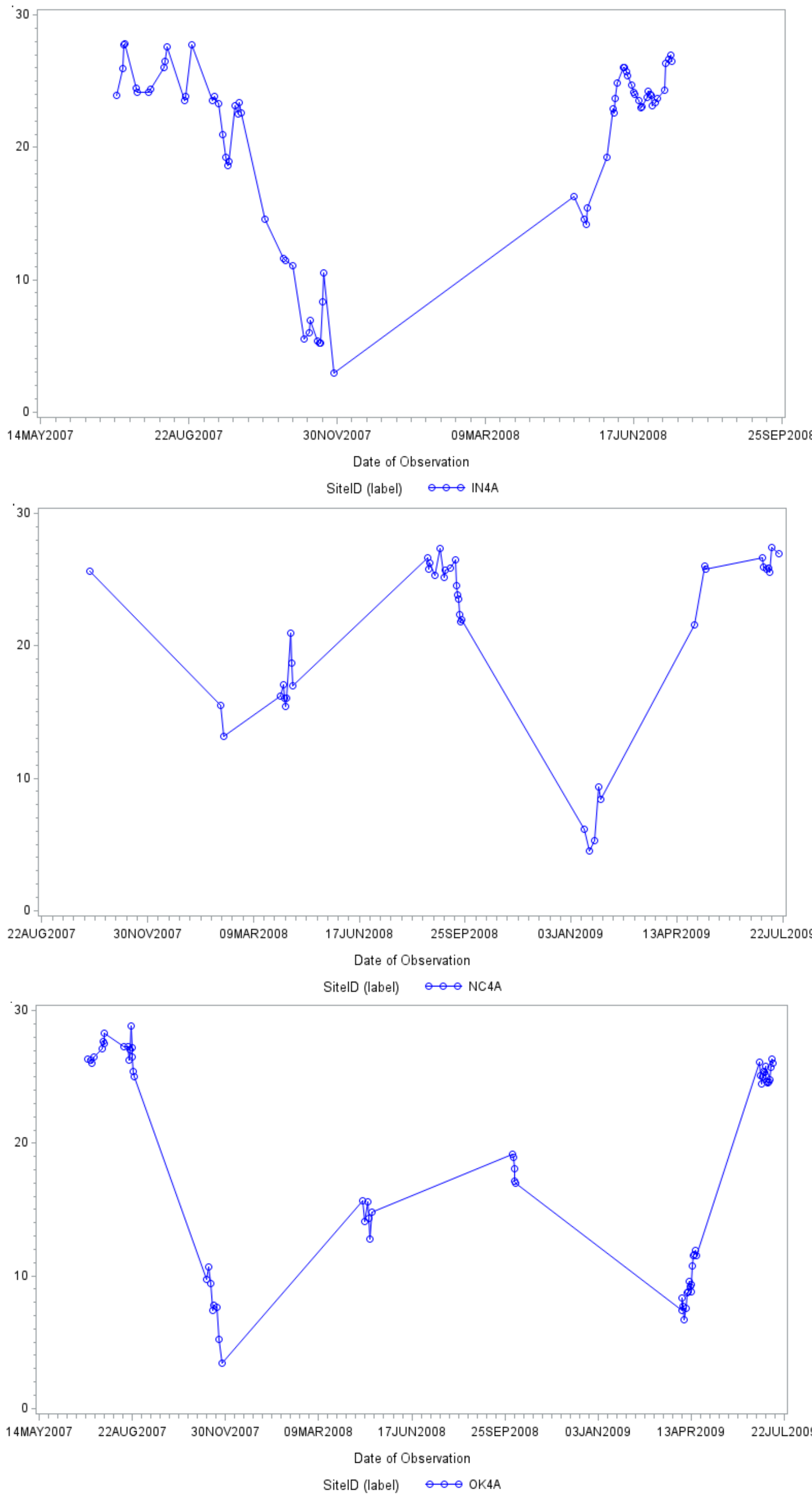
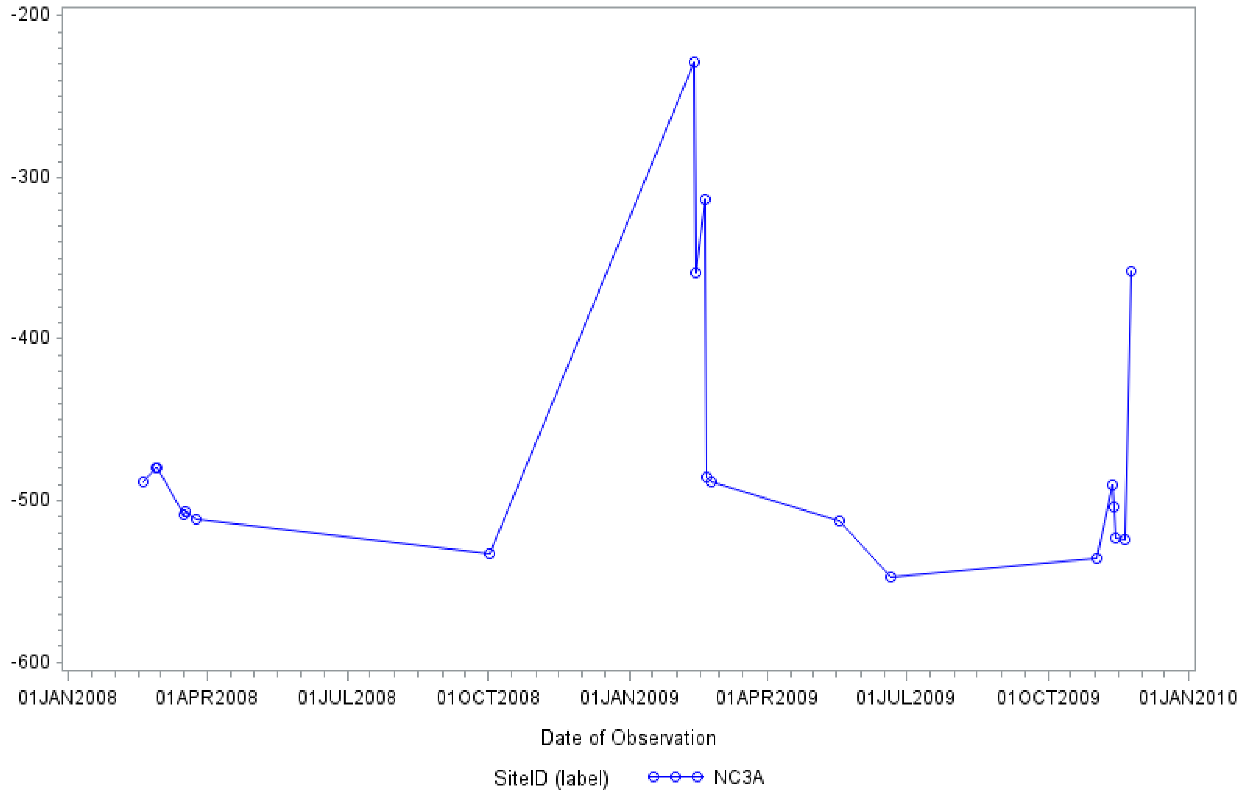


Figure D-33. Lagoon temperature trends at swine grow-finish open source sites. IN4A (top), NC4A (middle), and OK4A (bottom).



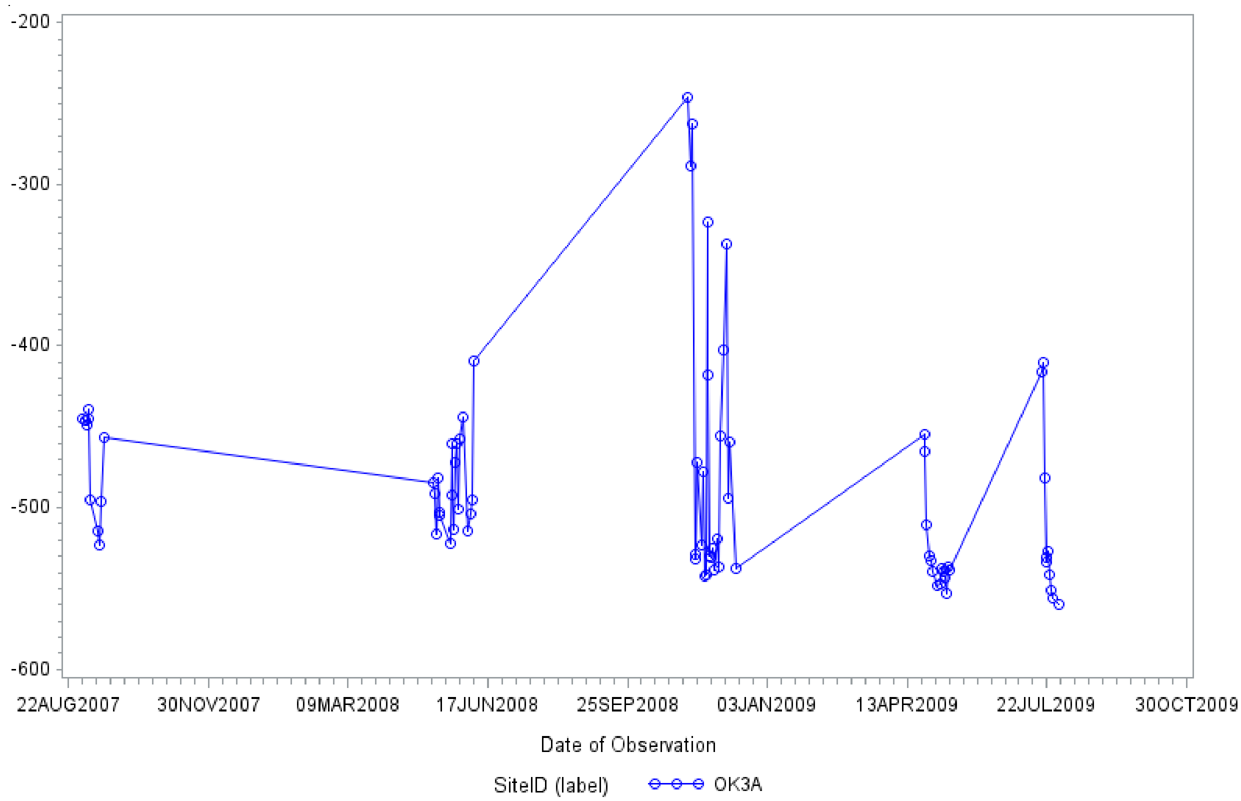


Figure D-34. ORP trends at swine breeding/gestation open source sites. NC4A (top) and OK4A (bottom).

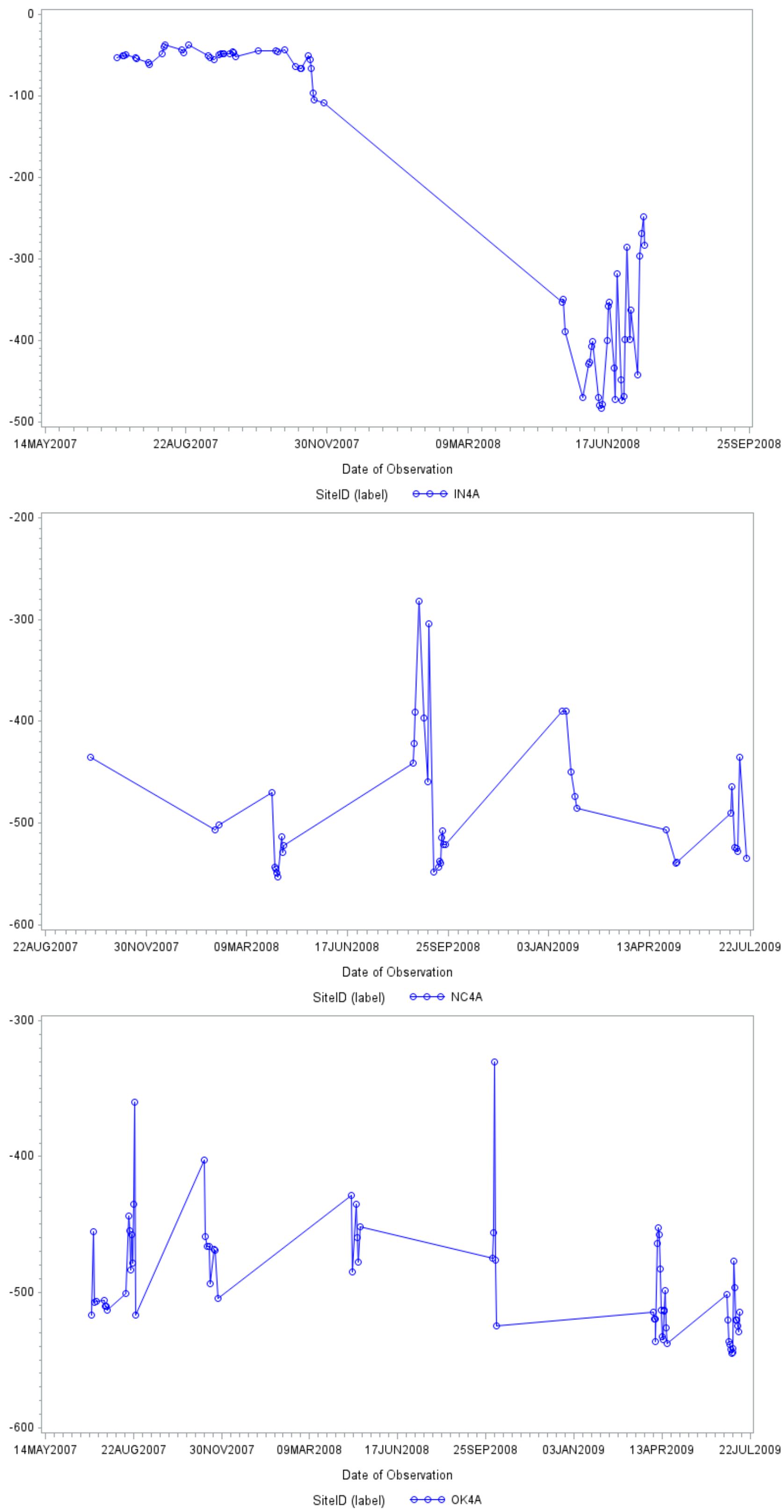


Figure D-35. ORP trends at swine grow-finish open source sites. IN4A (top), NC4A (middle), and OK4A (bottom).

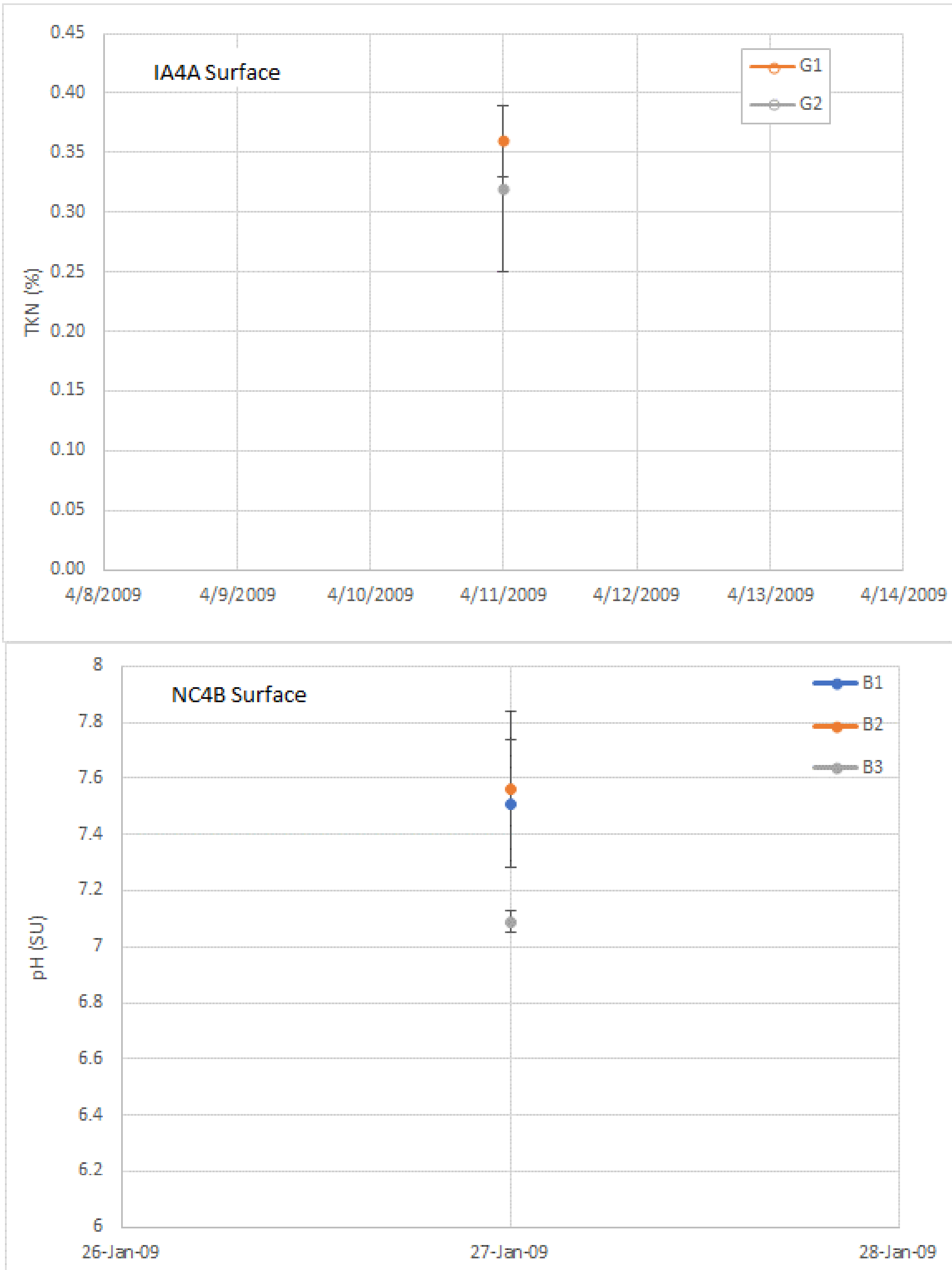


Figure D-36. Surface manure percent nitrogen for breeding and gestation sites

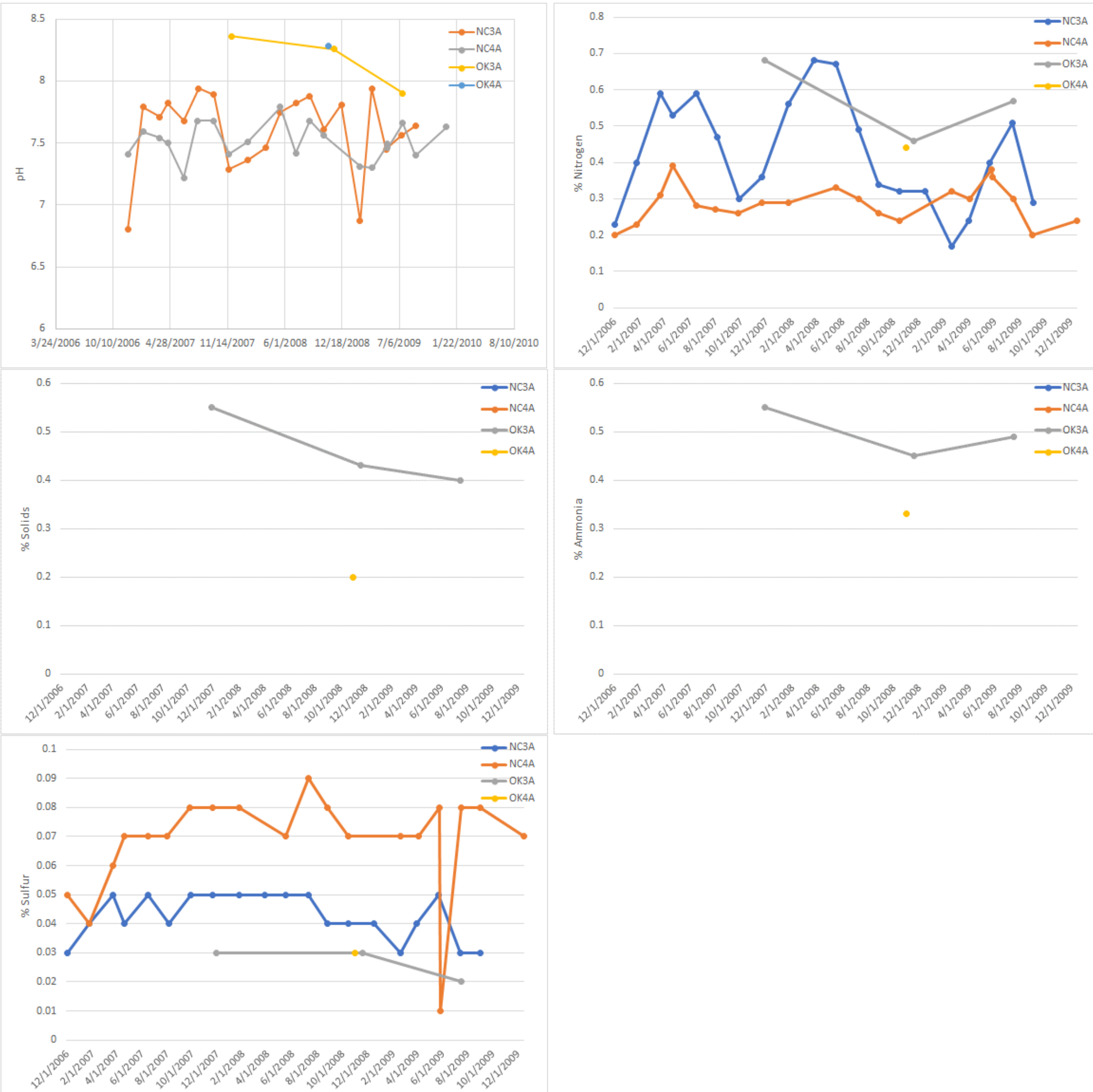


Figure D-37. Lagoon manure sample characteristics.

pH (top left), percent nitrogen (top right), percent solids (middle left), percent ammonia (middle right), and percent sulfur (bottom) at swine open source sites during the NAEMS monitoring period.

Appendix E – Scatter Plots

List of Figures

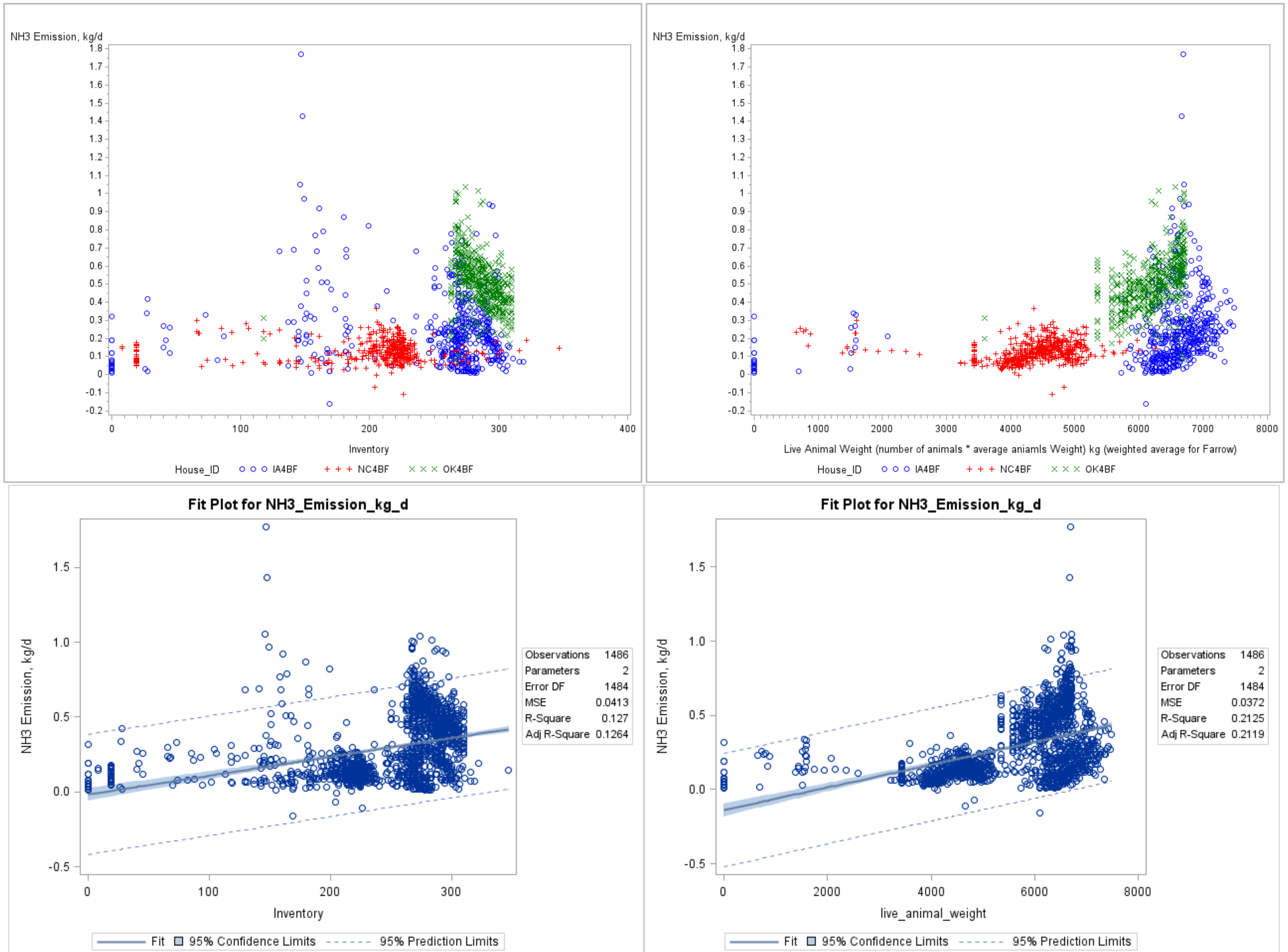


Figure E-1. Scatter plot of farrowing room NH_3 Emissions versus Inventory and scatter with regression (left column) and LAW (right column).

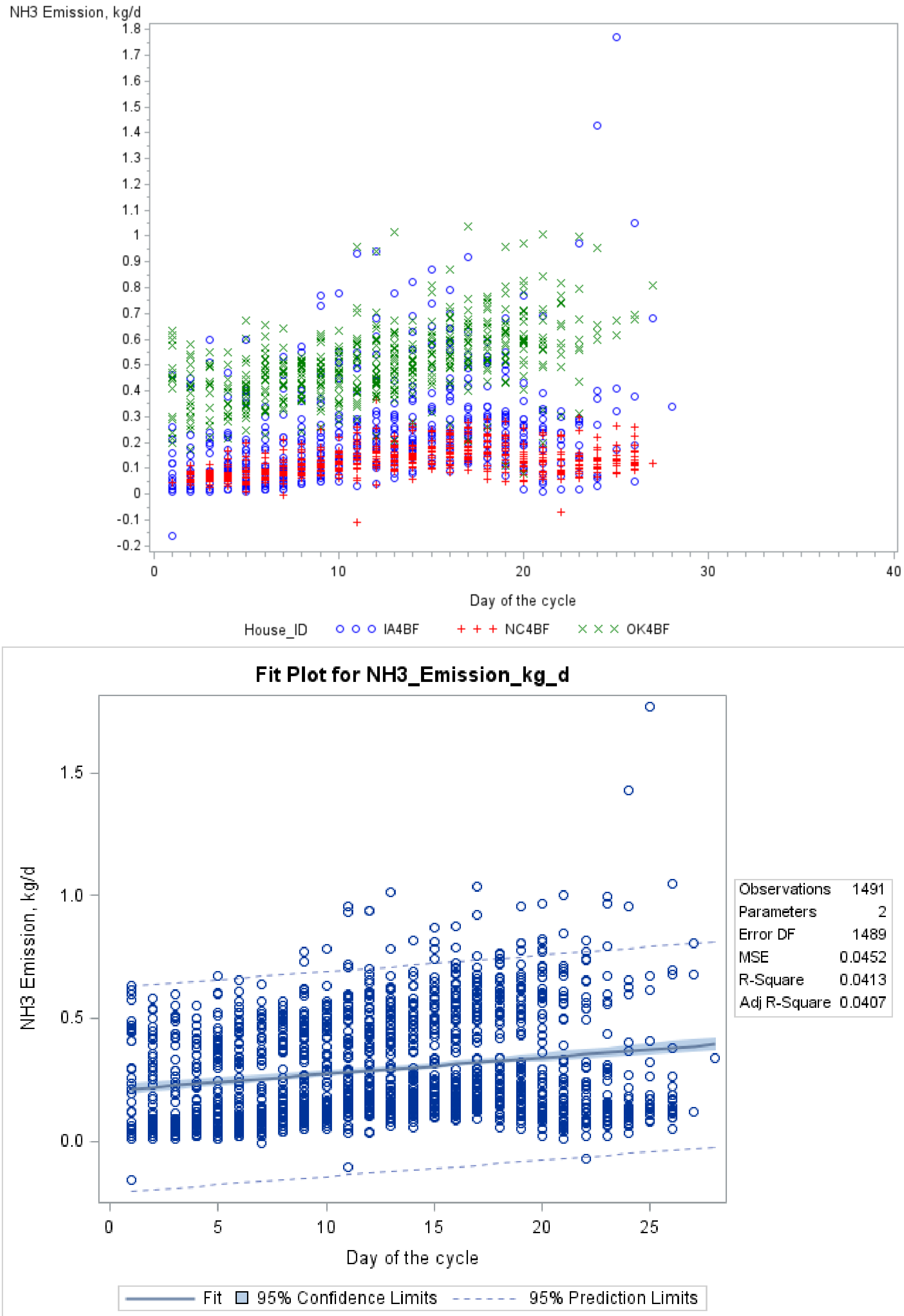


Figure E-2. Scatter plot of farrowing room NH_3 Emissions versus cycle day and scatter with regression.

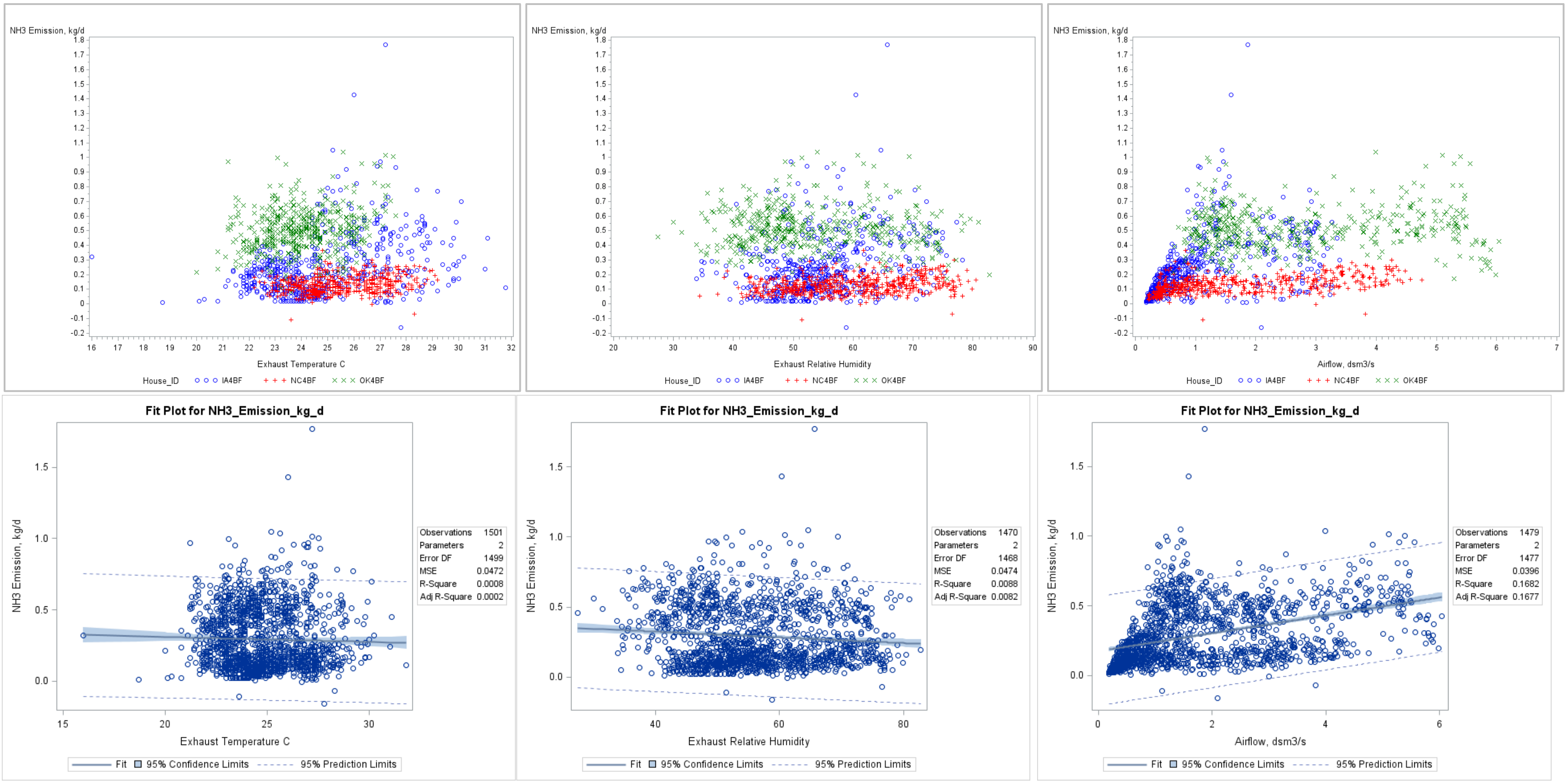


Figure E-3. Scatter plot of swine farrowing room NH_3 Emissions versus exhaust temperature and scatter with regression (left column), exhaust relative humidity (center column), and ventilation rate (right column).

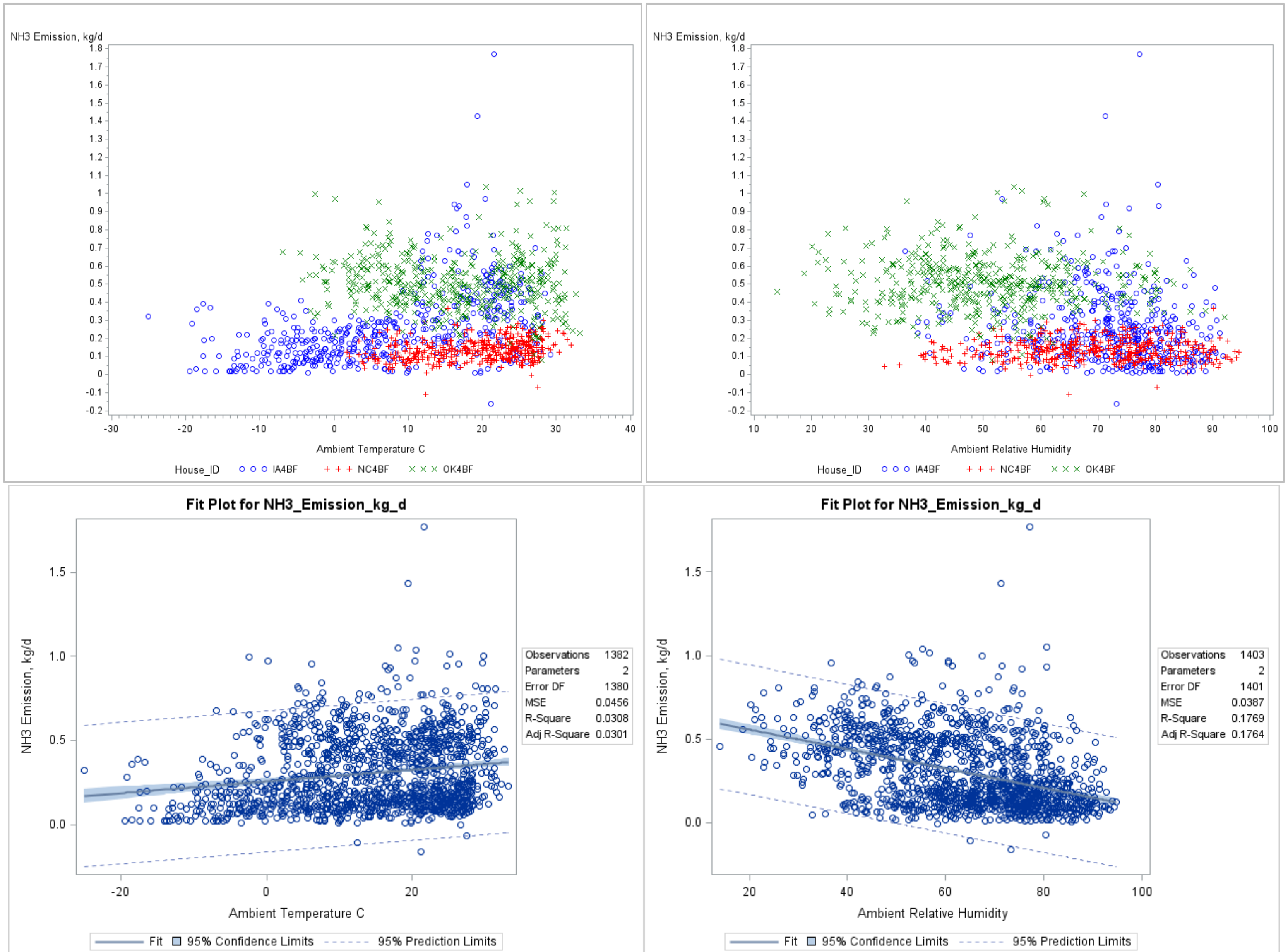


Figure E-4. Scatter plot of swine farrowing room NH_3 Emissions versus ambient temperature and scatter with regression (left column) and relative humidity (right column).

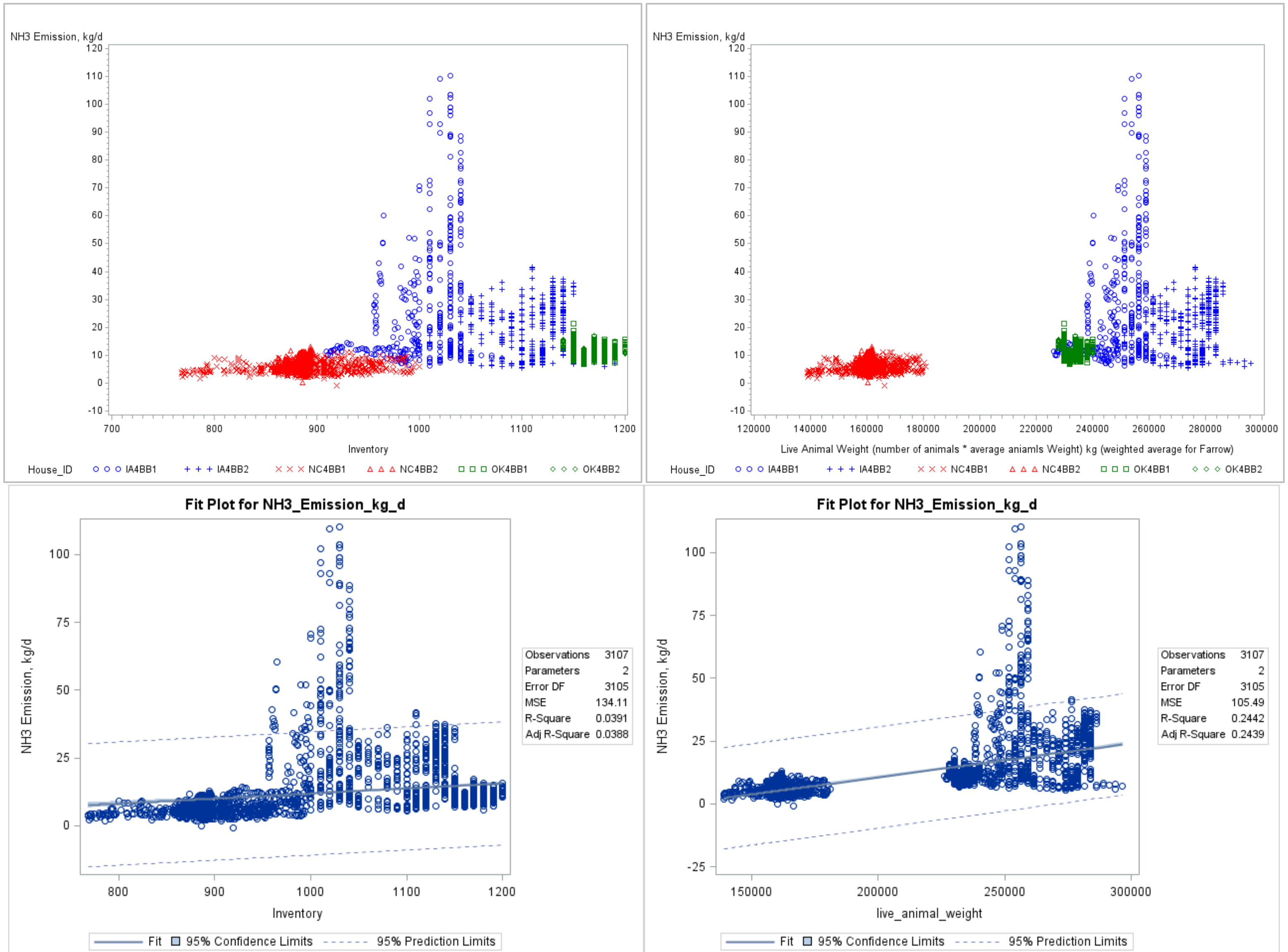


Figure E-5. Scatter plot of gestation barn NH_3 Emissions versus inventory and scatter with regression (left column) and LAW (right column).

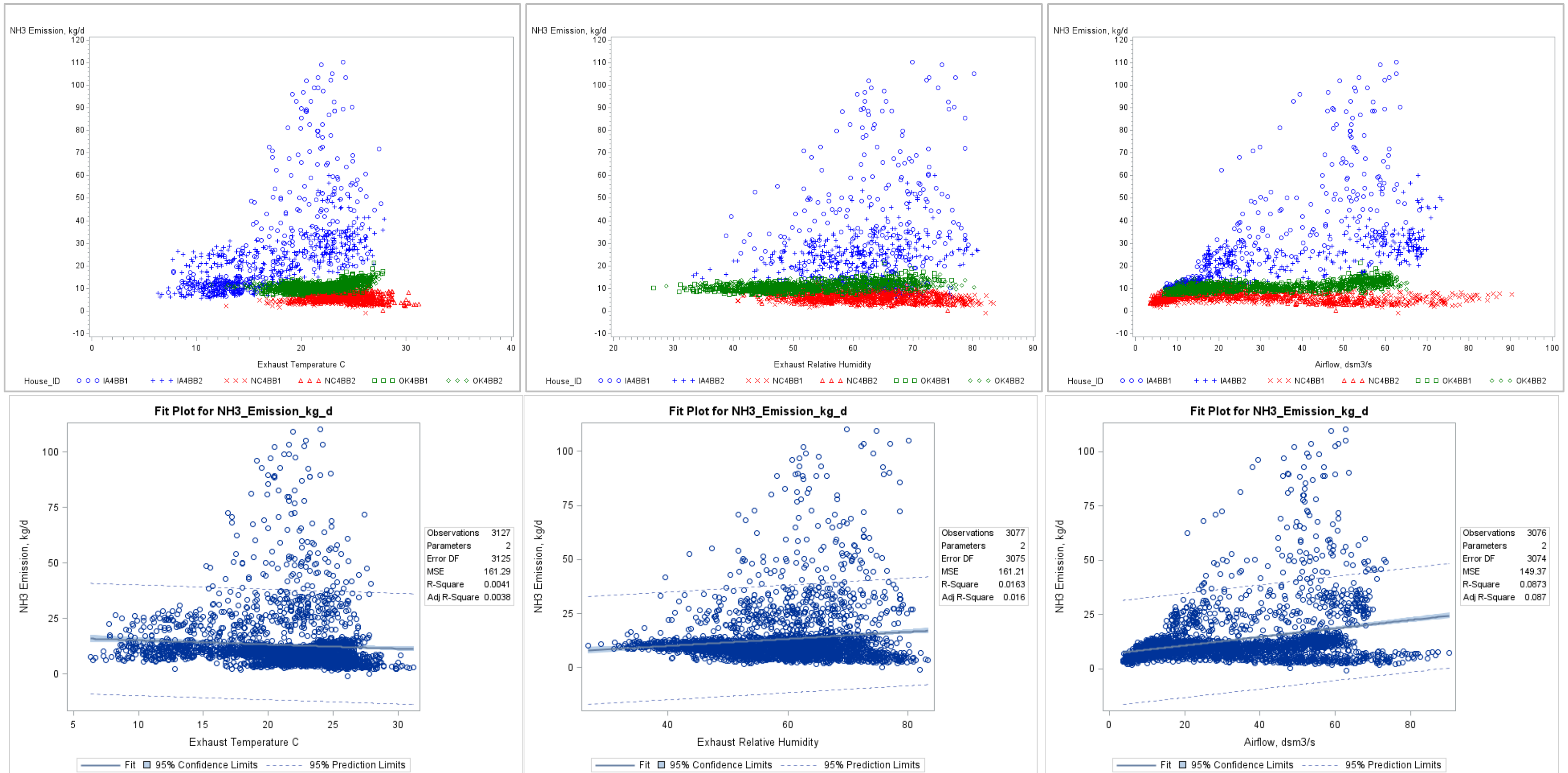


Figure E-6. Scatter plot of swine gestation barn NH_3 Emissions versus exhaust relative humidity and scatter with regression (left column), exhaust relative humidity (center column), and ventilation rate (right column).

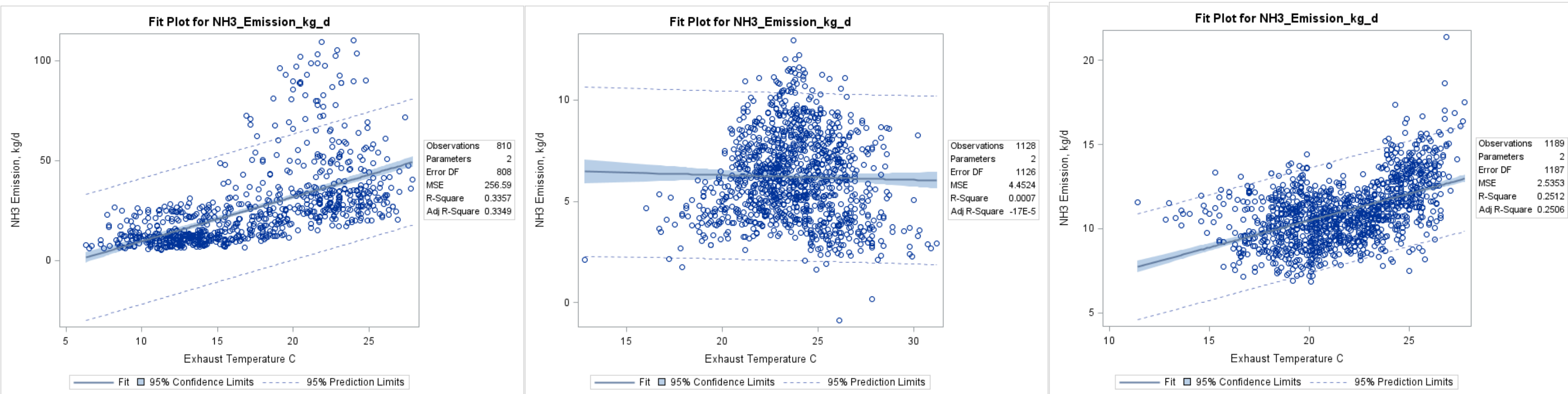


Figure E-7. Scatter plot of swine gestation room NH_3 Emissions versus exhaust temperature by site. IA4B (left column), NC4B (center column), and OK4B (right column).

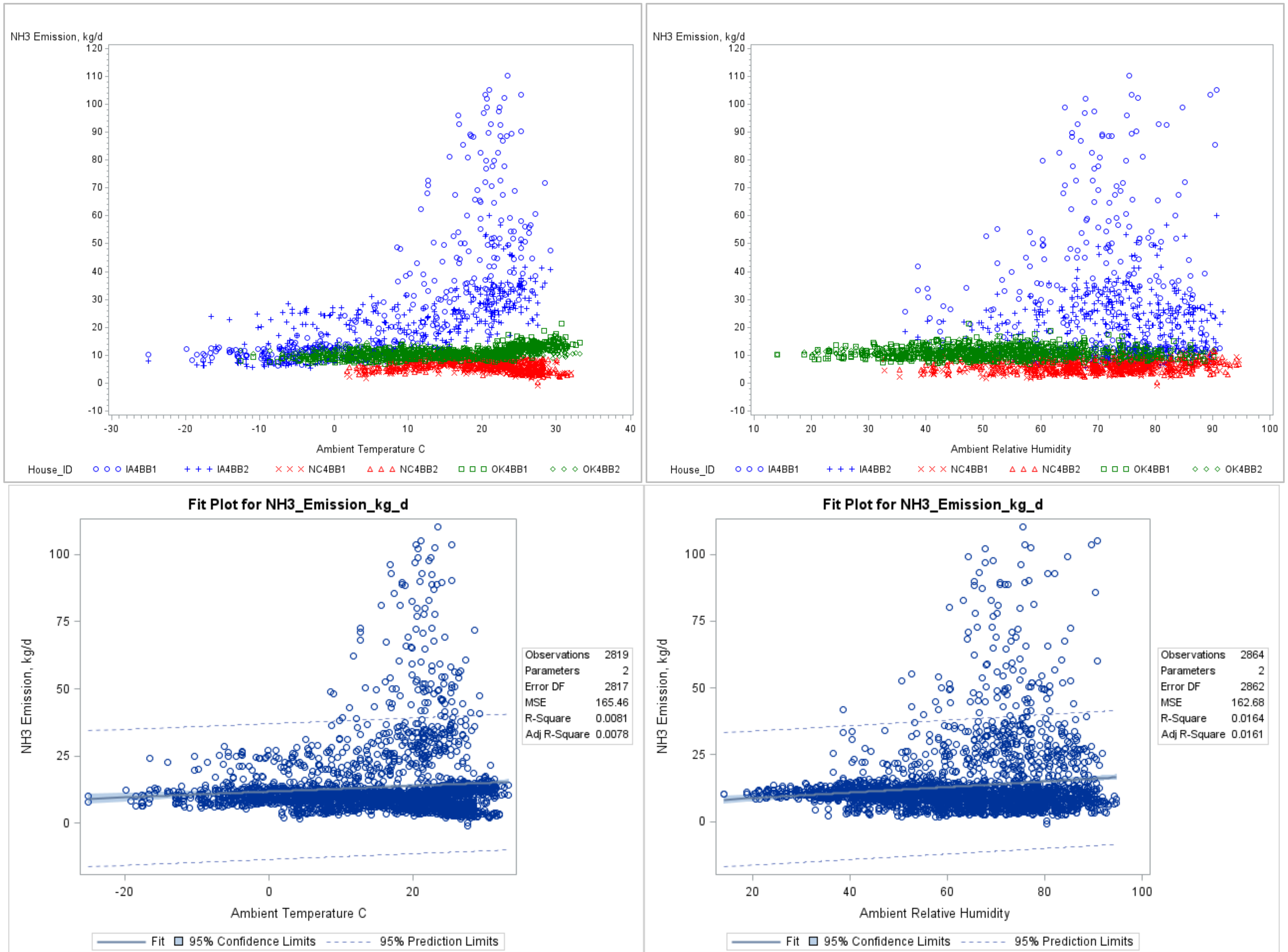


Figure E-8. Scatter plot of swine gestation barn NH_3 Emissions versus ambient temperature scatter with regression (left column) and ambient relative humidity (right column).

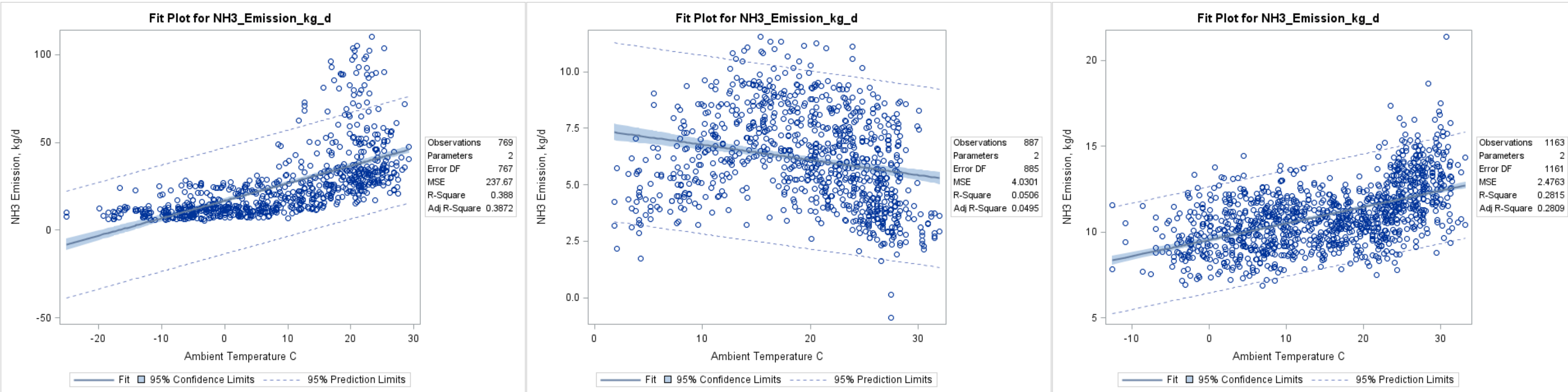
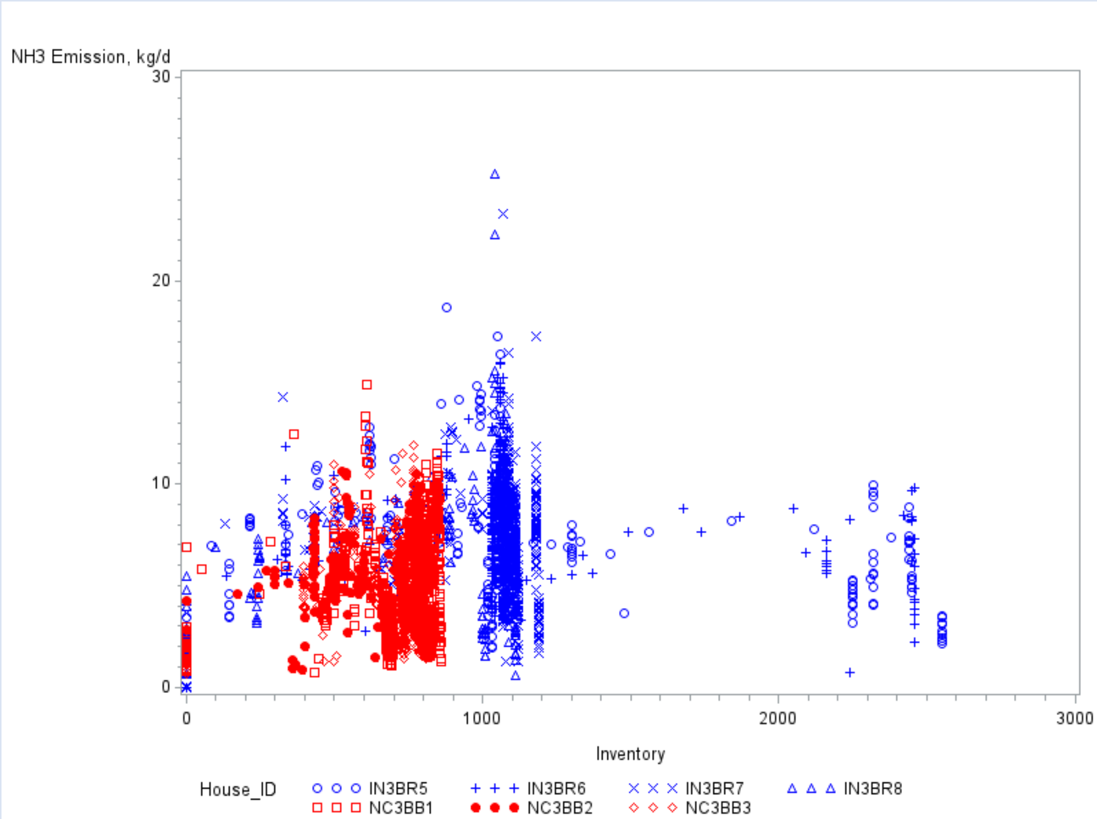


Figure E-9. Scatter plot of swine gestation room NH_3 Emissions versus ambient temperature by site. IA4B (left column), NC4B (center column), and OK4B (right column).



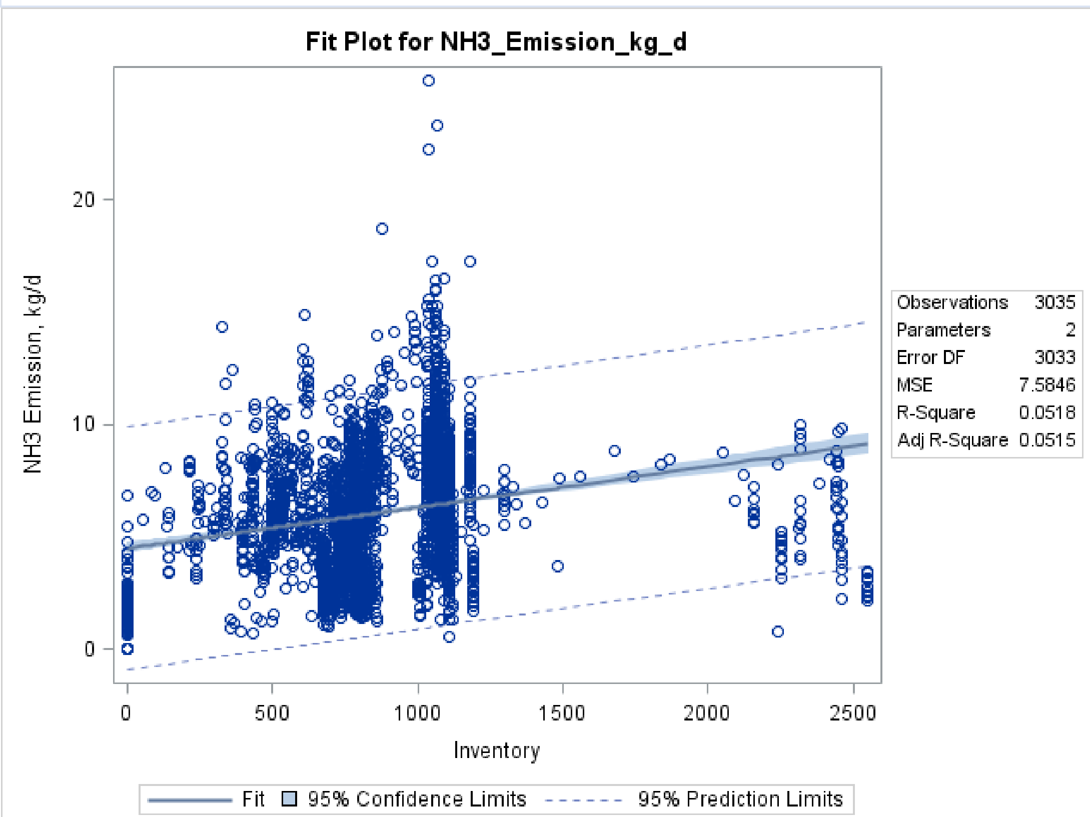
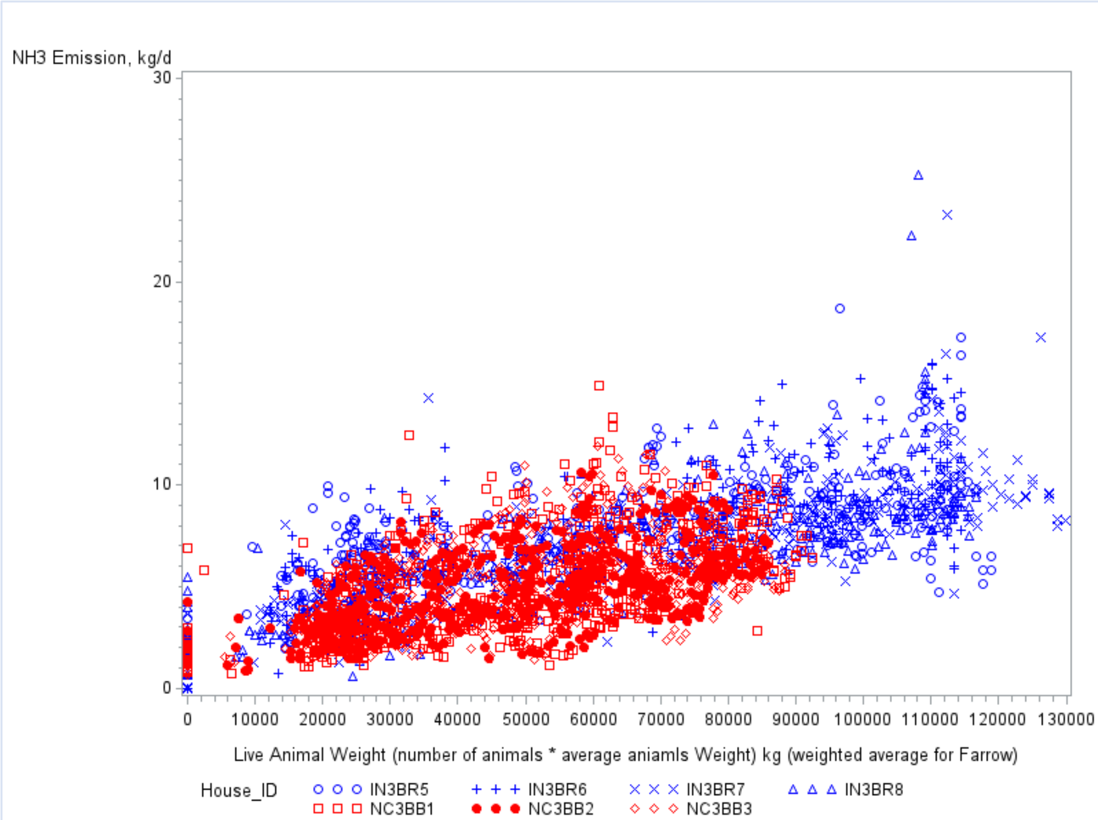


Figure E-10. Scatter plot of swine grow-finish NH_3 Emissions versus Inventory (left) and with regression (right).



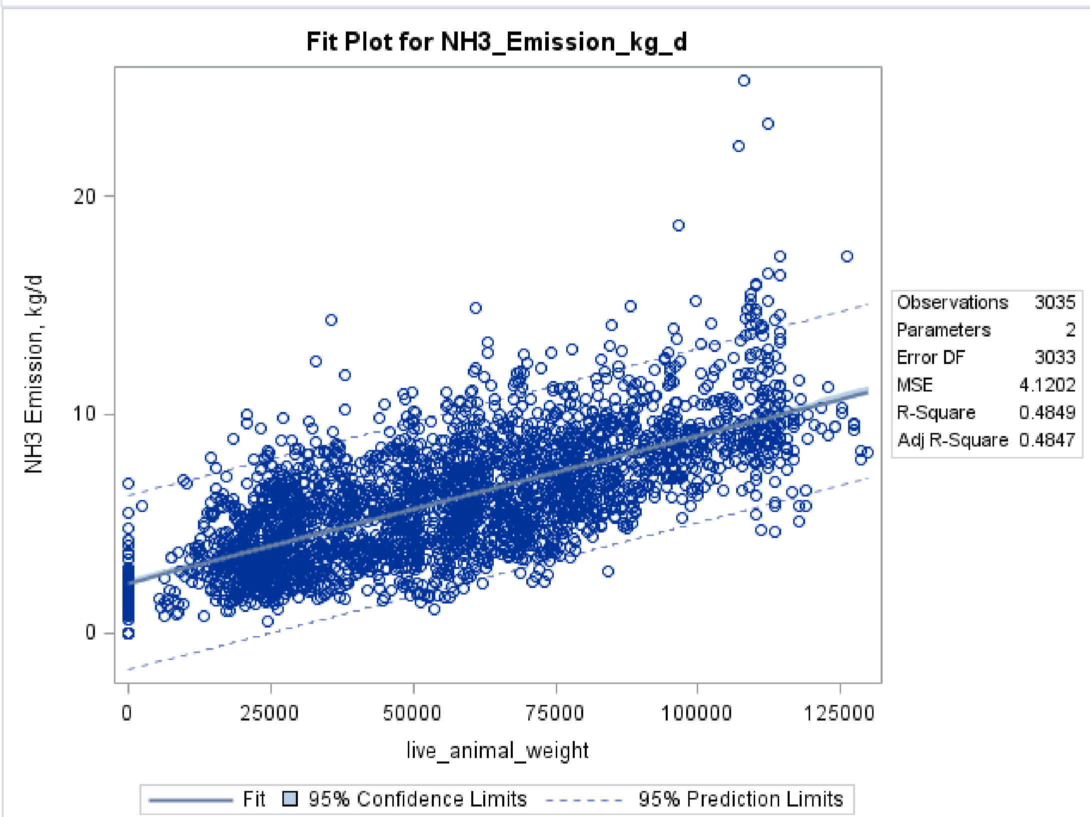


Figure E-11. Scatter plot of swine grow-finish NH_3 Emissions versus live animal weight (top) and with regression (bottom).

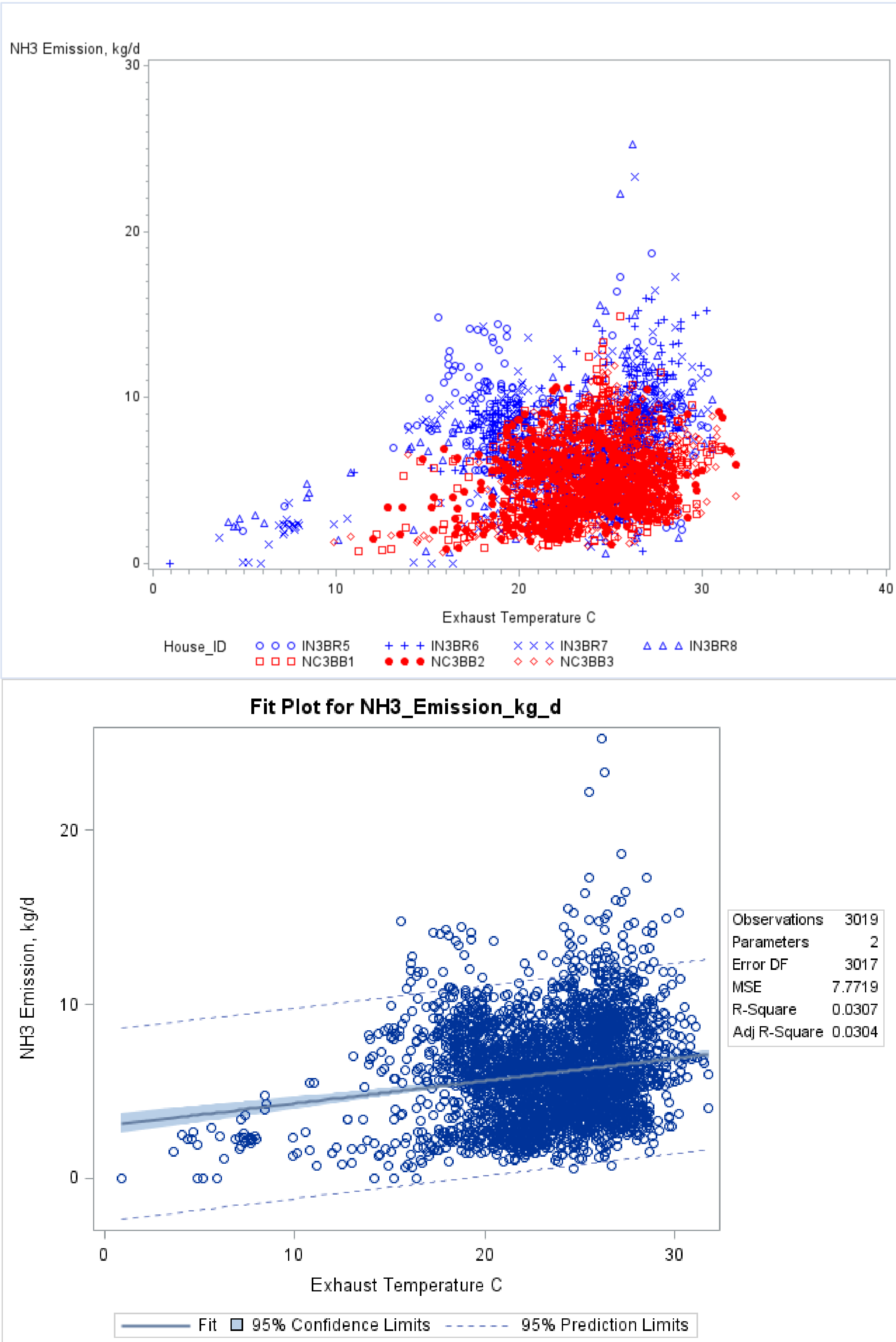
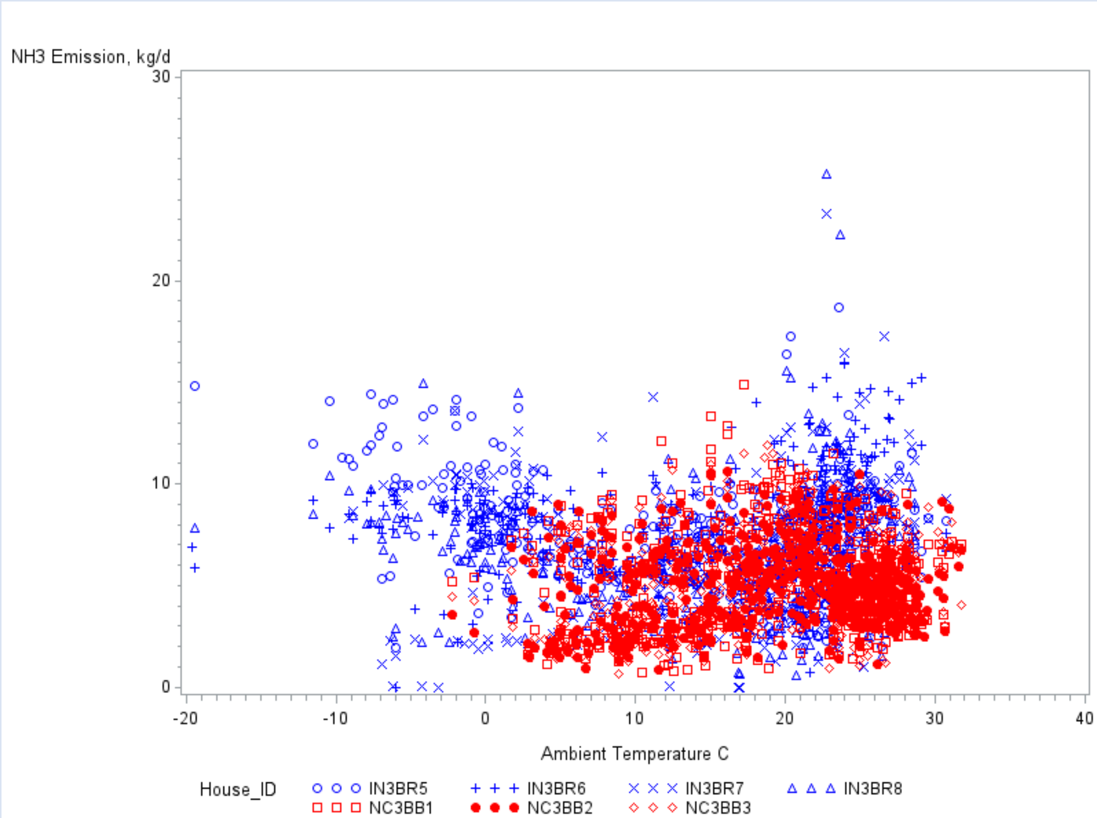


Figure E-12. Scatter plot of swine grow-finish NH_3 Emissions versus exhaust temperature (top) and with regression (bottom).



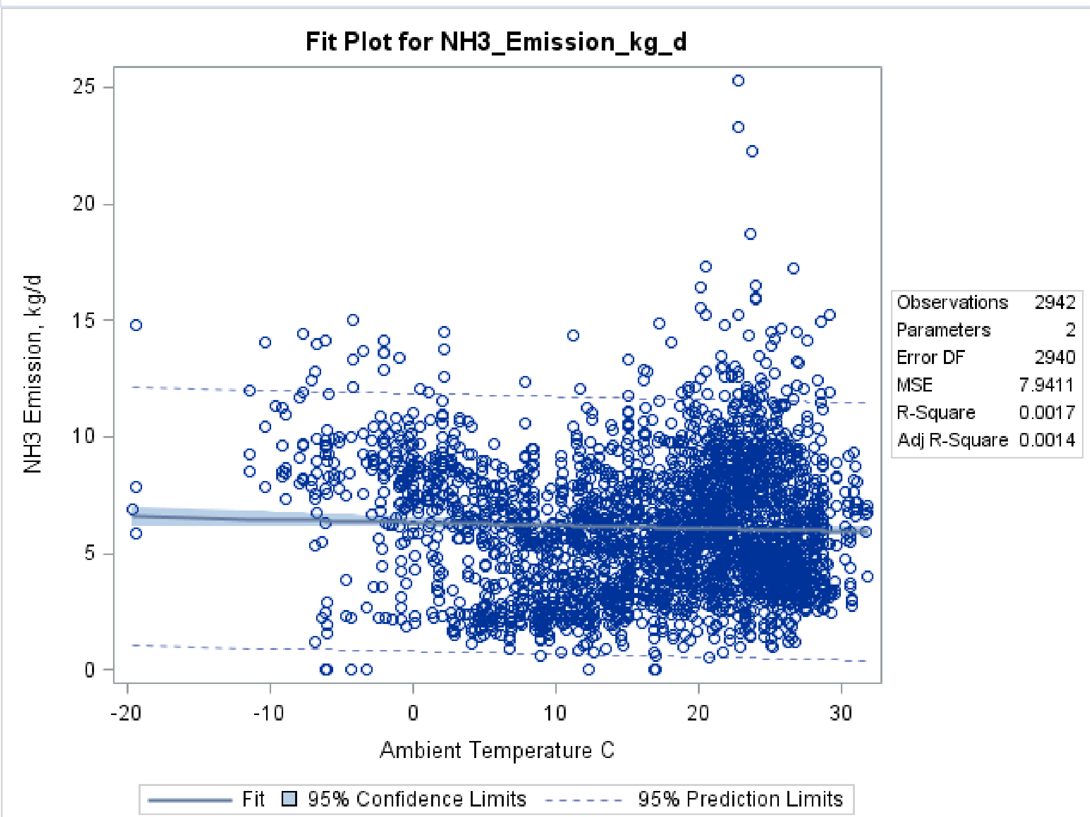


Figure E-13. Scatter plot of swine grow-finish NH_3 Emissions versus ambient temperature (top) and with regression (bottom).

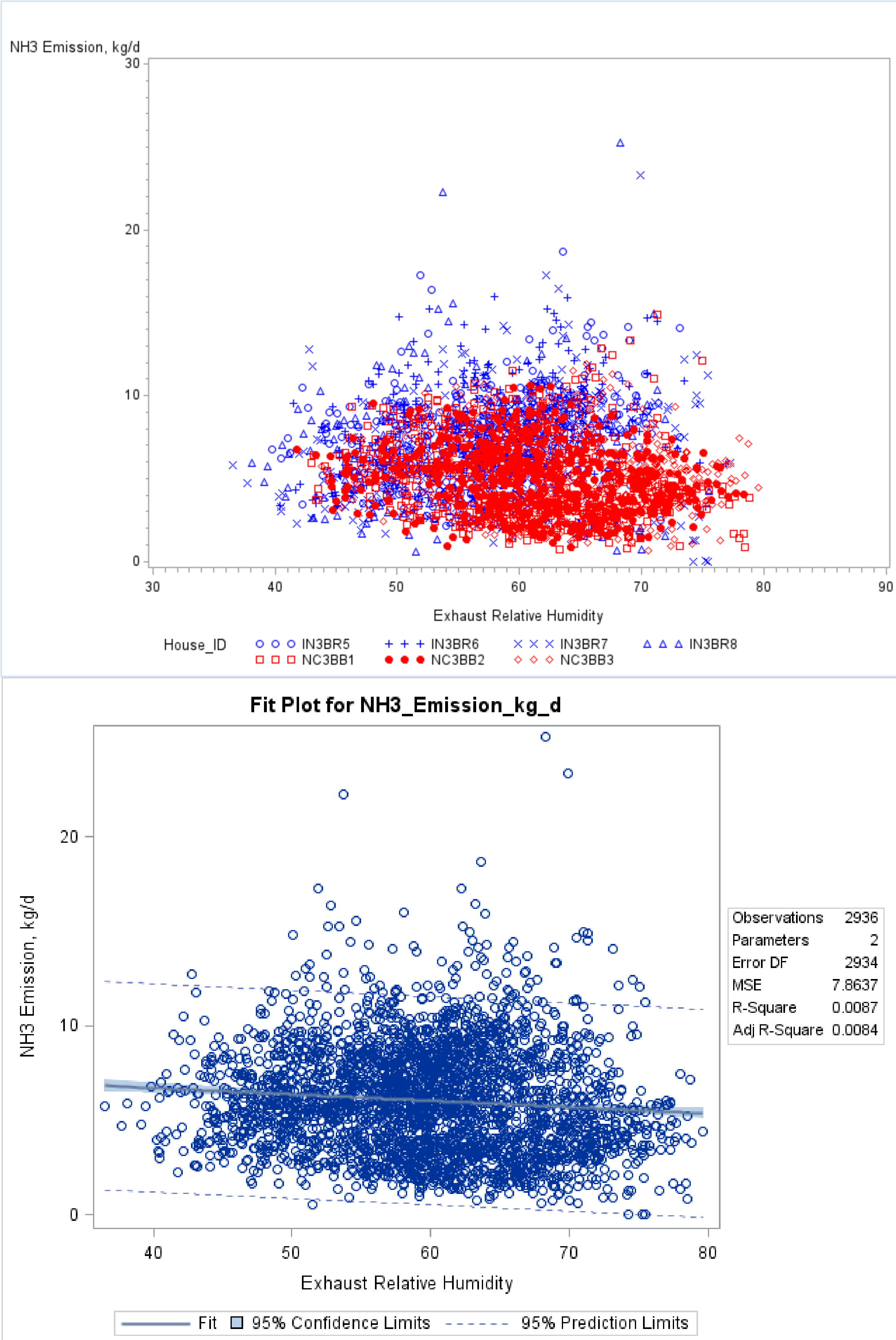


Figure E-14. Scatter plot of swine grow-finish NH_3 Emissions versus exhaust relative humidity (top) and with regression (bottom).

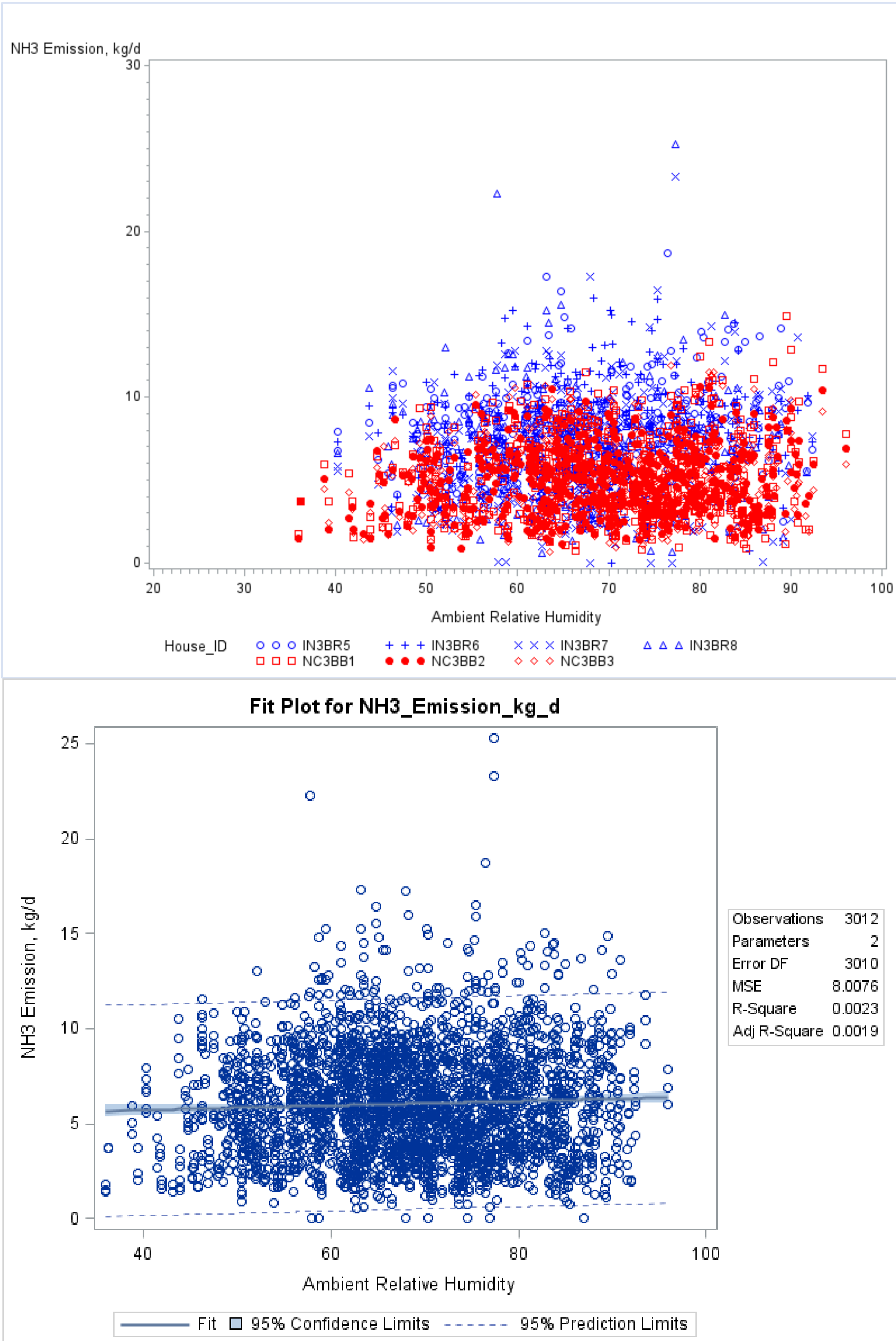


Figure E-15. Scatter plot of swine grow-finish NH_3 Emissions versus ambient relative humidity (top) and with regression (bottom).

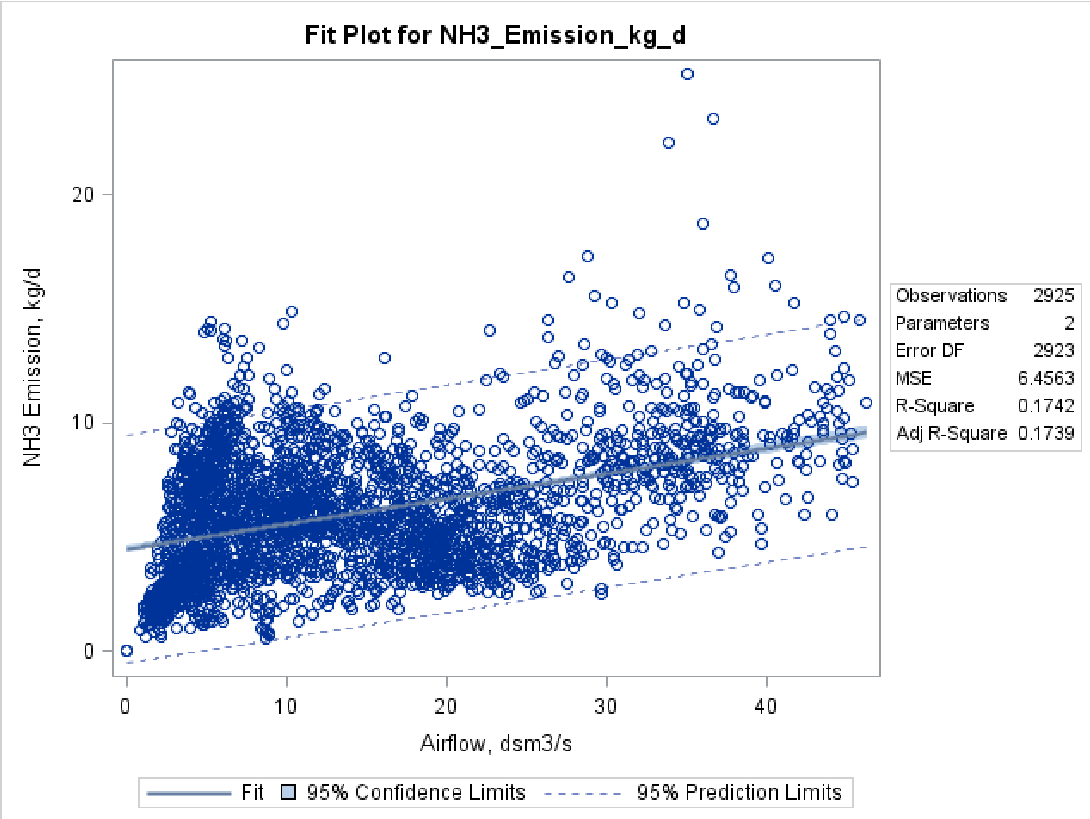


Figure E-16. Scatter plot of swine grow-finish NH_3 Emissions versus airflow (top) and with regression (bottom).

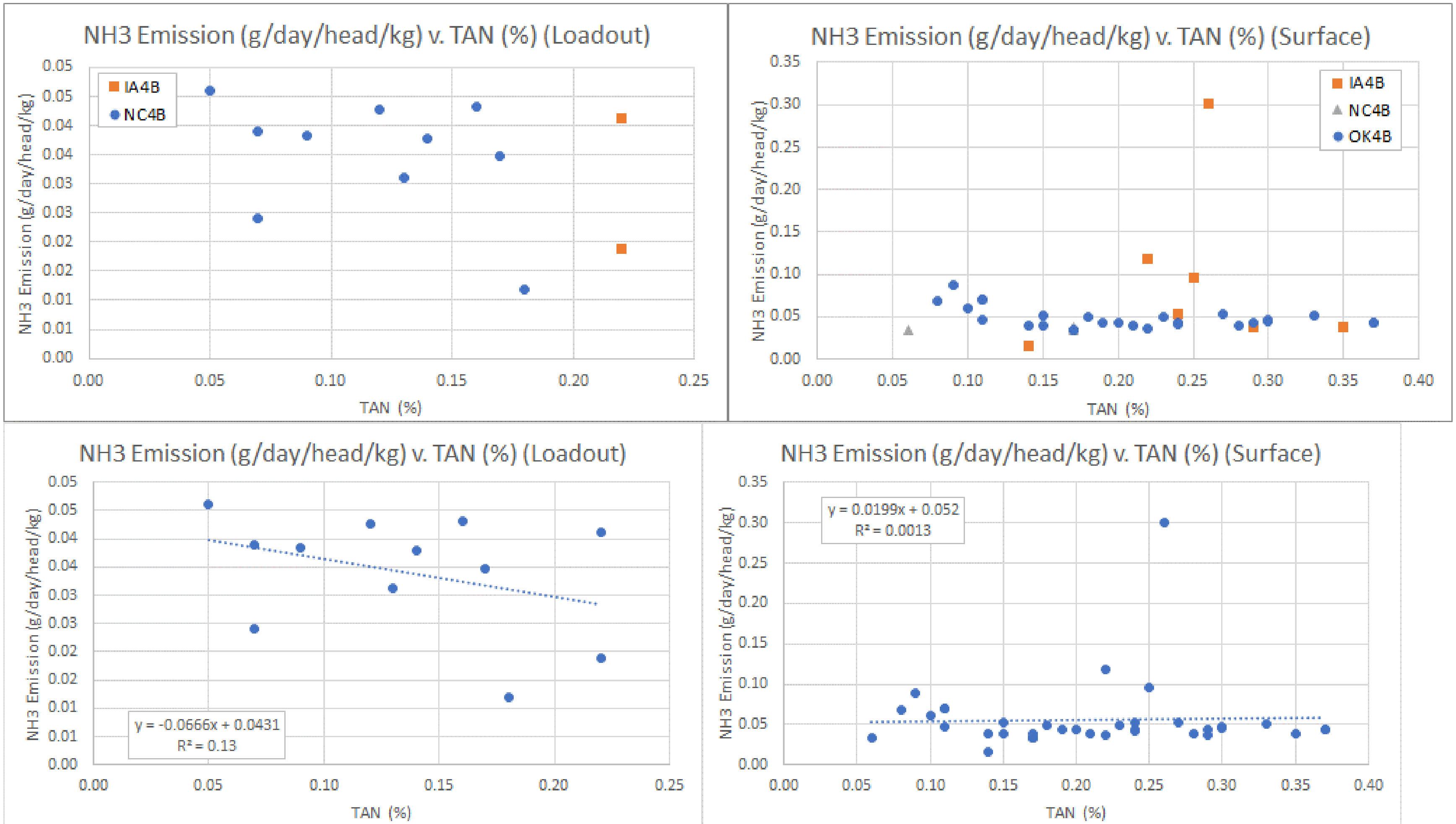
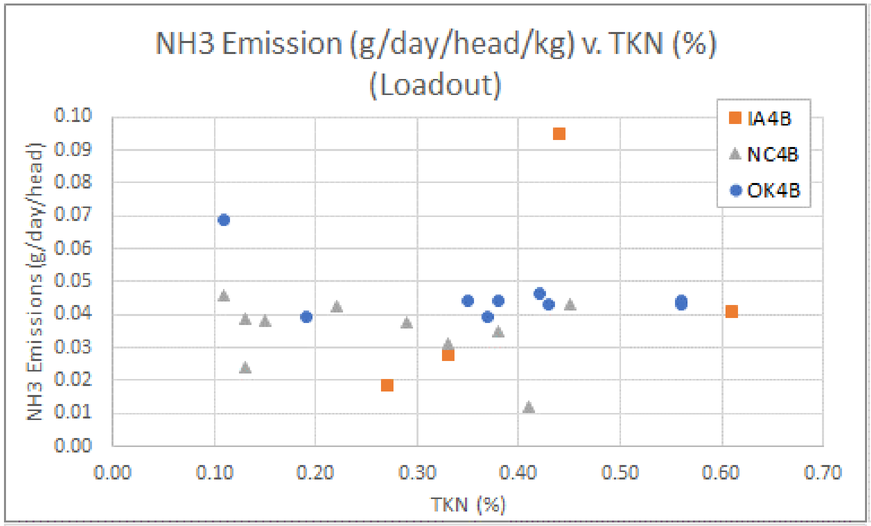
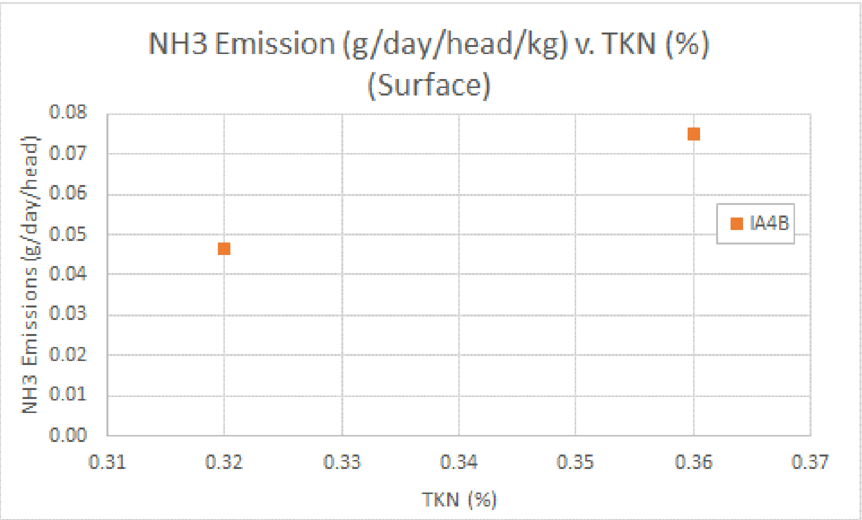


Figure E-17. Scatter plot of breeding and gestation NH_3 emissions versus percent ammonia for loadout (top left) and surface manure (top right). Plot with linear regression for loadout (bottom, left) and surface(bottom right).





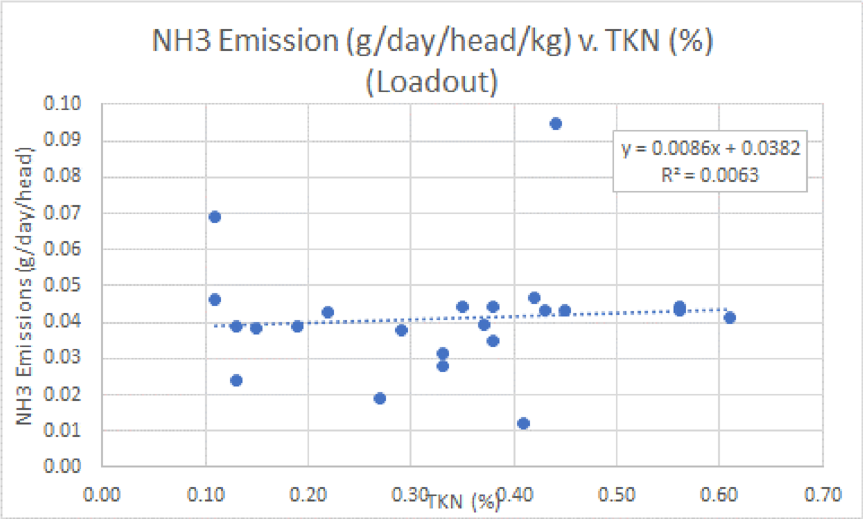


Figure E-18. Scatter plot of breeding and gestation NH_3 emissions versus percent Nitrogen for loadout (top left) and surface manure (top right). Plot with linear regression for loadout (bottom, left) and surface(bottom right).

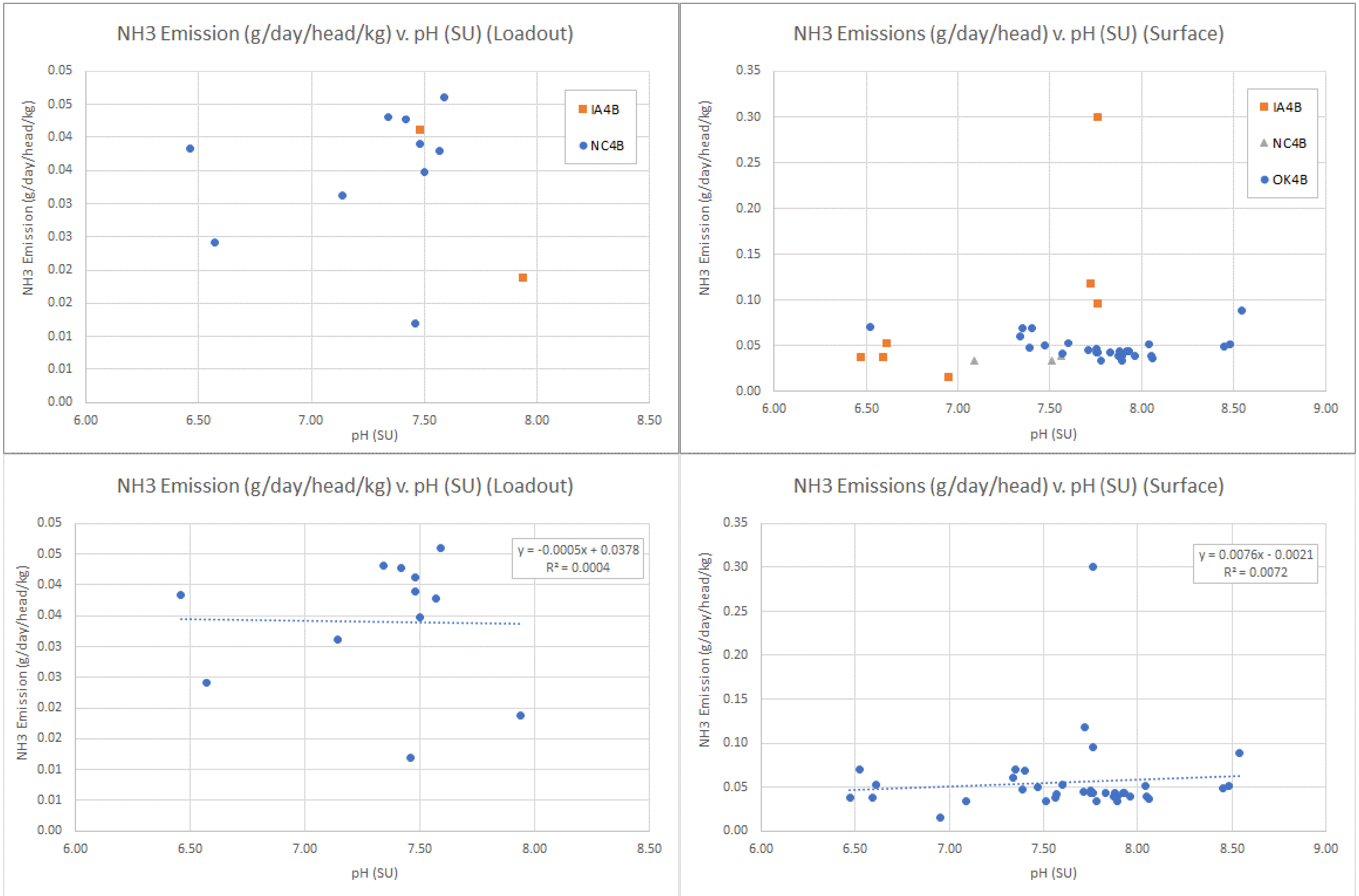


Figure E-19. Scatter plot of breeding and gestation NH_3 emissions versus pH for loadout (top left) and surface manure (top right). Plot with linear regression for loadout (bottom, left) and surface(bottom right).

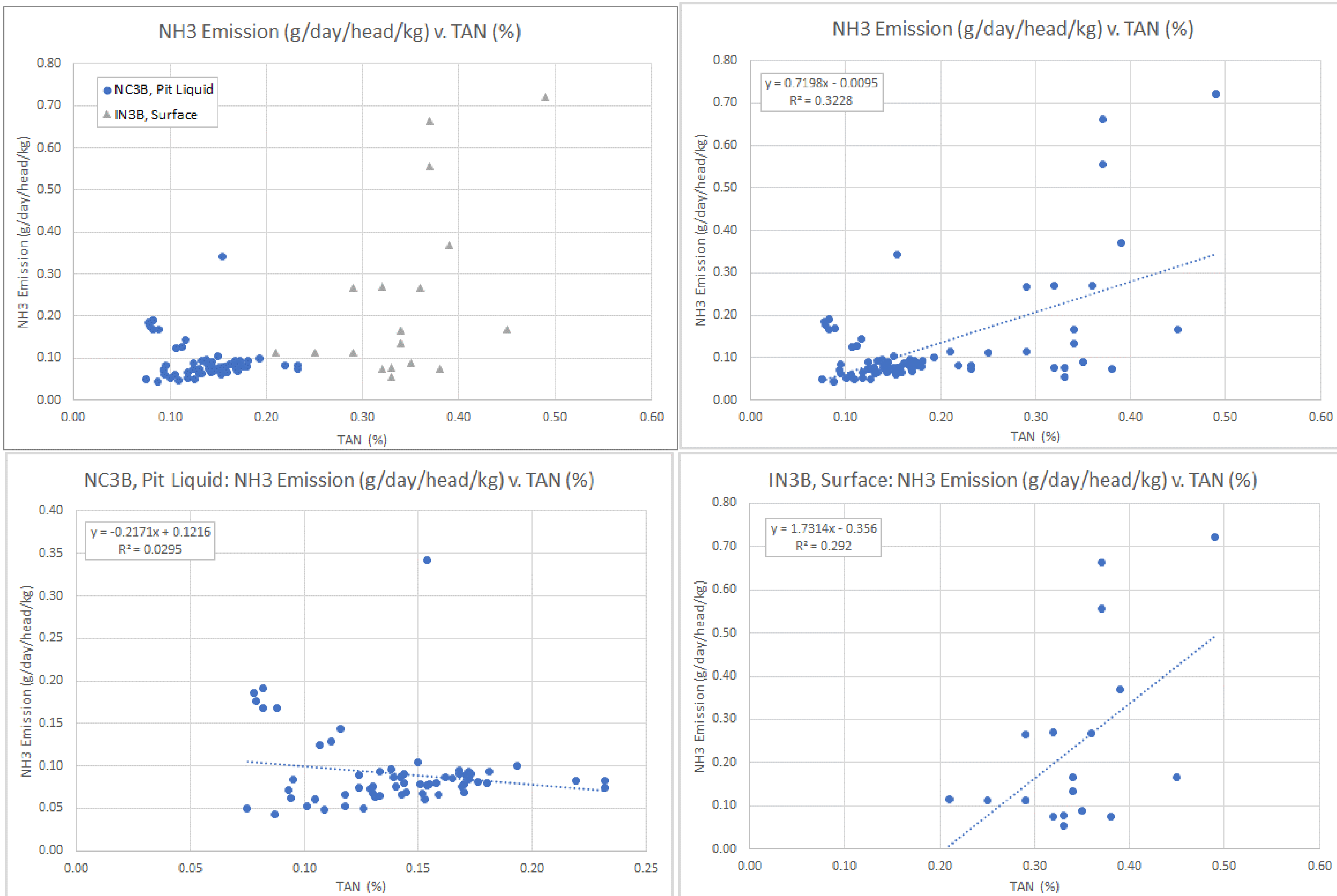


Figure E-20. Scatter plot for grow-finish site NH_3 emissions versus percent total ammoniacal nitrogen for surface manure samples (top left), with linear regression (top right) and separate plots for loadout (bottom left) and surface manure (bottom right).

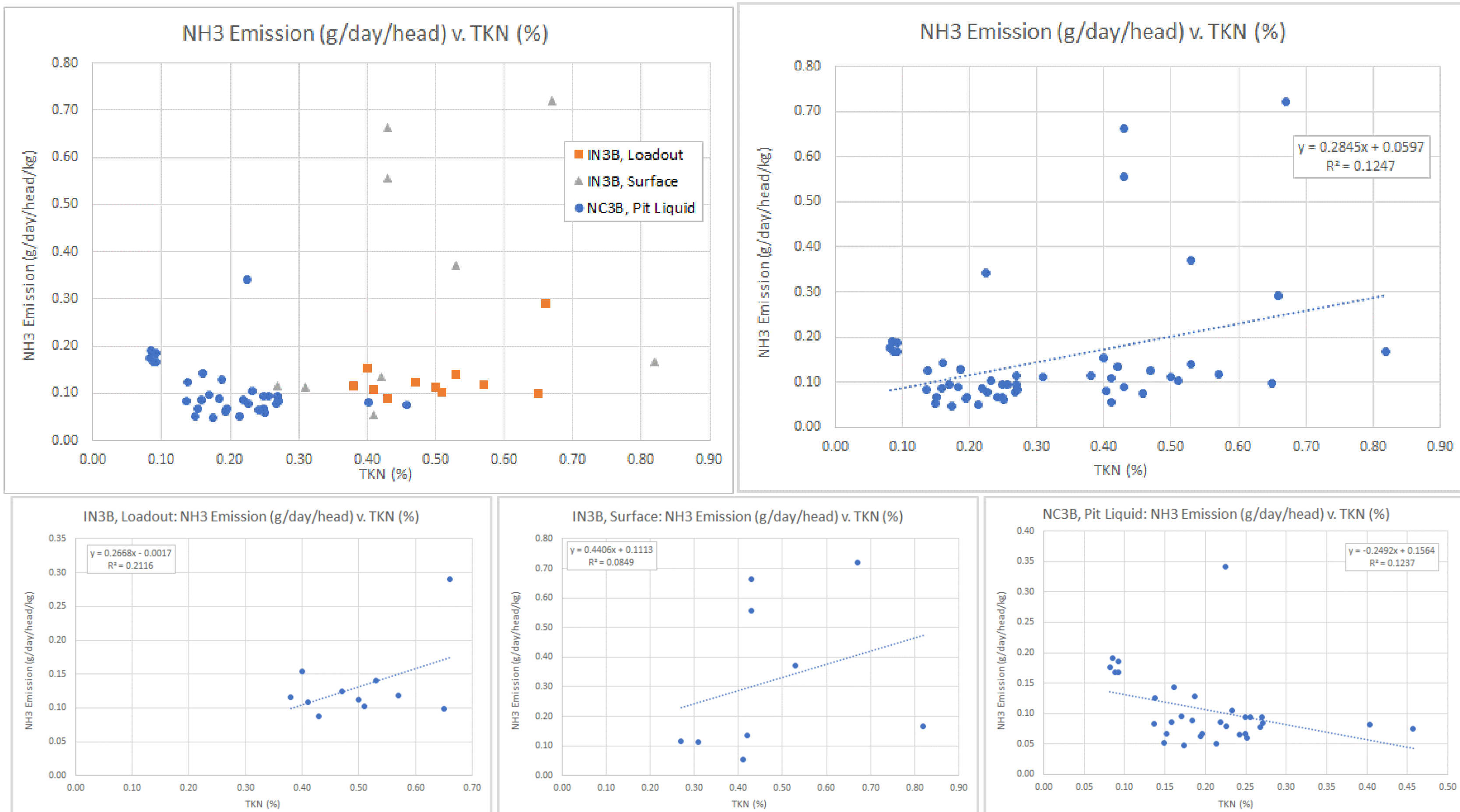


Figure E-21. Scatter plot for grow-finish site NH_3 emissions versus percent total Kjeldahl nitrogen for manure samples (top left), with linear regression (top right) and separate plots for loadout (bottom left), surface manure (bottom center) and pit liquid (bottom right).

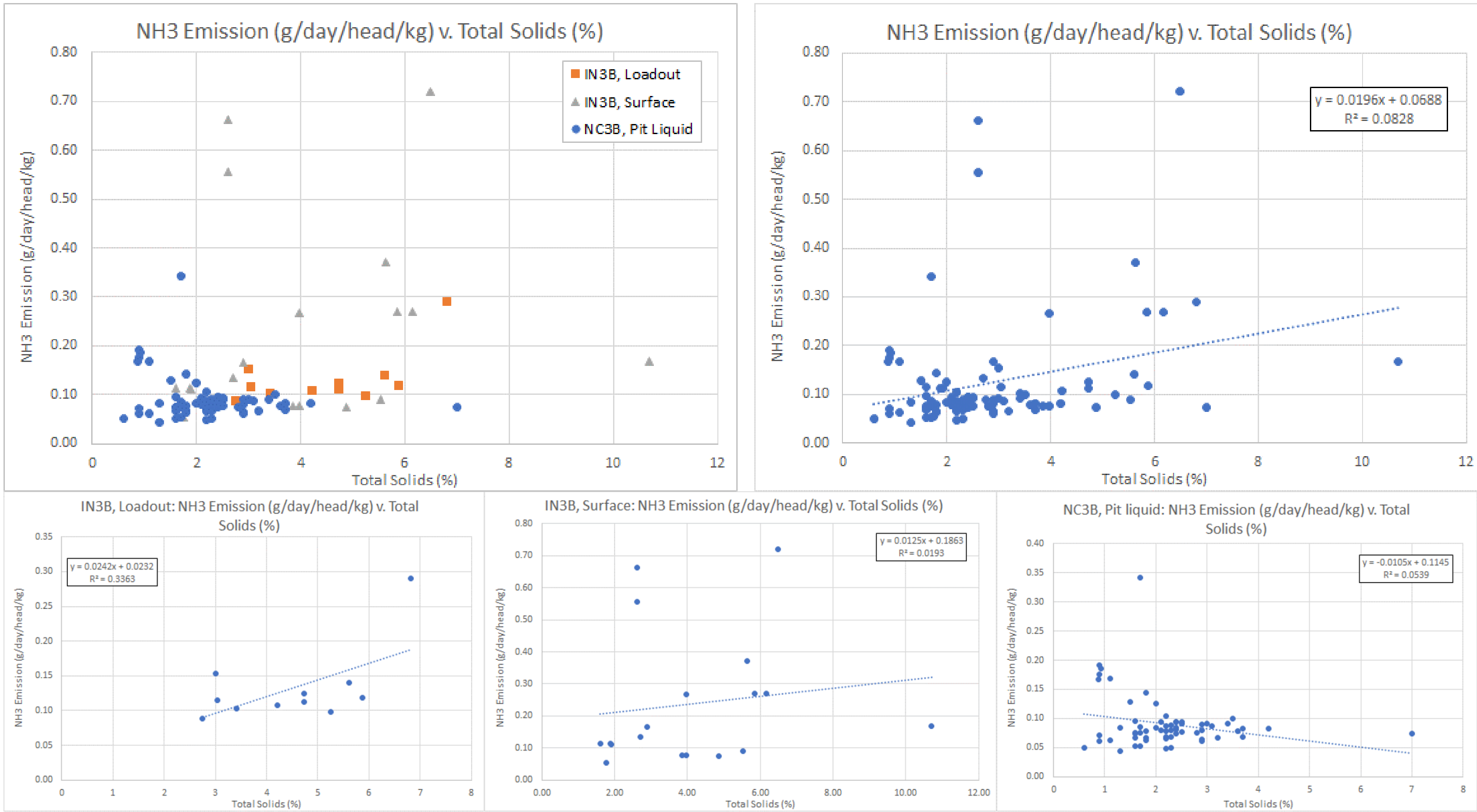


Figure E-22. Scatter plot for grow-finish site NH_3 emissions versus percent total solids for manure samples (top left), with linear regression (top right) and separate plots for loadout (bottom left), surface manure (bottom center) and pit liquid (bottom right).

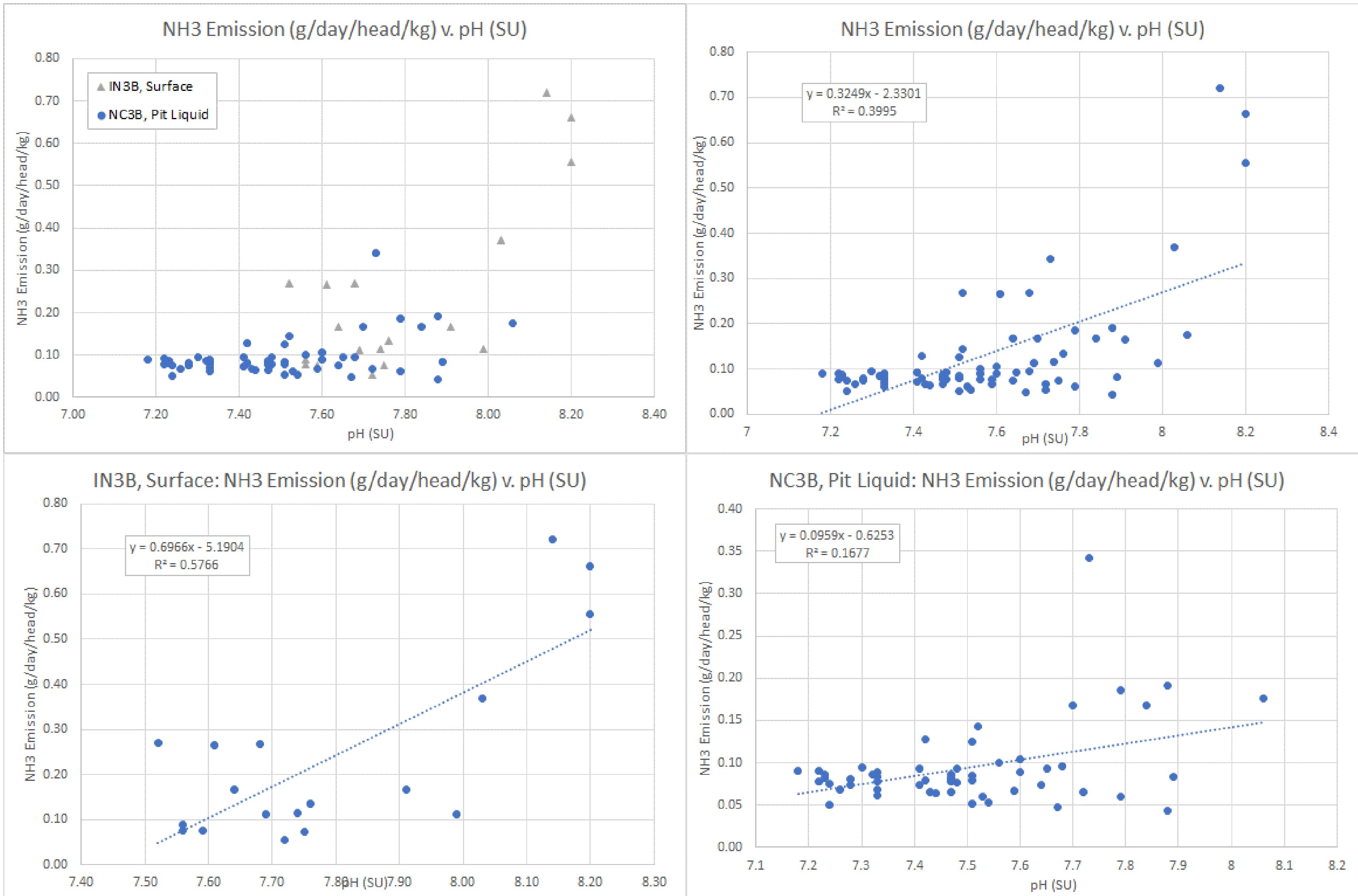
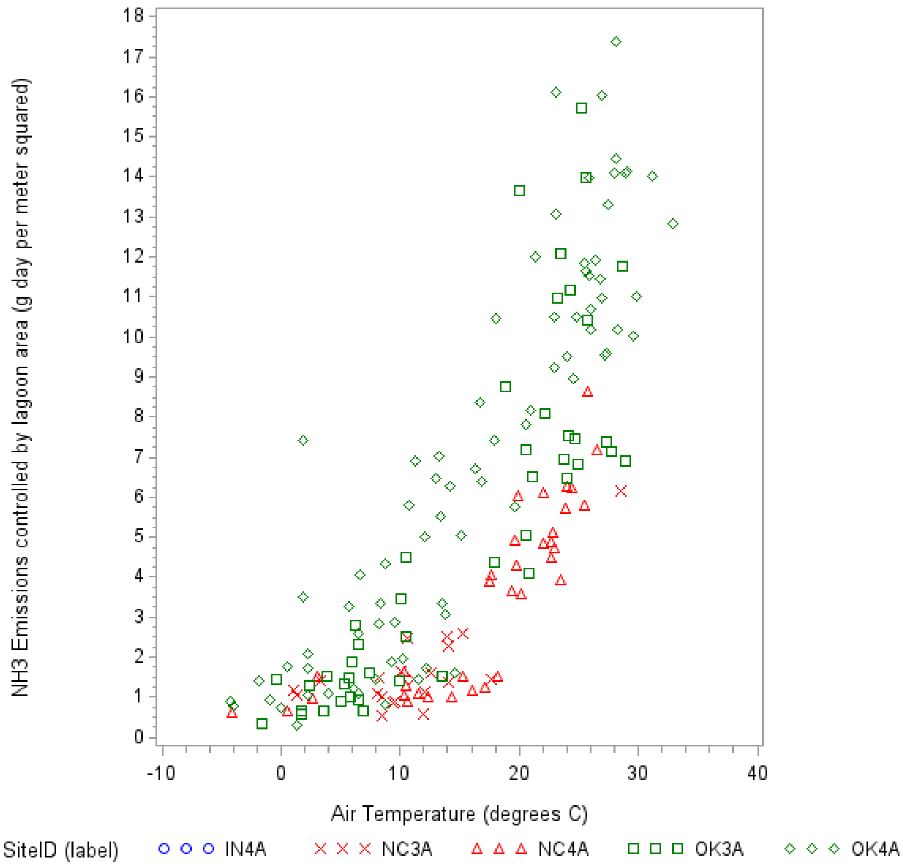


Figure E-23. Scatter plot of grow-finish site NH_3 emissions versus pH for manure samples (top left), with linear regression (top right) and separate plots for surface manure (bottom left) and pit liquid (bottom right).



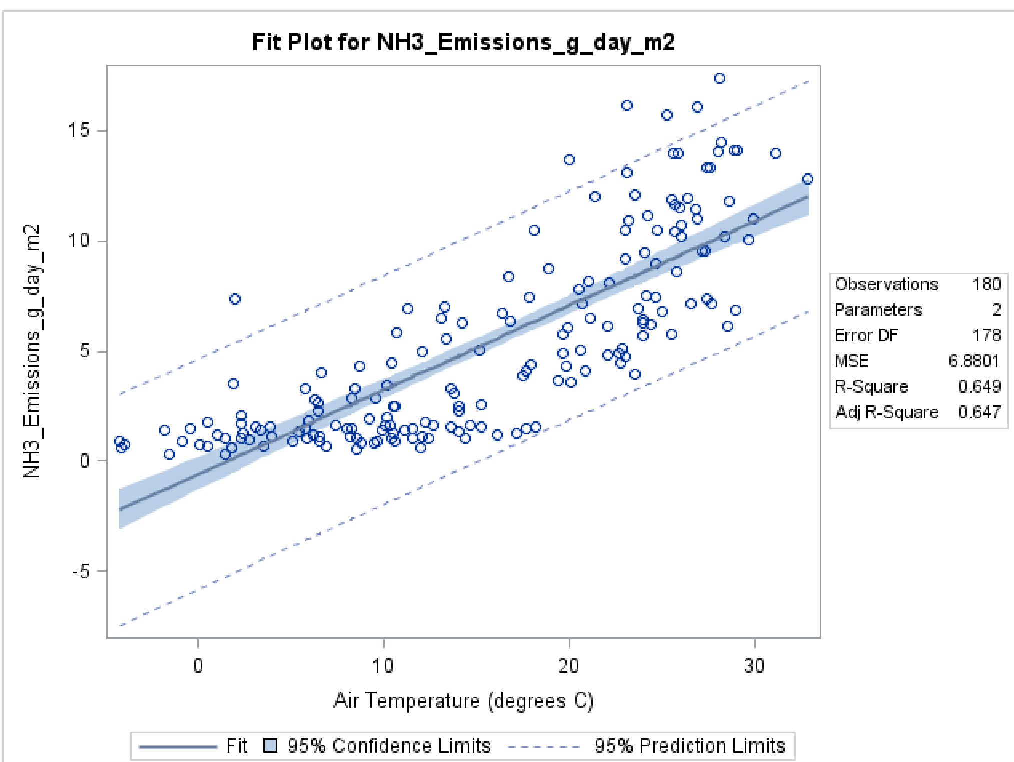
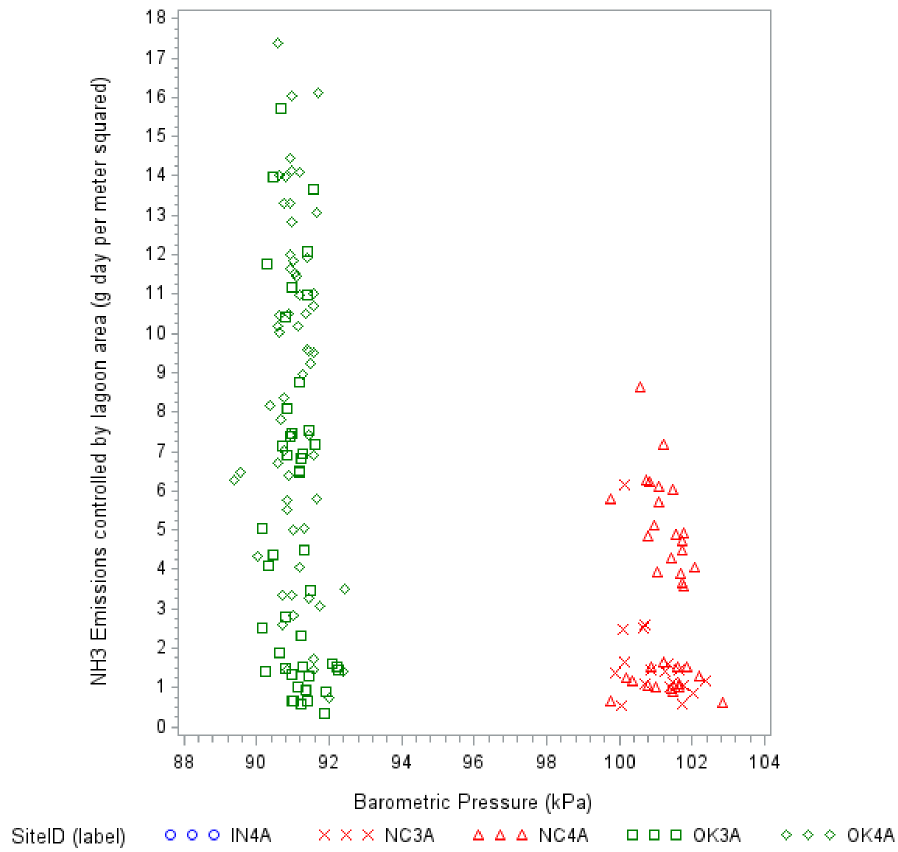


Figure E-24. Scatter plot of open source NH_3 Emissions versus ambient temperature (top) and with regression (bottom).



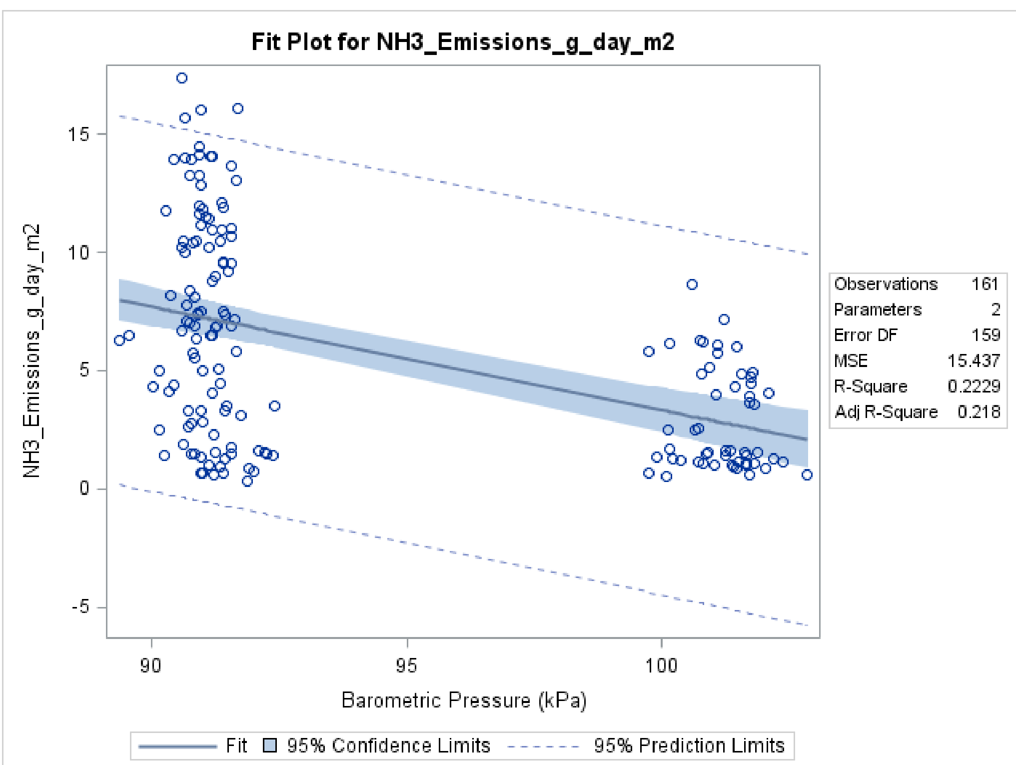
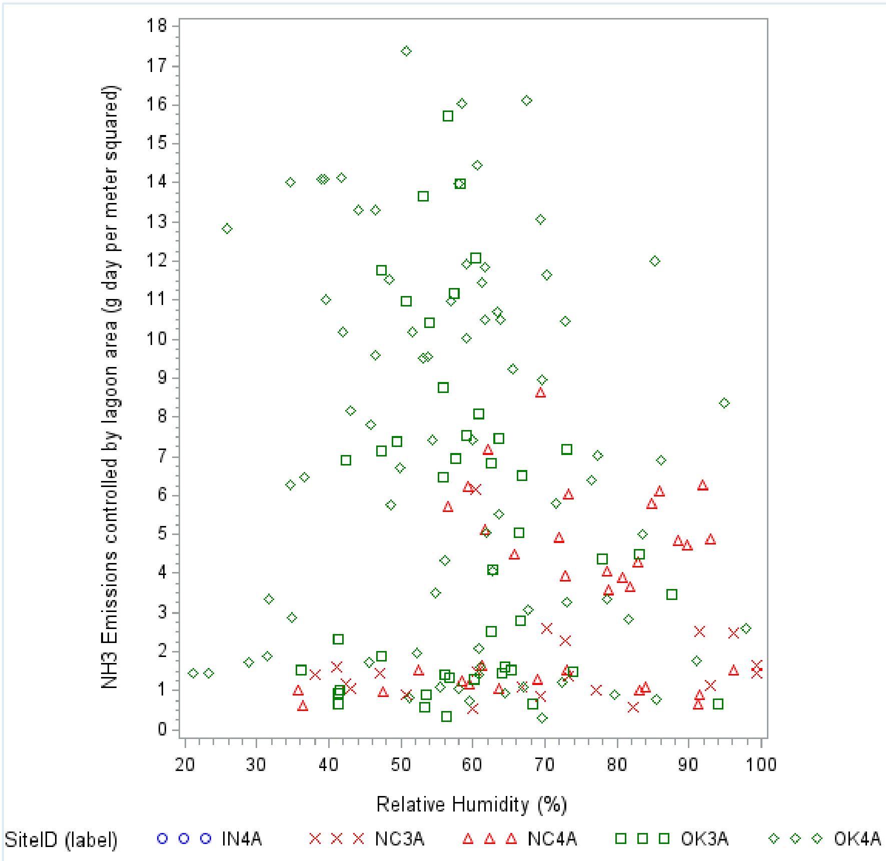


Figure E-25. Scatter plot of open source NH_3 Emissions versus barometric pressure (top) and with regression (bottom).



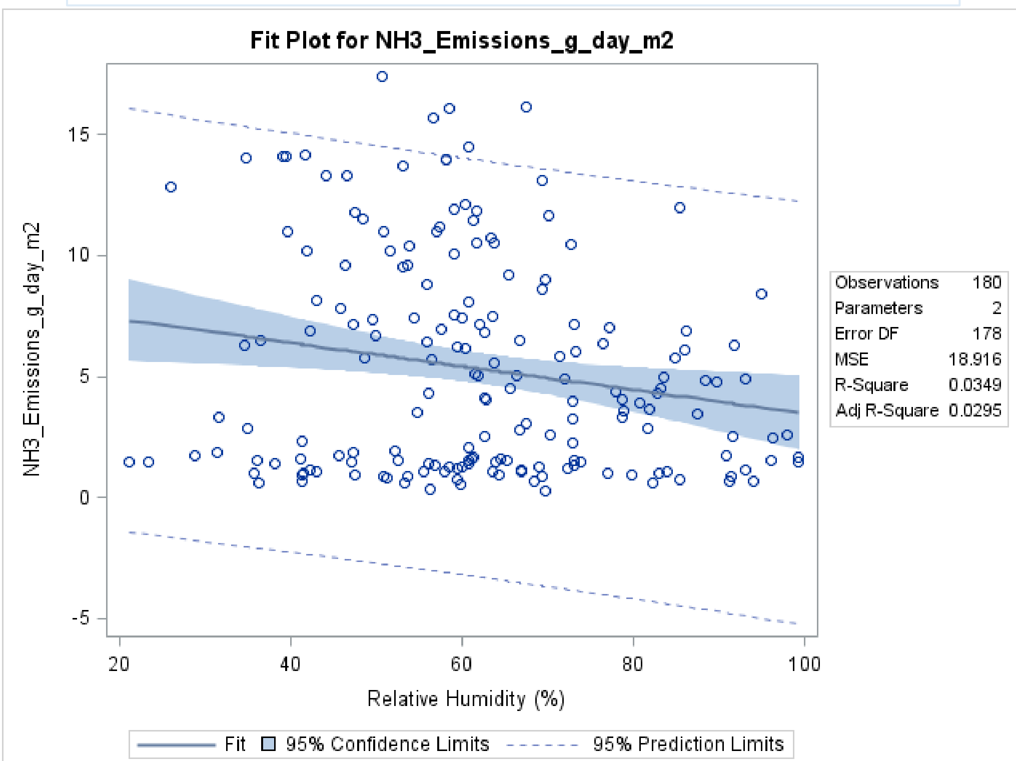
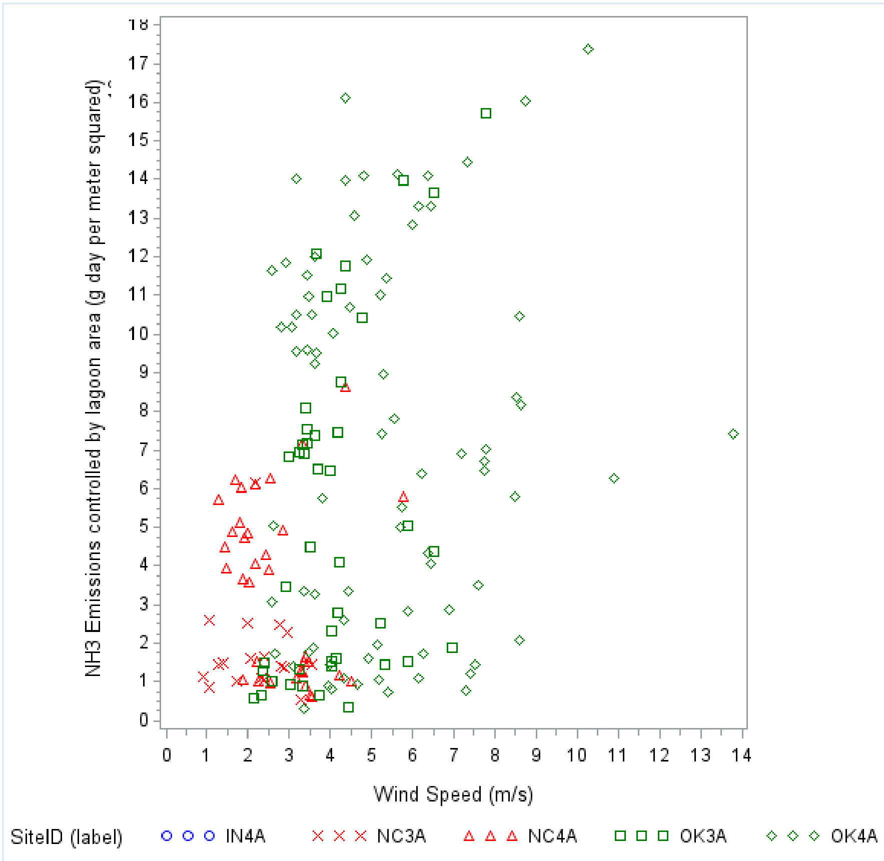


Figure E-26. Scatter plot of open source NH_3 Emissions versus relative humidity (top) and with regression (bottom).



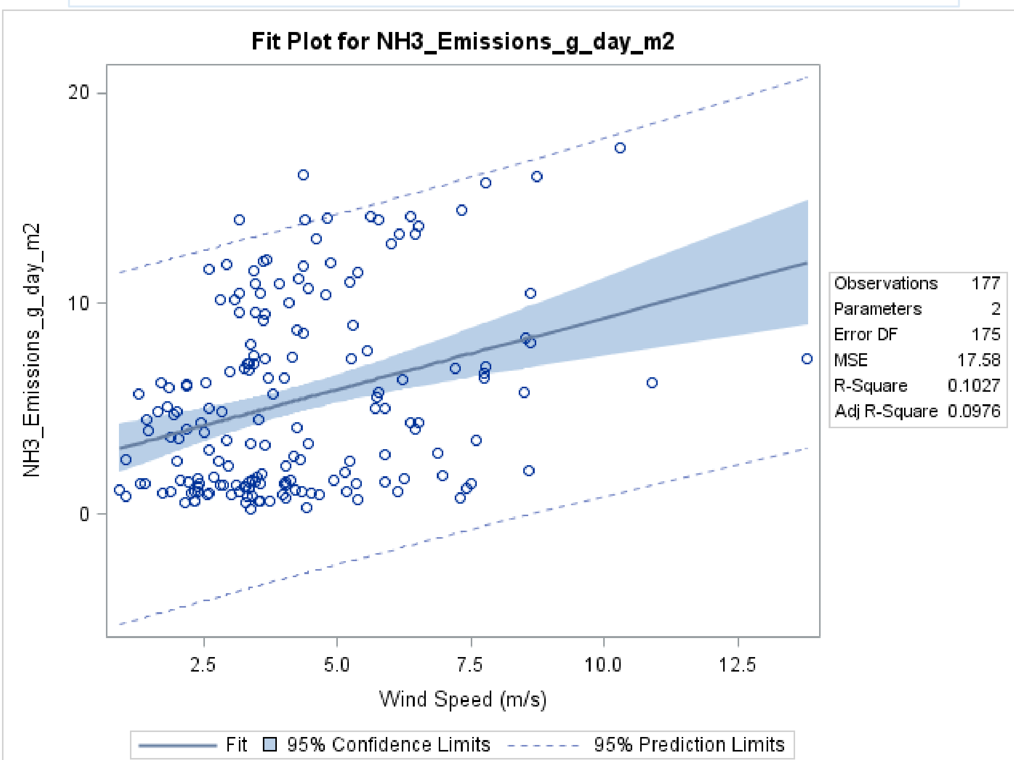


Figure E-27. Scatter plot of open source NH_3 Emissions versus wind (top) and with regression (bottom).

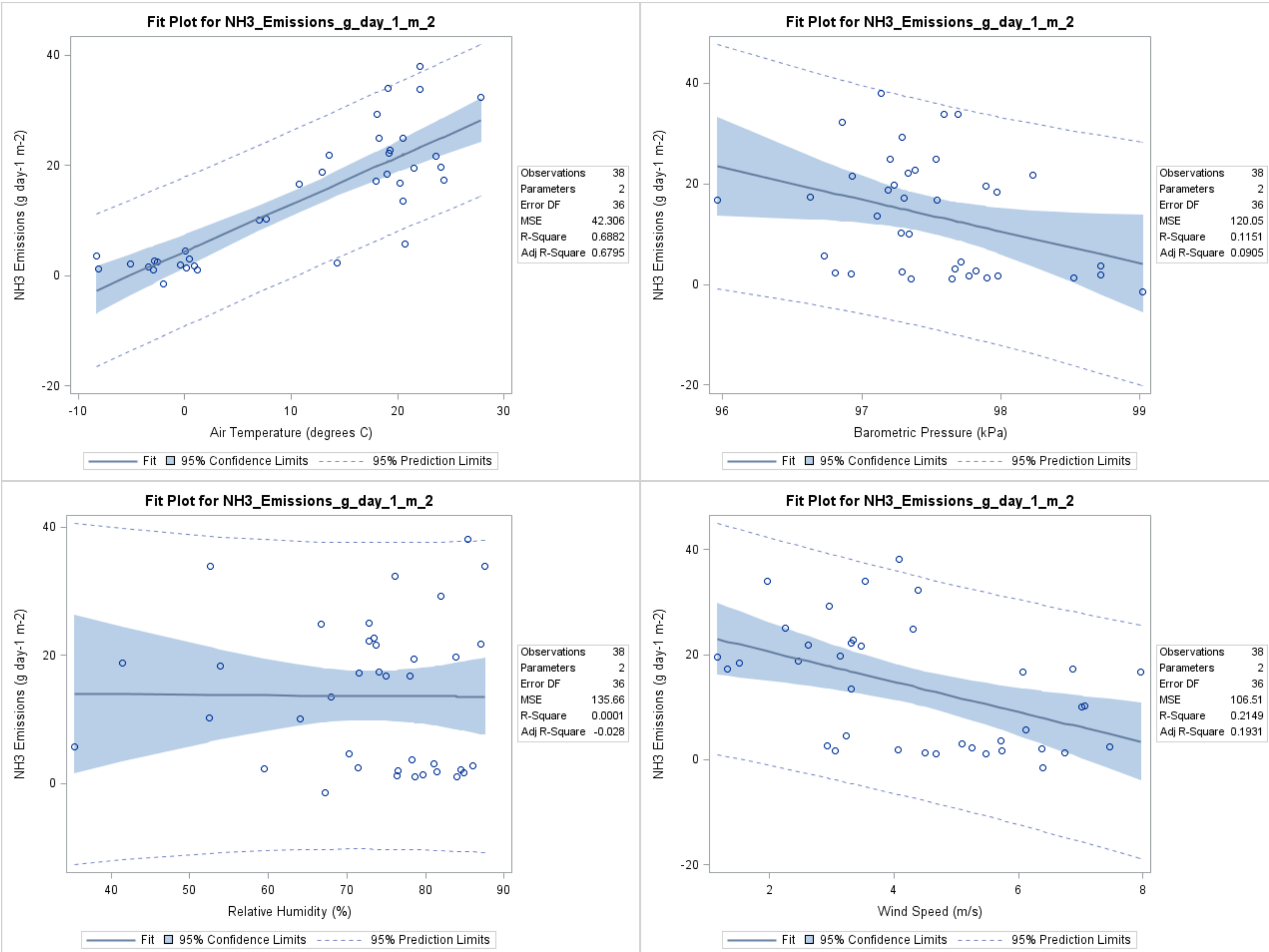


Figure E-28. Scatter plot and regression of basin NH_3 Emissions with air temperature (top left), pressure (top right), relative humidity (bottom left). and wind speed (bottom right).

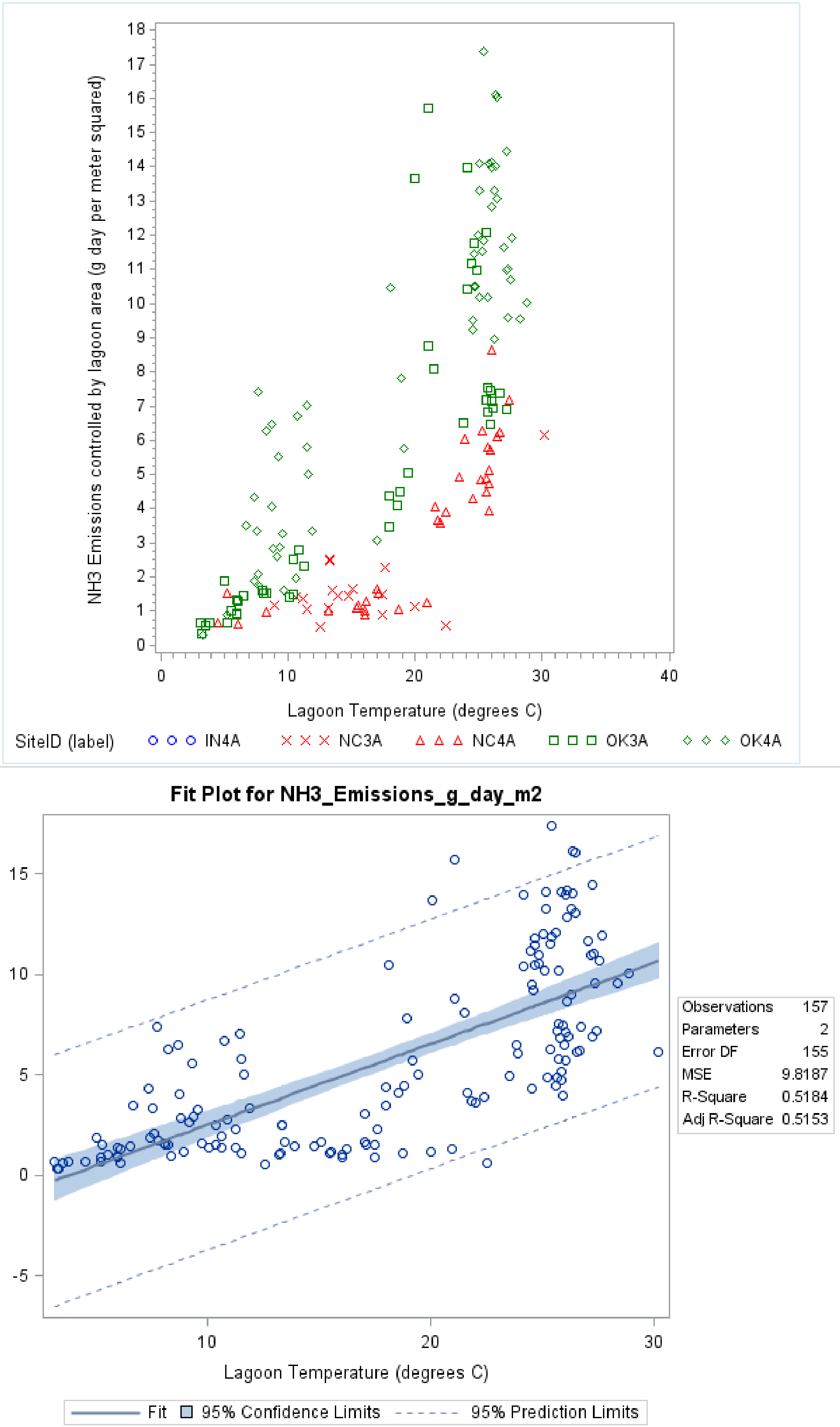
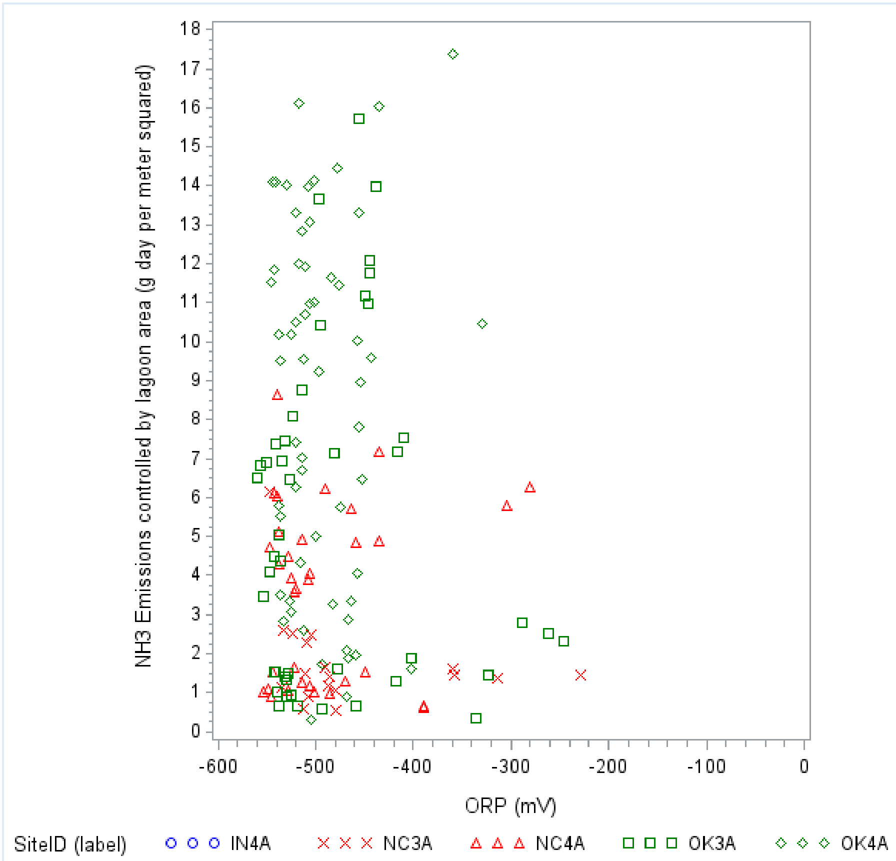


Figure E-29. Scatter plot of open source NH_3 Emissions versus lagoon temperature (top) and with regression (bottom).



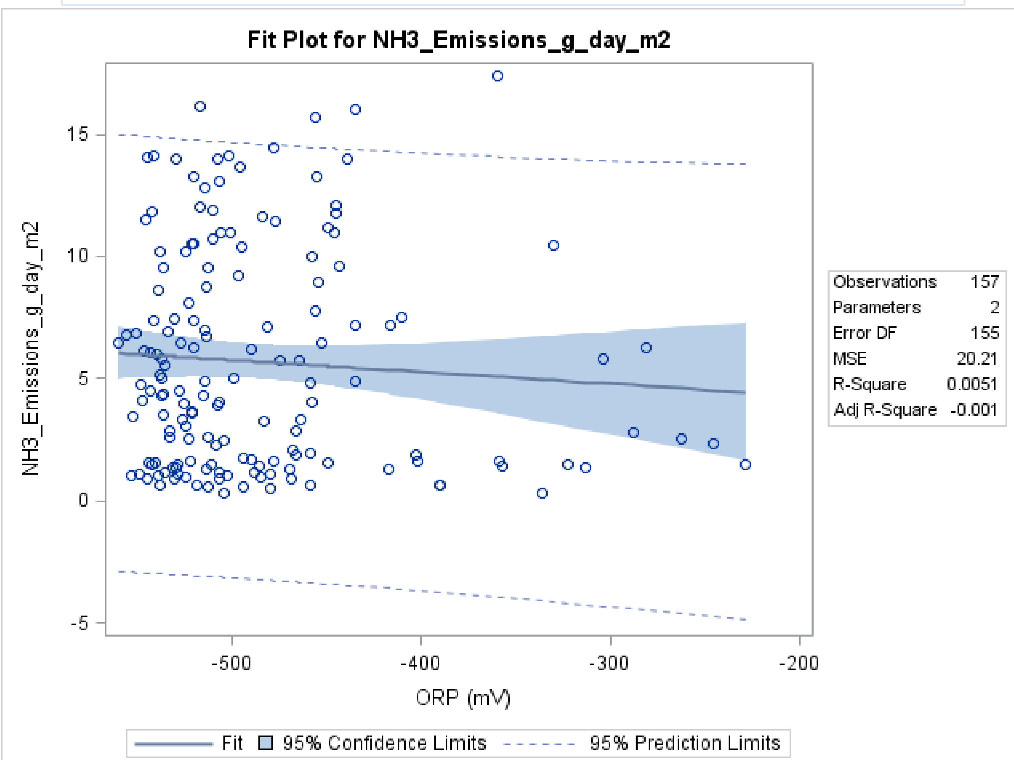


Figure E-30. Scatter plot of open source NH_3 Emissions versus oxidation reduction potential (top) and with regression (bottom).

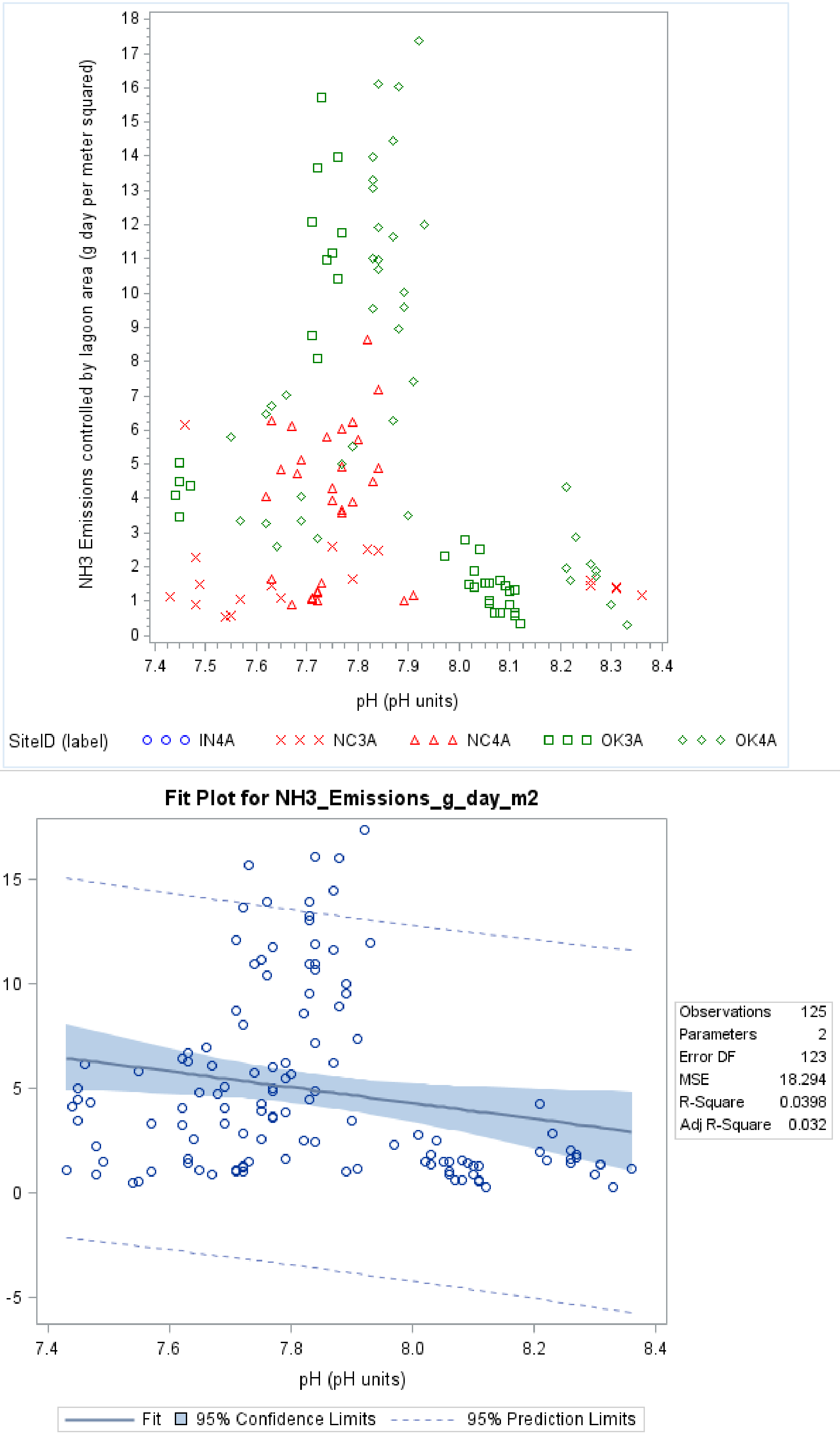


Figure E-31. Scatter plot of open source NH_3 Emissions versus pH (top) and with regression (bottom).

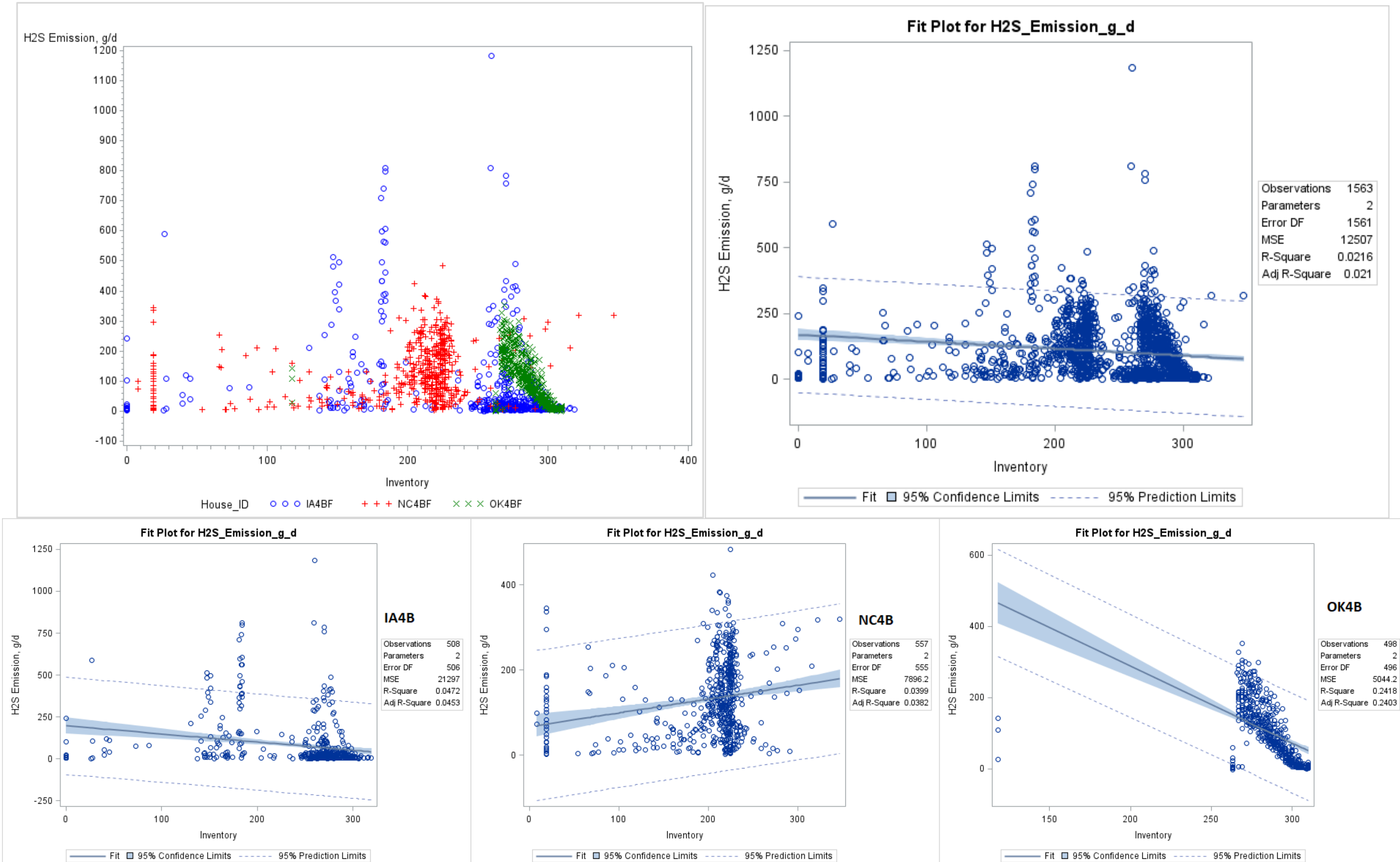


Figure E-32. Scatter plot of H_2S Emissions versus inventory and scatter with regression for farrowing room (top row) and by site (bottom row).

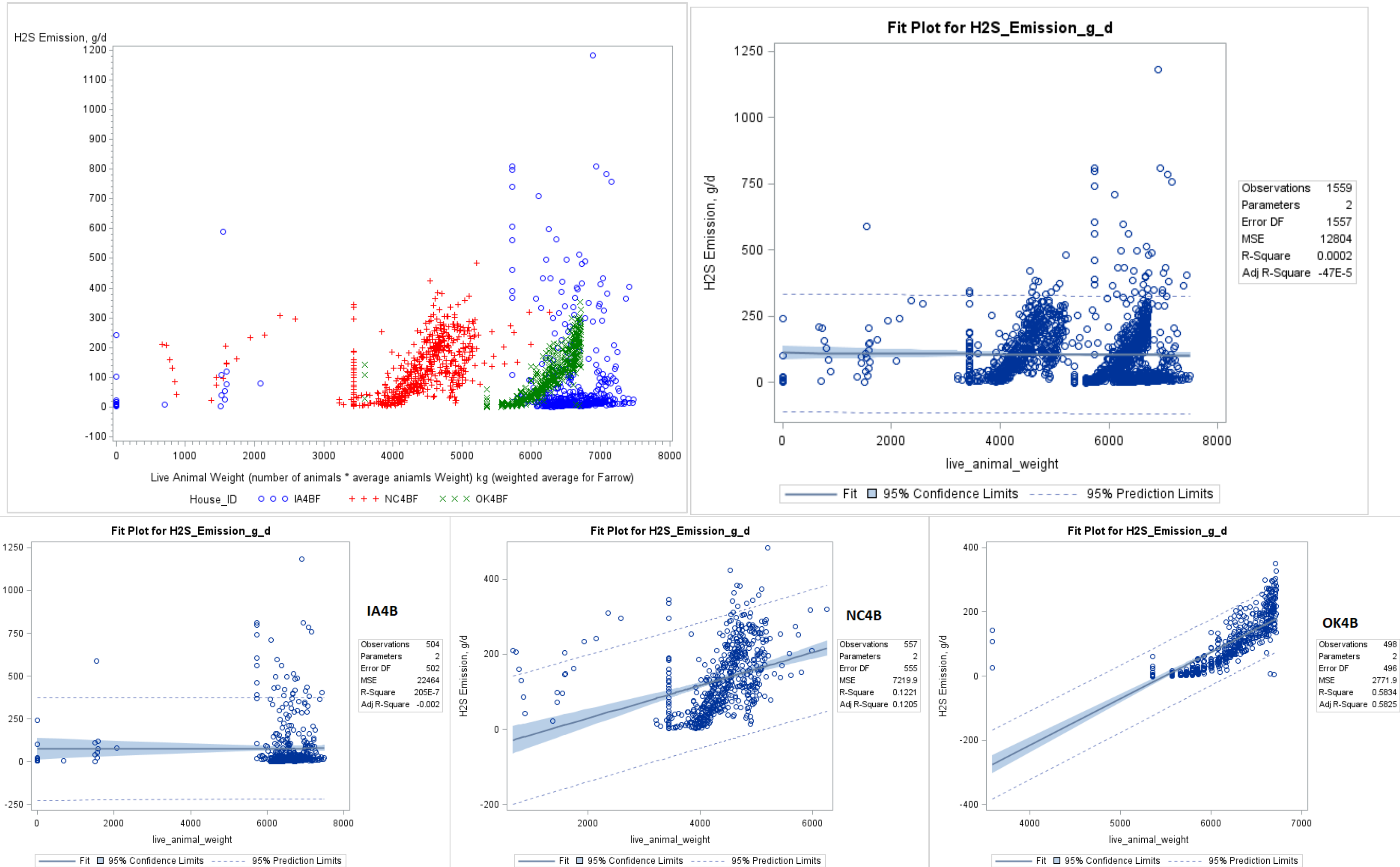


Figure E-33. Scatter plot of H_2S Emissions versus LAW and scatter with regression for farrowing room (top row) and by site (bottom row).

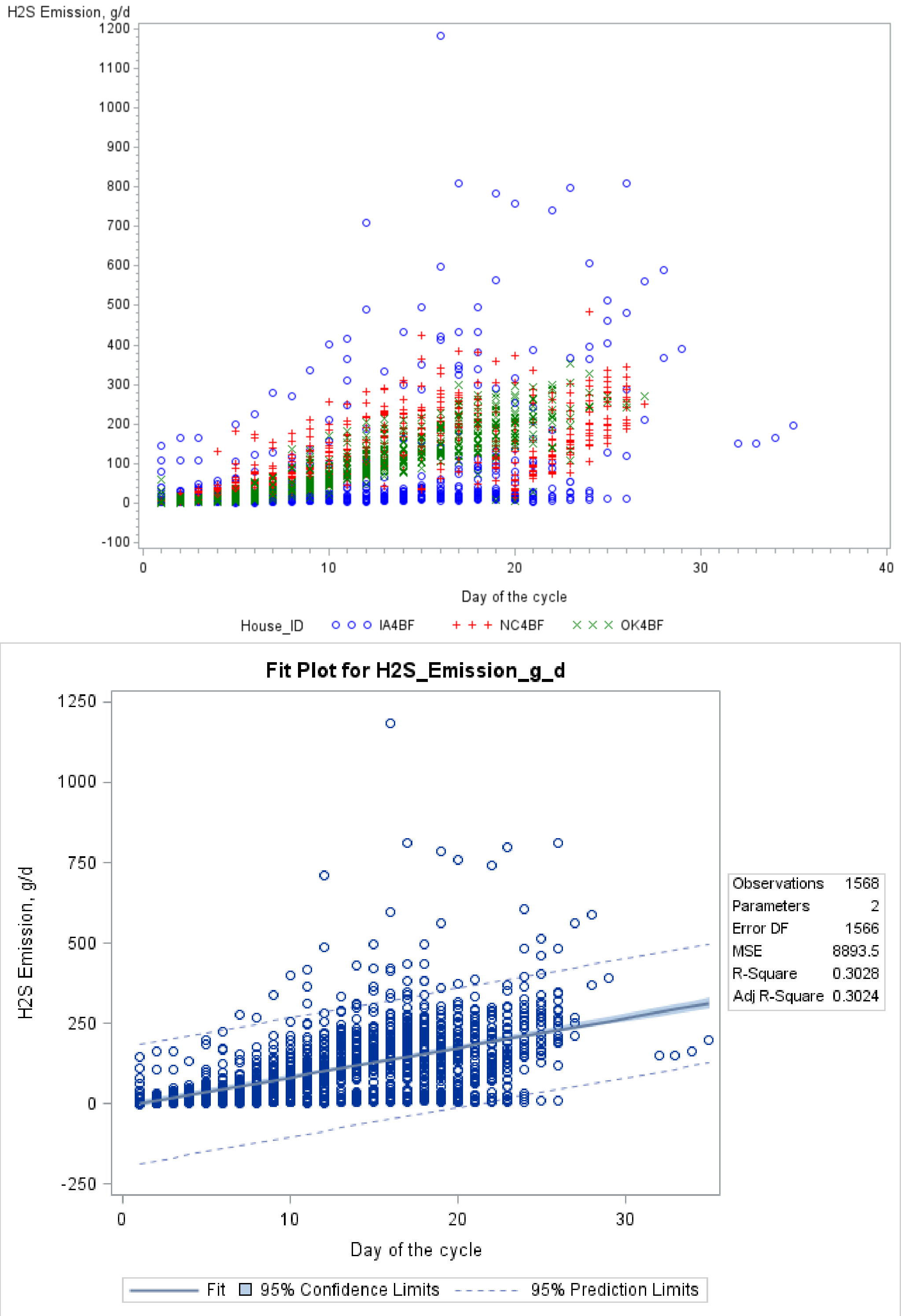


Figure E-34. Scatter plot of H_2S Emissions versus cycle day and scatter with regression for farrowing room (top row) and by site (bottom row).

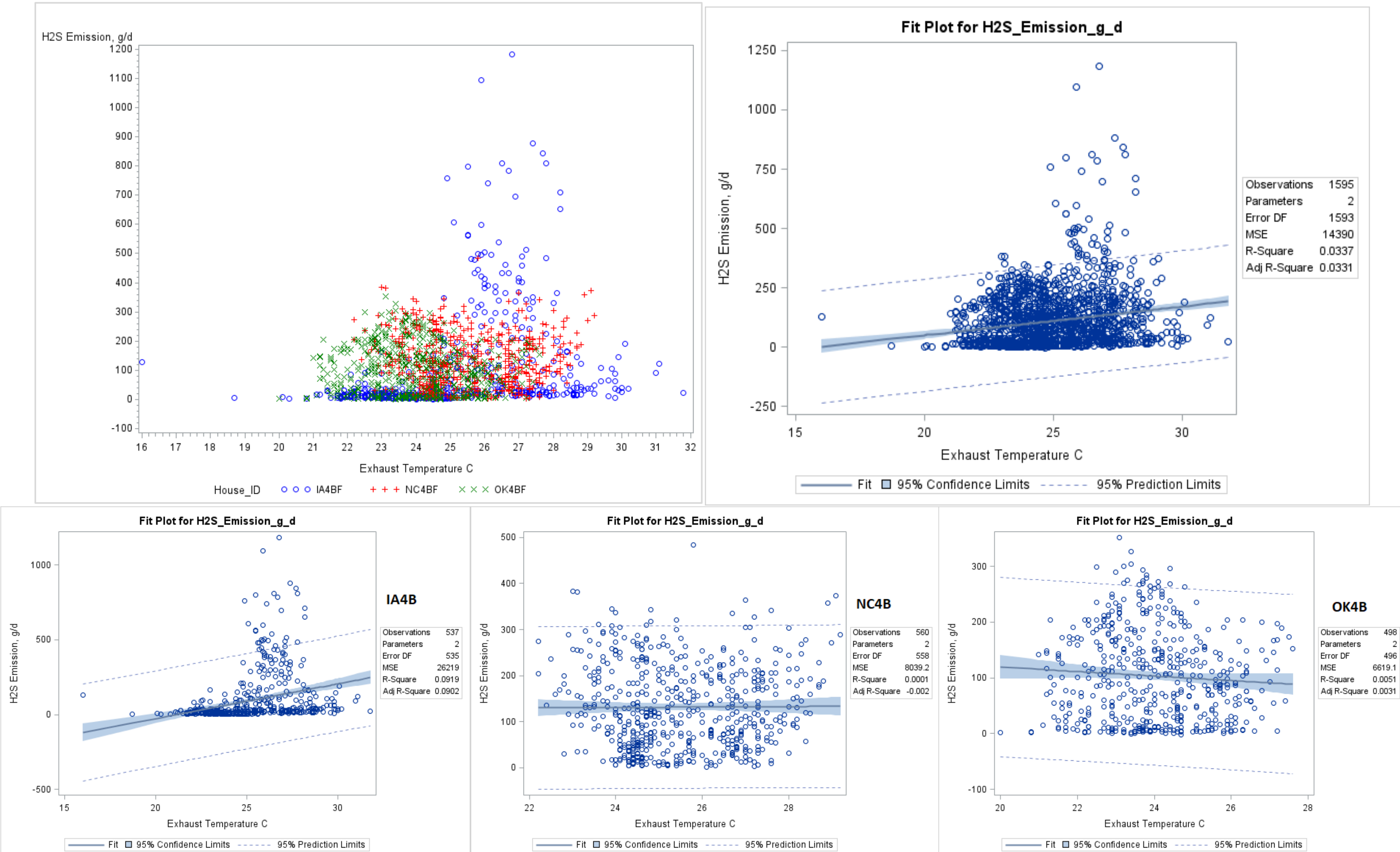


Figure E-35. Scatter plot of H_2S Emissions versus exhaust temperature and scatter with regression for farrowing room (top row) and by site (bottom row).

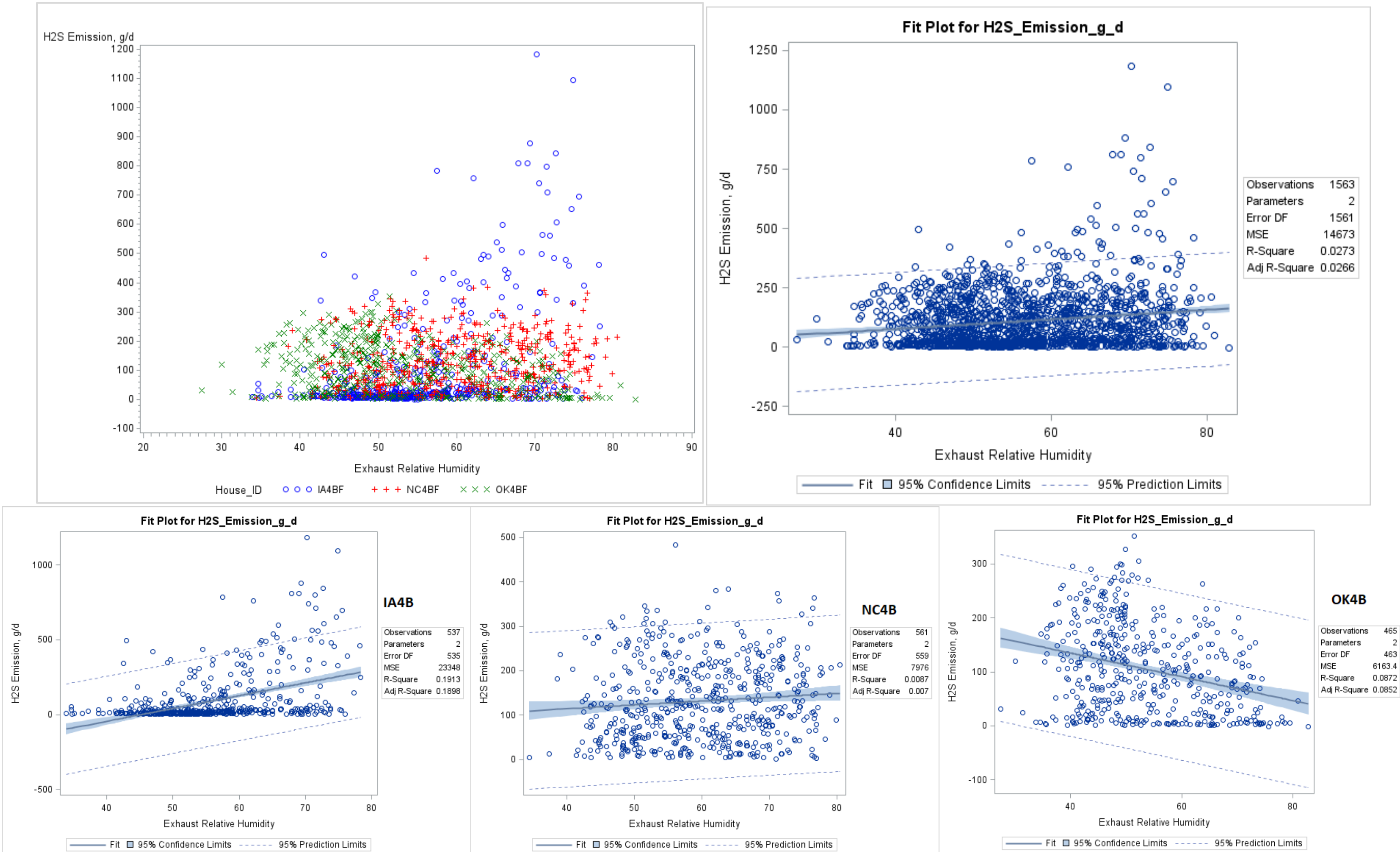


Figure E-36. Scatter plot of H_2S Emissions versus exhaust relative humidity and scatter with regression for farrowing room (top row) and by site (bottom row).

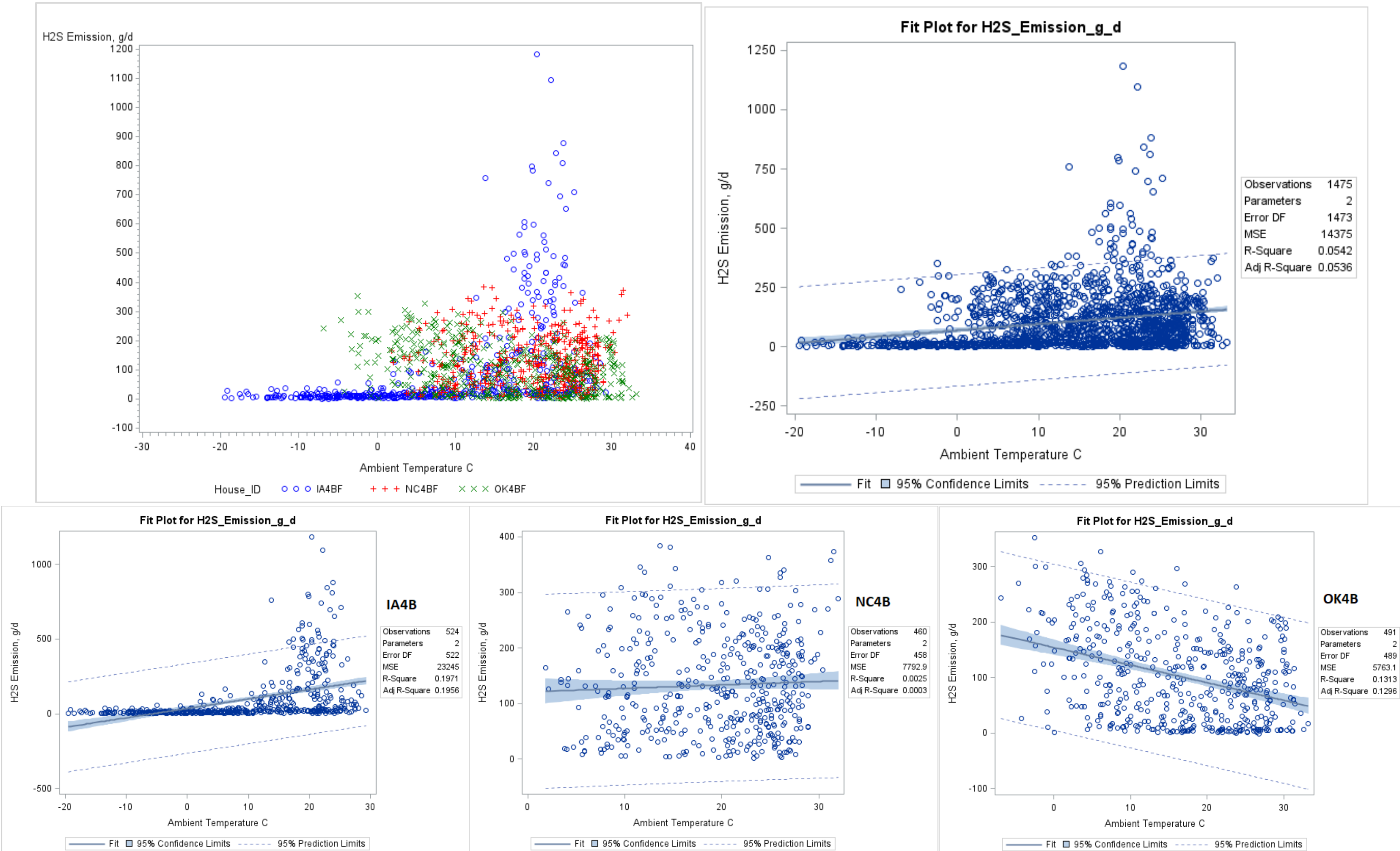


Figure E-37. Scatter plot of H_2S Emissions versus ambient temperature and scatter with regression for farrowing room (top row) and by site (bottom row).

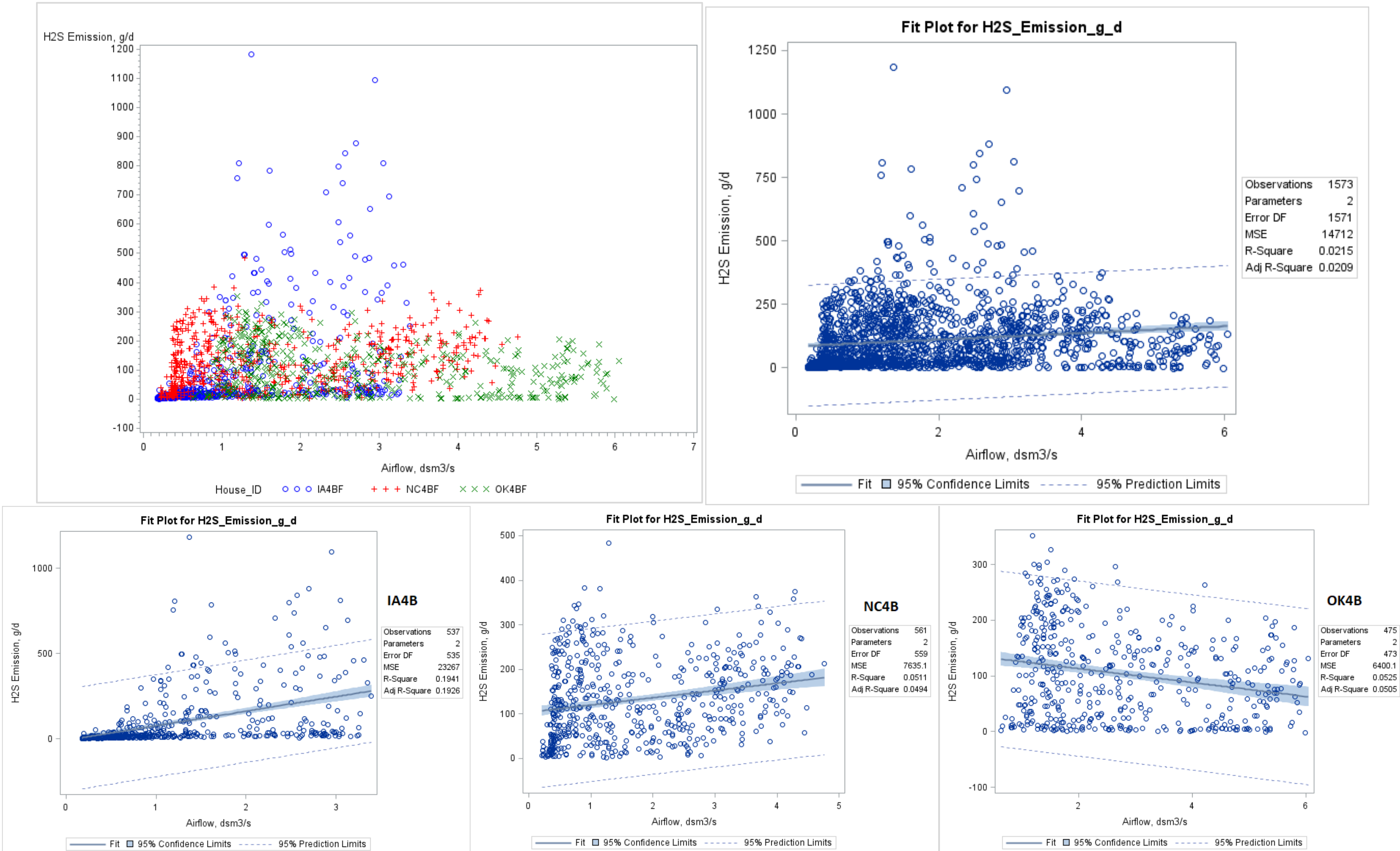


Figure E-38. Scatter plot of H_2S Emissions versus ventilation rate and scatter with regression for farrowing room (top row) and by site (bottom row).

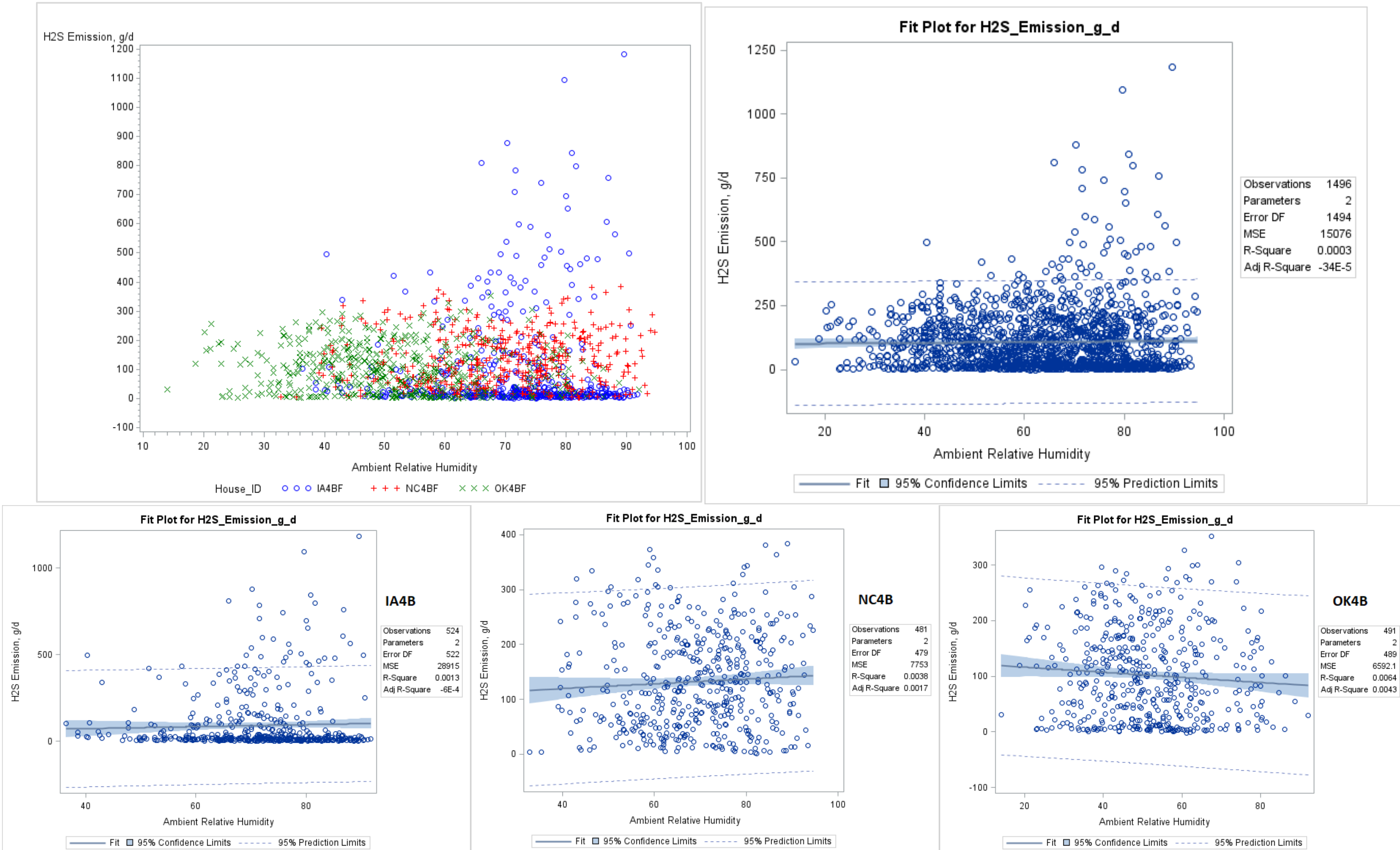


Figure E-39. Scatter plot of H_2S Emissions versus ambient relative humidity and scatter with regression for farrowing room (top row) and by site (bottom row).

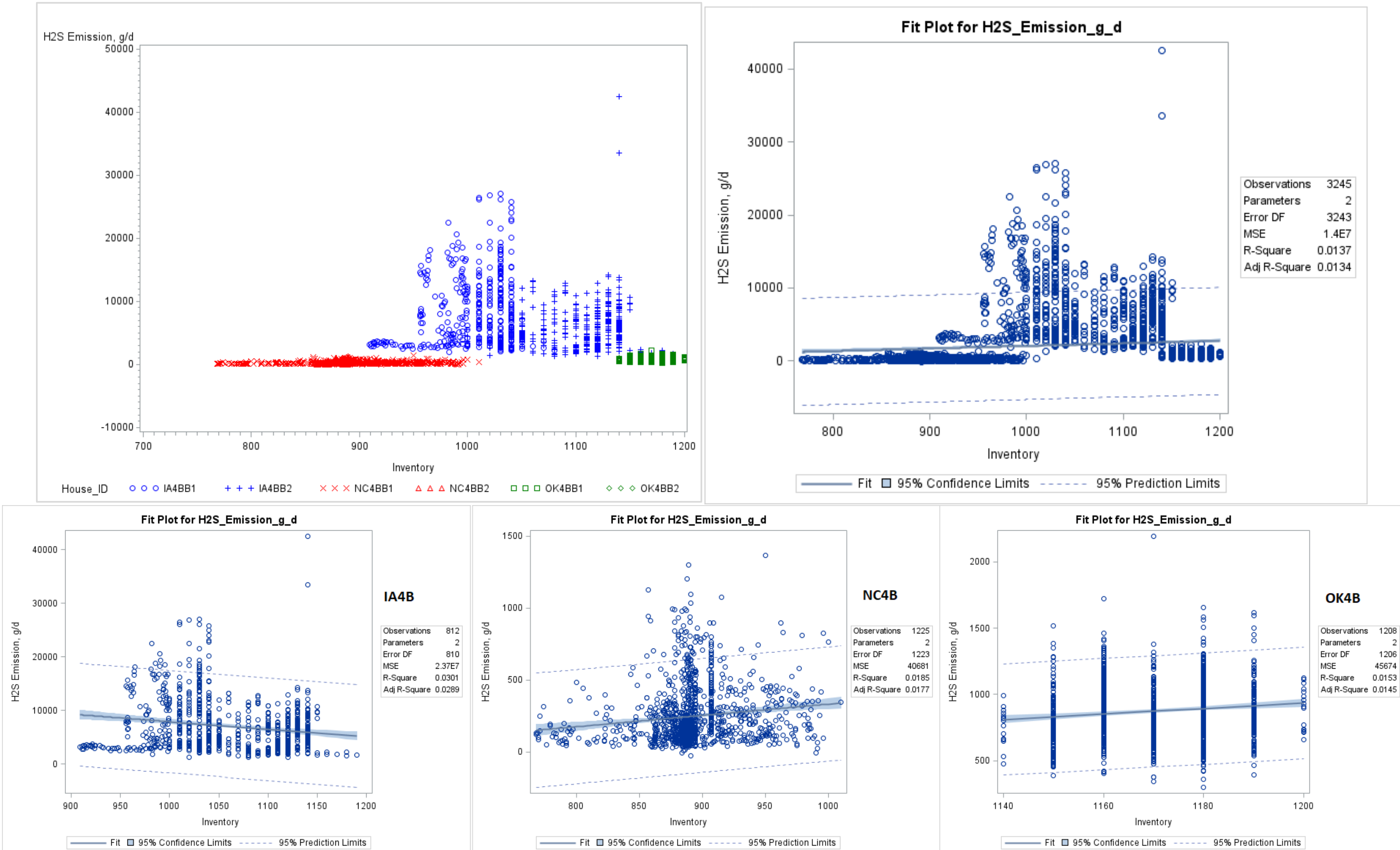


Figure E-40. Scatter plot of H_2S Emissions versus inventory and scatter with regression for gestation barns (top row) and by site (bottom row).

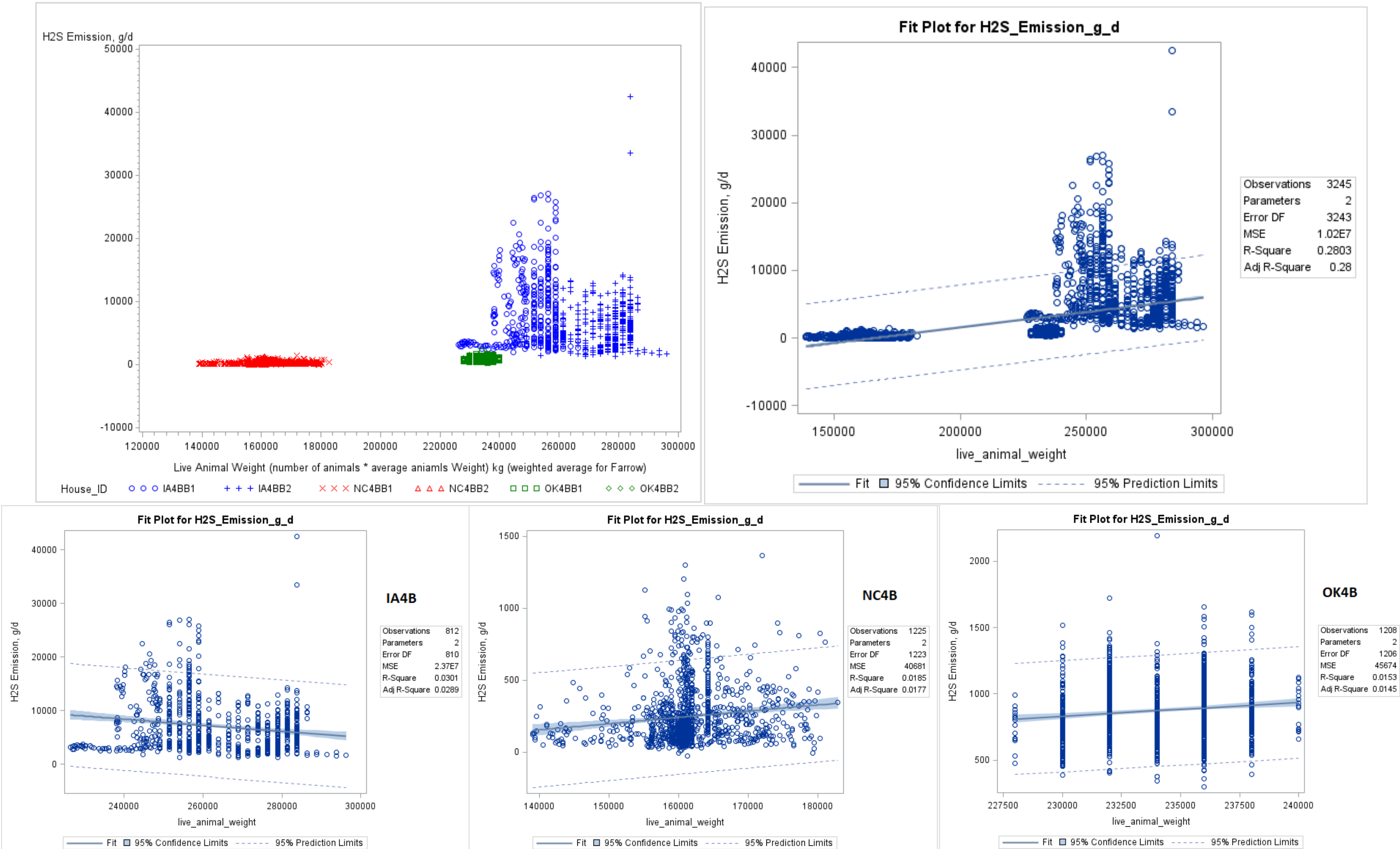


Figure E-41. Scatter plot of H_2S Emissions versus LAW and scatter with regression for gestation barns (top row) and by site (bottom row).

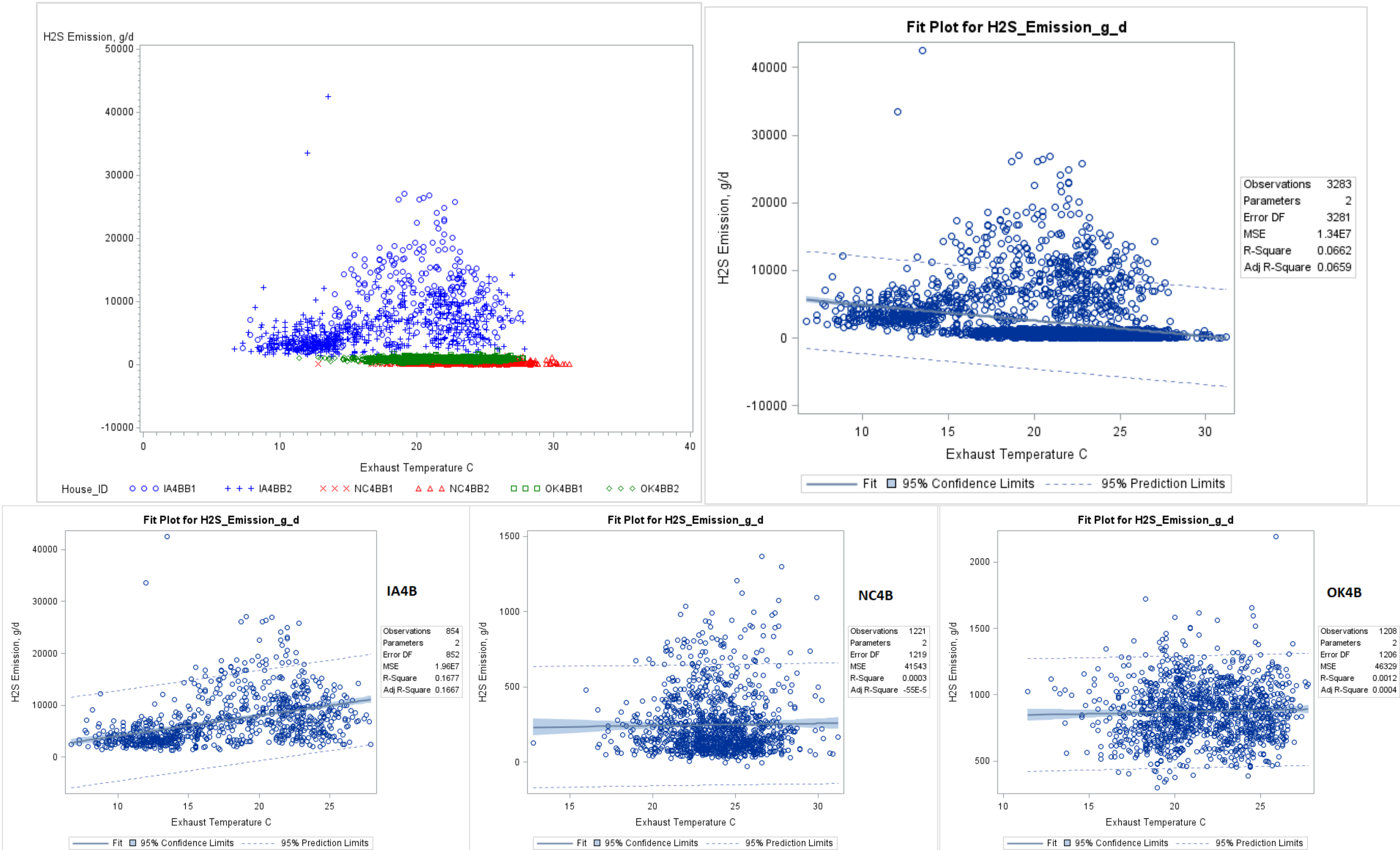


Figure E-42. Scatter plot of H_2S Emissions versus exhaust temperature and scatter with regression for gestation barns (top row) and by site (bottom row).

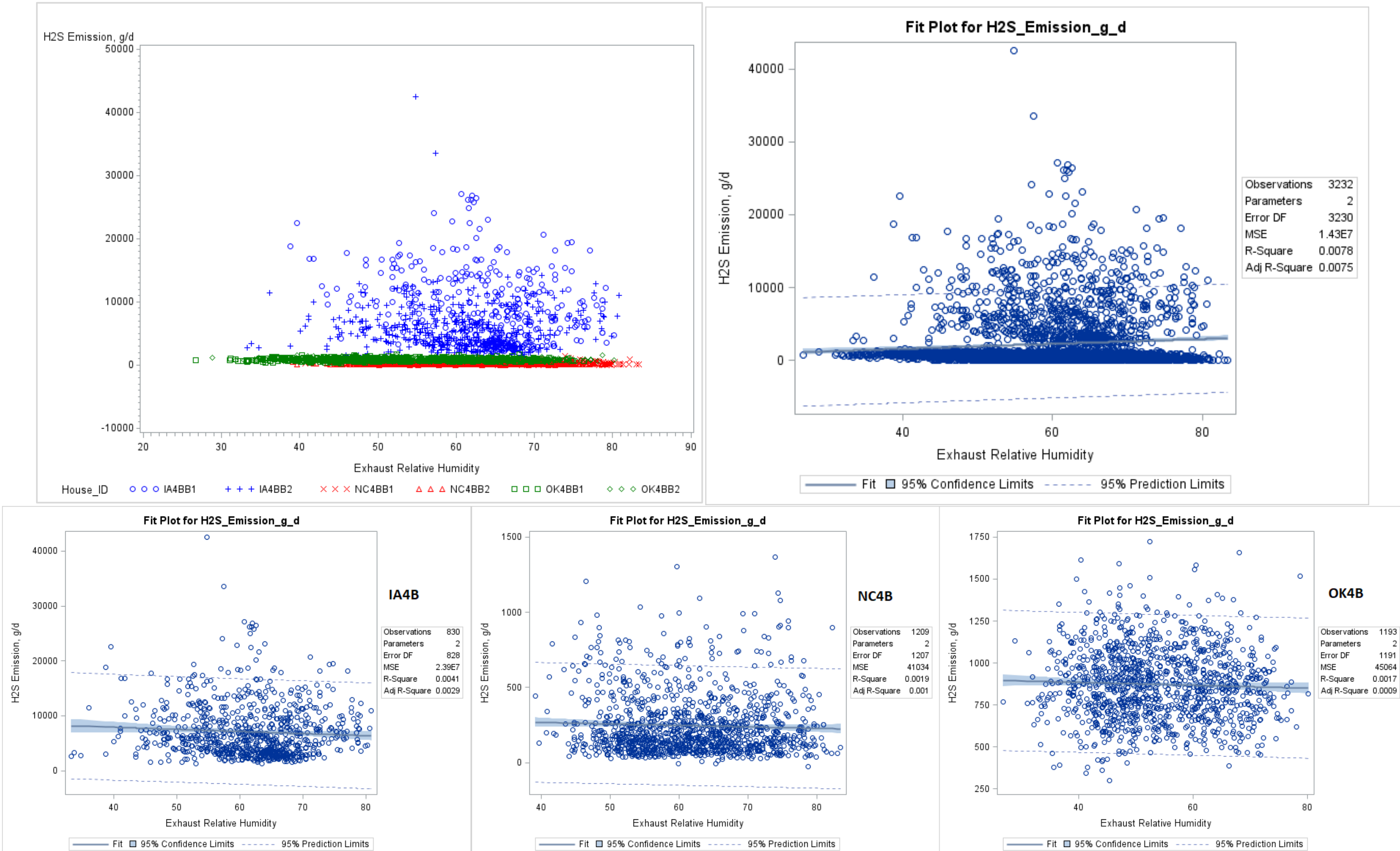


Figure E-43. Scatter plot of H_2S Emissions versus exhaust relative humidity and scatter with regression for gestation barns (top row) and by site (bottom row).

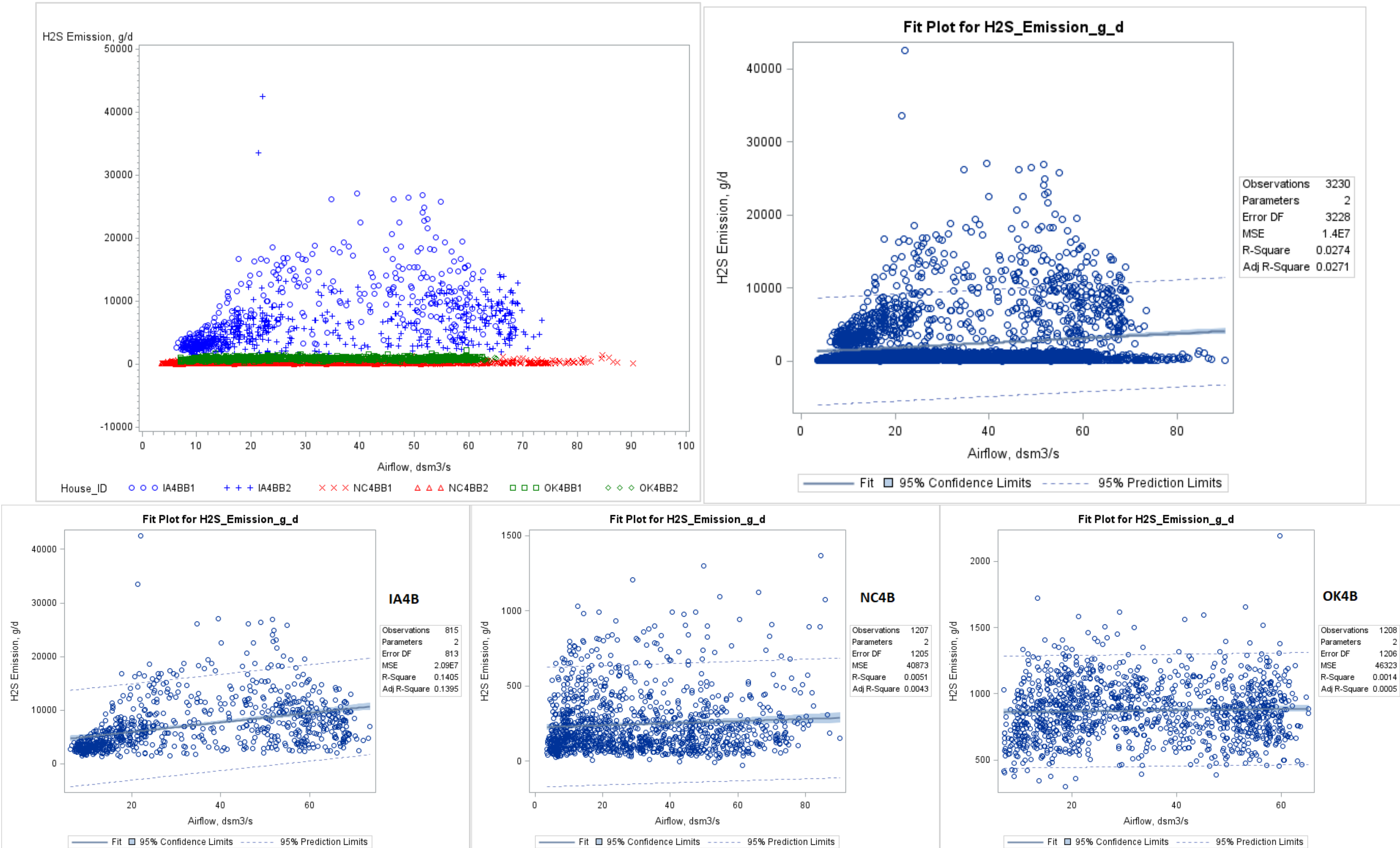


Figure E-44. Scatter plot of H_2S Emissions versus ventilation rate and scatter with regression for gestation barns (top row) and by site (bottom row).

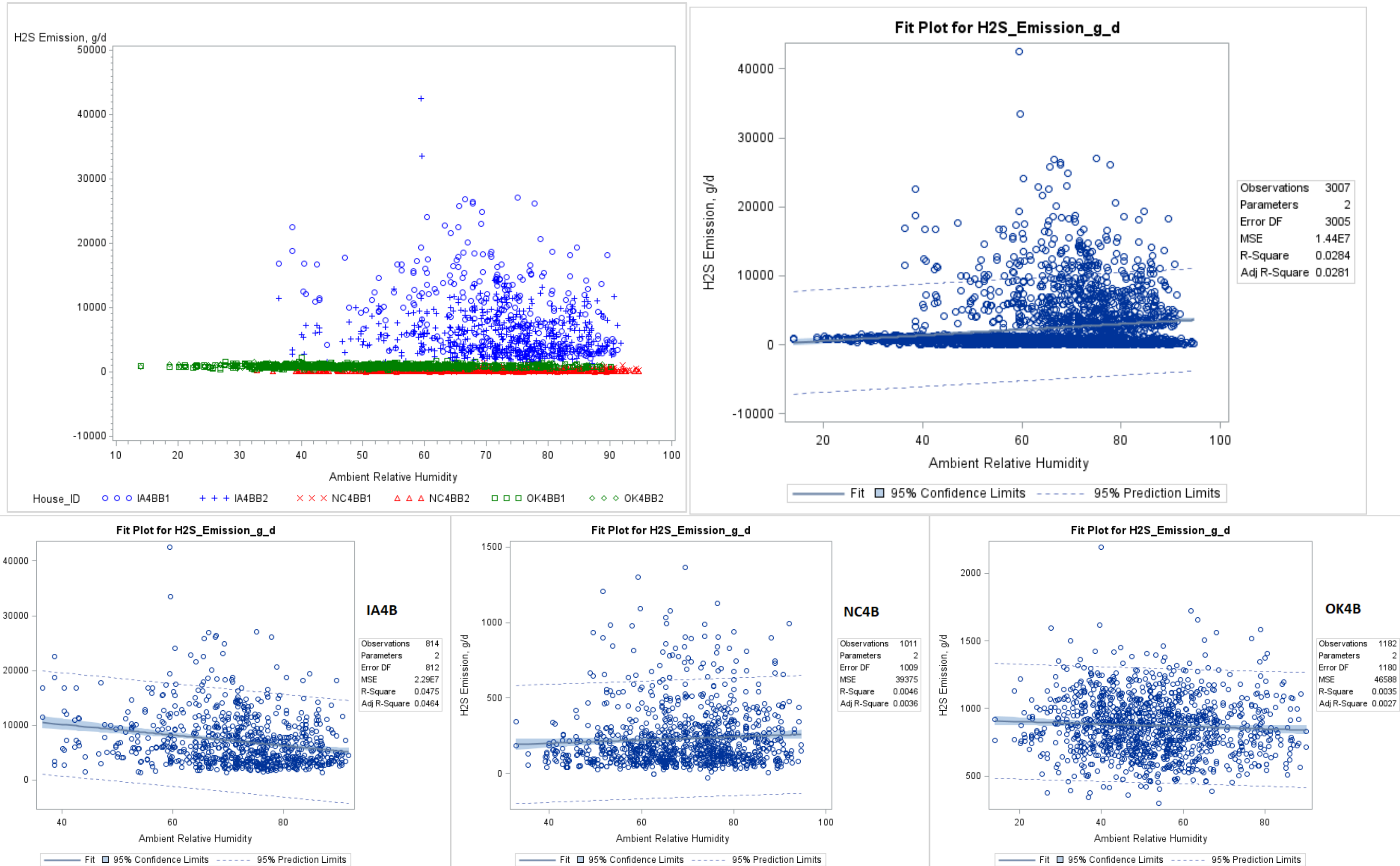


Figure E-45. Scatter plot of H_2S Emissions versus ambient relative humidity and scatter with regression for gestation barns (top row) and by site (bottom row).

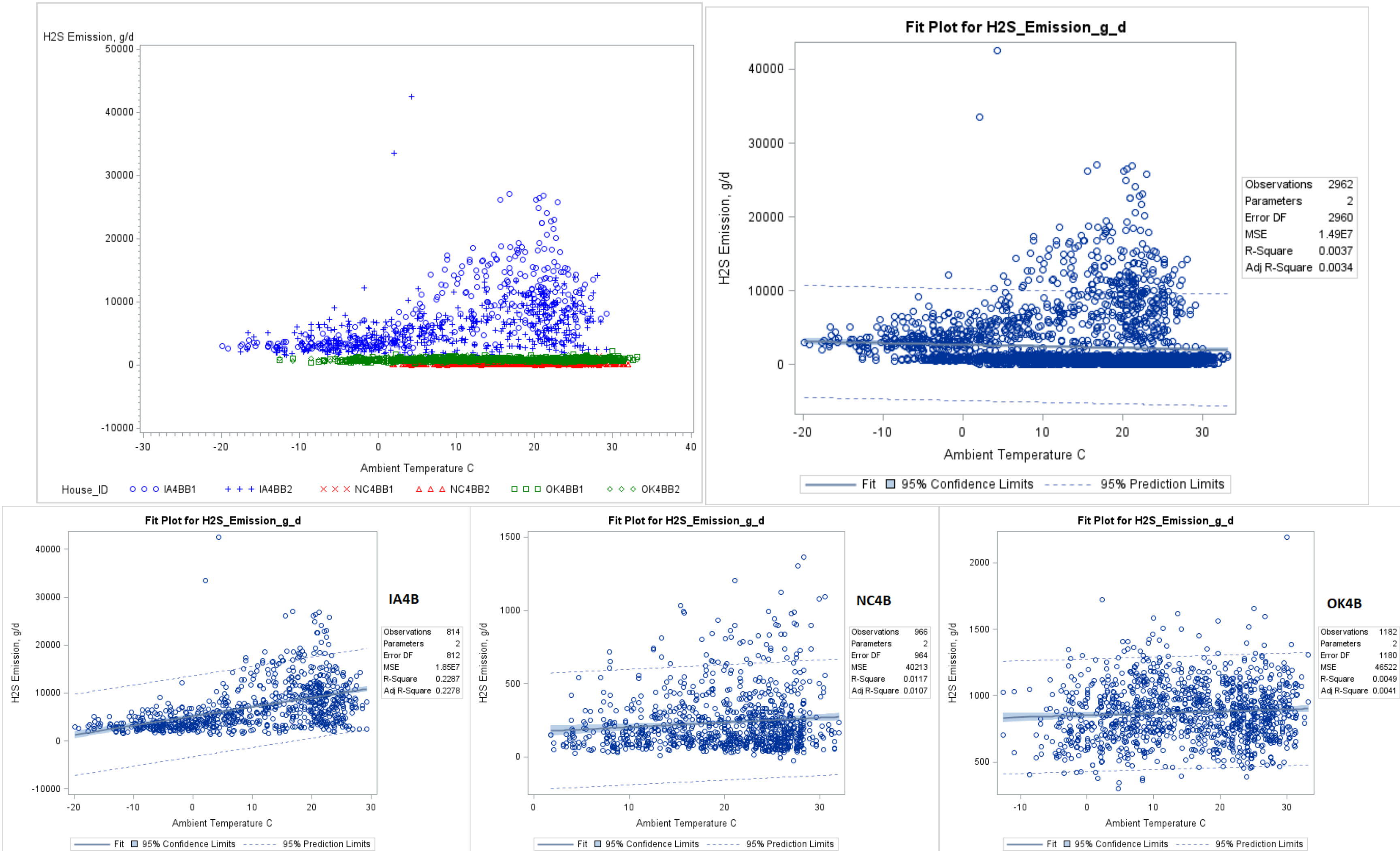


Figure E-46. Scatter plot of H_2S Emissions versus ambient temperature and scatter with regression for gestation barns (top row) and by site (bottom row).

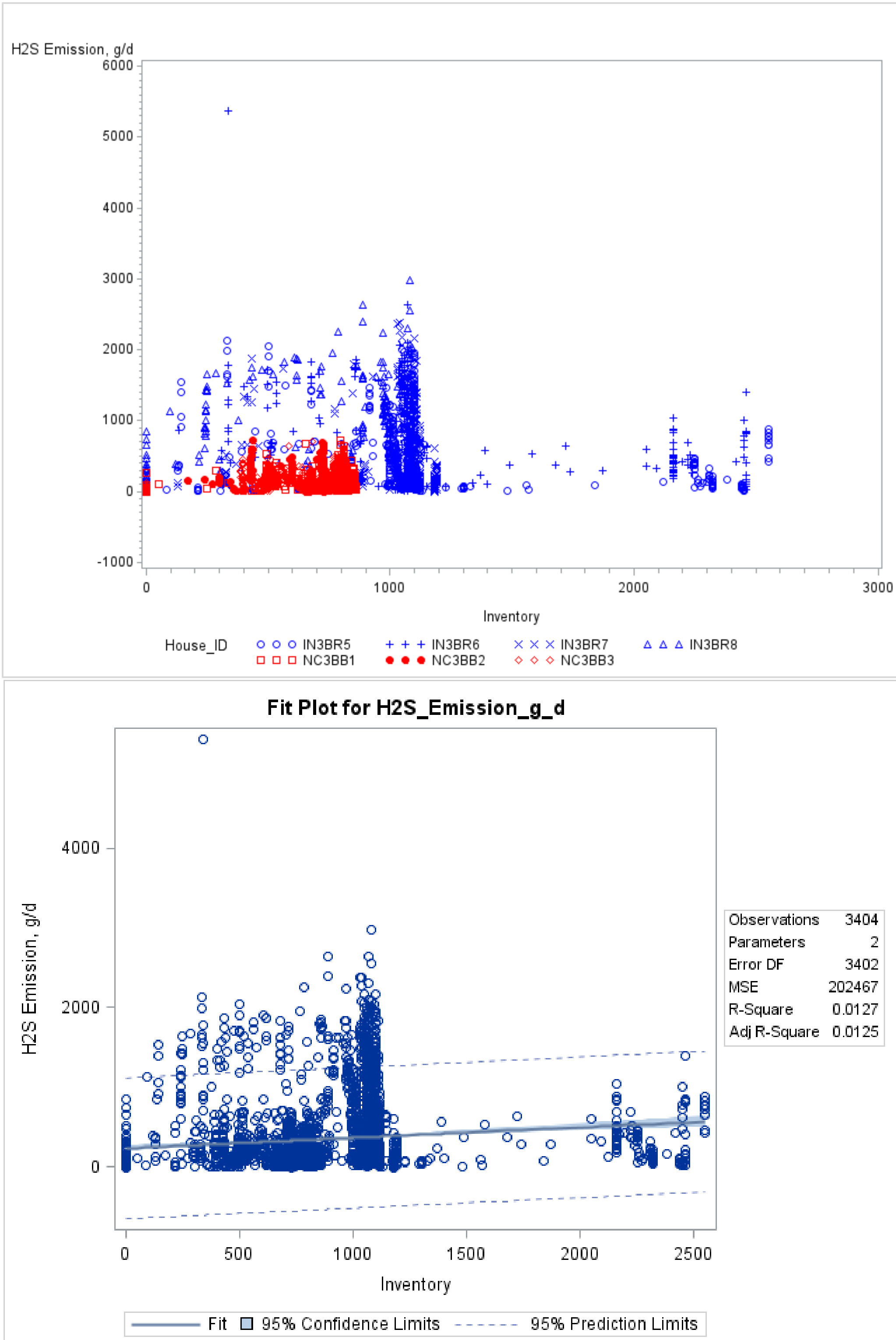
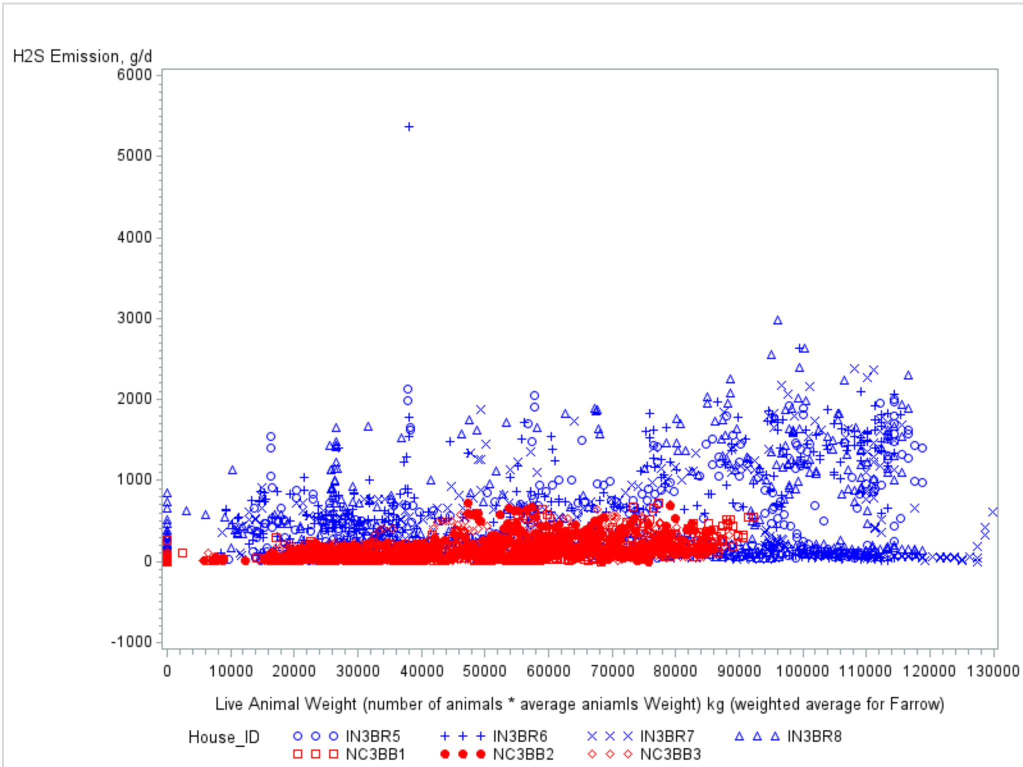


Figure E-47. Scatter plot of swine grow-finish H_2S Emissions versus Inventory (top) and with regression (bottom).



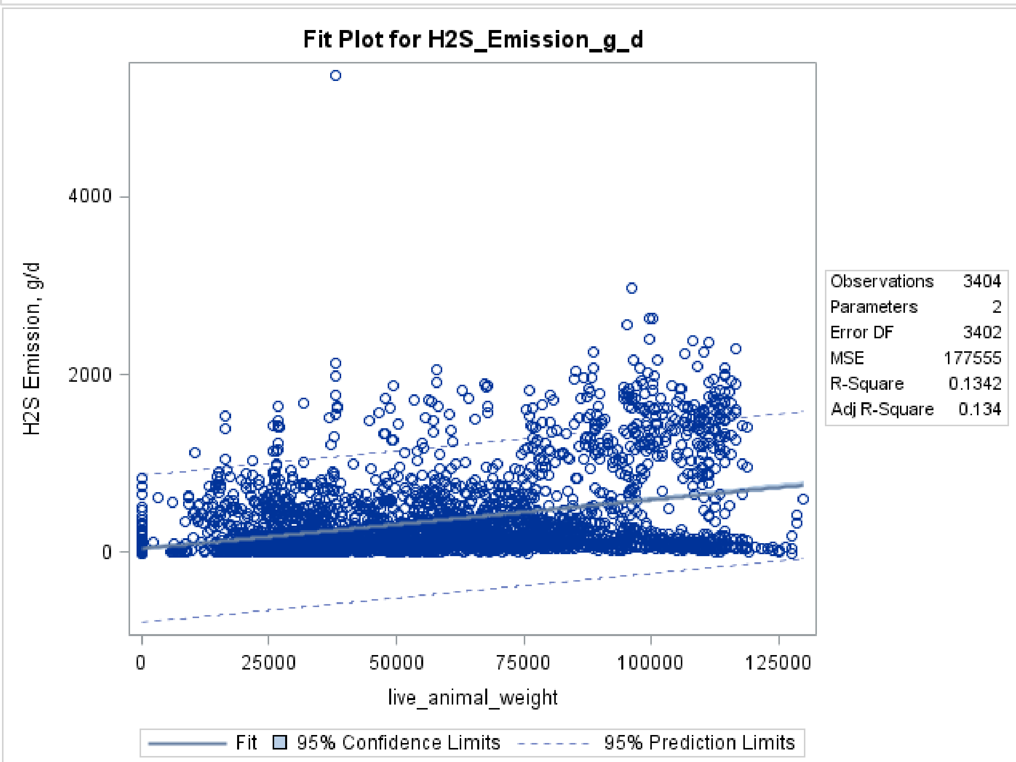


Figure E-48. Scatter plot of swine grow-finish H_2S Emissions versus live animal weight (top) and with regression (bottom).

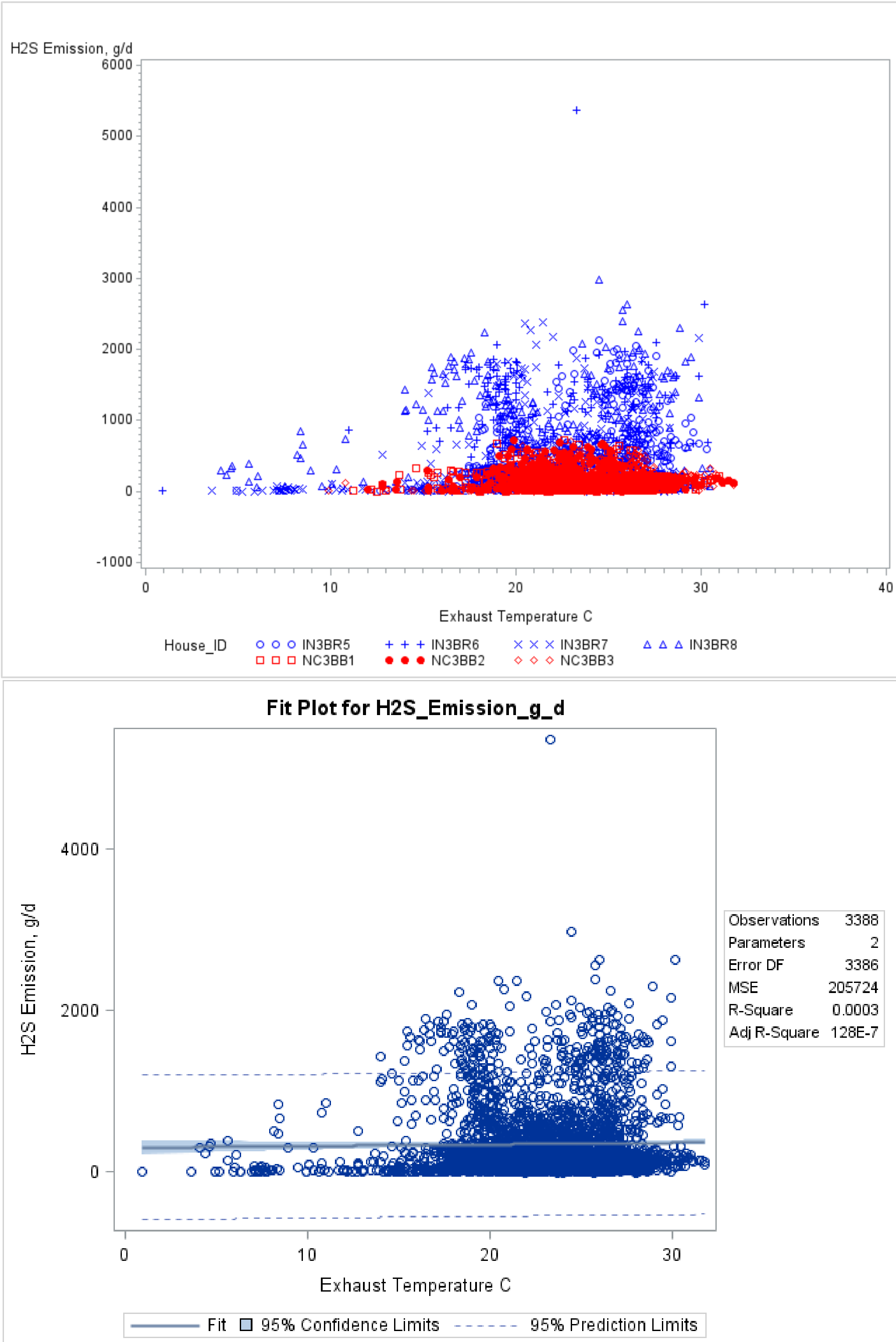
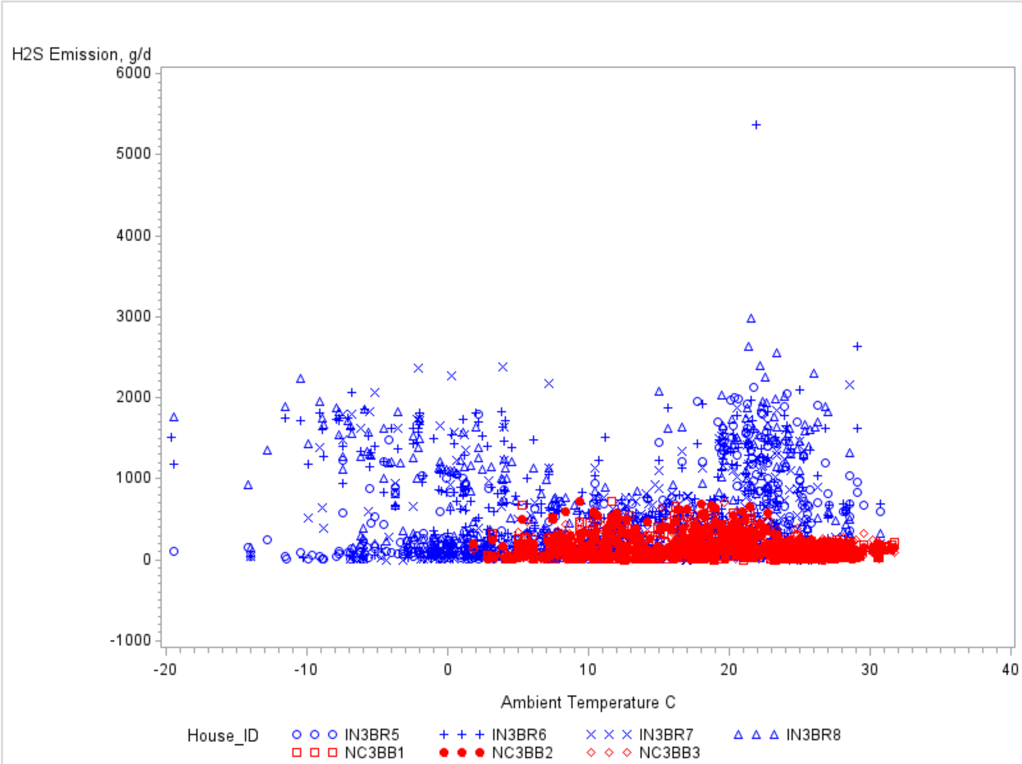


Figure E-49. Scatter plot of swine grow-finish H_2S Emissions versus exhaust temperature (top) and with regression (bottom).



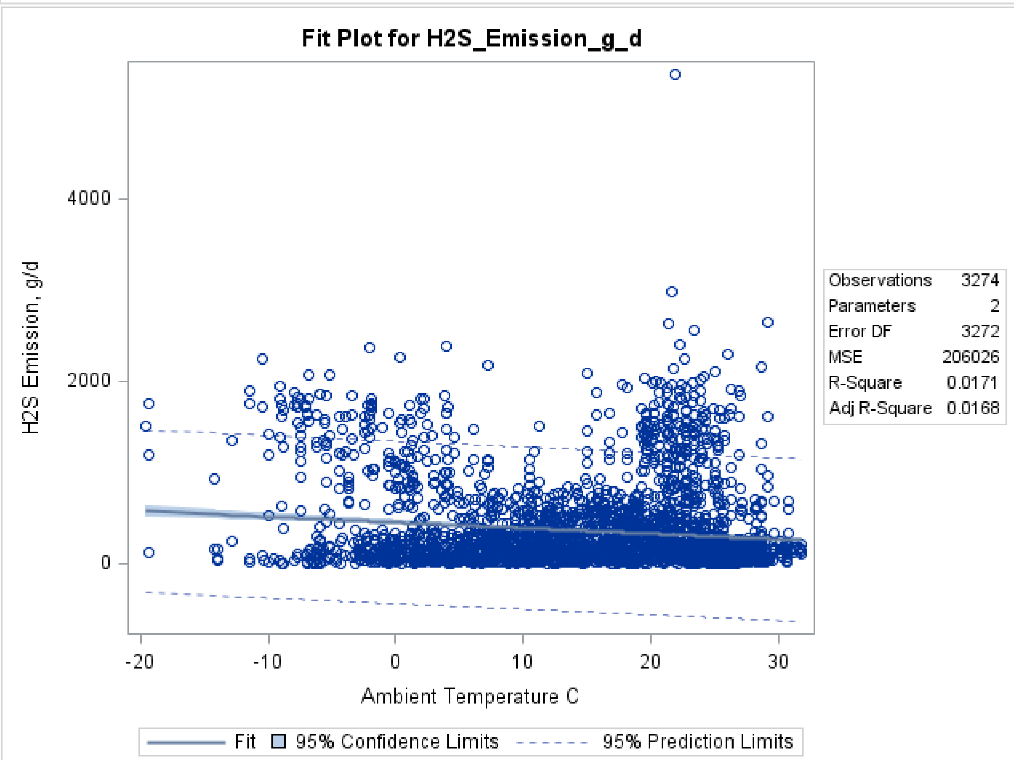


Figure E-50. Scatter plot of swine grow-finish H_2S Emissions versus ambient temperature (top) and with regression (bottom).

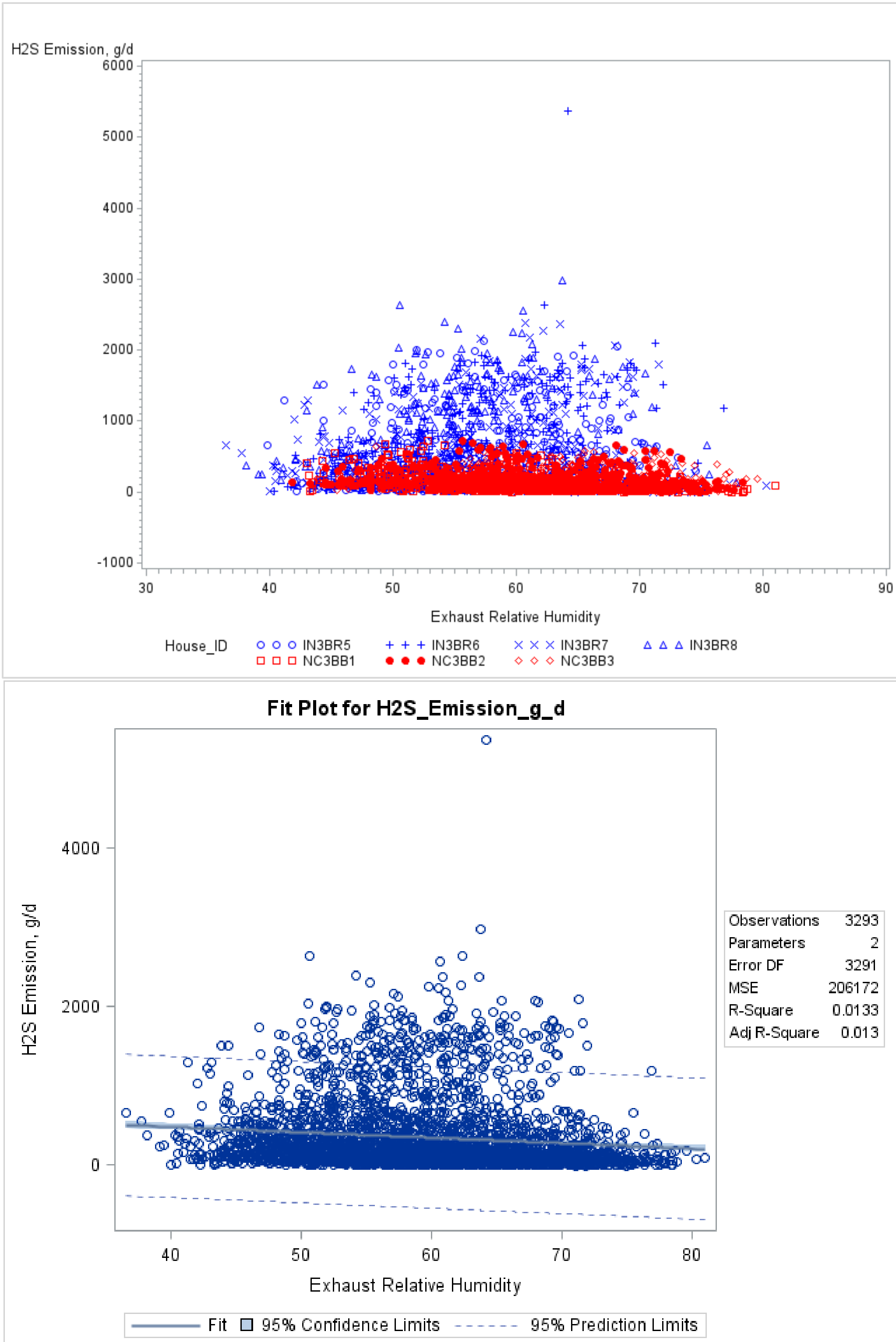


Figure E-51. Scatter plot of swine grow-finish H_2S Emissions versus exhaust relative humidity (top) and with regression (bottom).

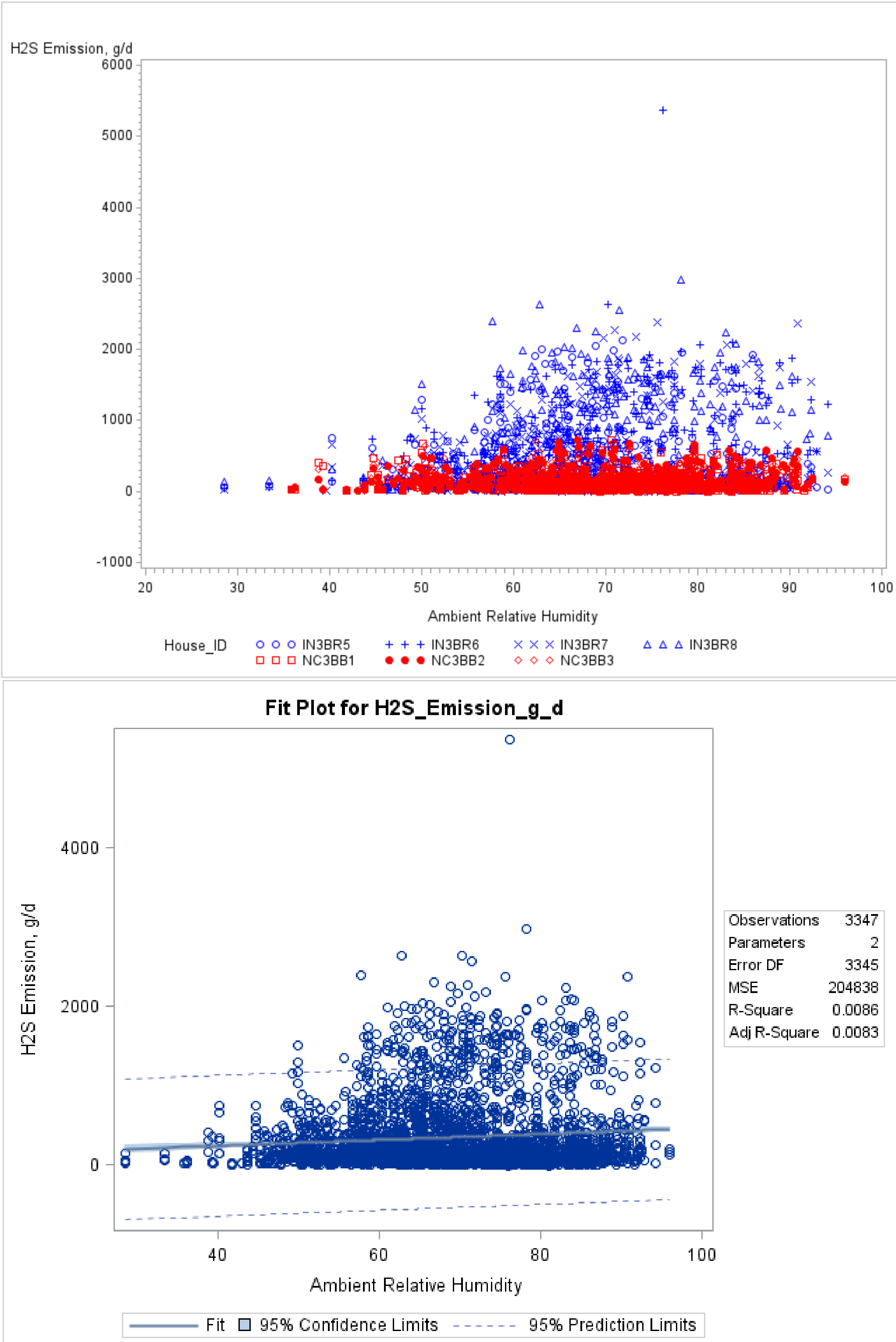
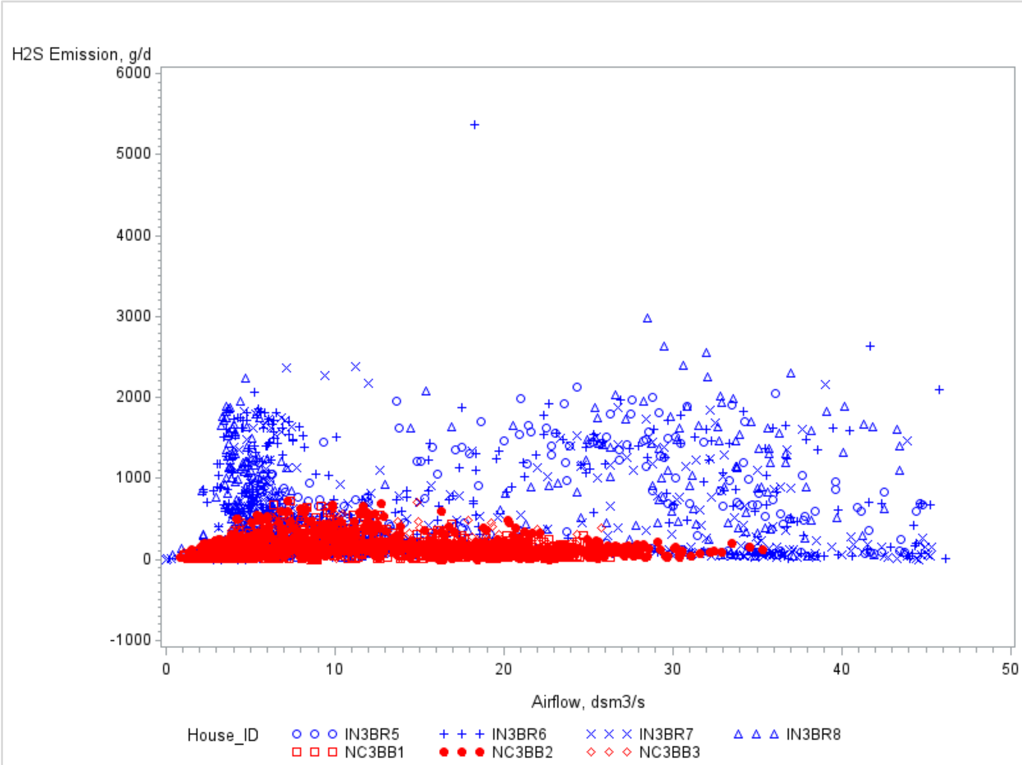


Figure E-52. Scatter plot of swine grow-finish H_2S Emissions versus ambient relative humidity (top) and with regression (bottom).



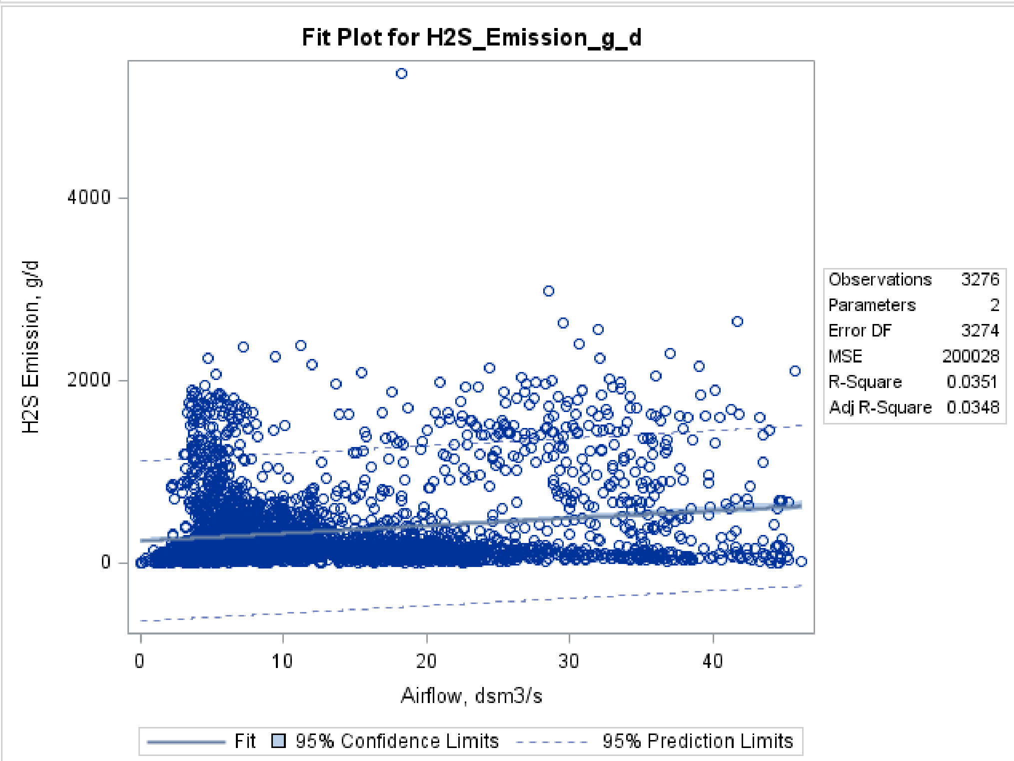


Figure E-53. Scatter plot of swine grow-finish H_2S Emissions versus airflow (top) and with regression (bottom).

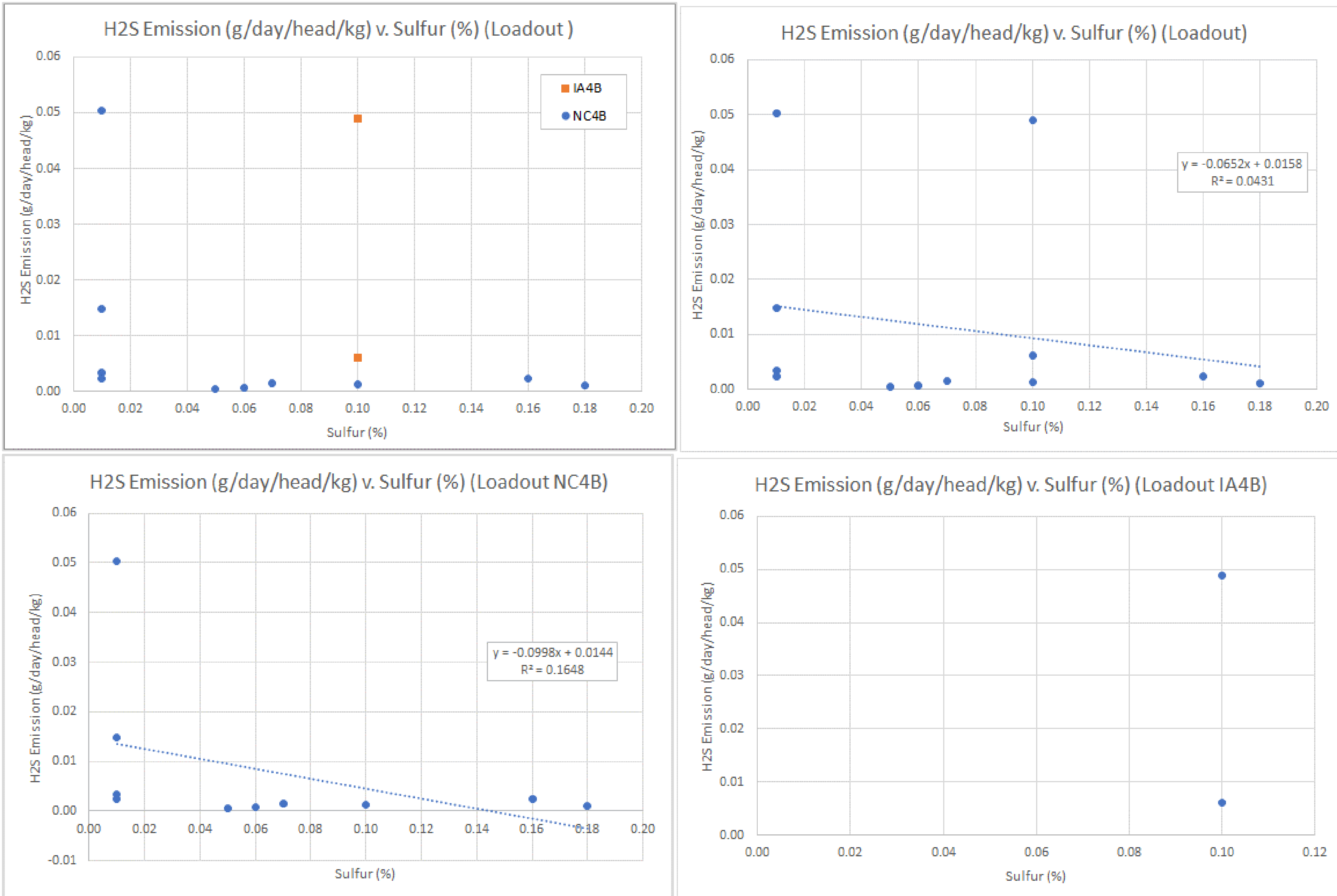
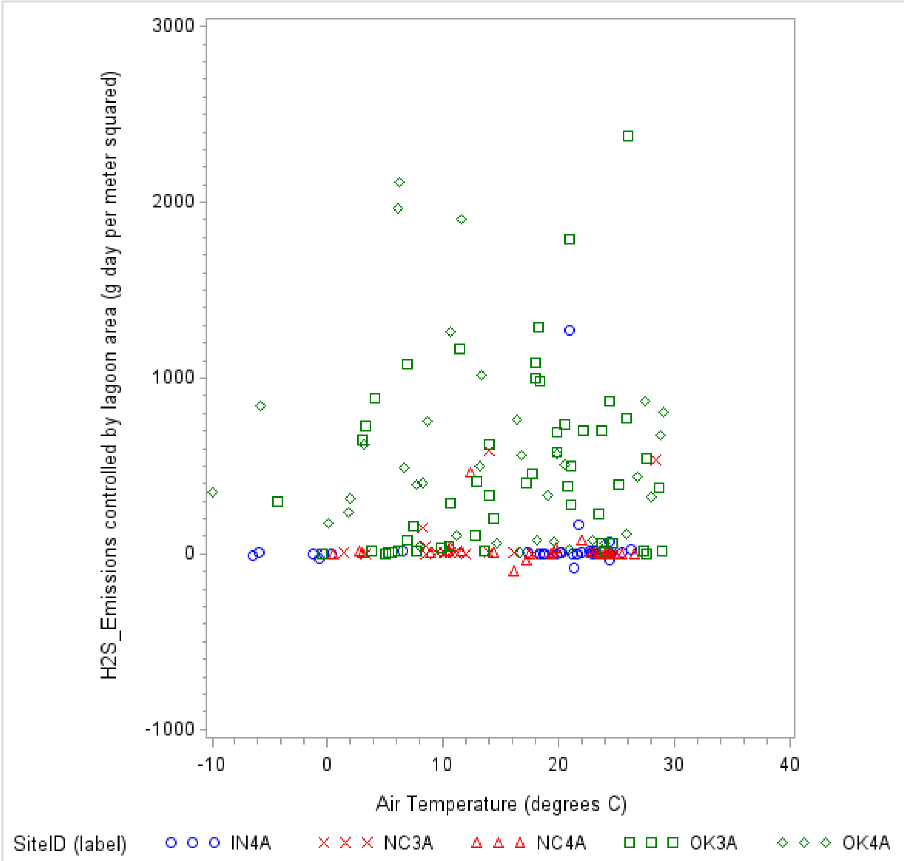


Figure E-54. Scatter plot of breeding and gestation H_2S emissions versus sulfur for loadout (left) and plot with linear regression for loadout (right).



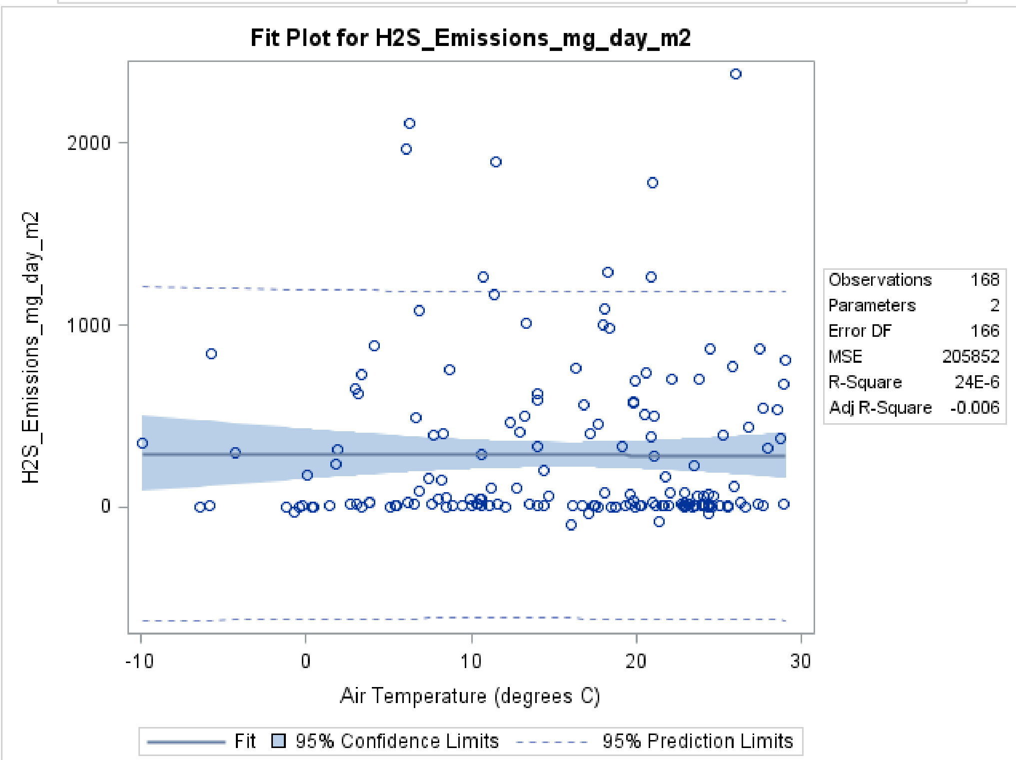
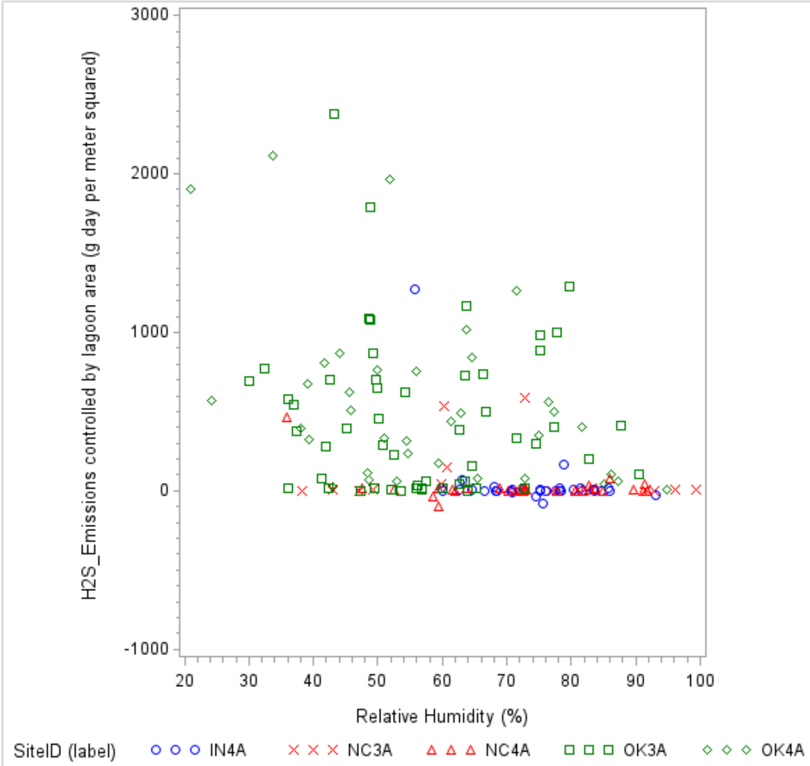


Figure E-55. Scatter plot of open source H_2S Emissions versus ambient temperature (top) and with regression (bottom).



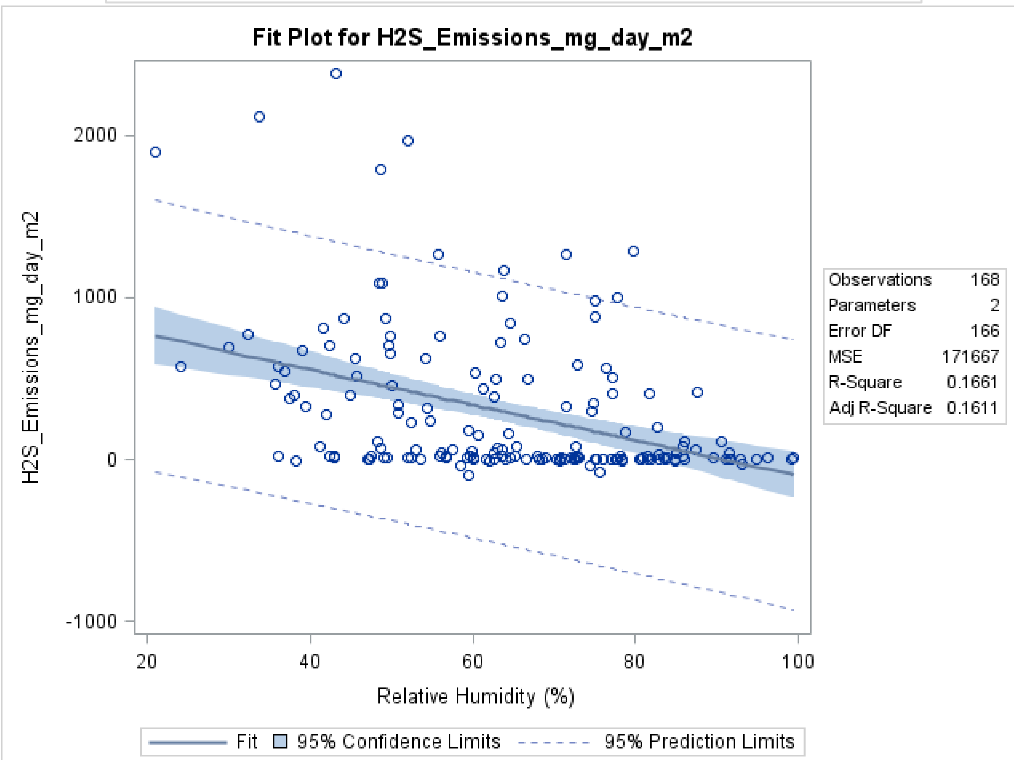
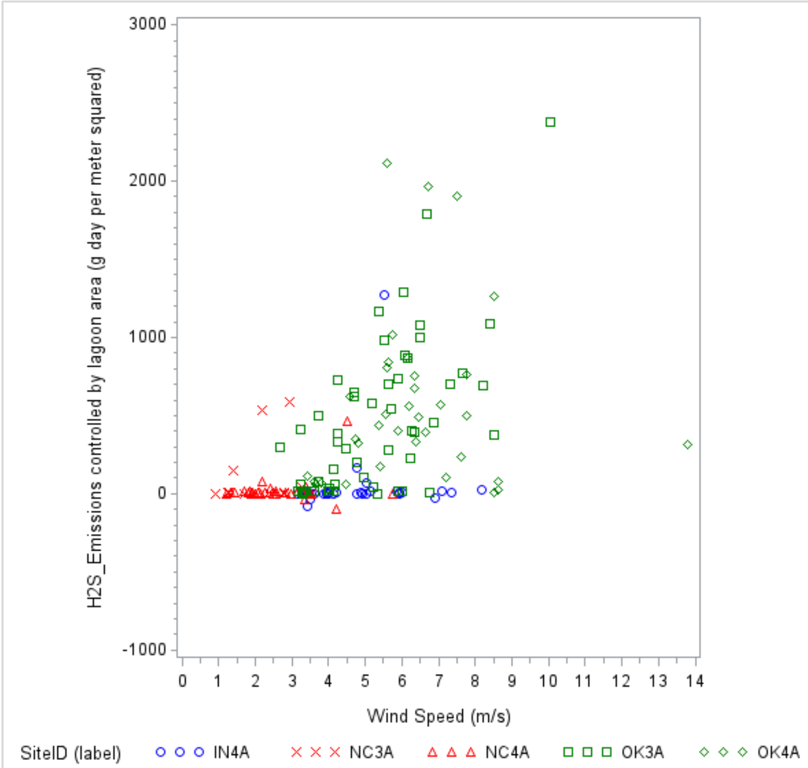


Figure E-56. Scatter plot of open source H_3S Emissions versus relative humidity (top) and with regression (bottom).



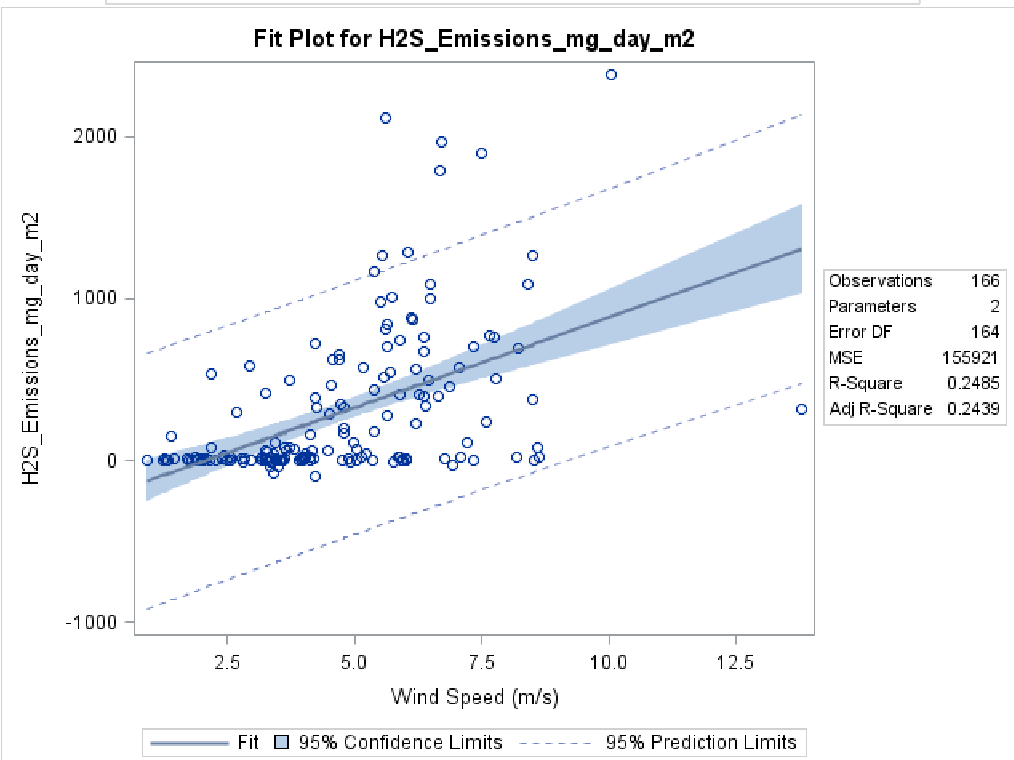


Figure E-57. Scatter plot of open source H_2S Emissions versus wind speed (left) and with regression (bottom).

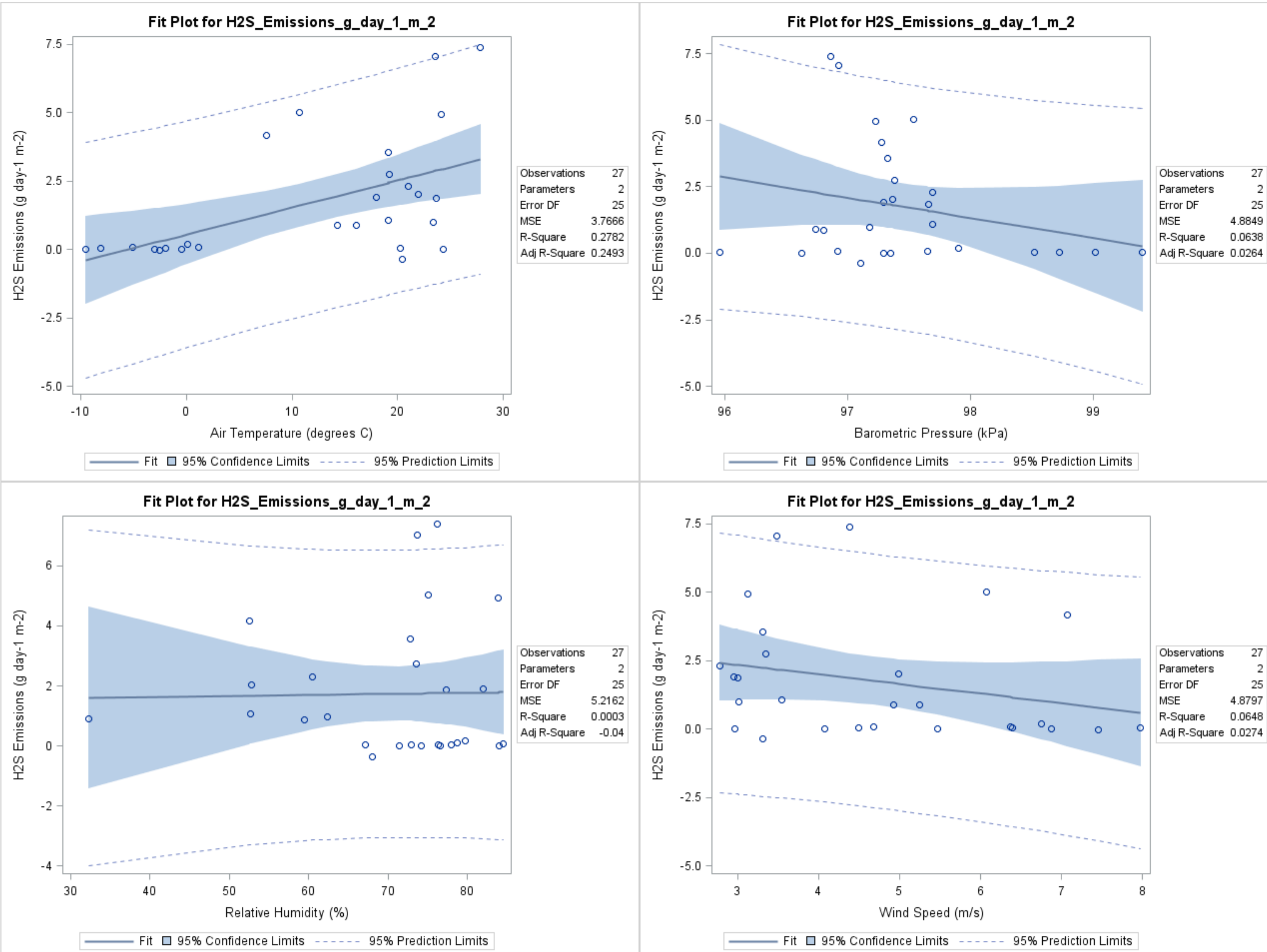


Figure E-58. Scatter plot and regression of basin H_2S Emissions with air temperature (top left), pressure (top right), relative humidity (bottom left). and wind speed (bottom right).

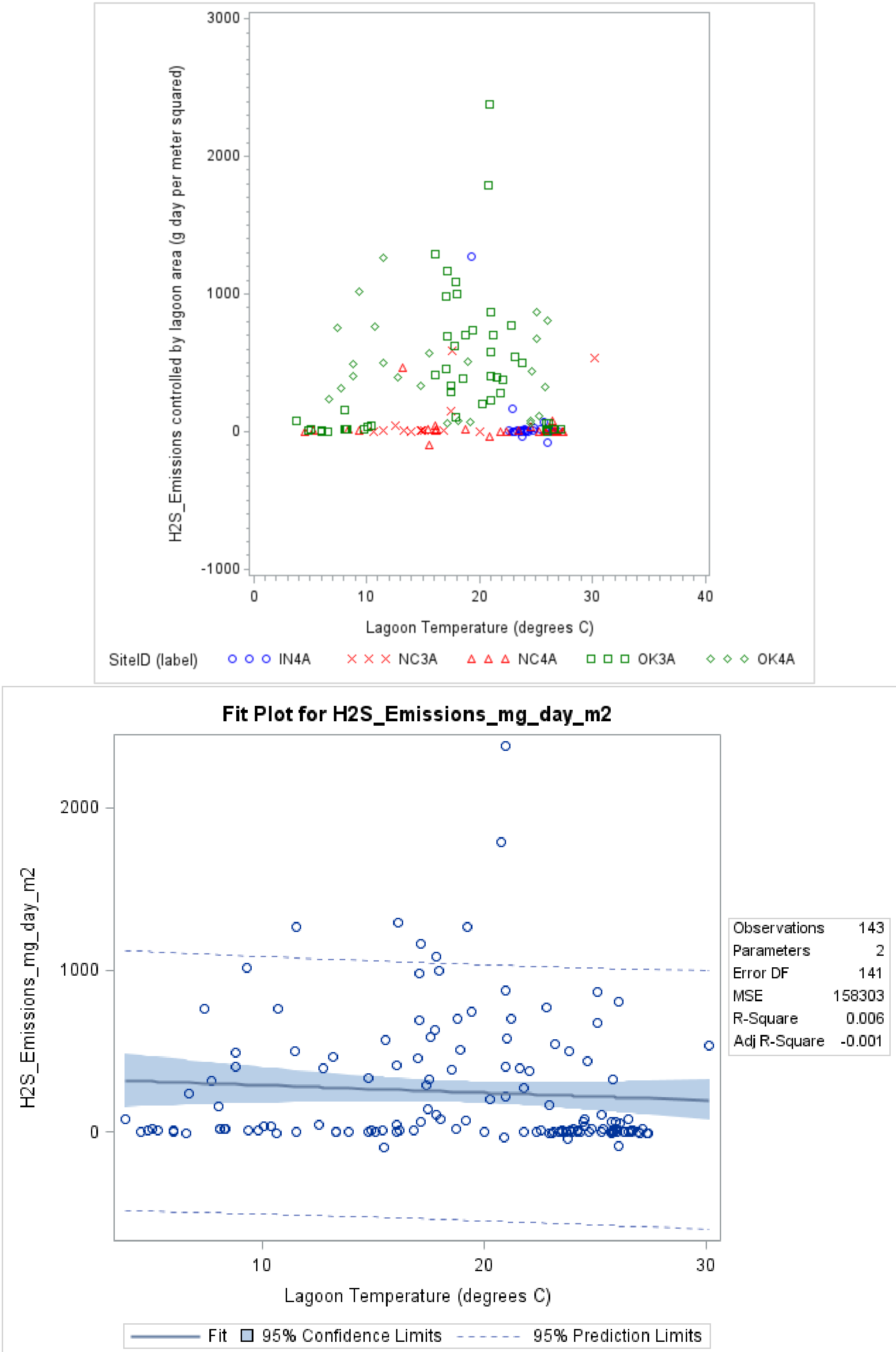
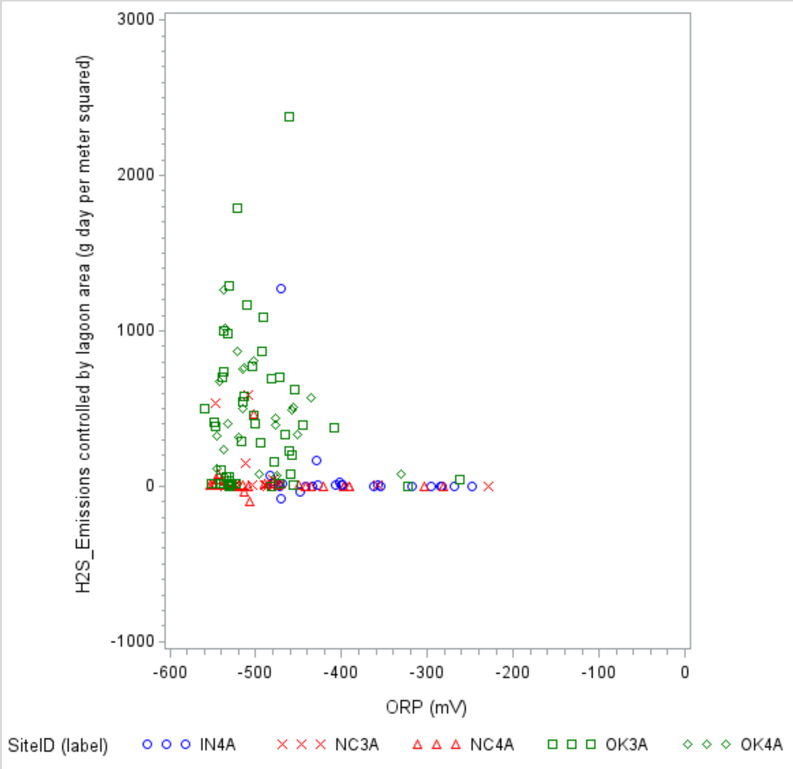


Figure E-59. Scatter plot of open source H_3S Emissions versus lagoon temperature (top) and with regression (bottom).



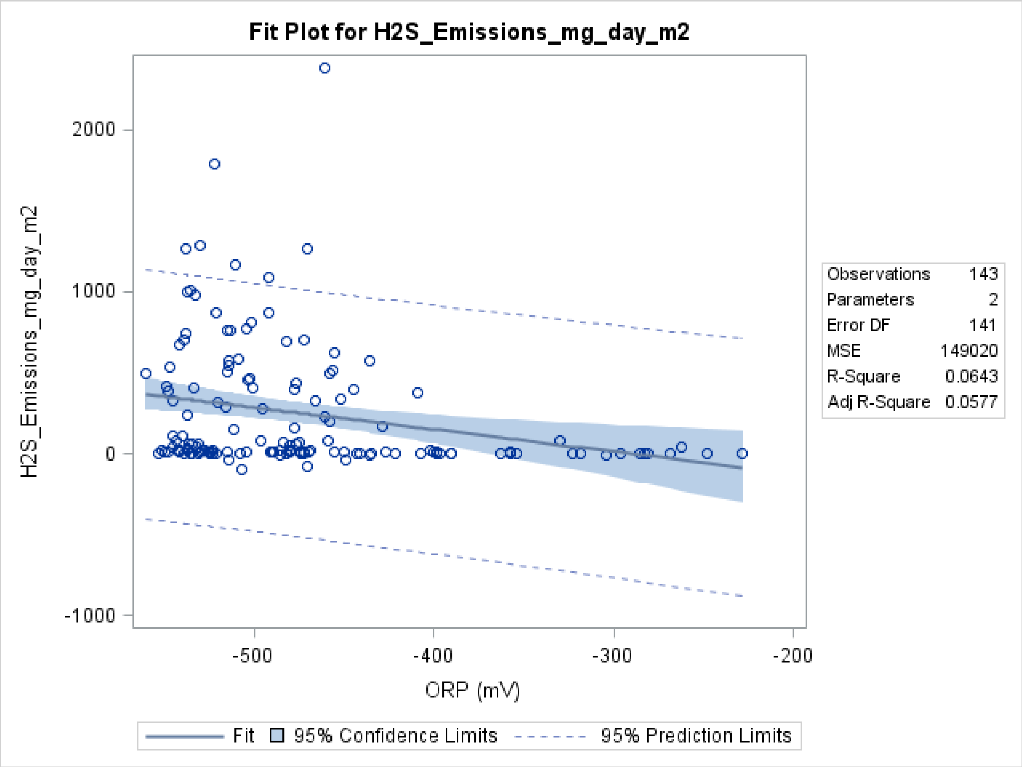


Figure E-60. Scatter plot of open source H_3S Emissions versus ORP (top) and with regression (bottom).

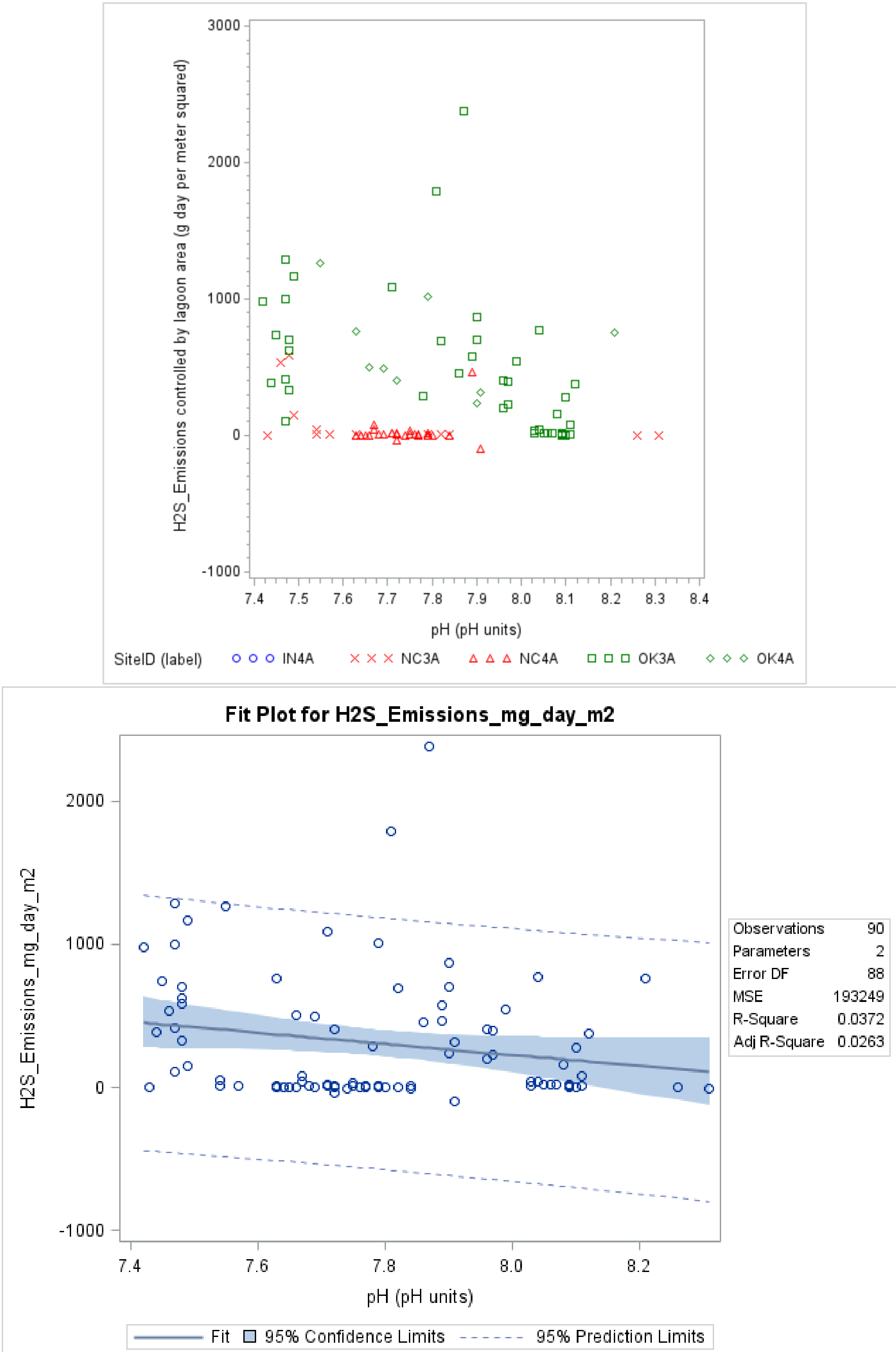


Figure E-61. Scatter plot of open source H_3S Emissions versus lagoon pH (top) and with regression (bottom).

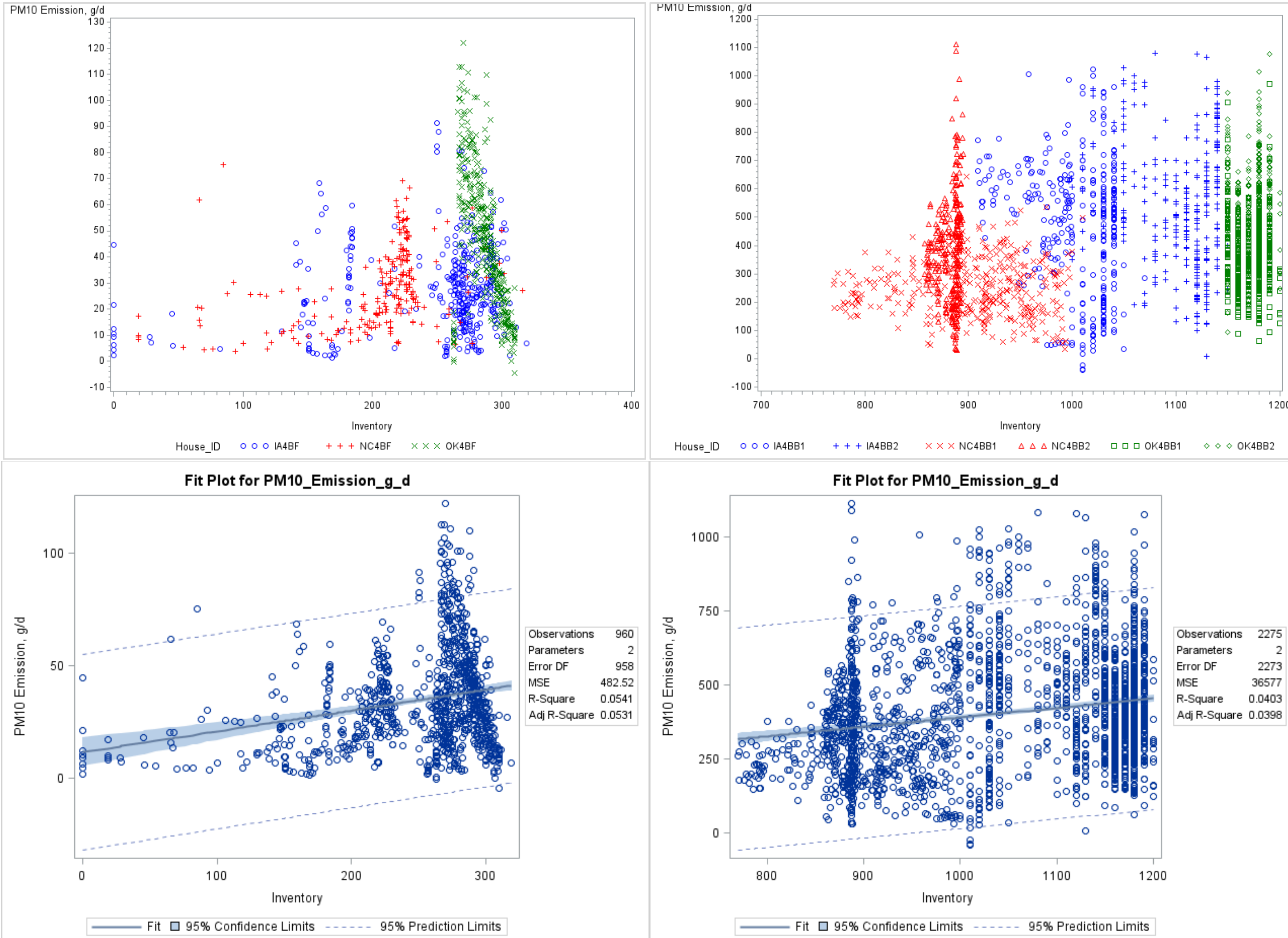


Figure E-62. Scatter plot of PM_{10} Emissions versus inventory and scatter with regression for farrowing room (left column) and gestation barns (right column).

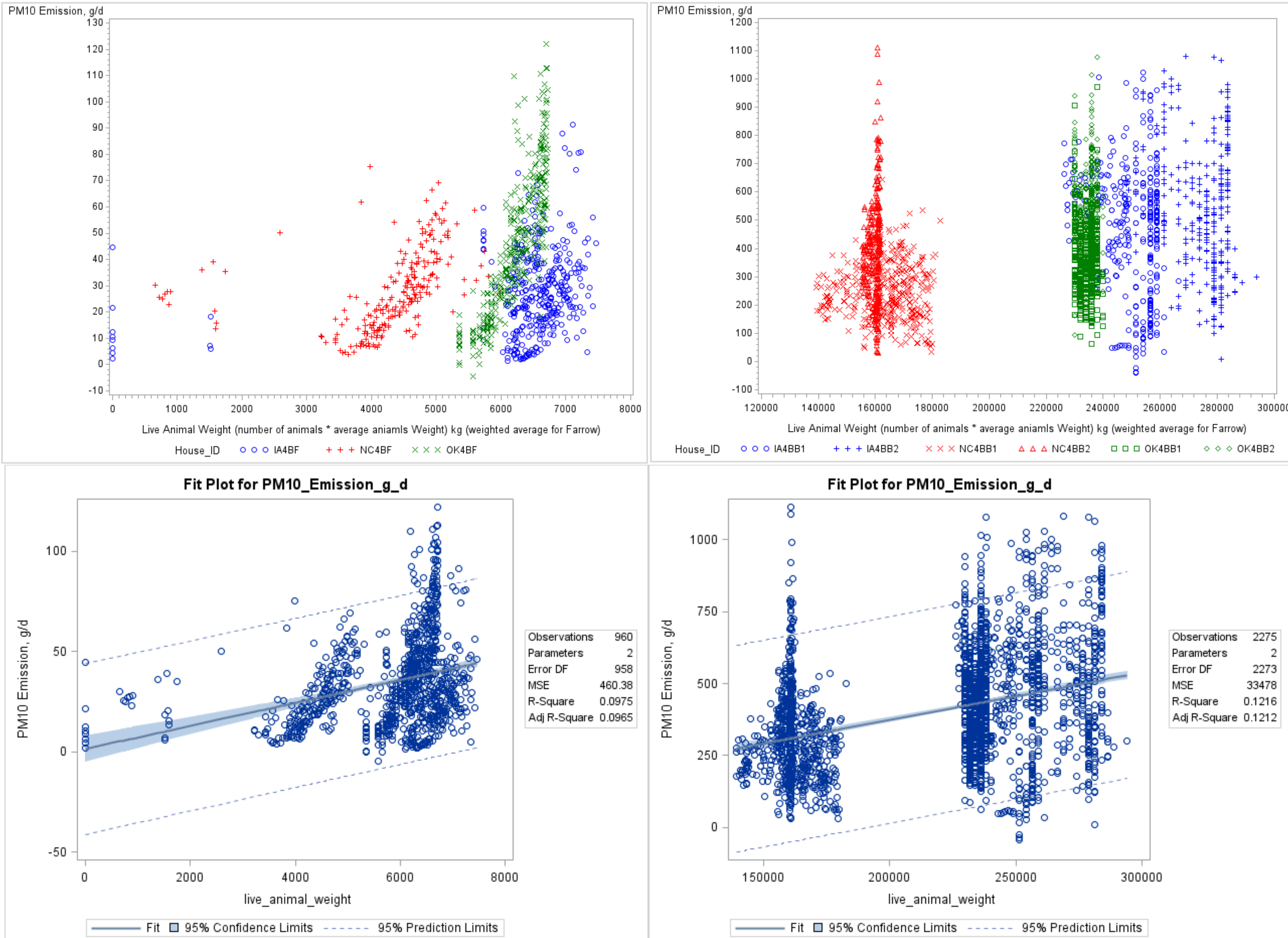
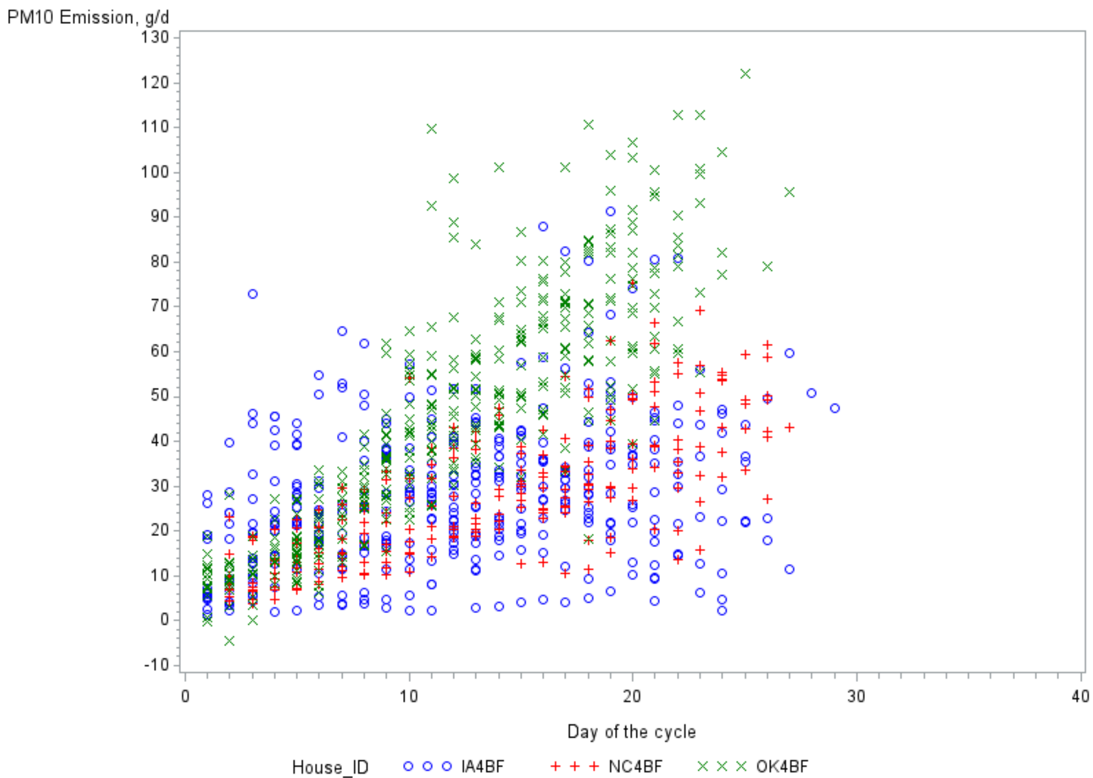


Figure E-63. Scatter plot of PM_{10} Emissions versus LAW and scatter with regression for farrowing room (left column) and gestation barns (right column).



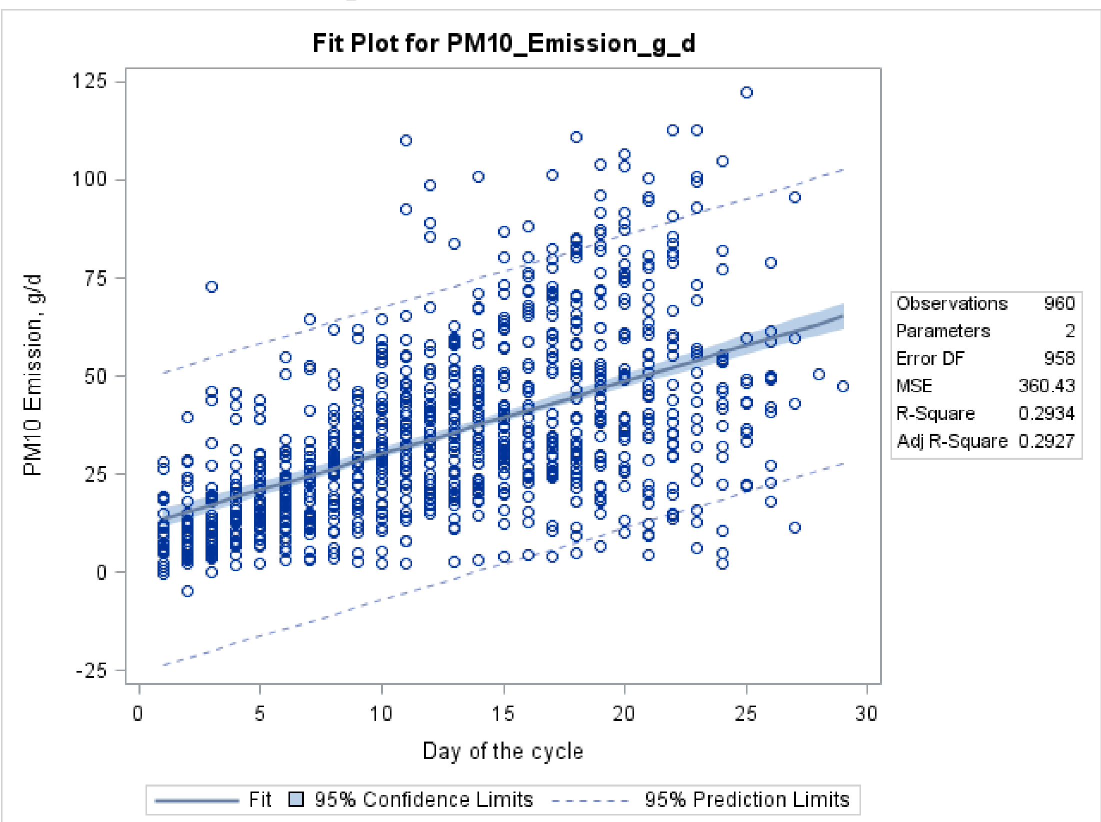


Figure E-64. Scatter plot of PM_{10} Emissions versus cycle day and scatter with regression for farrowing room.

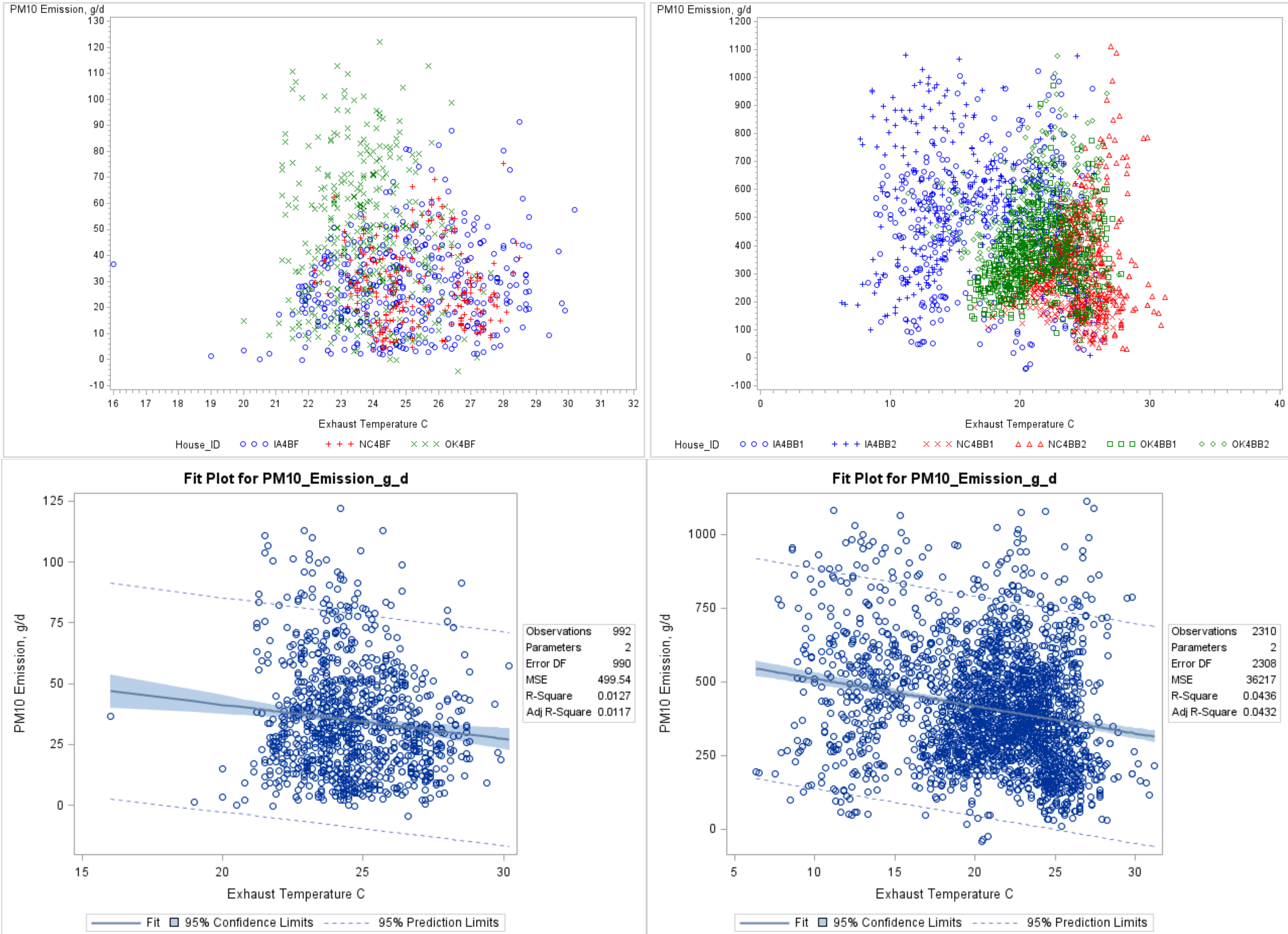


Figure E-65. Scatter plot of PM_{10} Emissions versus exhaust temperature and scatter with regression for farrowing room (left column) and gestation barns (right column).

Figure E-66. Scatter plot of PM_{10} Emissions versus exhaust relative humidity and scatter with regression for farrowing room (left column) and gestation barns (right column).

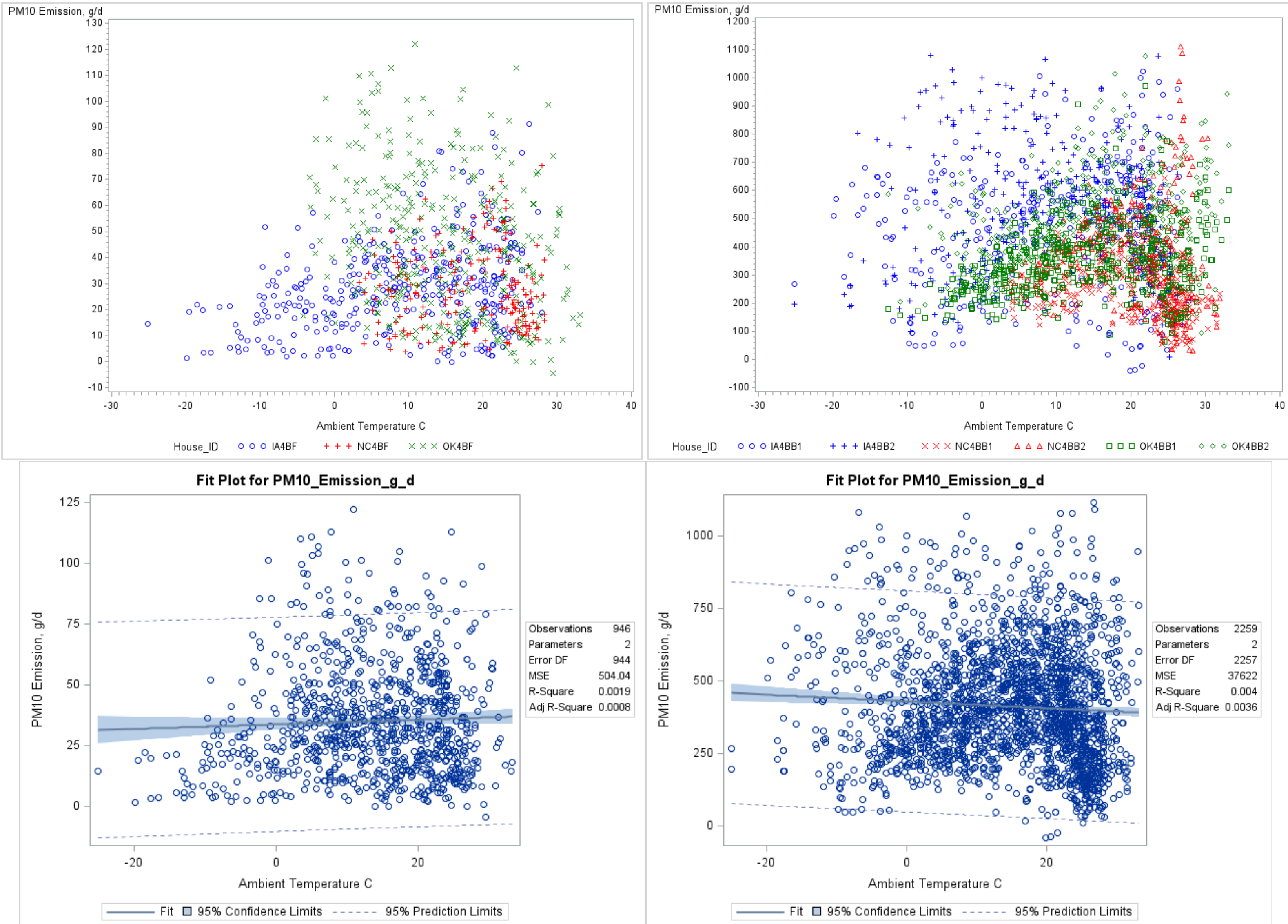


Figure E-67. Scatter plot of PM_{10} Emissions versus ambient temperature and scatter with regression for farrowing room (left column) and gestation barns (right column).

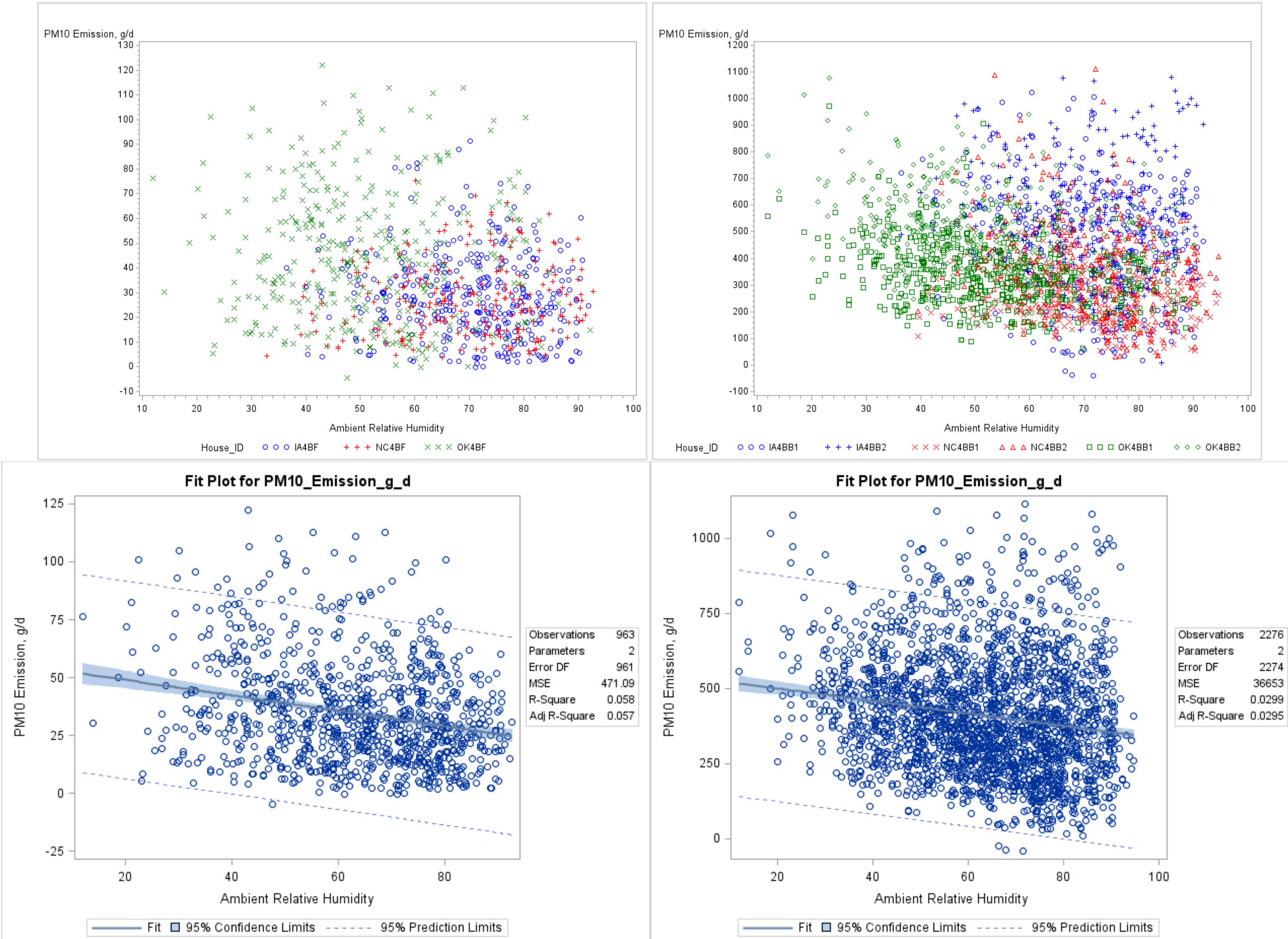


Figure E-68. Scatter plot of PM_{10} Emissions versus ambient relative humidity and scatter with regression for farrowing room (left column) and gestation barns (right column).

Figure E-69. Scatter plot of PM_{10} Emissions versus ventilation rate and scatter with regression for farrowing room (left column) and gestation barns (right column).

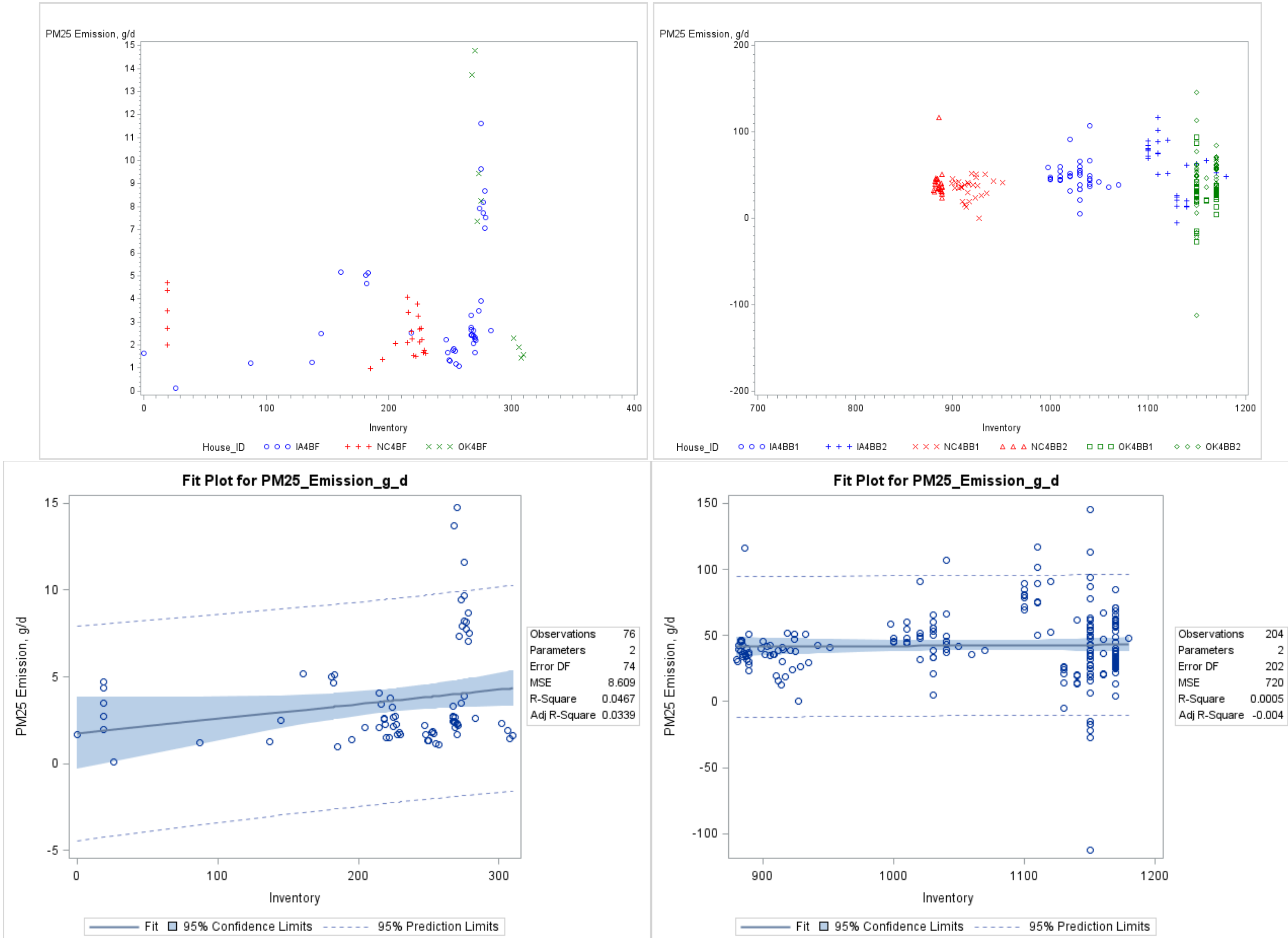


Figure E-70. Scatter plot of $PM_{2.5}$ Emissions versus inventory and scatter with regression for farrowing room (left column) and gestation barns (right column).

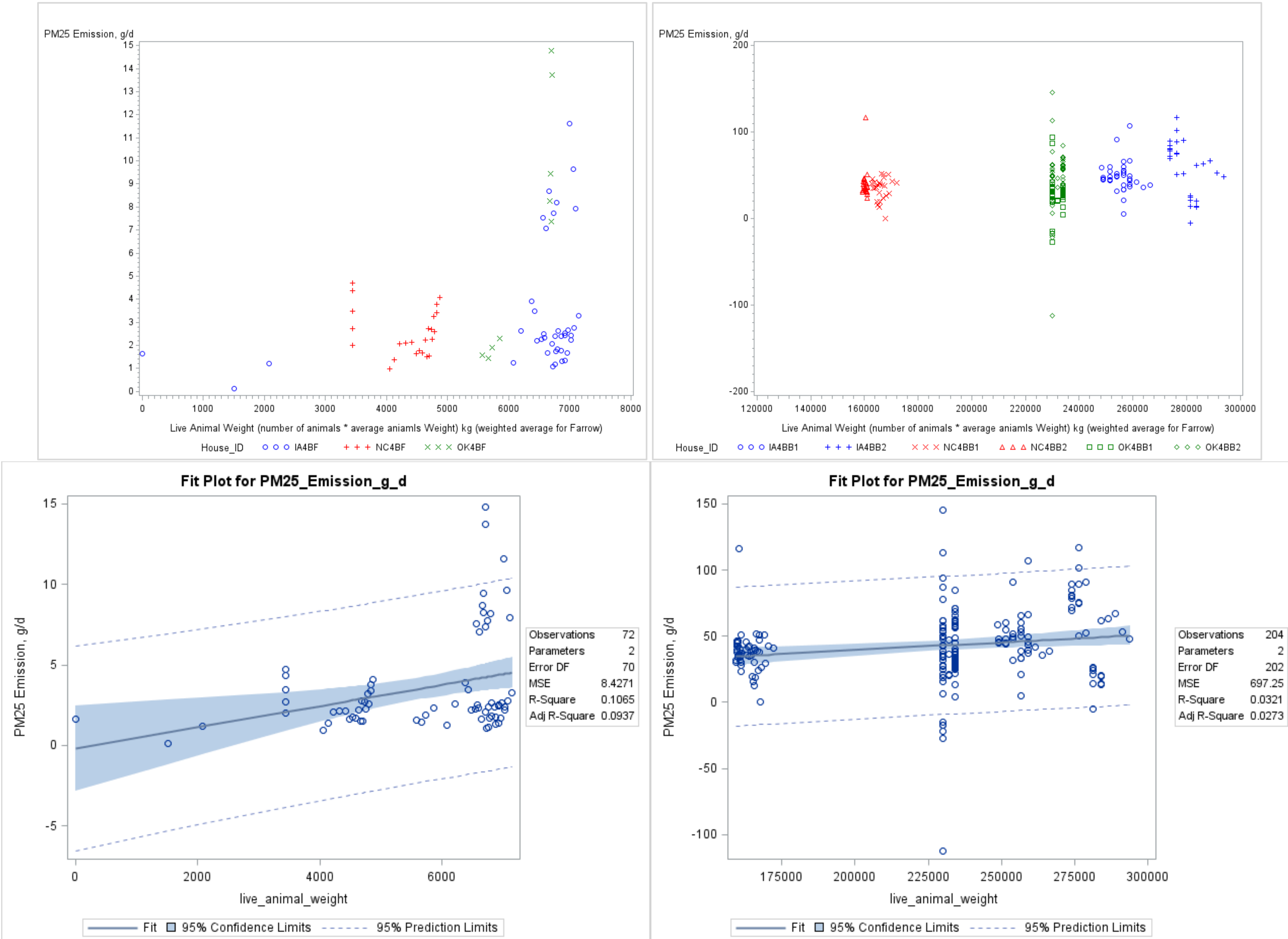
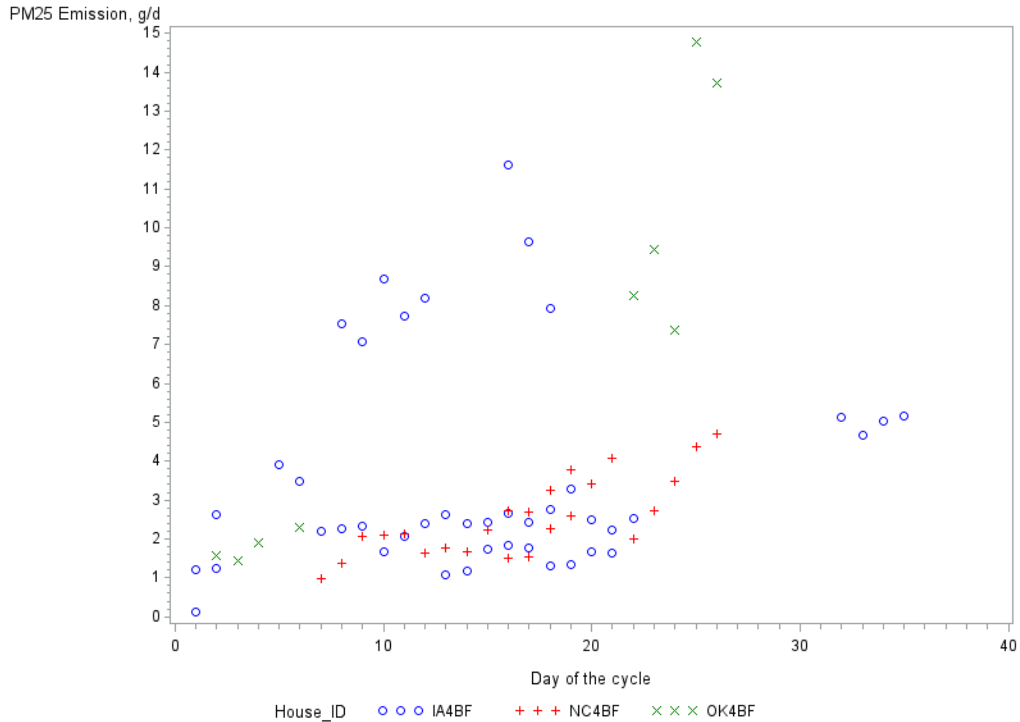


Figure E-71. Scatter plot of $PM_{2.5}$ Emissions versus LAW and scatter with regression for farrowing room (left column) and gestation barns (right column).



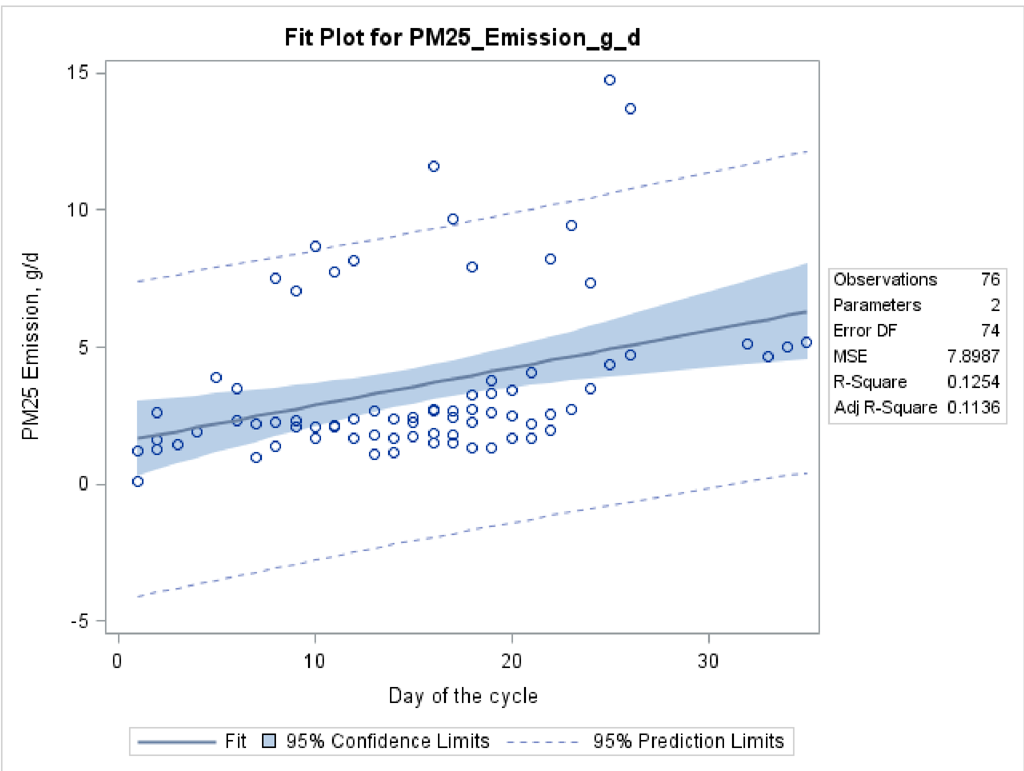


Figure E-72. Scatter plot of $PM_{2.5}$ Emissions versus cycle day and scatter with regression for farrowing rooms.

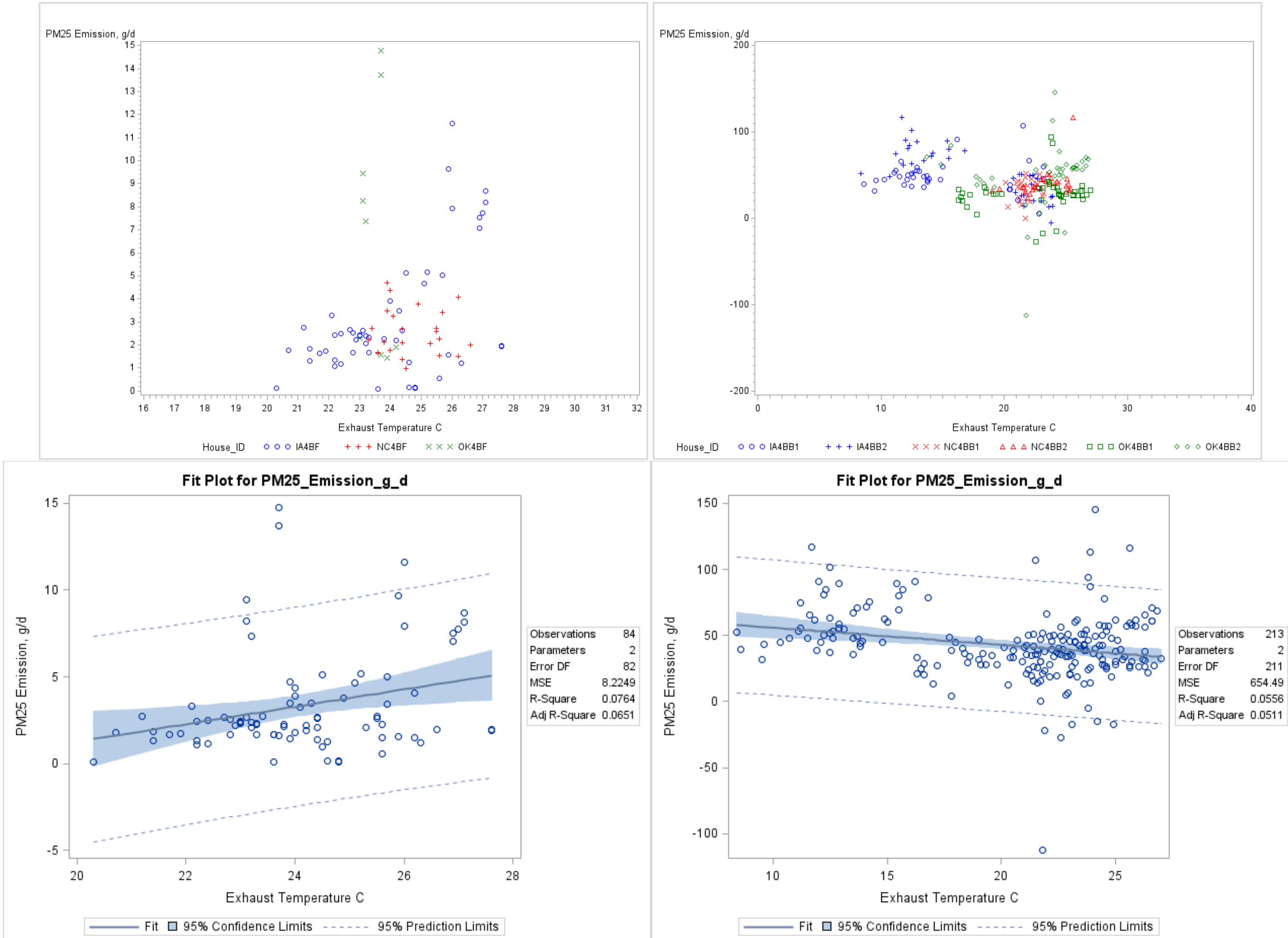


Figure E-73. Scatter plot of $PM_{2.5}$ Emissions versus exhaust temperature and scatter with regression for farrowing room (left column) and gestation barns (right column).

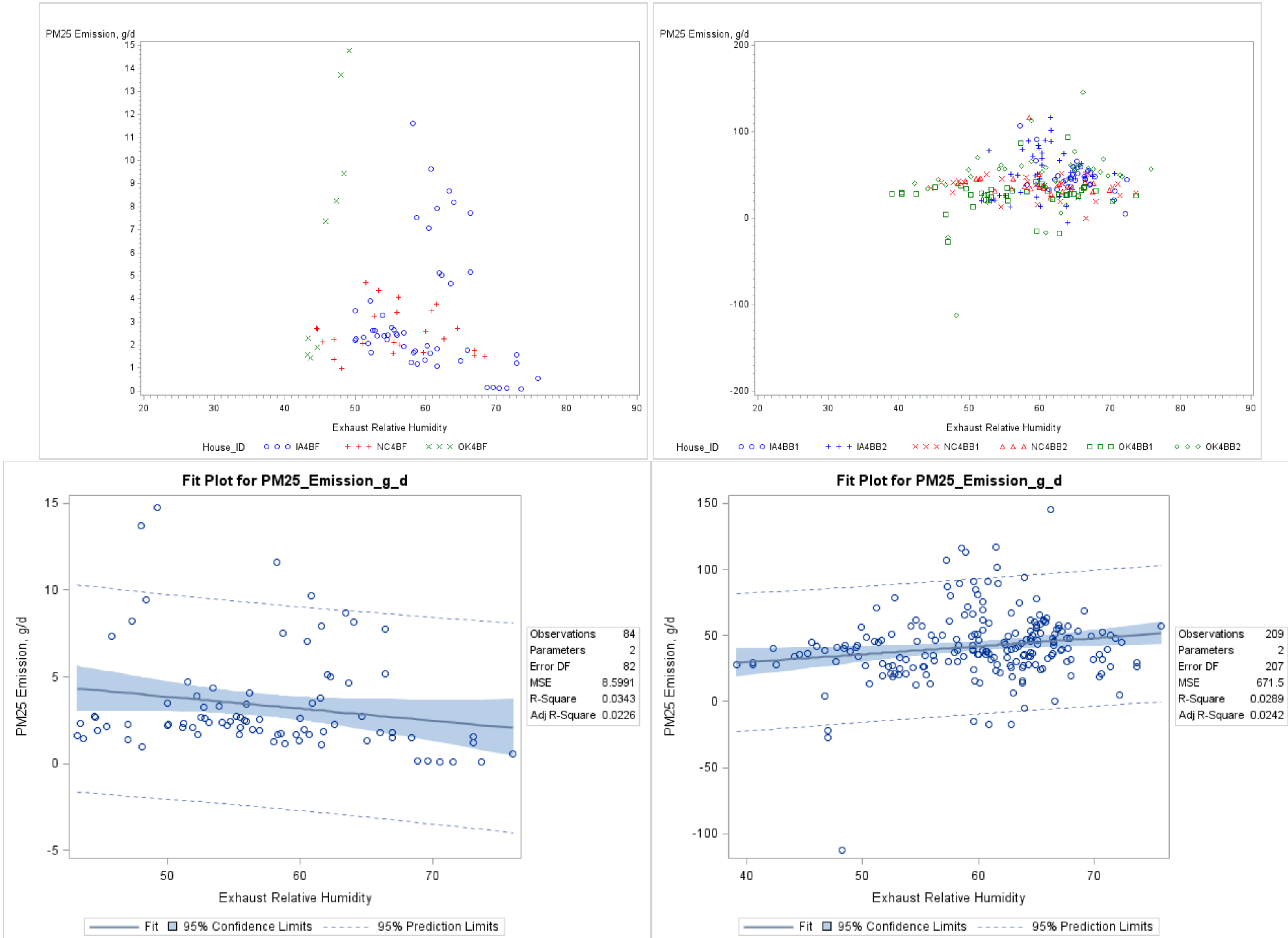


Figure E-74. Scatter plot of $PM_{2.5}$ Emissions versus exhaust relative humidity and scatter with regression for farrowing room (left column) and gestation barns (right column).

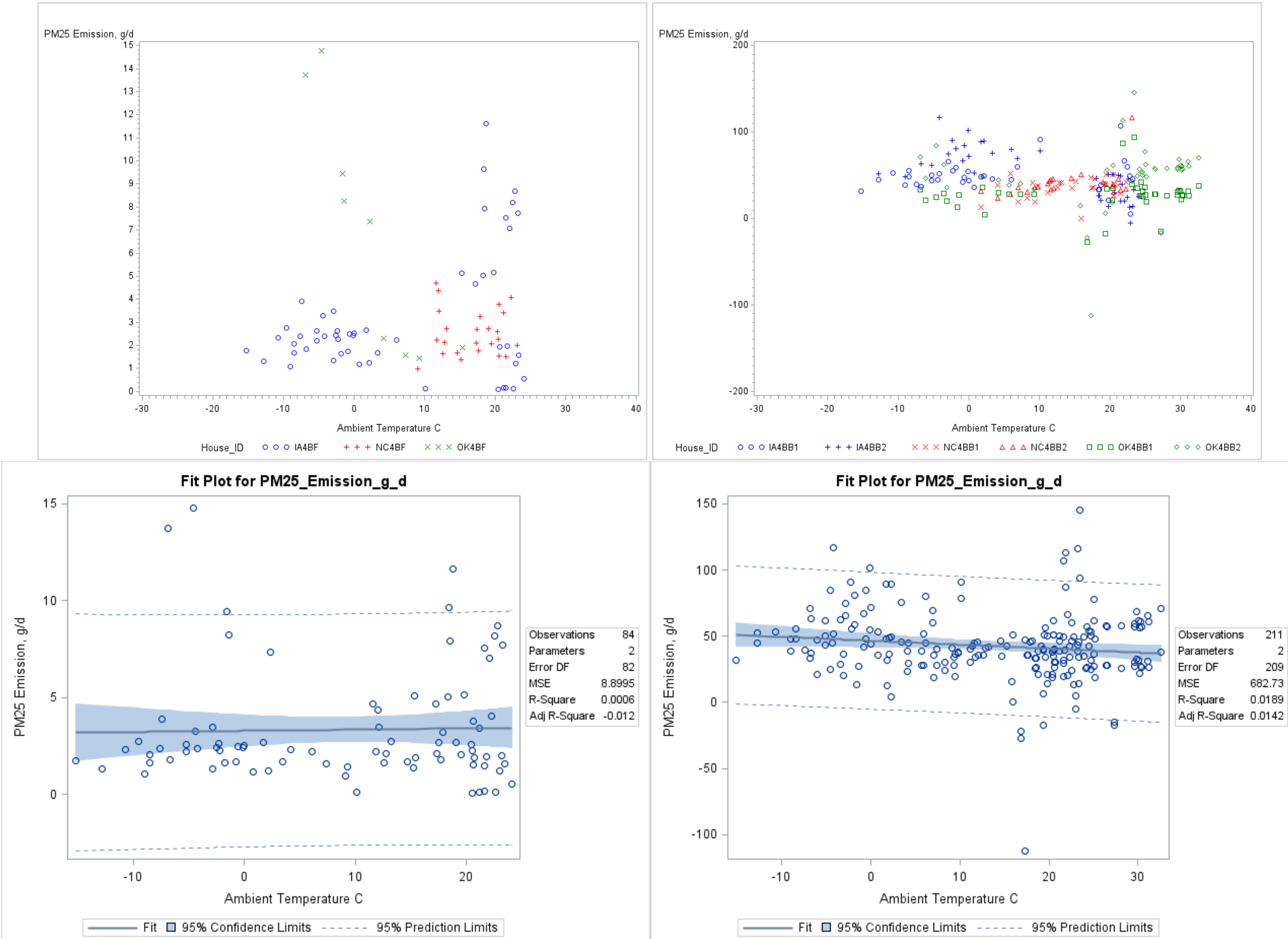


Figure E-75. Scatter plot of $PM_{2.5}$ Emissions versus ambient temperature and scatter with regression for farrowing room (left column) and gestation barns (right column).

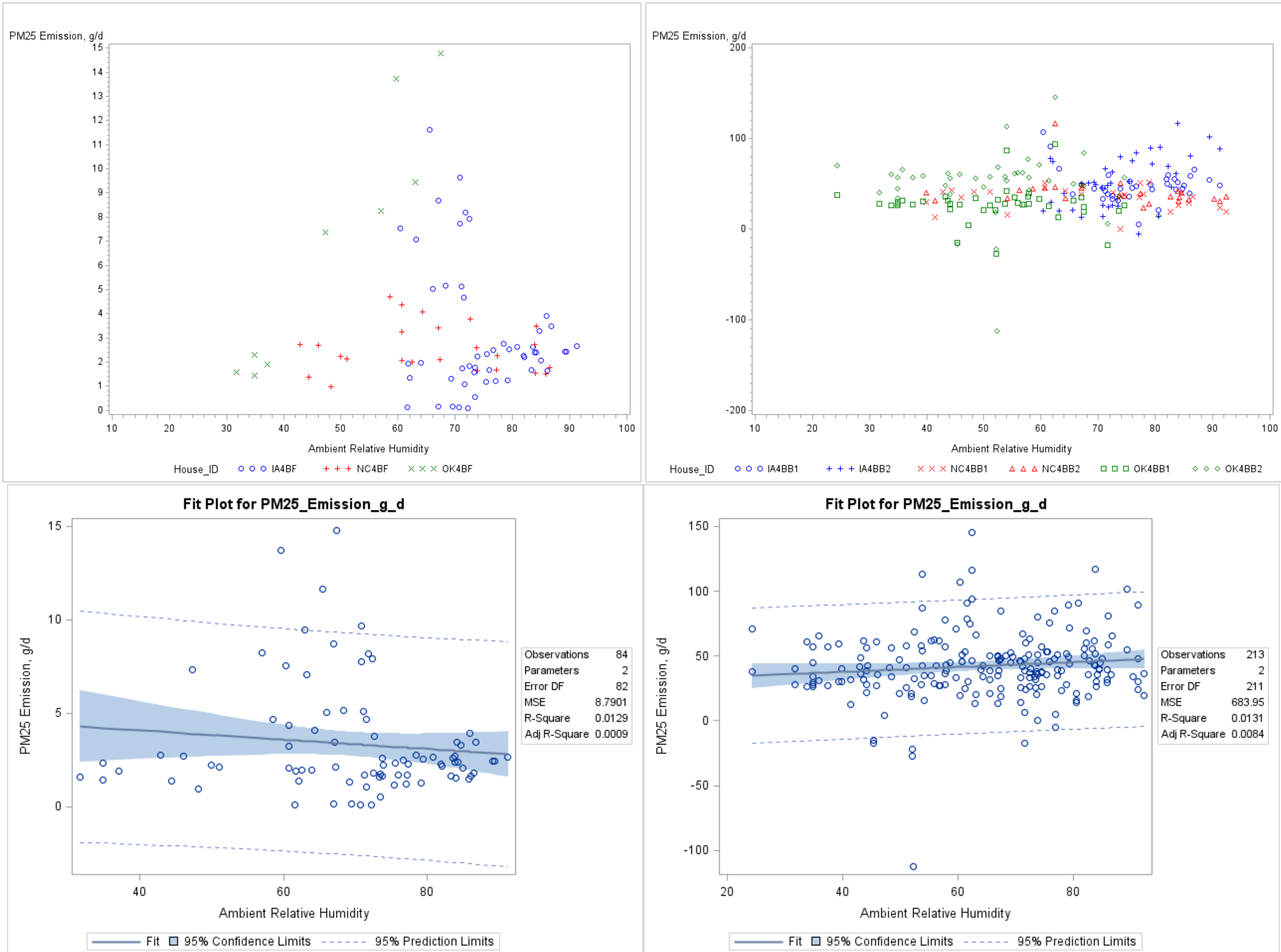


Figure E-76. Scatter plot of $PM_{2.5}$ Emissions versus ambient relative humidity and scatter with regression for farrowing room (left column) and gestation barns (right column).

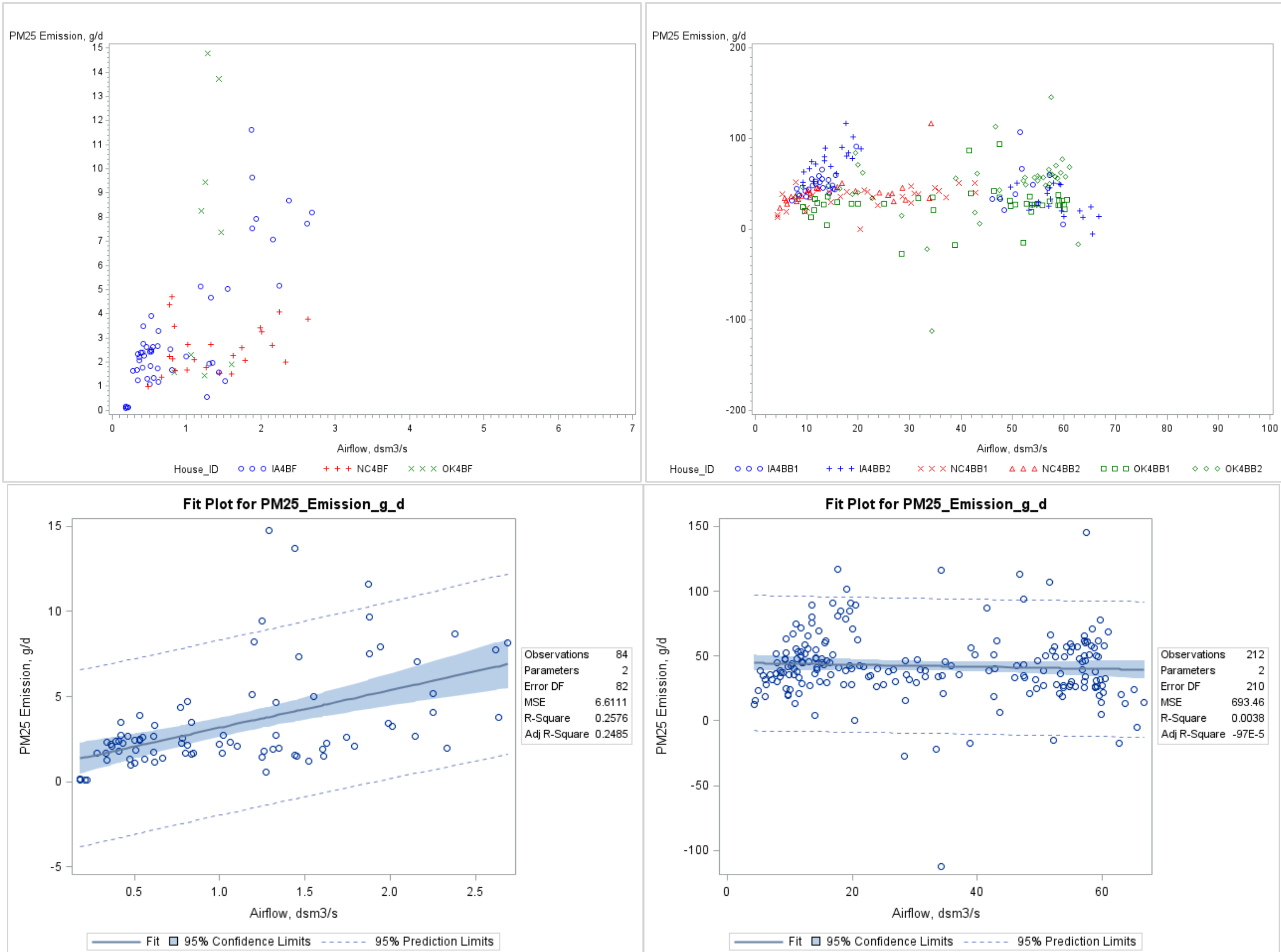


Figure E-77. Scatter plot of $PM_{2.5}$ Emissions versus ventilation rate and scatter with regression for farrowing room (left column) and gestation barns (right column).

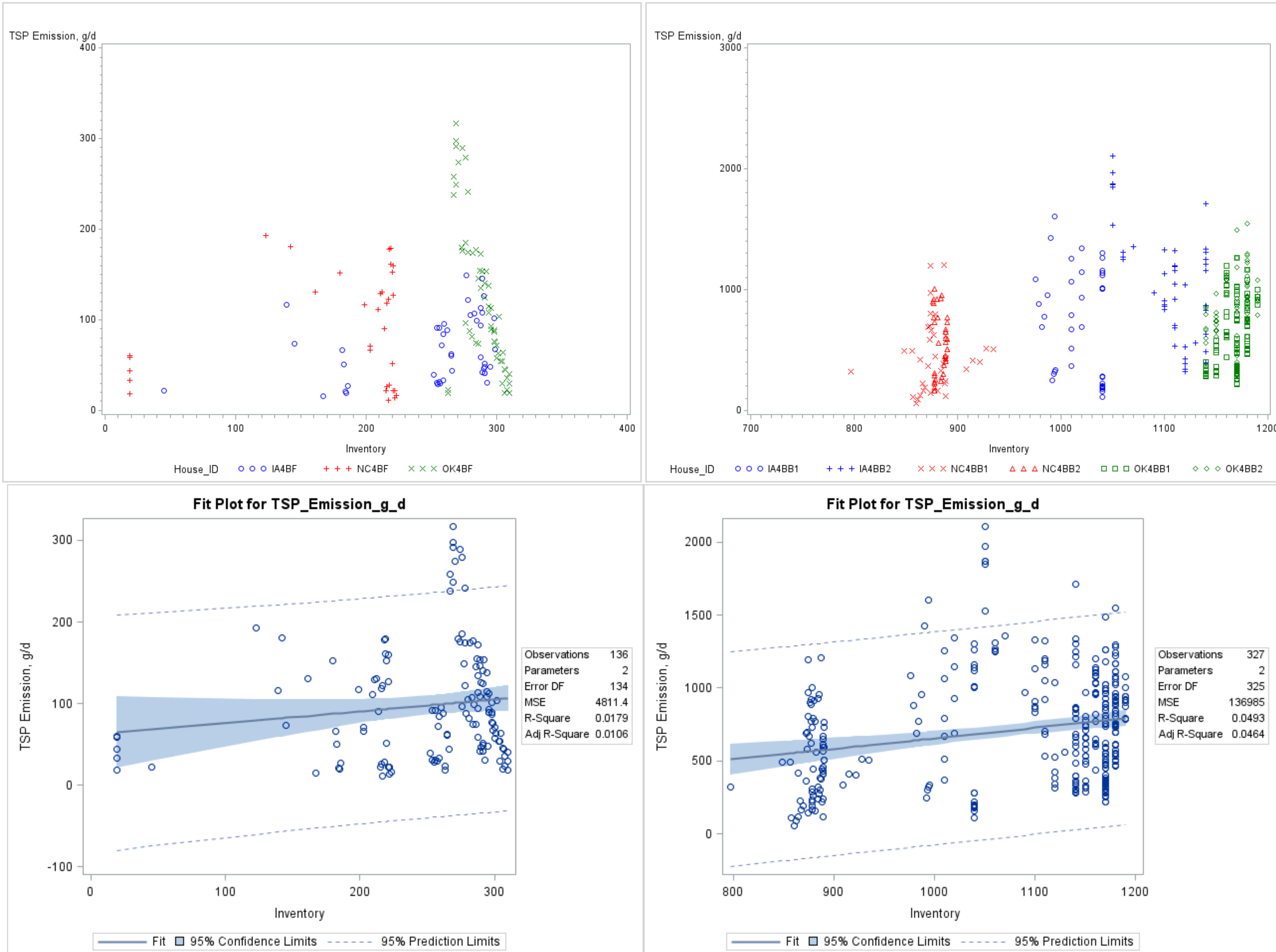


Figure E-78. Scatter plot of TSP Emissions versus inventory and scatter with regression for farrowing room (left column) and gestation barns (right column).

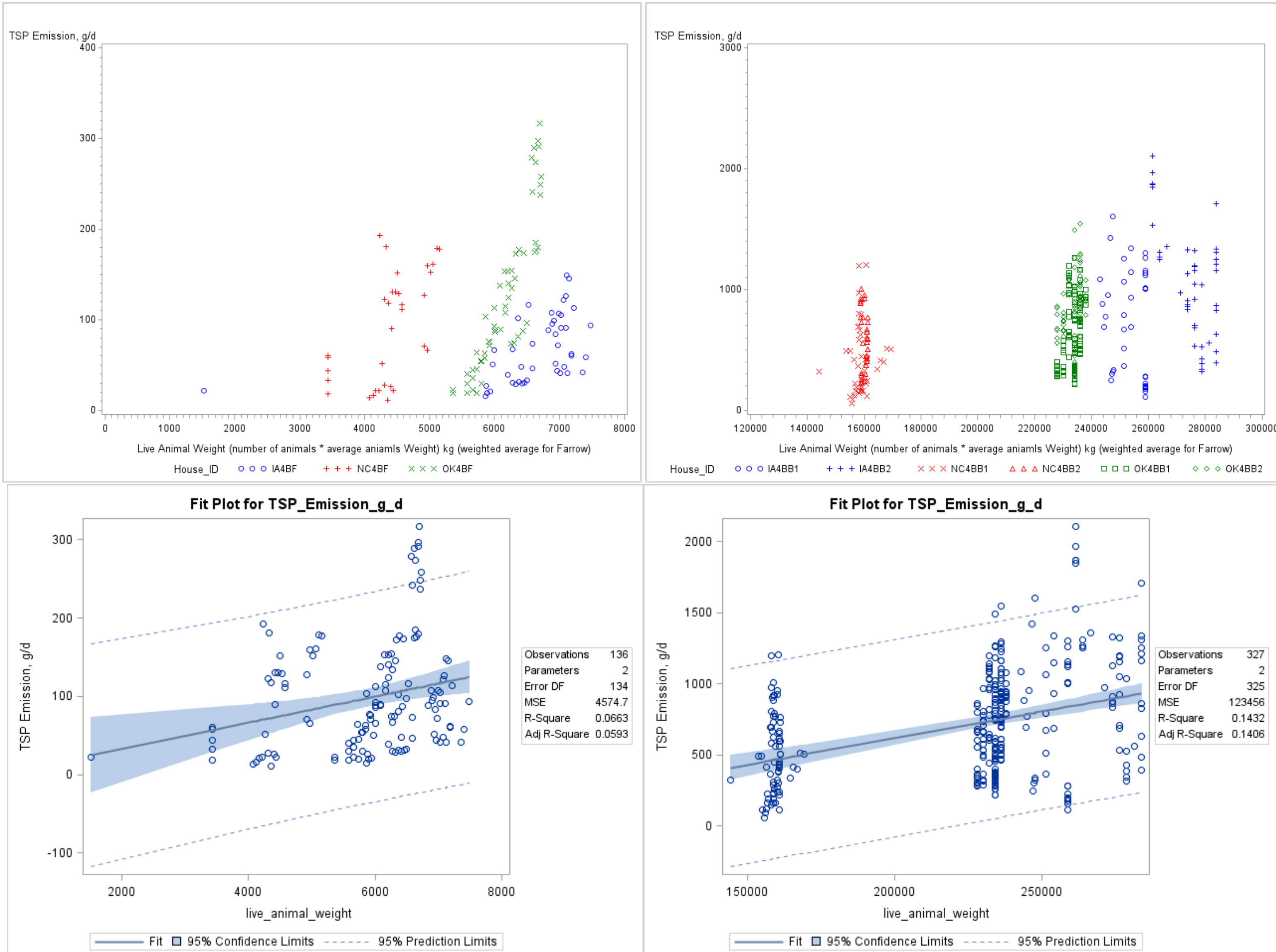
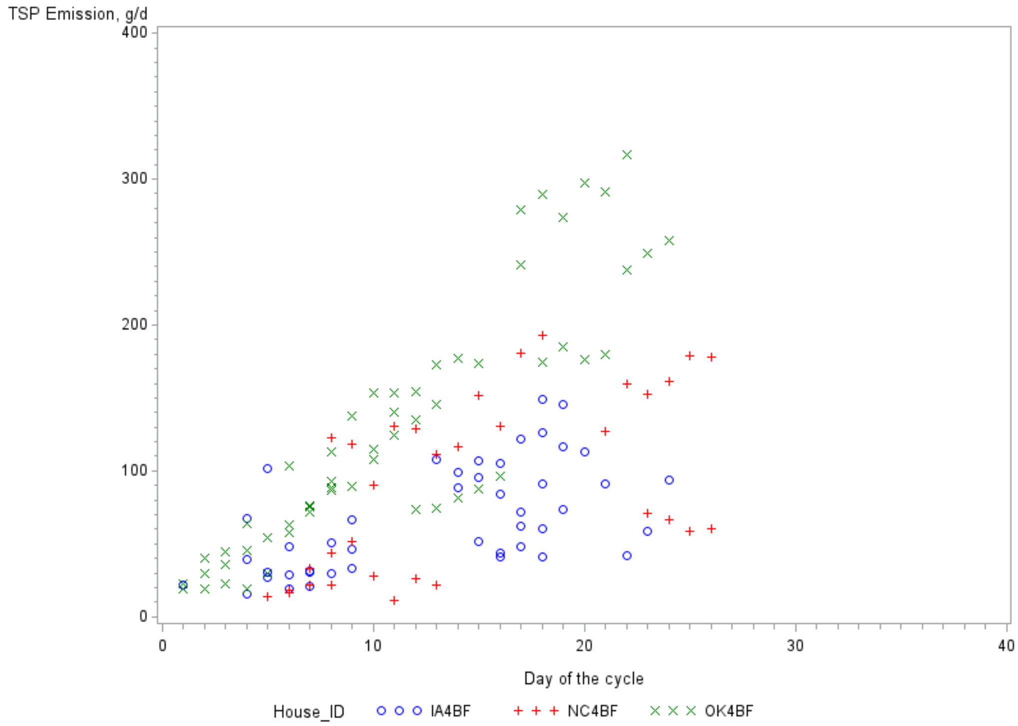


Figure E-79. Scatter plot of TSP Emissions versus LAW and scatter with regression for farrowing room (left column) and gestation barns (right column).



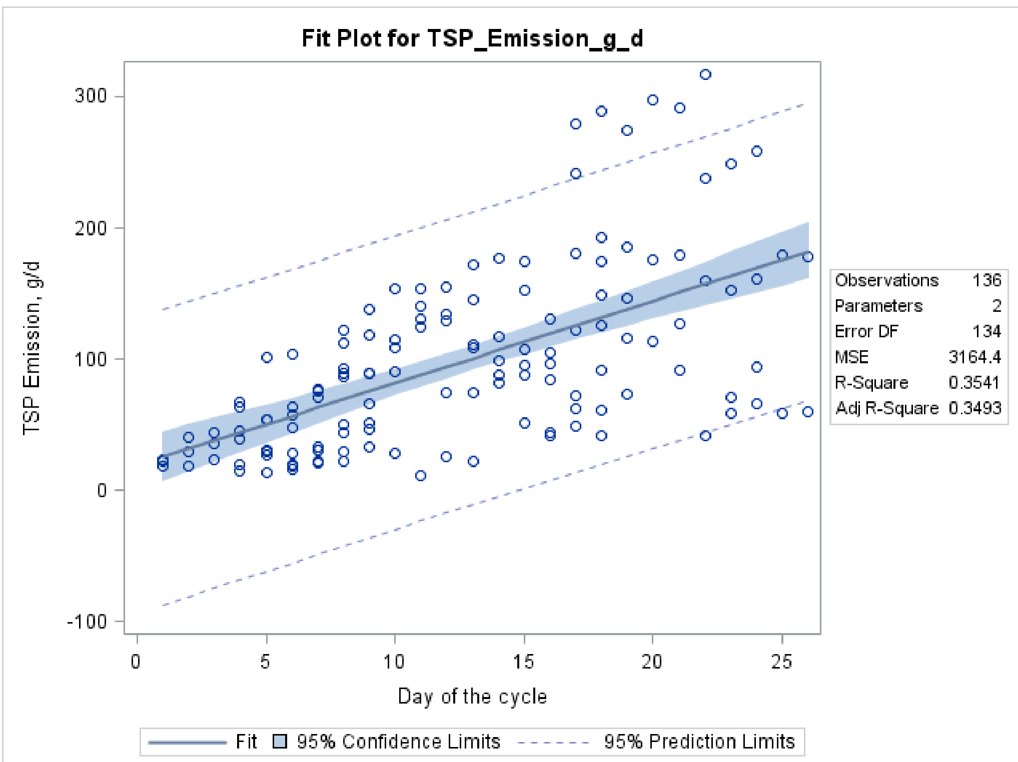


Figure E-80. Scatter plot of TSP Emissions versus cycle day and scatter with regression for farrowing rooms.

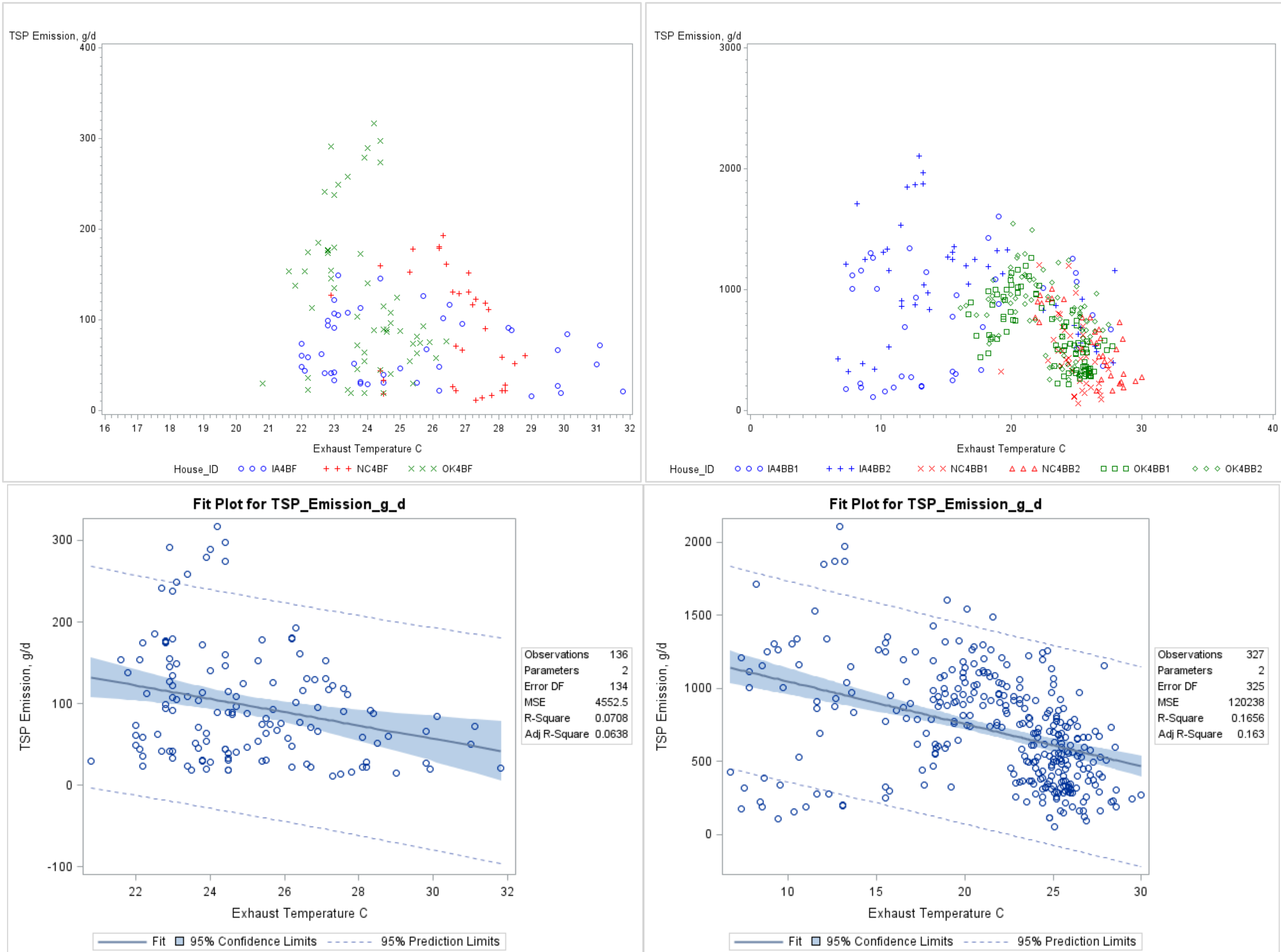


Figure E-81. Scatter plot of TSP Emissions versus exhaust temperature and scatter with regression for farrowing room (left column) and gestation barns (right column).

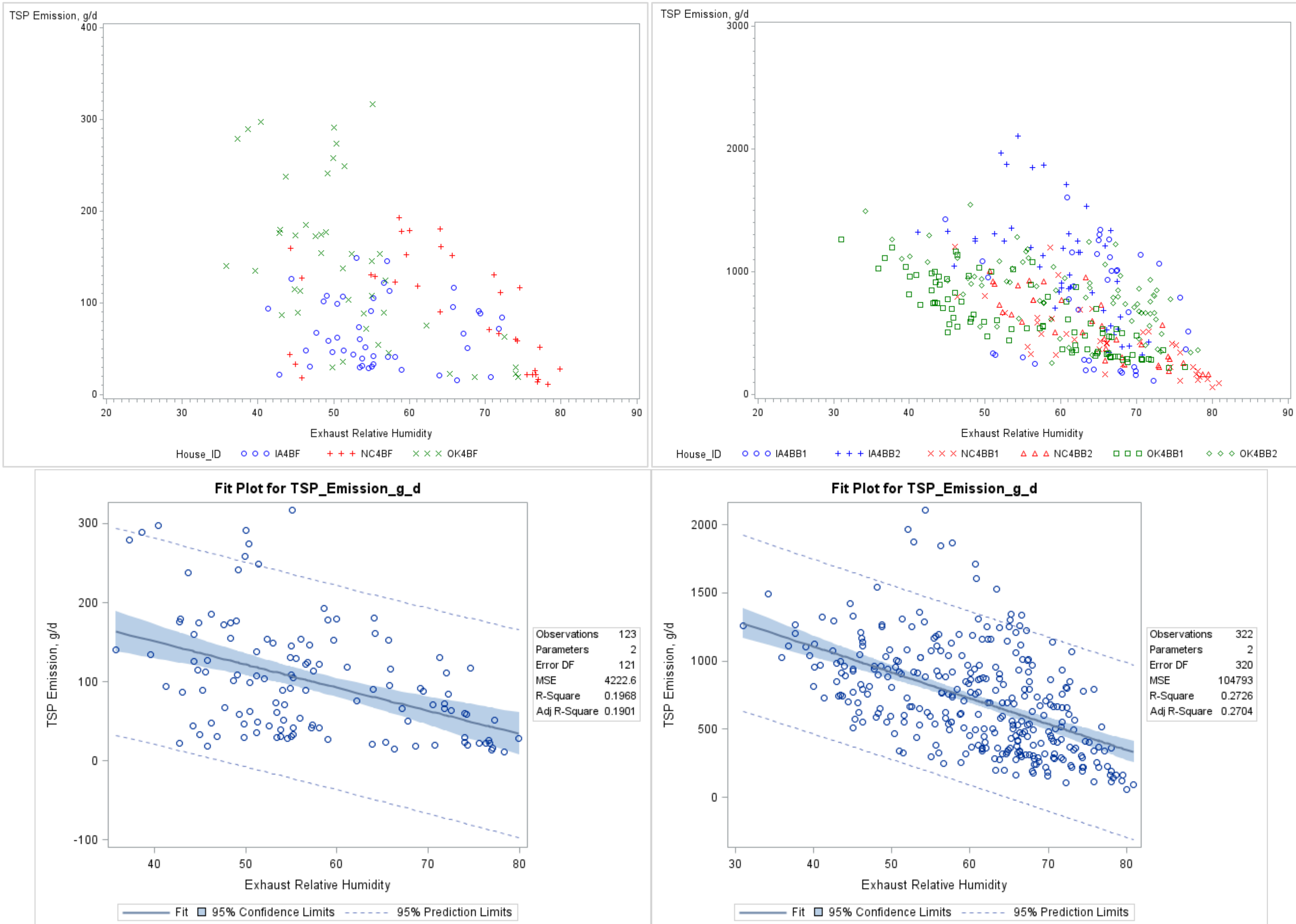


Figure E-82. Scatter plot of TSP Emissions versus exhaust relative humidity and scatter with regression for farrowing room (left column) and gestation barns (right column).

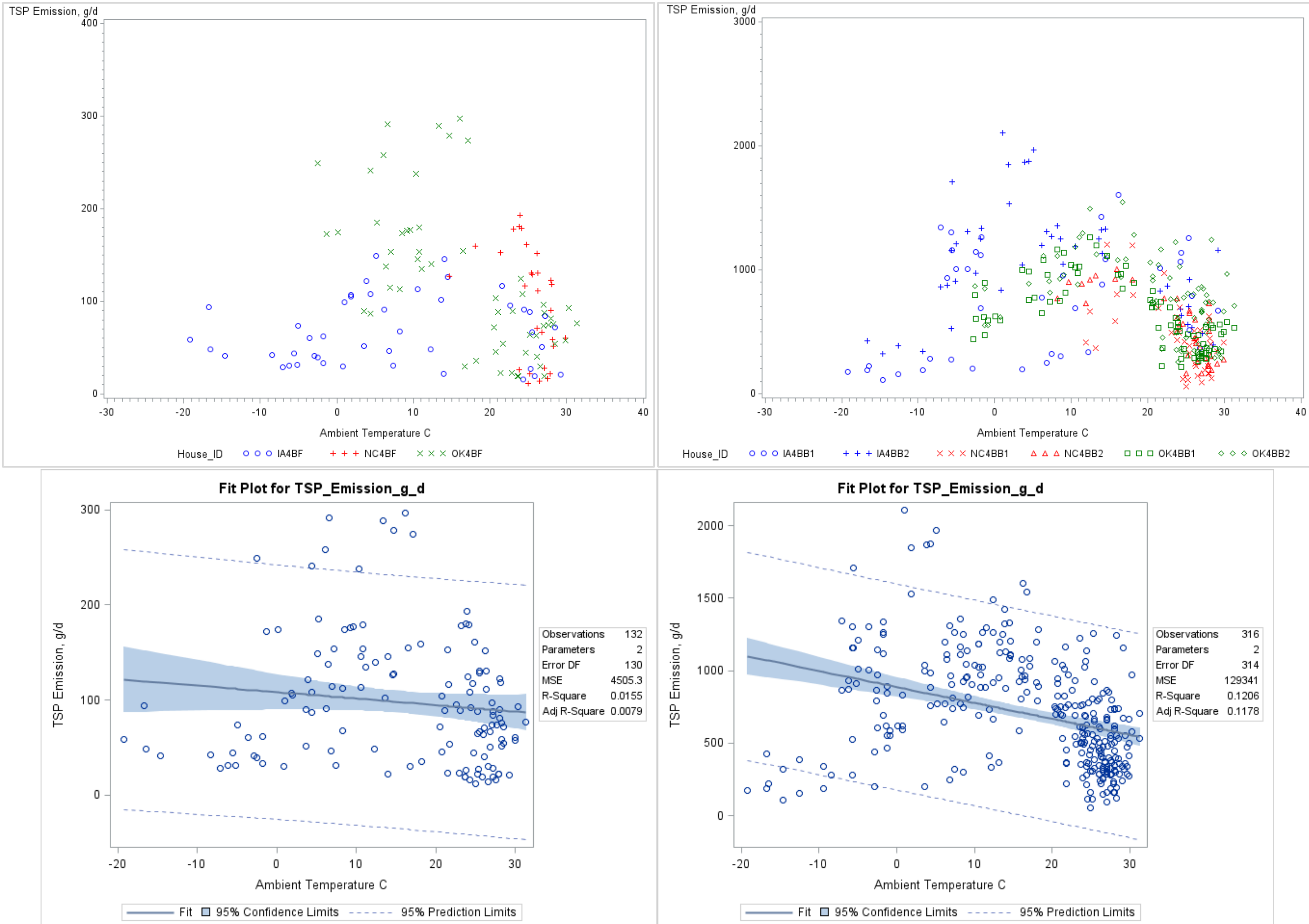


Figure E-83. Scatter plot of TSP Emissions versus ambient temperature and scatter with regression for farrowing room (left column) and gestation barns (right column).

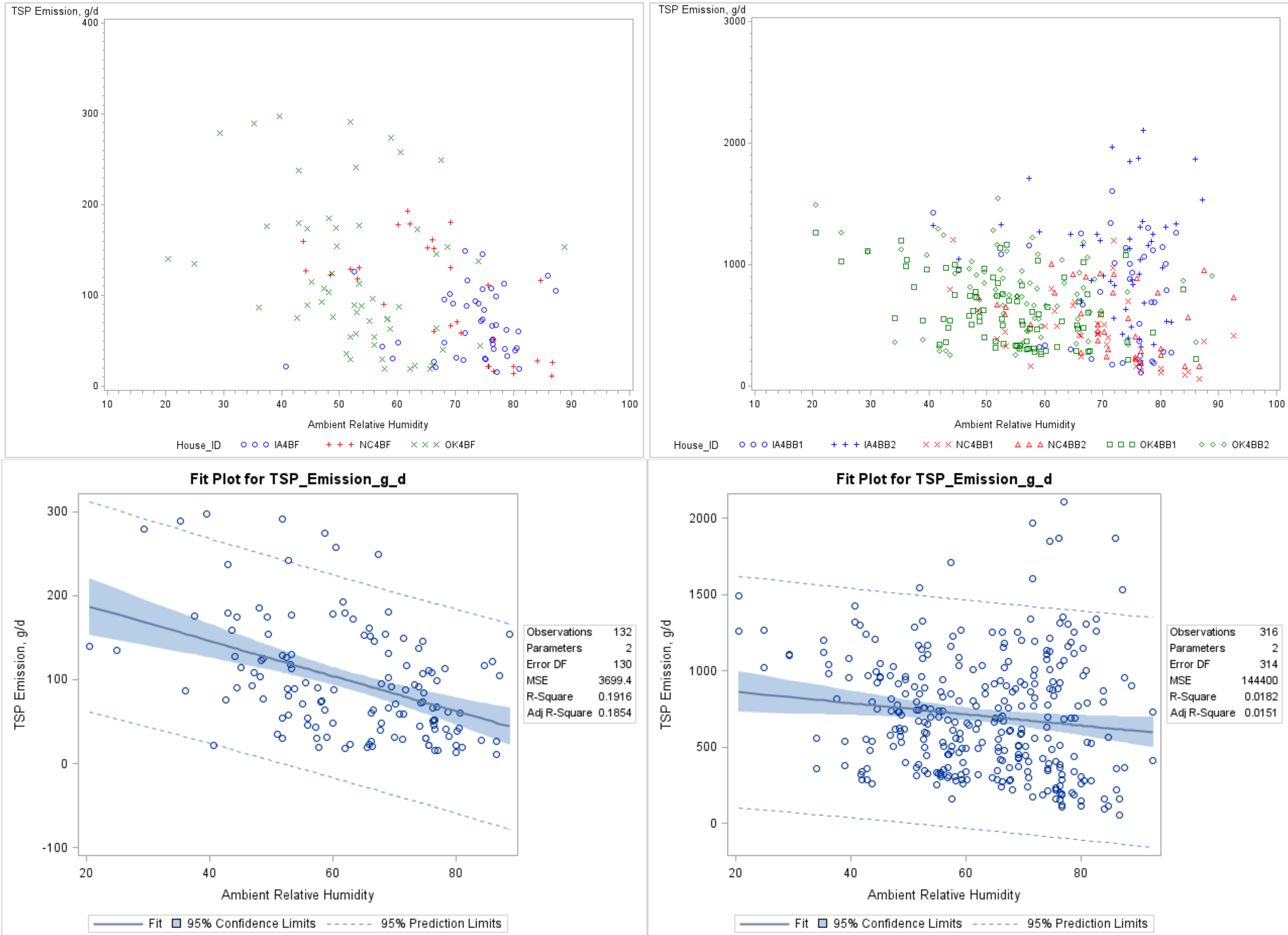


Figure E-84. Scatter plot of TSP Emissions versus ambient relative humidity and scatter with regression for farrowing room (left column) and gestation barns (right column).

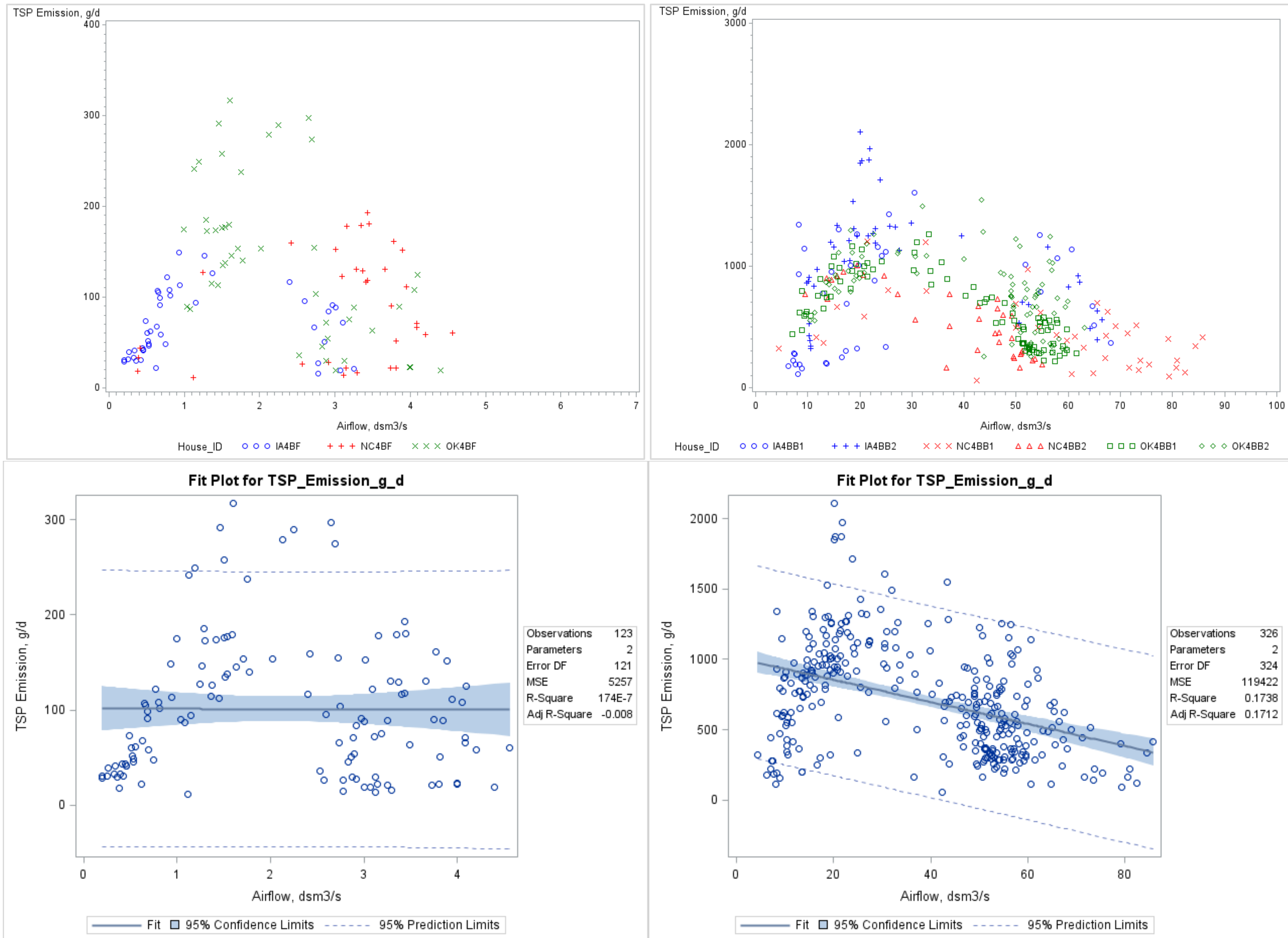


Figure E-85. Scatter plot of TSP Emissions versus ventilation rate and scatter with regression for farrowing room (left column) and gestation barns (right column).

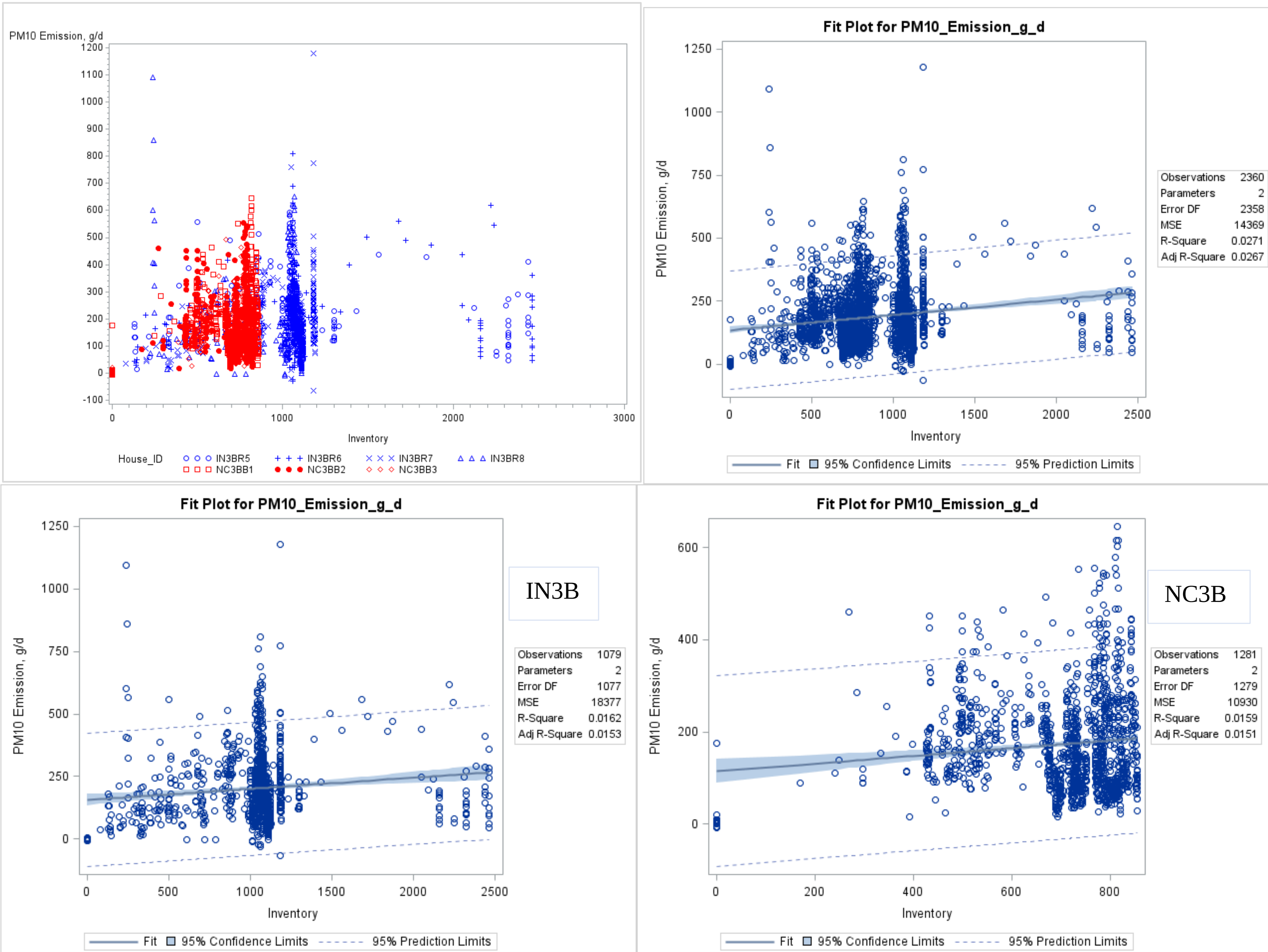


Figure E-86. Scatter plot of swine grow-finish PM_{10} Emissions versus Inventory (top left), with regression (top right), IN3B only (bottom left), NC3B only (bottom right).

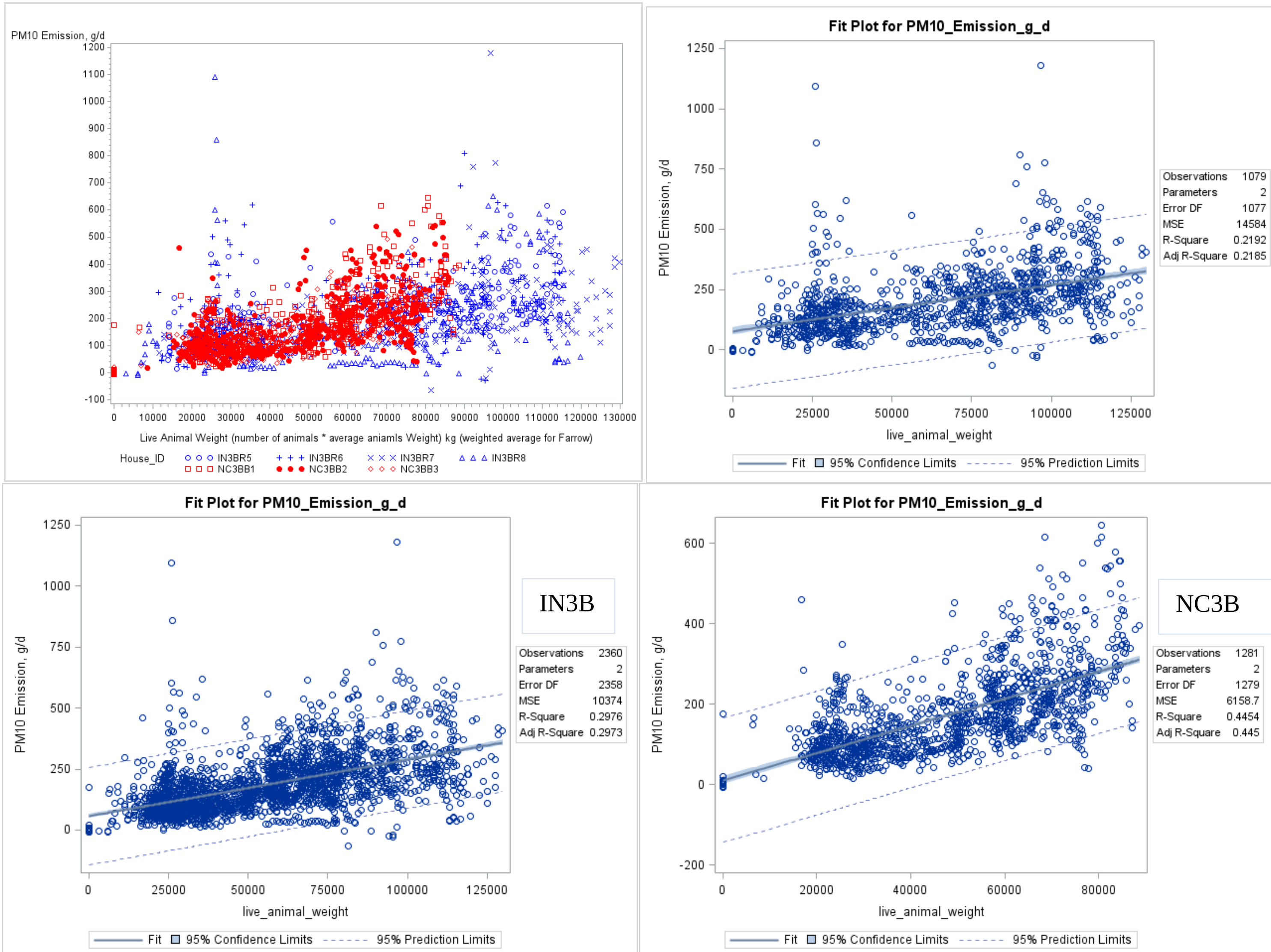


Figure E-87. Scatter plot of swine grow-finish PM_{10} Emissions versus live animal weight (top left), with regression (top right), IN3B only (bottom left), NC3B only (bottom right).

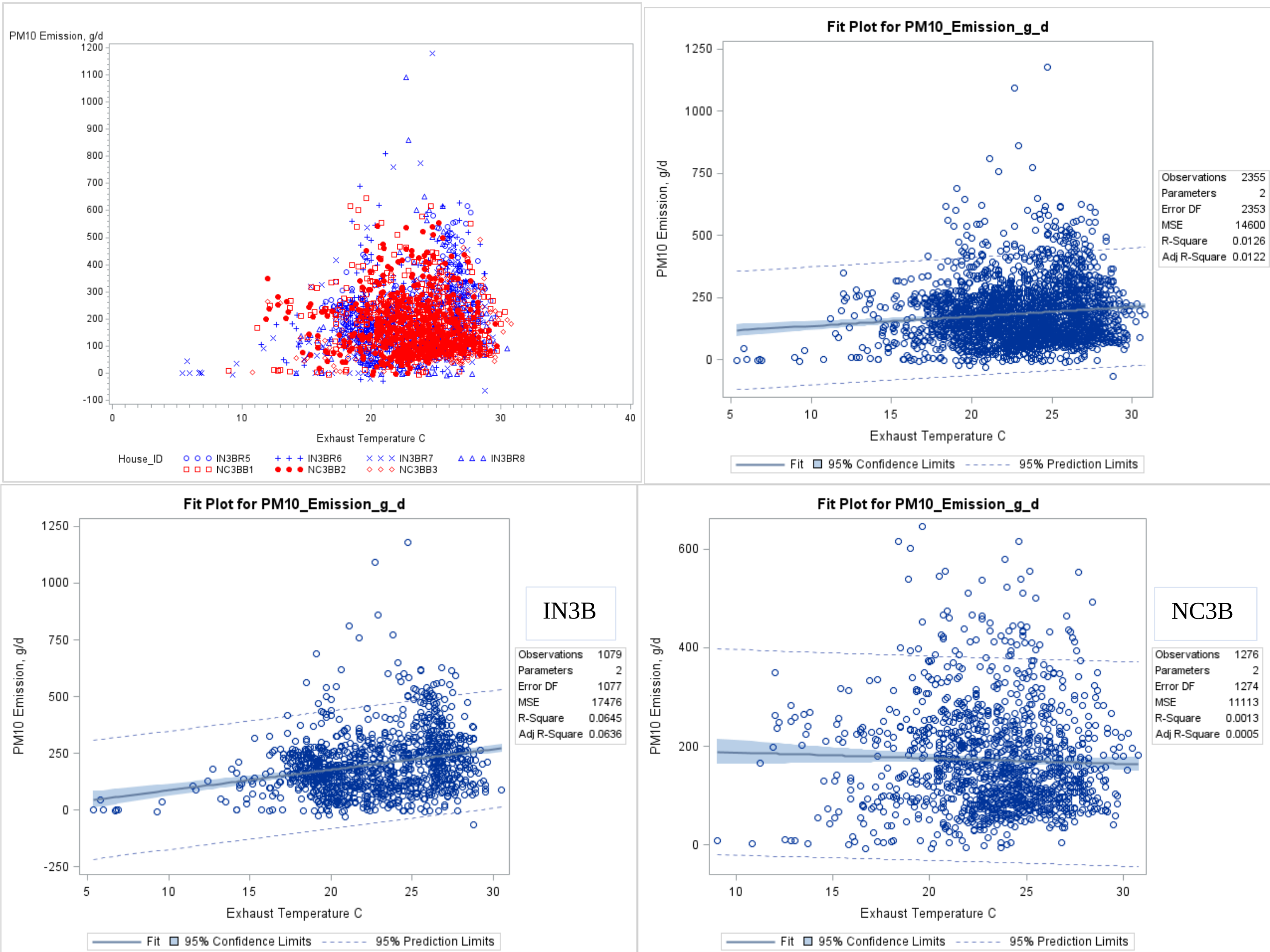


Figure E-88. Scatter plot of swine grow-finish PM_{10} Emissions versus exhaust temperature (top left), with regression (top right), IN3B only (bottom left), NC3B only (bottom right).

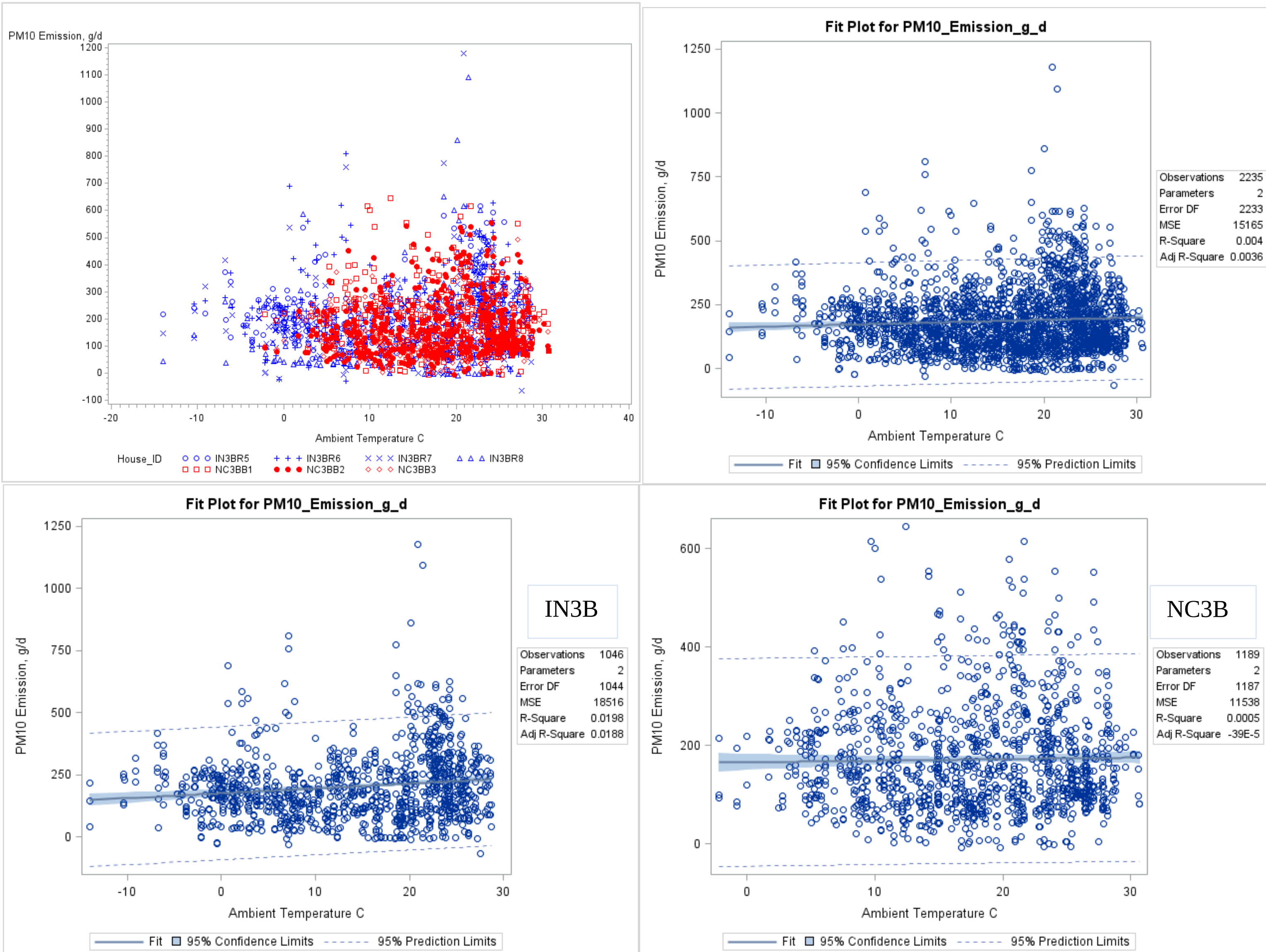


Figure E-89. Scatter plot of swine grow-finish PM_{10} Emissions versus ambient relative temperature (top left), with regression (top right), IN3B only (bottom left), NC3B only (bottom right).

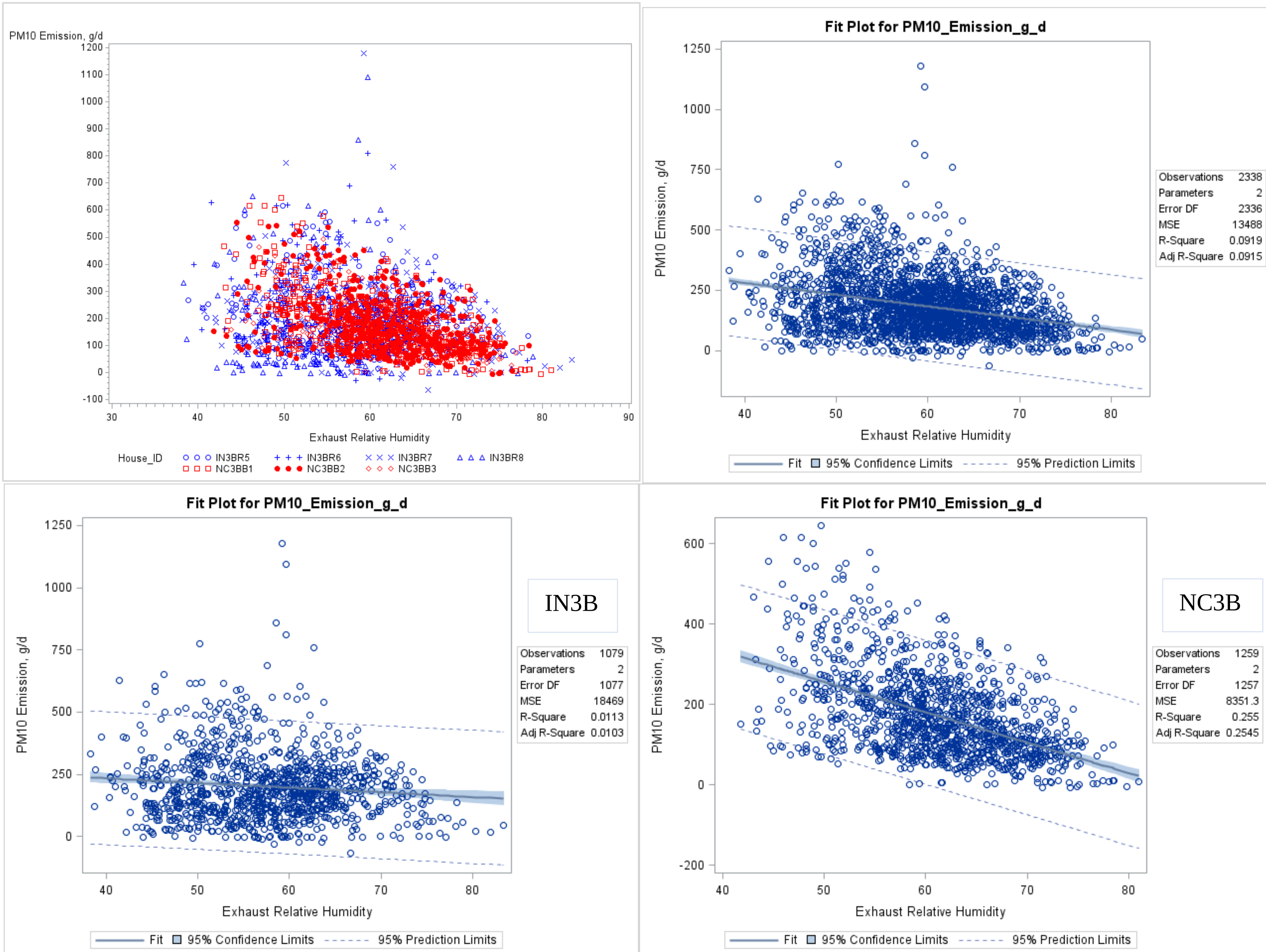


Figure E-90. Scatter plot of swine grow-finish PM_{10} Emissions versus exhaust relative humidity (top left), with regression (top right), IN3B only (bottom left), NC3B only (bottom right).

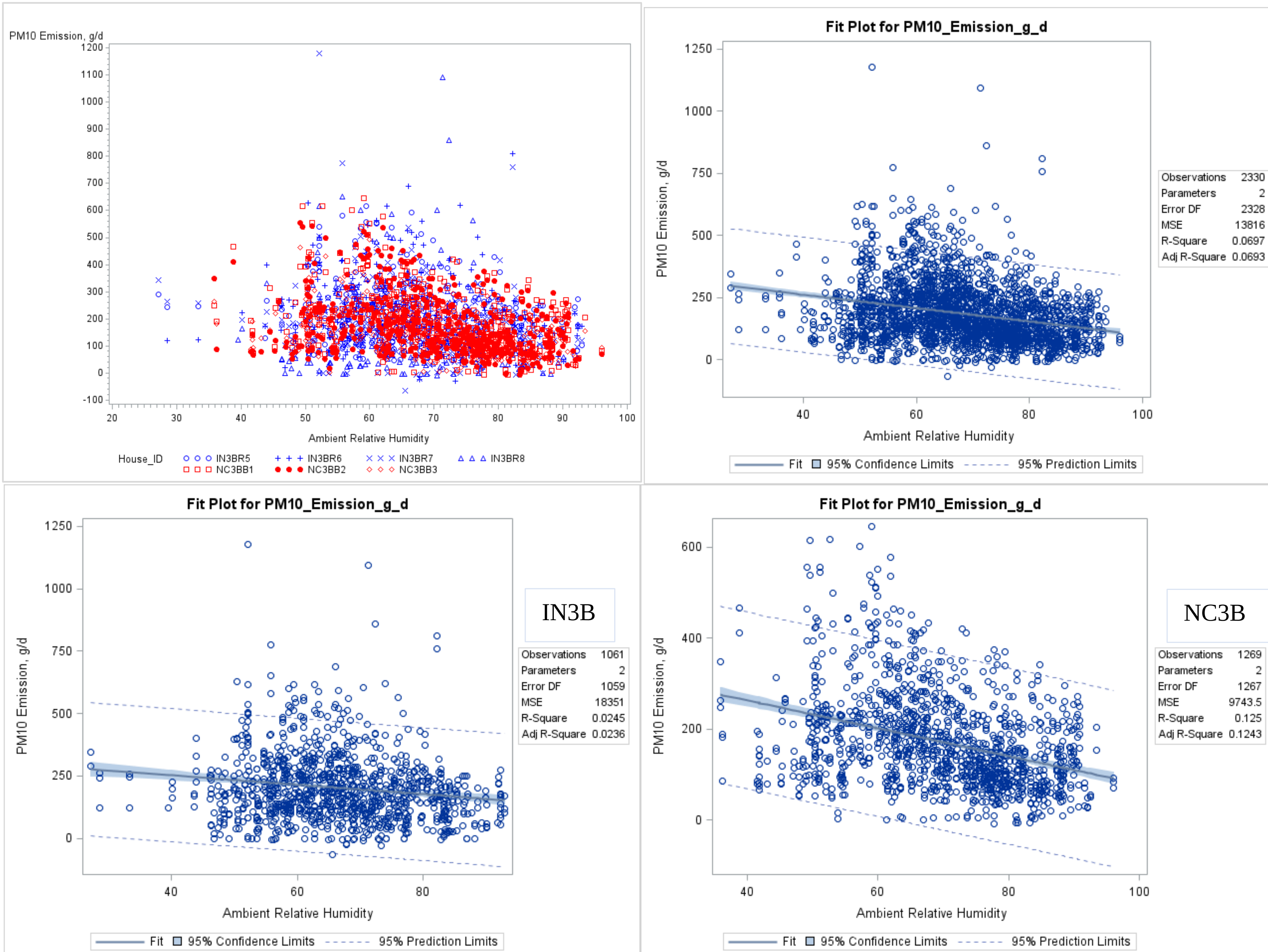


Figure E-91. Scatter plot of swine grow-finish PM_{10} Emissions versus ambient relative humidity (top left), with regression (top right), IN3B only (bottom left), NC3B only (bottom right).

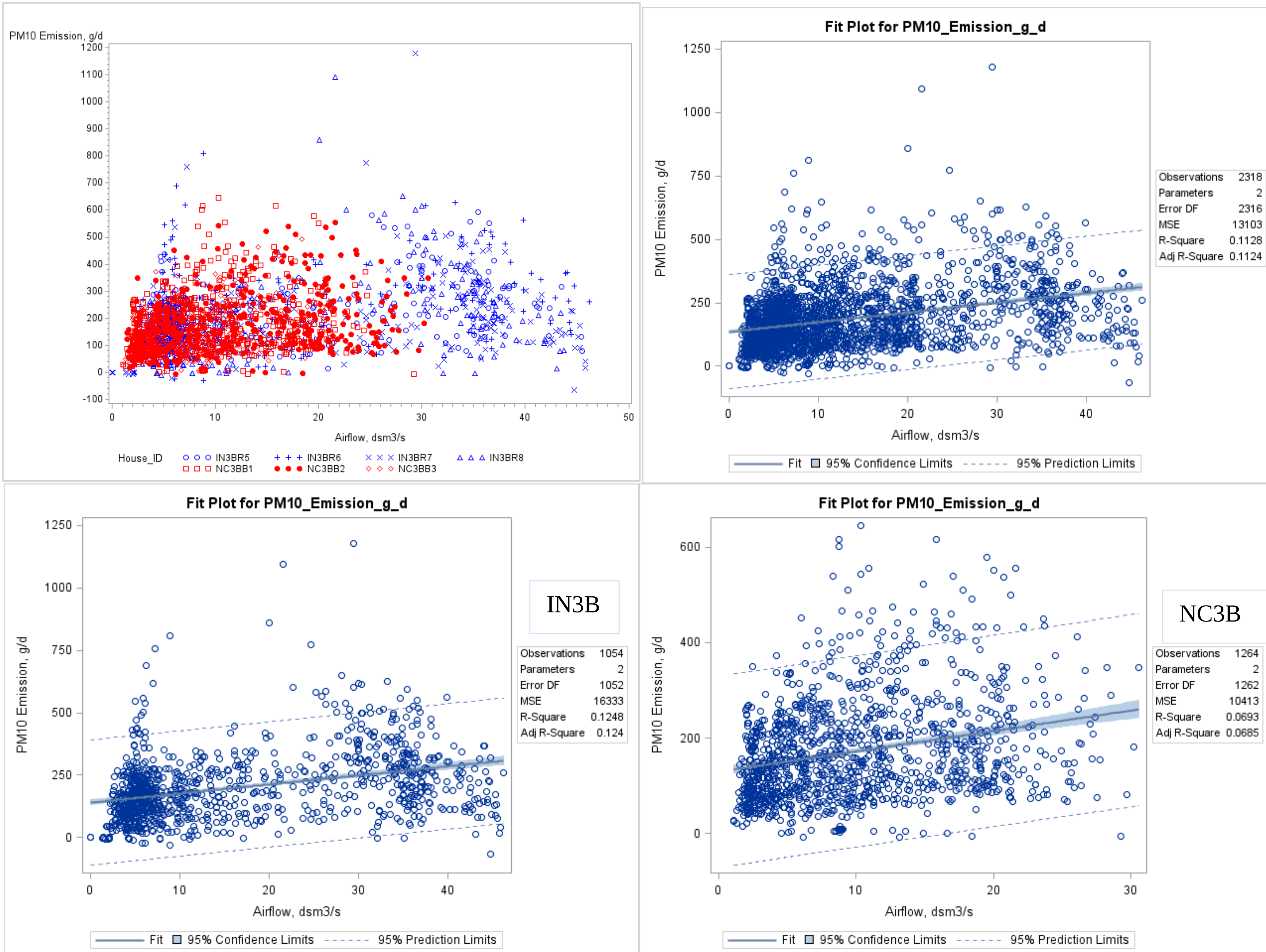


Figure E-92. Scatter plot of swine grow-finish PM_{10} Emissions versus airflow (top left), with regression (top right), IN3B only (bottom left), NC3B only (bottom right).

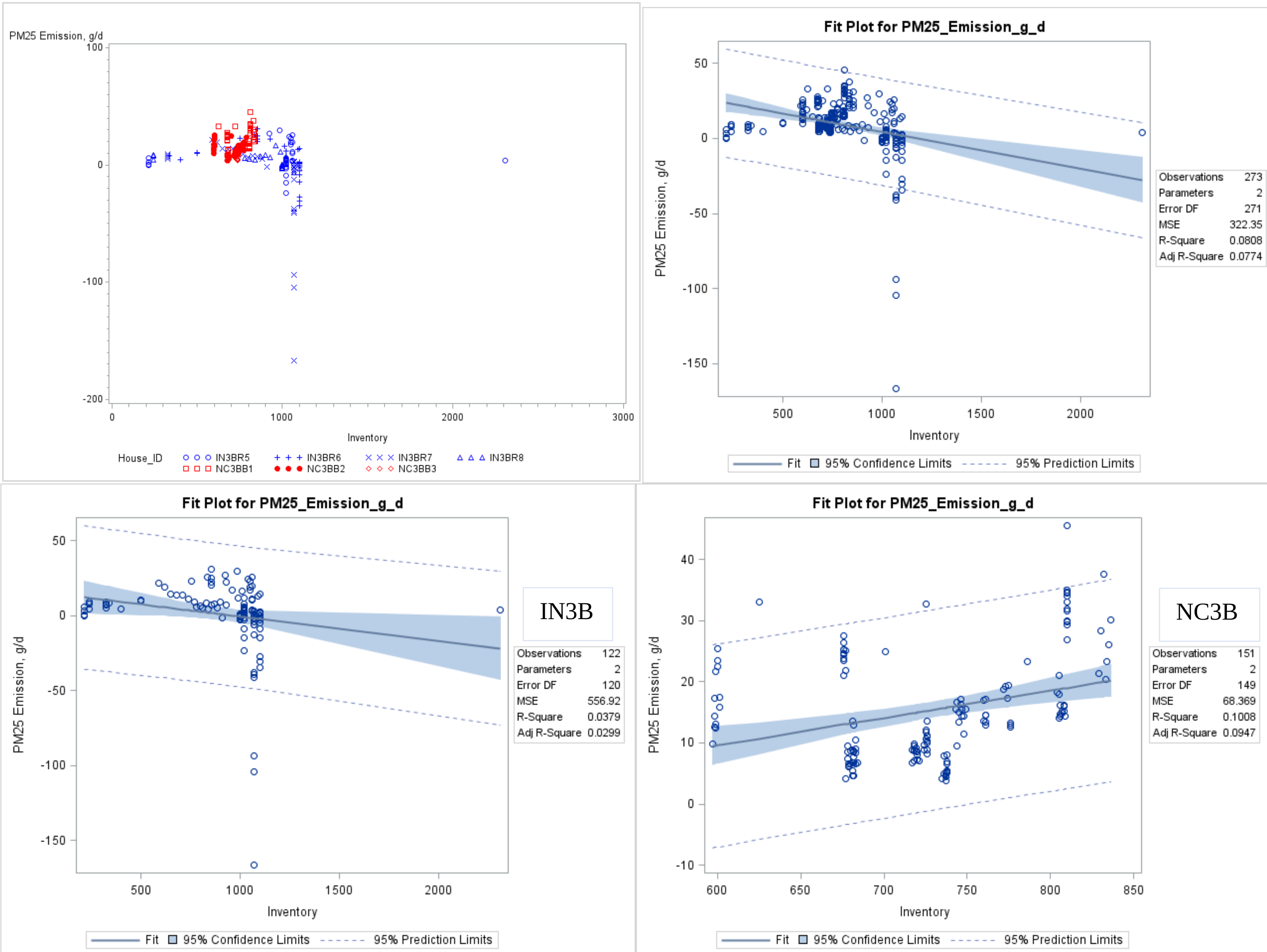


Figure E-93. Scatter plot of swine grow-finish $PM_{2.5}$ Emissions versus Inventory (top left), with regression (top right), IN3B only (bottom left), NC3B only (bottom right).

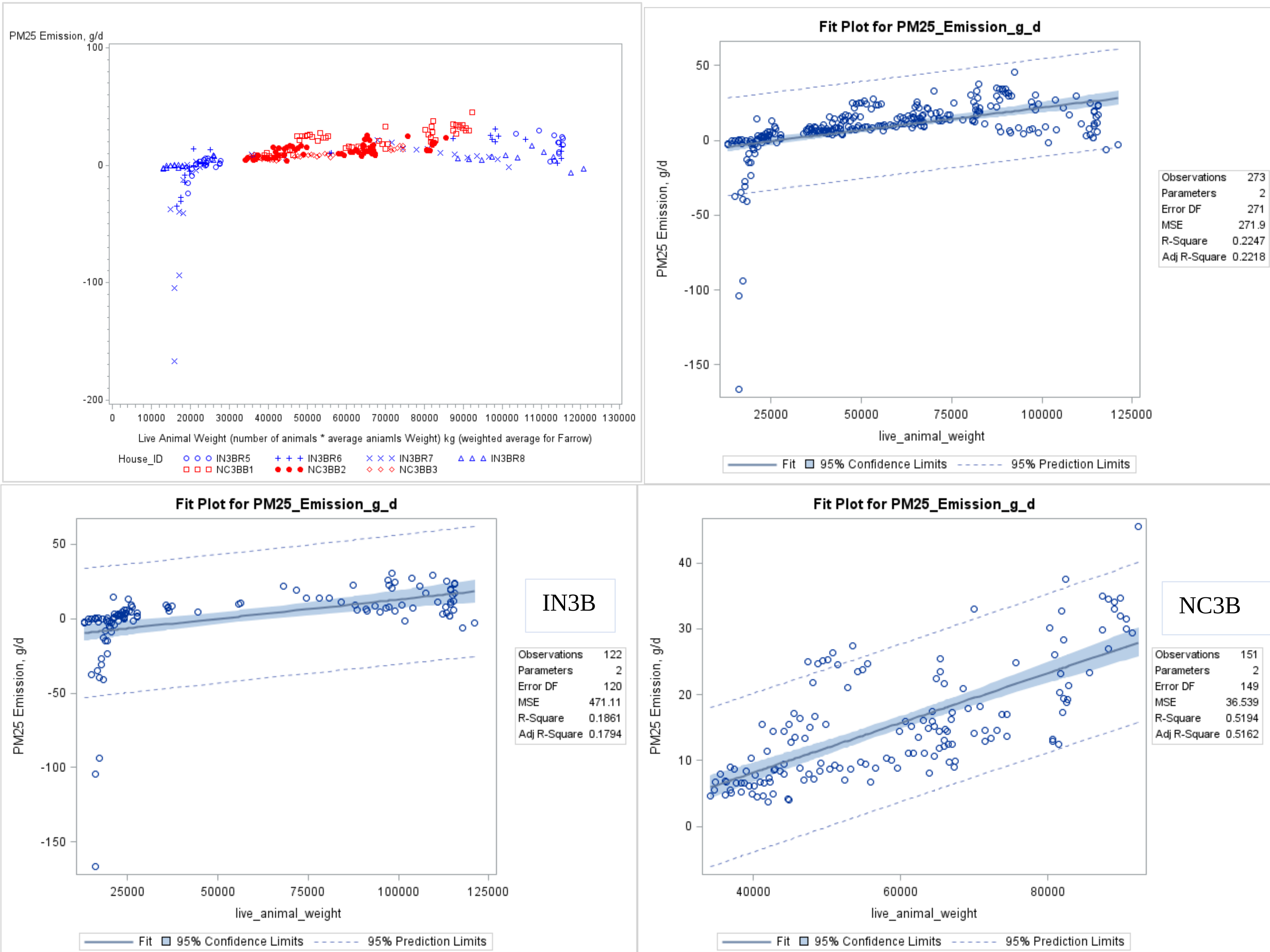


Figure E-94. Scatter plot of swine grow-finish $PM_{2.5}$ emissions versus live animal weight (top left), with regression (top right), IN3B only (bottom left), NC3B only (bottom right).

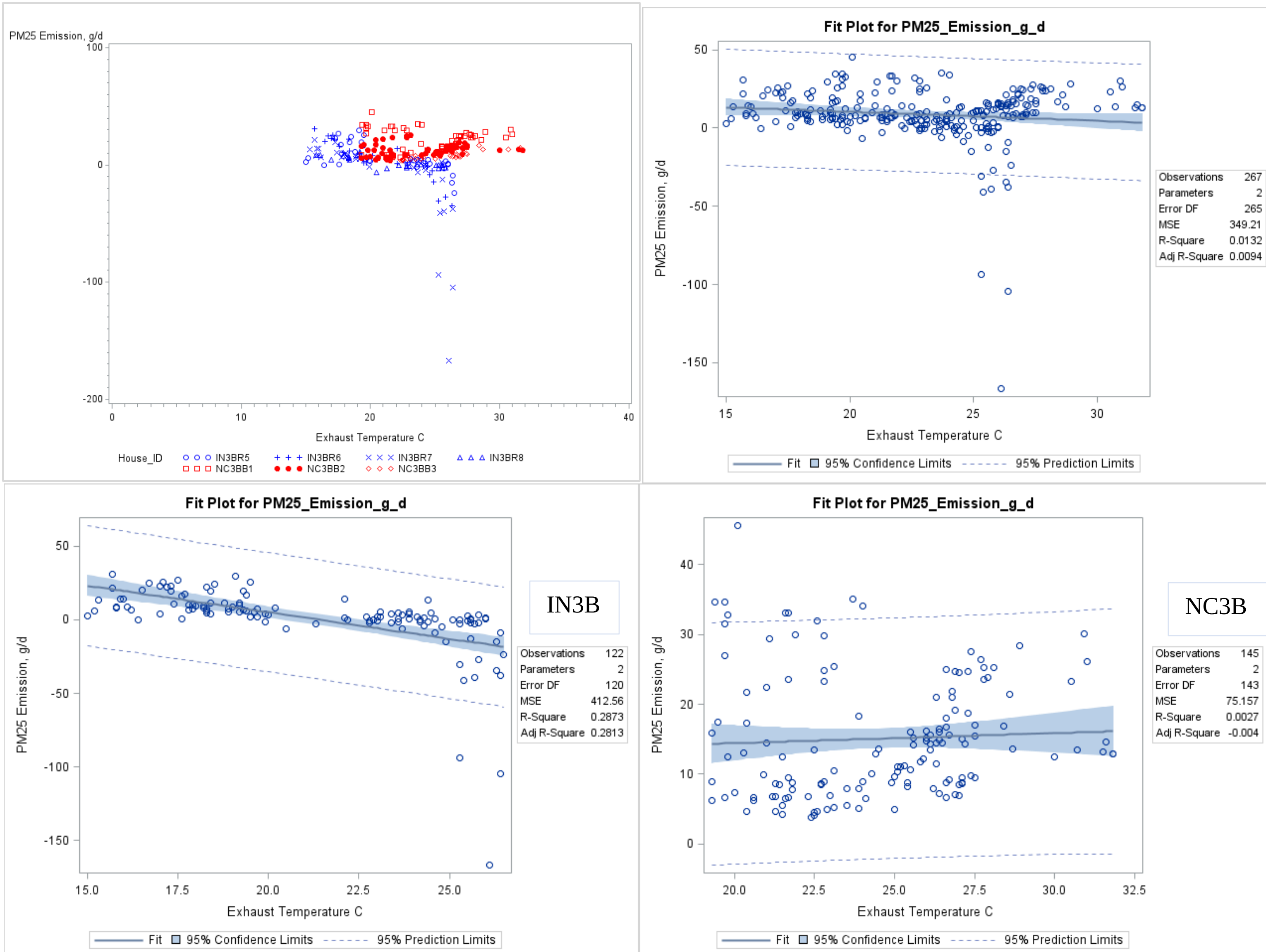


Figure E-95. Scatter plot of swine grow-finish $PM_{2.5}$ Emissions versus exhaust temperature (top left), with regression (top right), IN3B only (bottom left), NC3B only (bottom right).

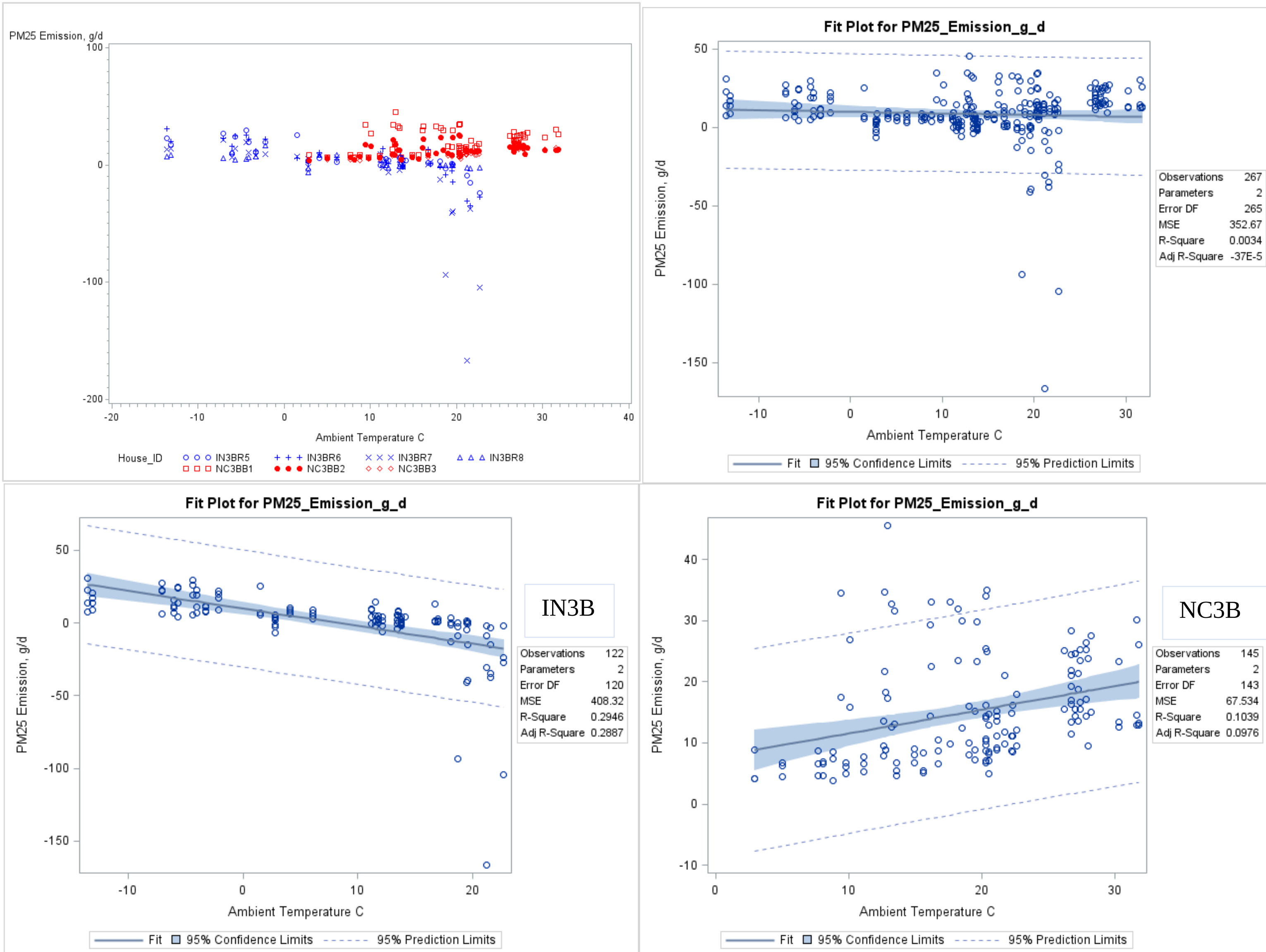


Figure E-96. Scatter plot of swine grow-finish $PM_{2.5}$ Emissions versus ambient relative temperature (top left), with regression (top right), IN3B only (bottom left), NC3B only (bottom right).

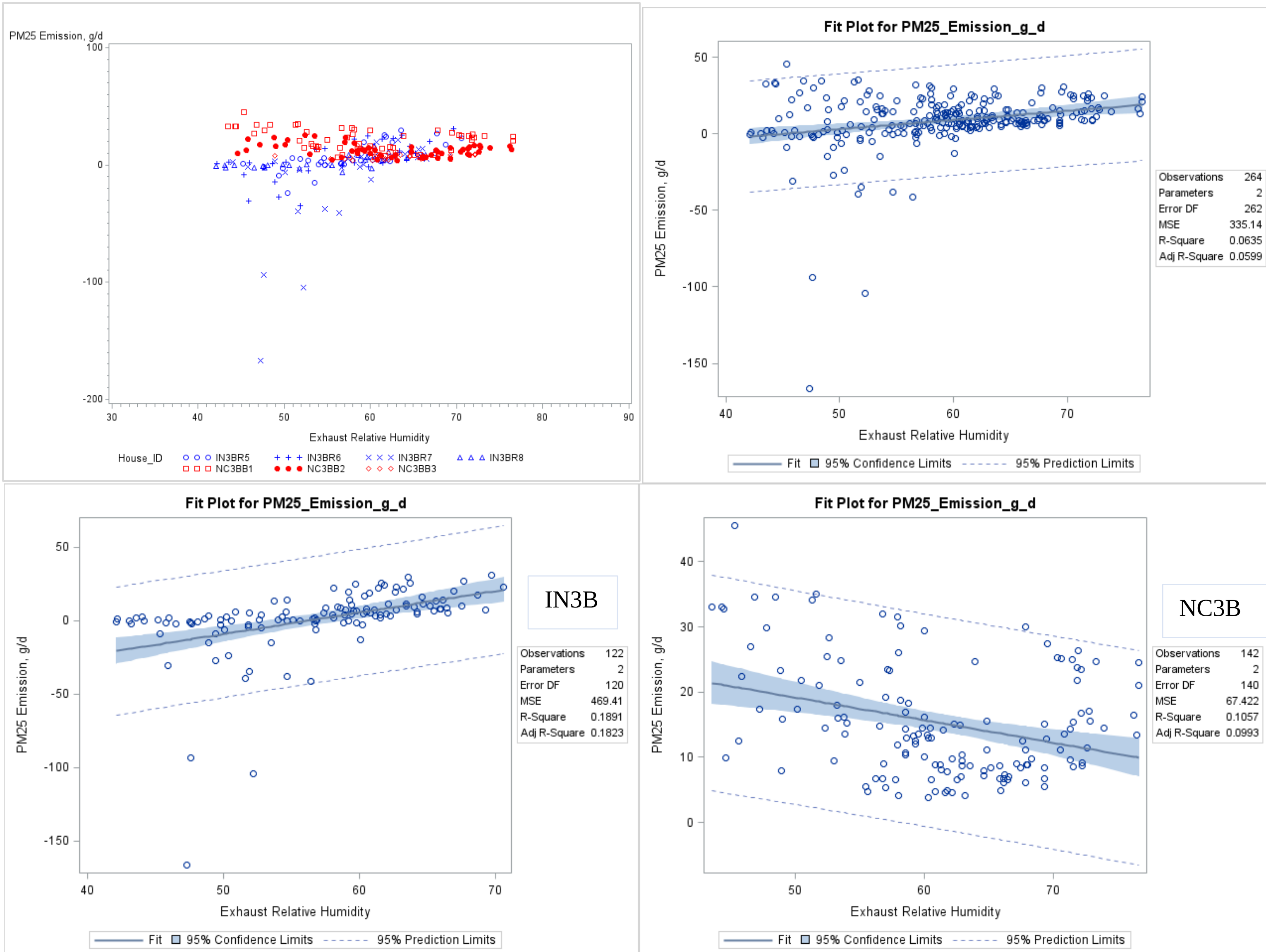


Figure E-97. Scatter plot of swine grow-finish $PM_{2.5}$ Emissions versus exhaust relative humidity (top left), with regression (top right), IN3B only (bottom left), NC3B only (bottom right).

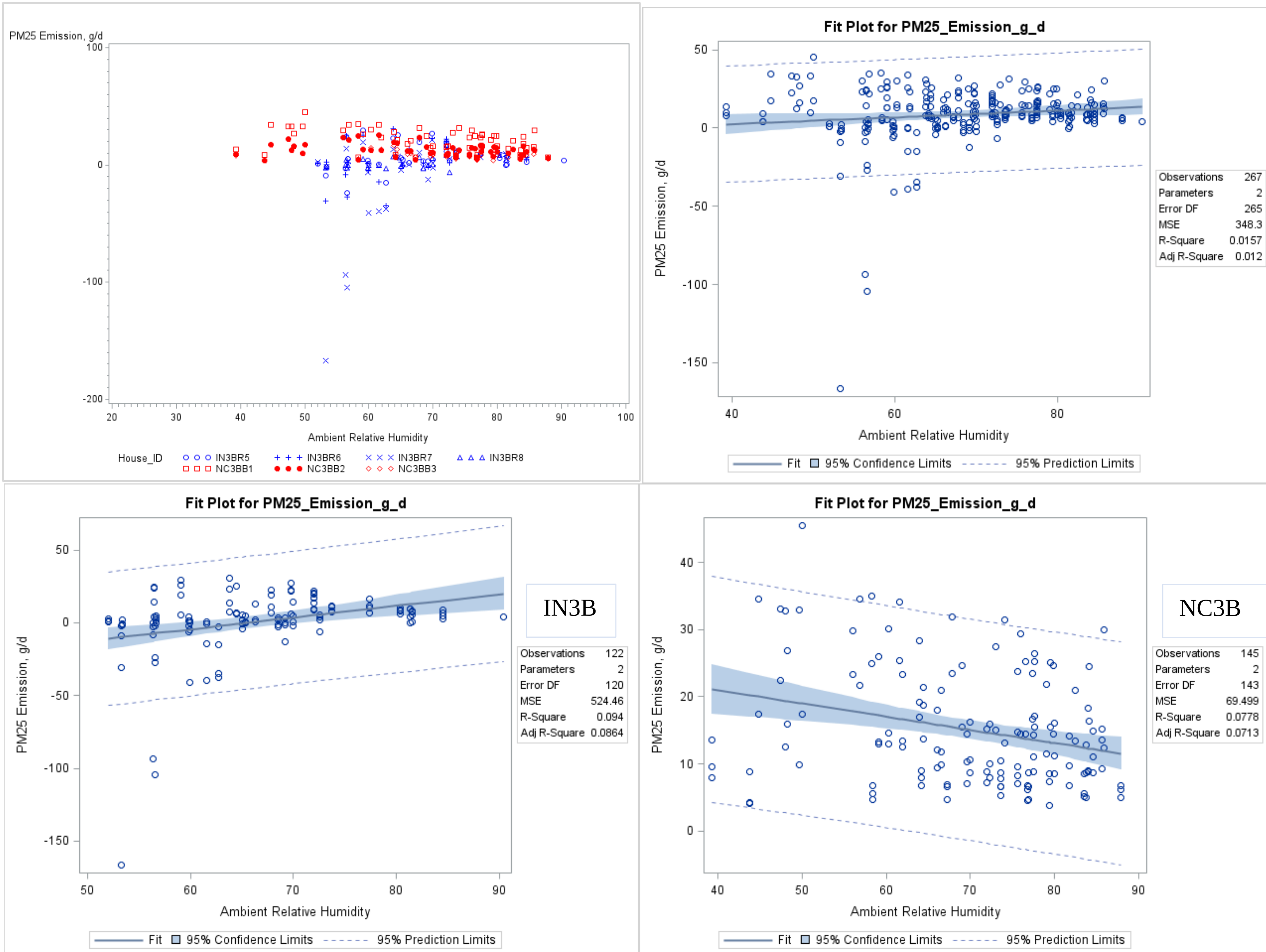


Figure E-98. Scatter plot of swine grow-finish $PM_{2.5}$ Emissions versus ambient relative humidity (top left), with regression (top right), IN3B only (bottom left), NC3B only (bottom right).

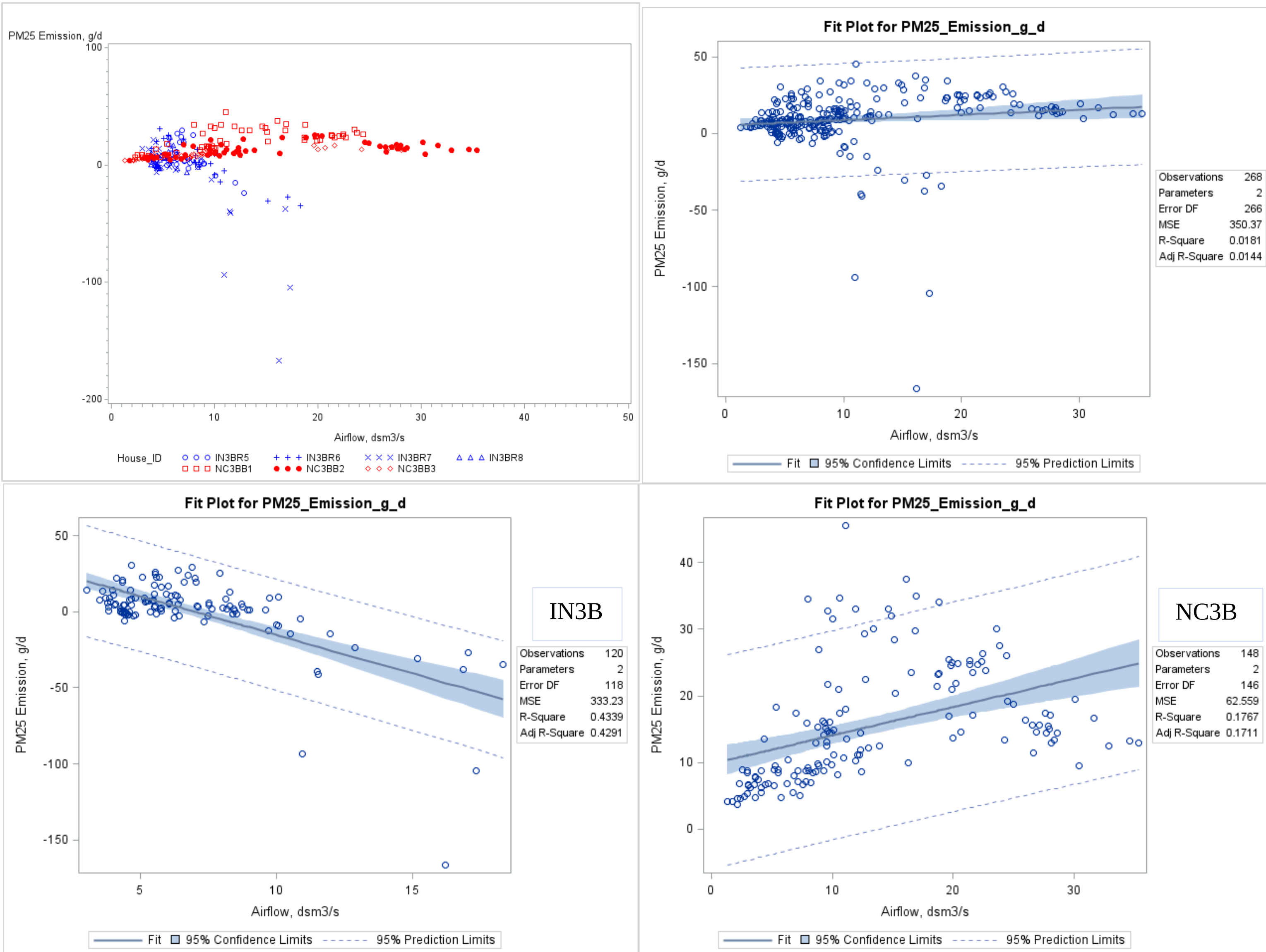


Figure E-99. Scatter plot of swine grow-finish $PM_{2.5}$ Emissions versus airflow (top left), with regression (top right), IN3B only (bottom left), NC3B only (bottom right).

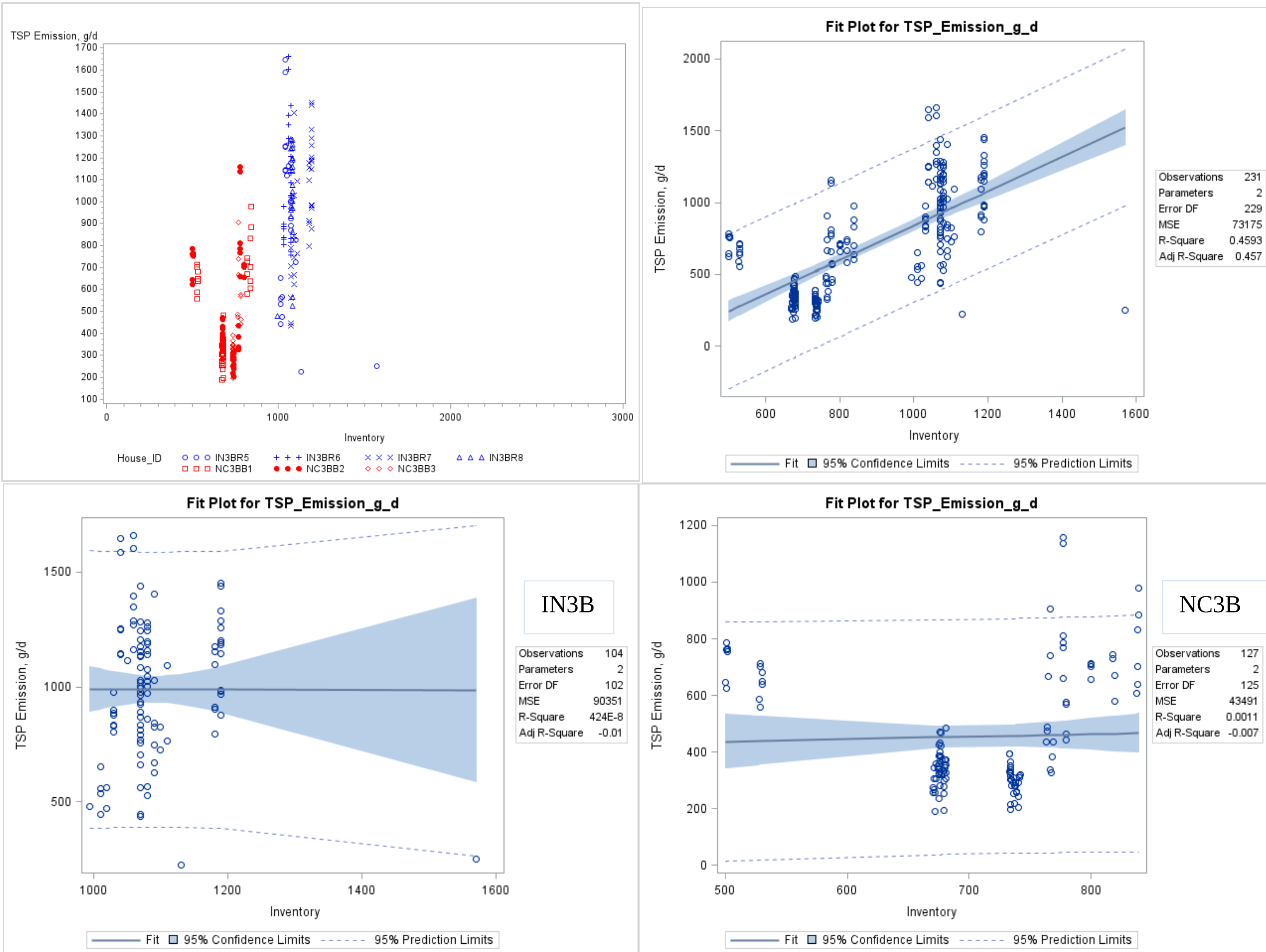


Figure E-100. Scatter plot of swine grow-finish TSP Emissions versus Inventory (top left), with regression (top right), IN3B only (bottom left), NC3B only (bottom right).

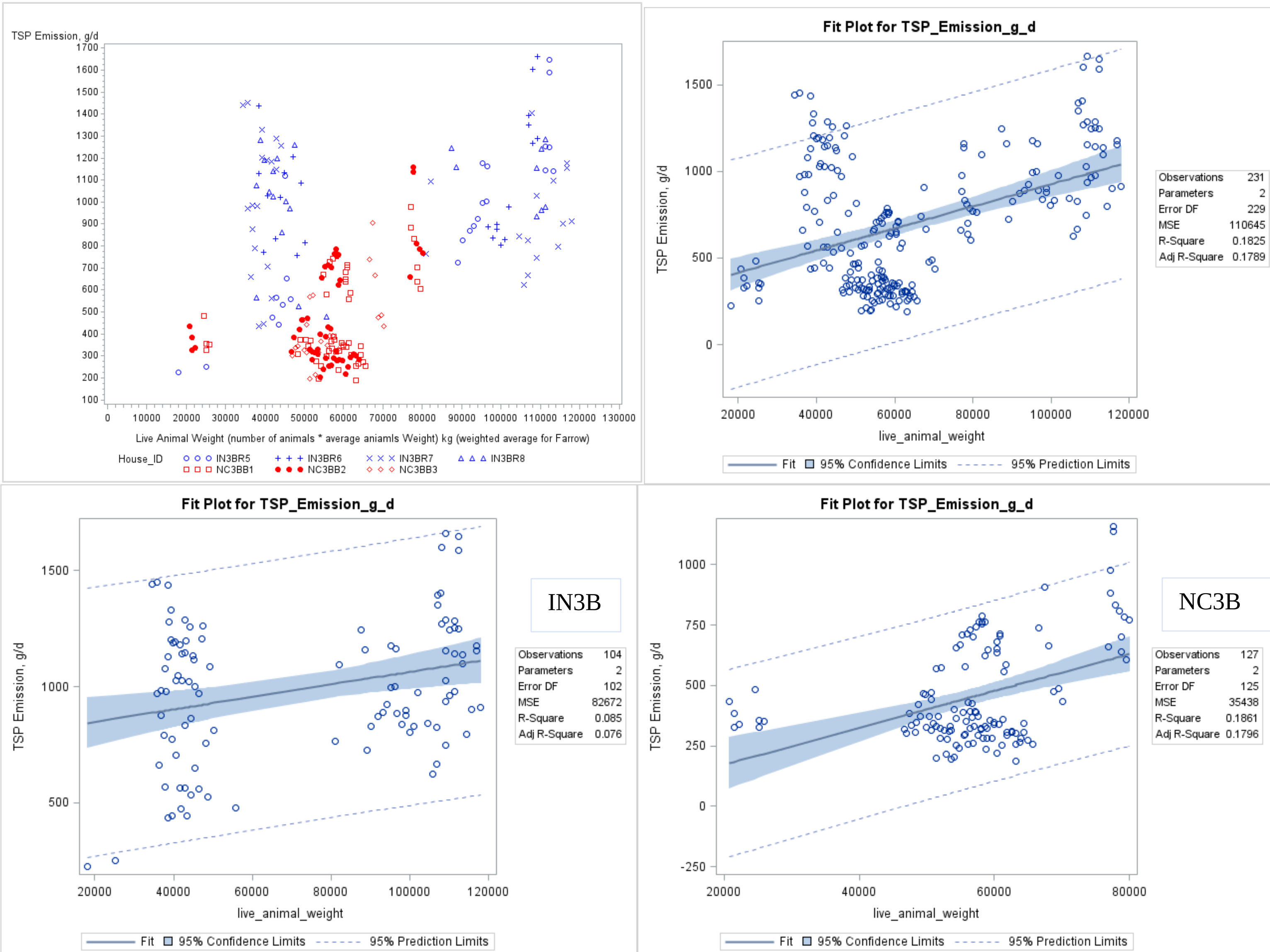


Figure E-101. Scatter plot of swine grow-finish TSP Emissions versus live animal weight (top left), with regression (top right), IN3B only (bottom left), NC3B only (bottom right).

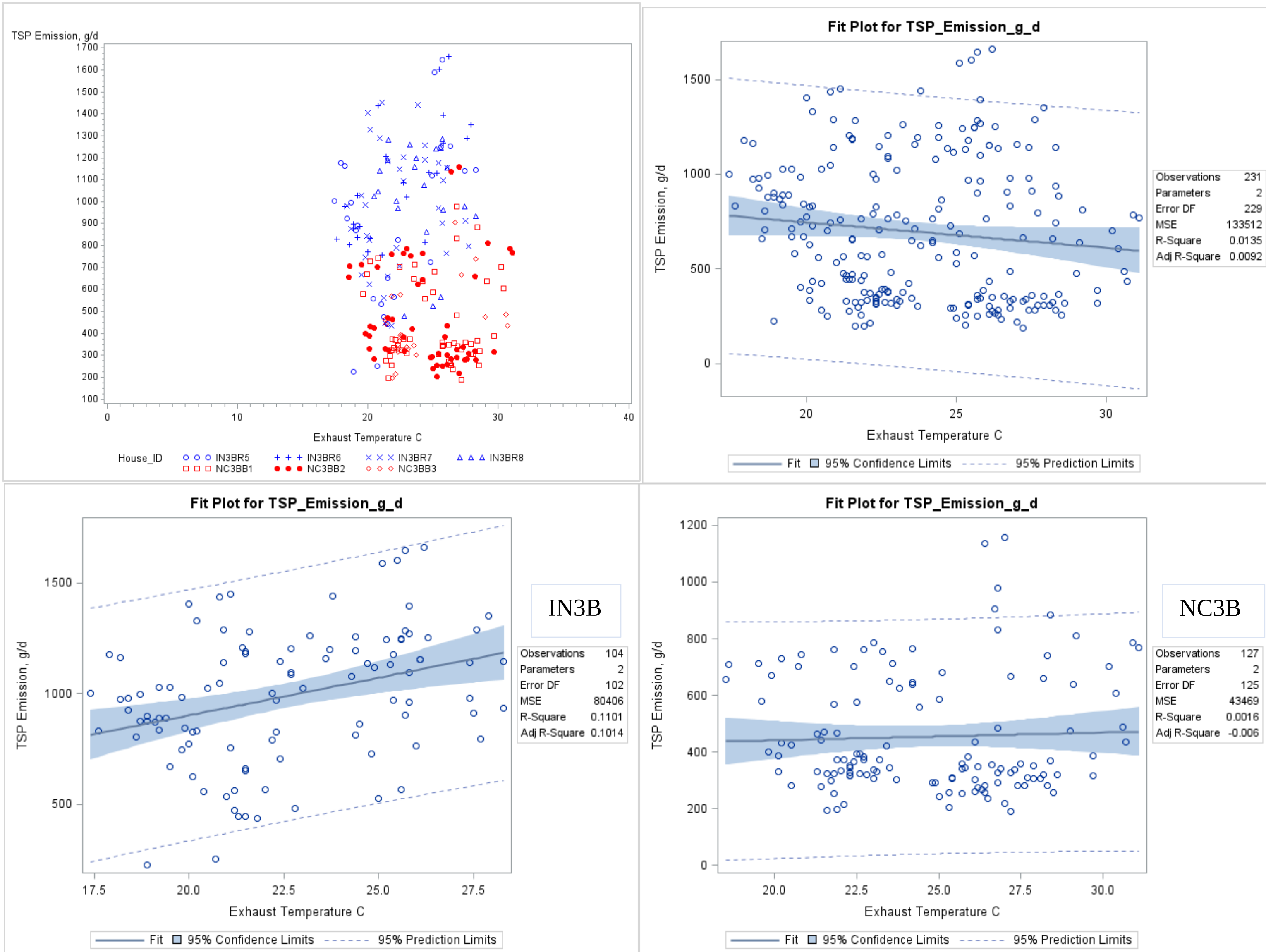


Figure E-102. Scatter plot of swine grow-finish TSP Emissions versus exhaust temperature (top left), with regression (top right), IN3B only (bottom left), NC3B only (bottom right).

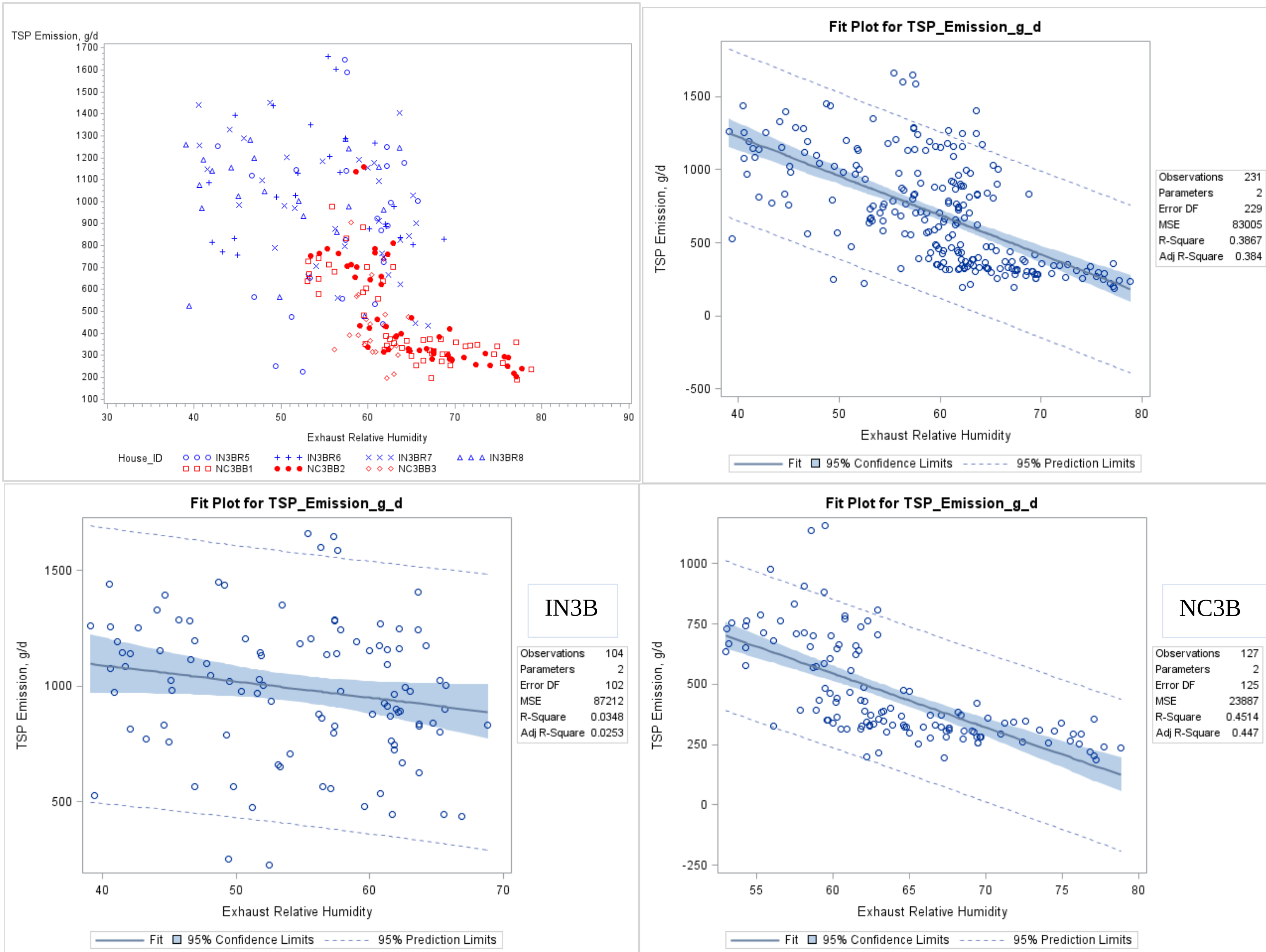


Figure E-103. Scatter plot of swine grow-finish TSP Emissions versus exhaust relative humidity (top left), with regression (top right), IN3B only (bottom left), NC3B only (bottom right).

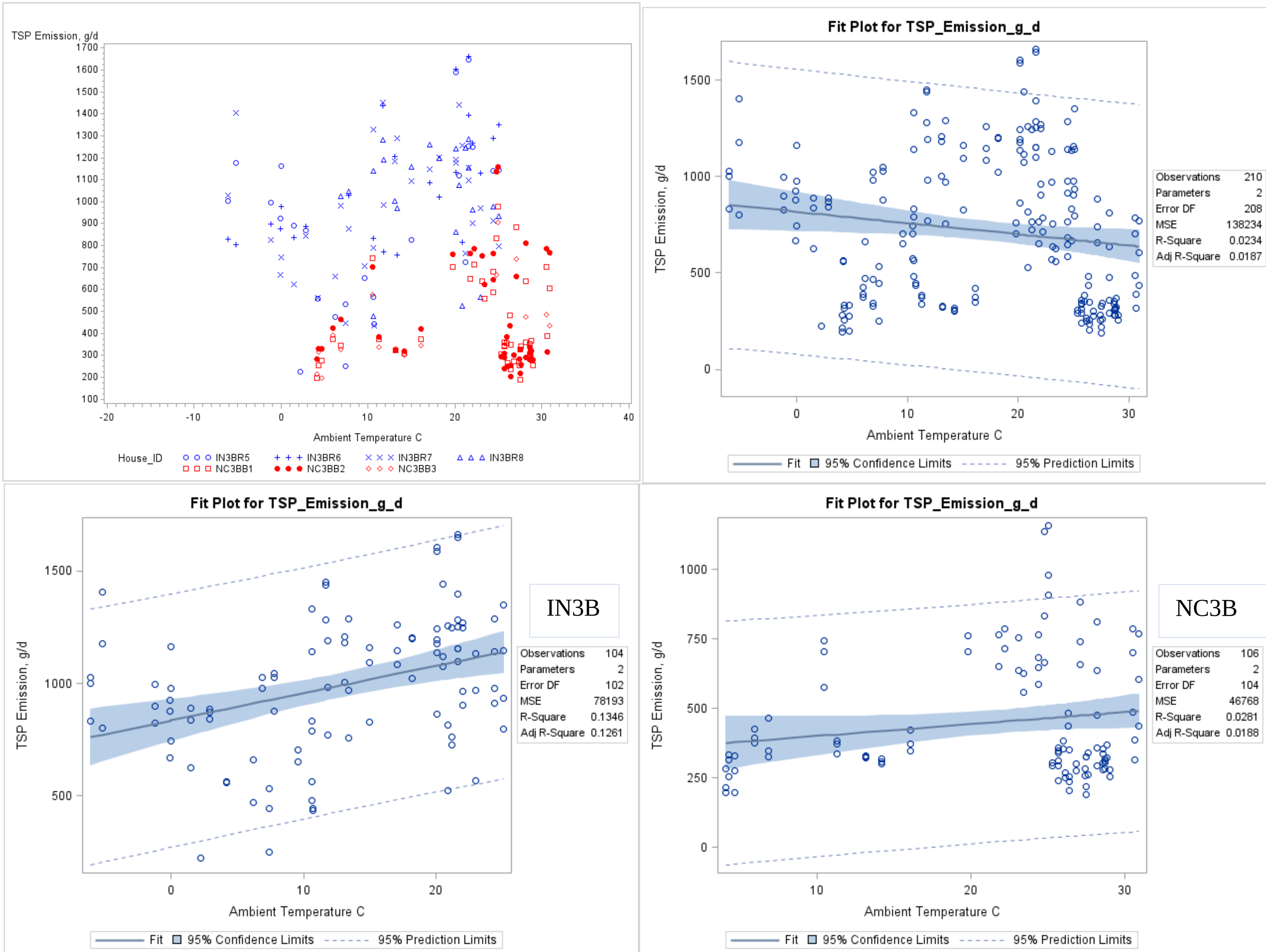


Figure E-104. Scatter plot of swine grow-finish TSP Emissions versus ambient temperature (top left), with regression (top right), IN3B only (bottom left), NC3B only (bottom right).

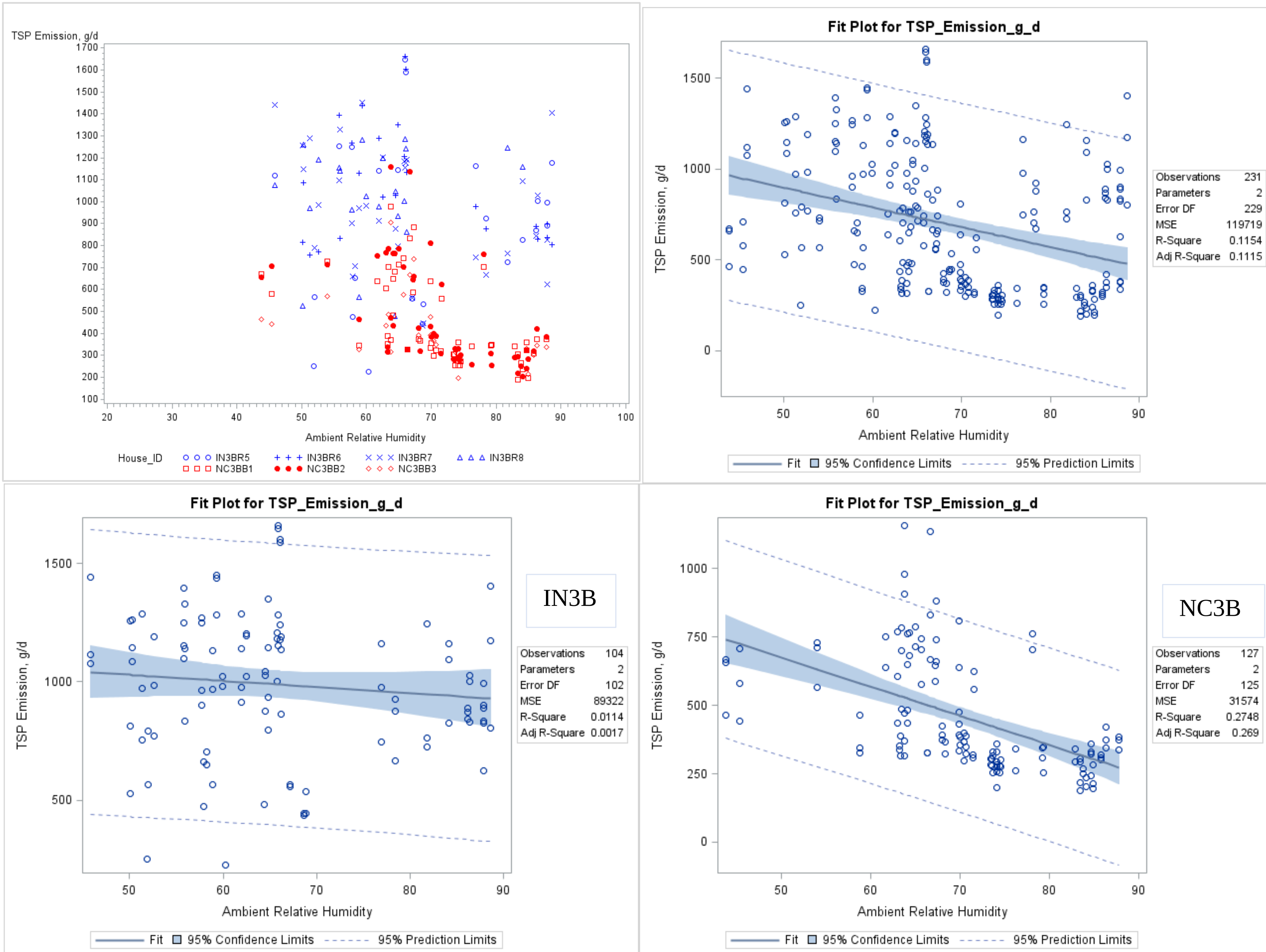


Figure E-105. Scatter plot of swine grow-finish TSP Emissions versus ambient relative humidity (top left), with regression (top right), IN3B only (bottom left), NC3B only (bottom right).

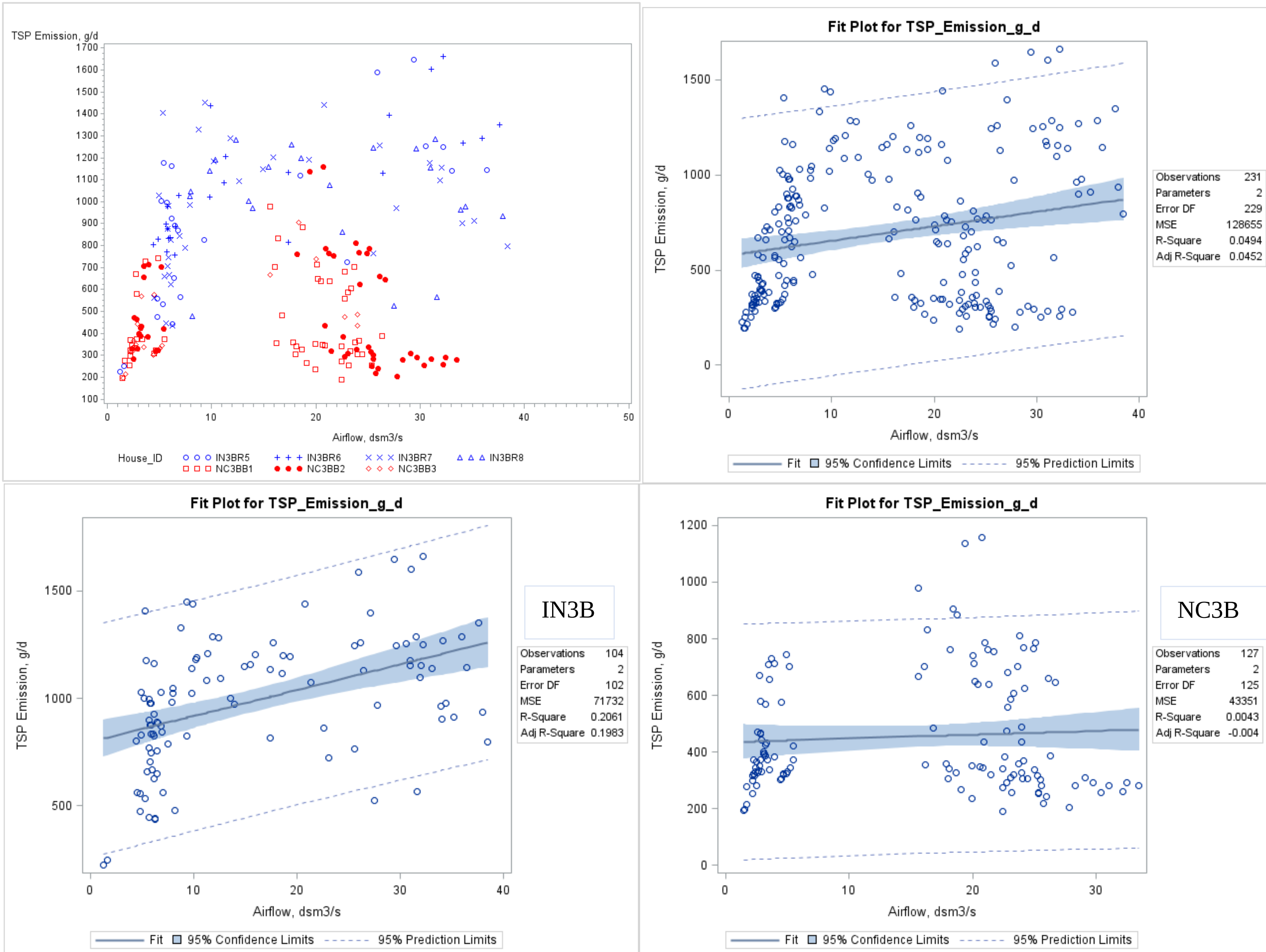


Figure E-106. Scatter plot of swine grow-finish TSP Emissions versus airflow (top left), with regression (top right), IN3B only (bottom left), NC3B only (bottom right).

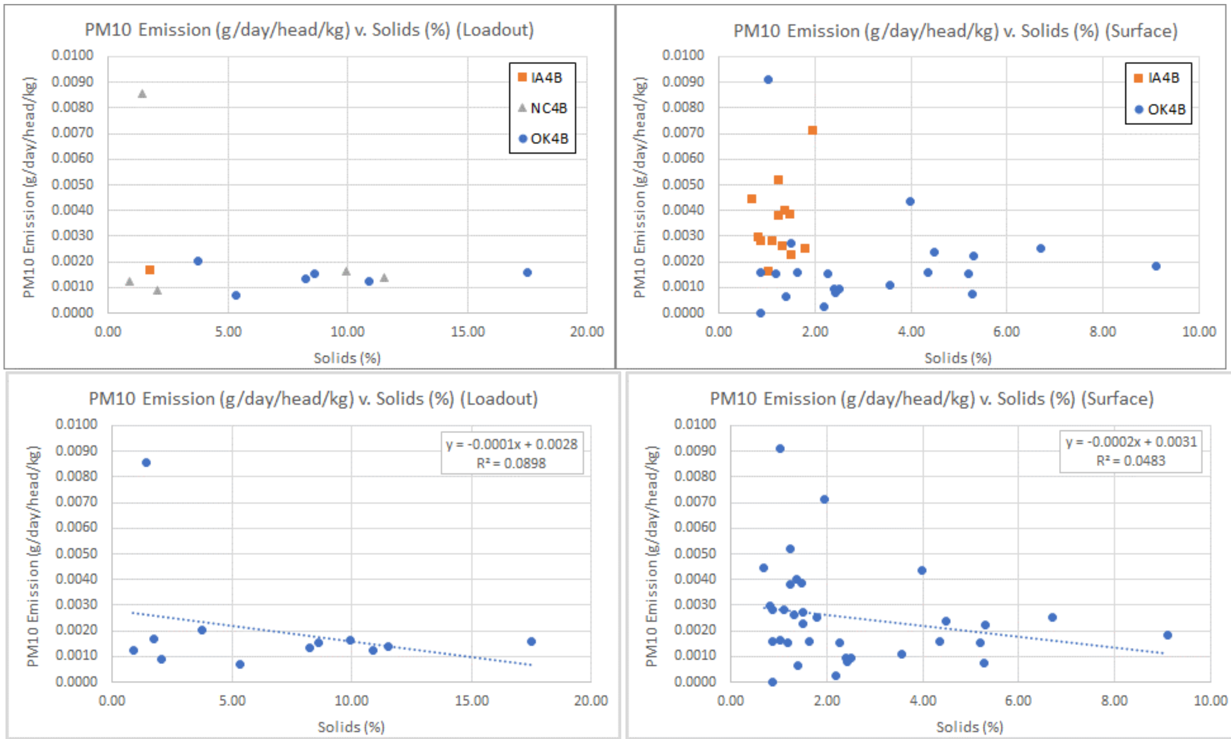


Figure E-107. Scatter plot of breeding and gestation PM_{10} emissions versus percent solids.
Scatter plot for loadout (top left) and surface manure (top right). Plot with linear regression for loadout (bottom, left) and surface(bottom right).

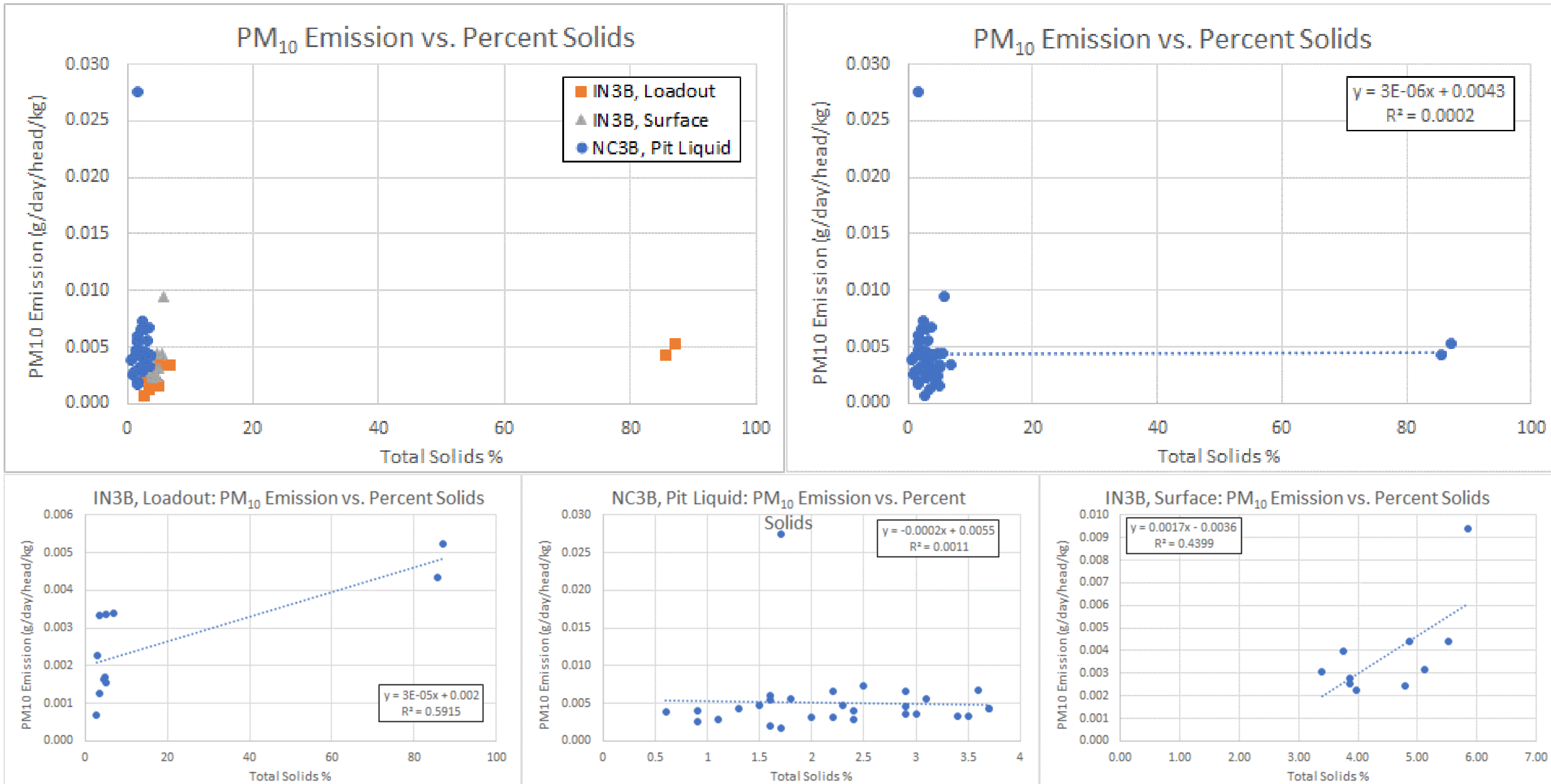


Figure E-108. Scatter plot of grow-finish PM_{10} emissions versus percent solids.
Scatter plot for all samples (top left) and with regression (top right). Plot with linear regression for loadout (bottom, left), pit liquid (bottom center), and surface(bottom right).

Appendix F Model one-to-one Plots

List of Figures

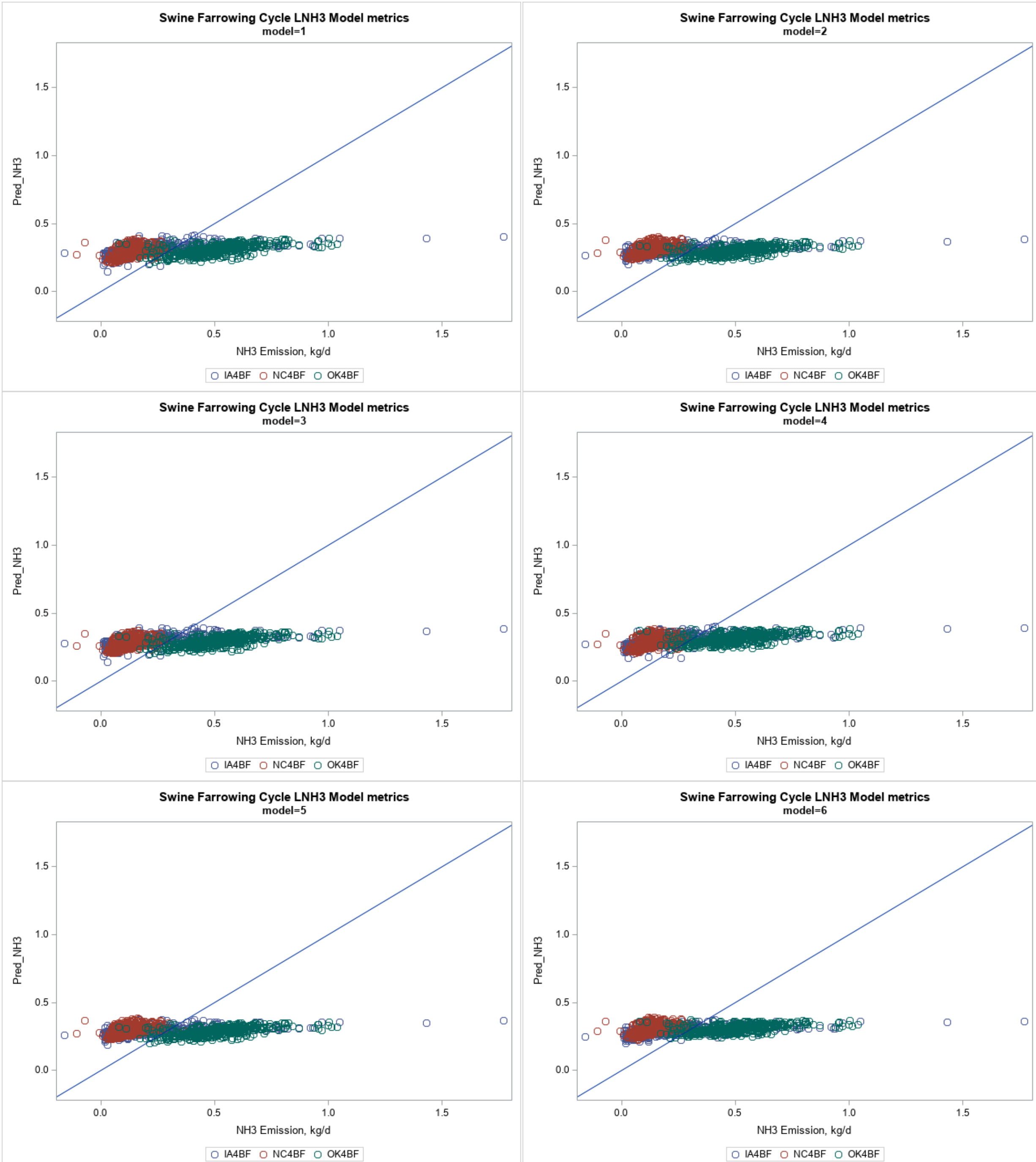
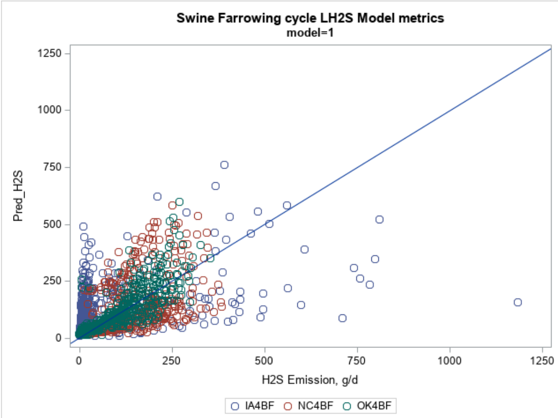
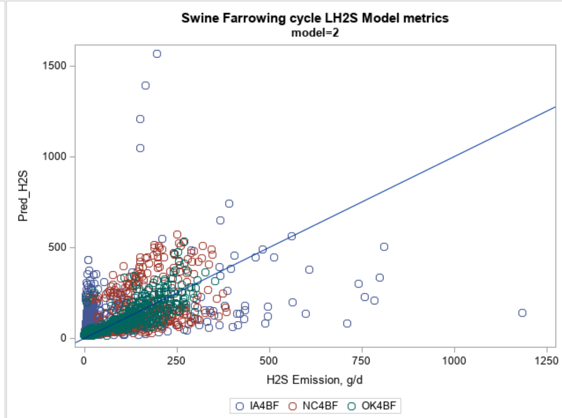
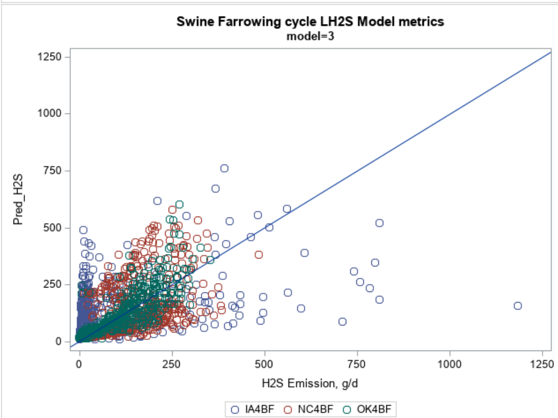


Figure F-109 Farrowing room NH_3 model results model one-to-one plots.


Swine Farrowing cycle LH2S Model metrics
model=1
Pred_H2S
H2S Emission, g/d
IA4BF NC4BF OK4BF


Swine Farrowing cycle LH2S Model metrics
model=2
Pred_H2S
H2S Emission, g/d
IA4BF NC4BF OK4BF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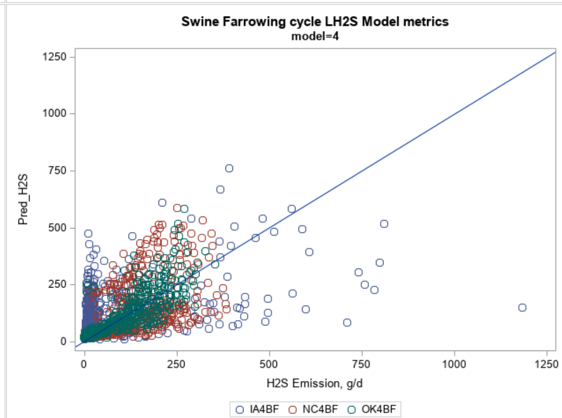
model=3
Pred_H2S
H2S Emission, g/d
IA4BF NC4BF OK4BF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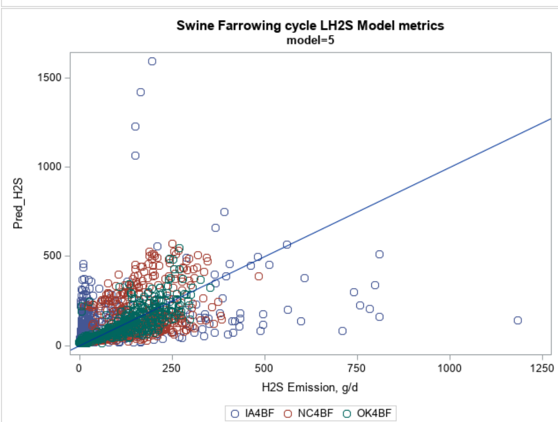
model=4
Pred_H2S
H2S Emission, g/d
IA4BF NC4BF OK4BF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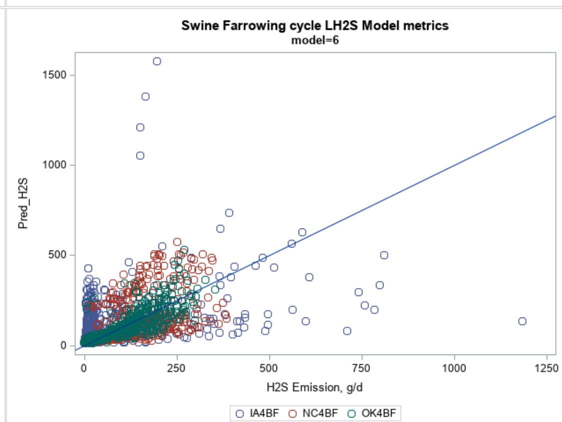
model=5
Pred_H2S
H2S Emission, g/d
IA4BF NC4BF OK4BF


Swine Farrowing cycle LH2S Model metrics
model=6
Pred_H2S
H2S Emission, g/d
IA4BF NC4BF OK4BF

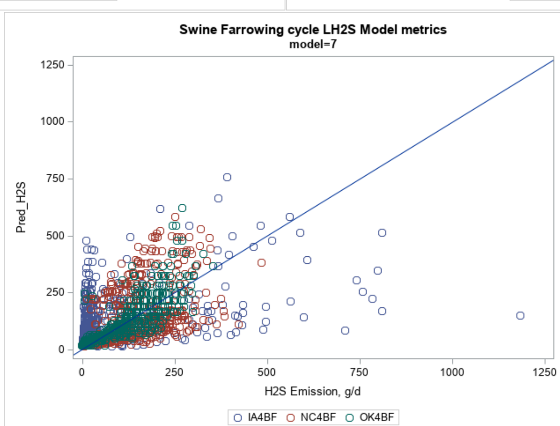

Swine Farrowing cycle LH2S Model metrics
model=7
Pred_H2S
H2S Emission, g/d
IA4BF NC4BF OK4BF

Figure F-110 Farrowing room H_2S model results model one-to-one plots.

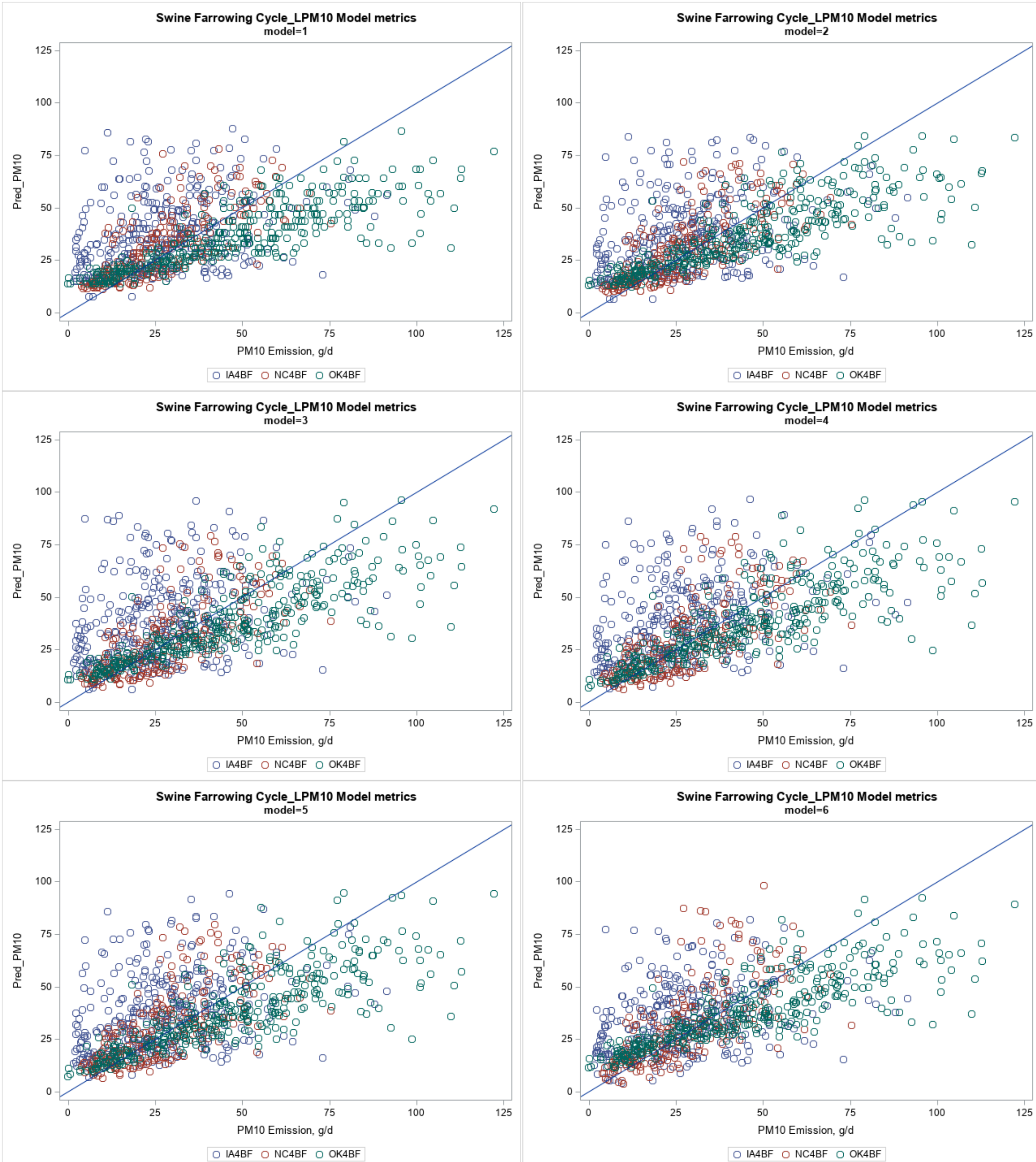


Figure F-111 Farrowing room PM_{10} one-to-one plots models 1 through 6.

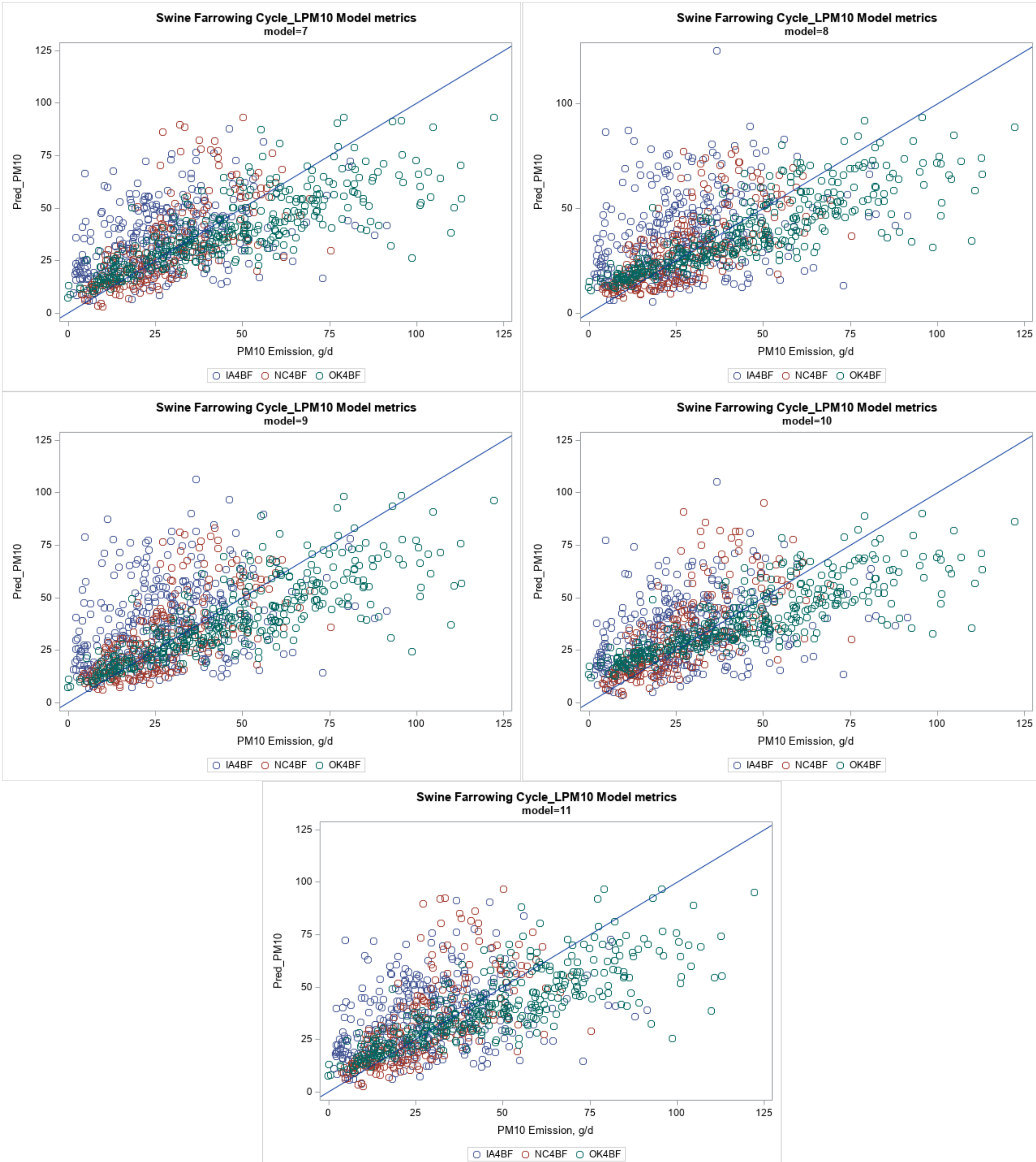


Figure F-112 Farrowing room PM_{10} one-to-one plots models 7 through 11.

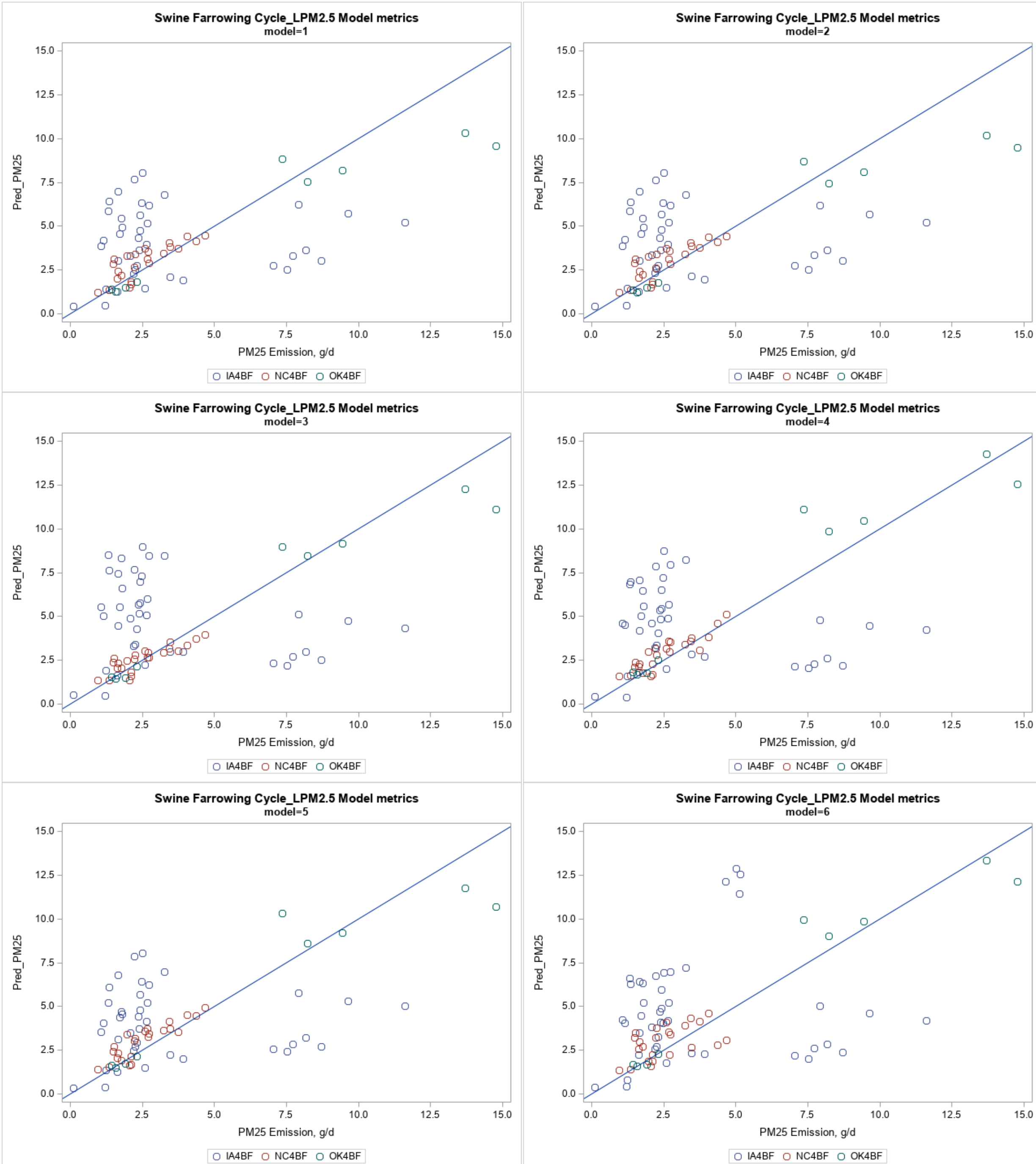


Figure F-113 Farrowing room $PM_{2.5}$ one-to-one plots models 1 through 6.

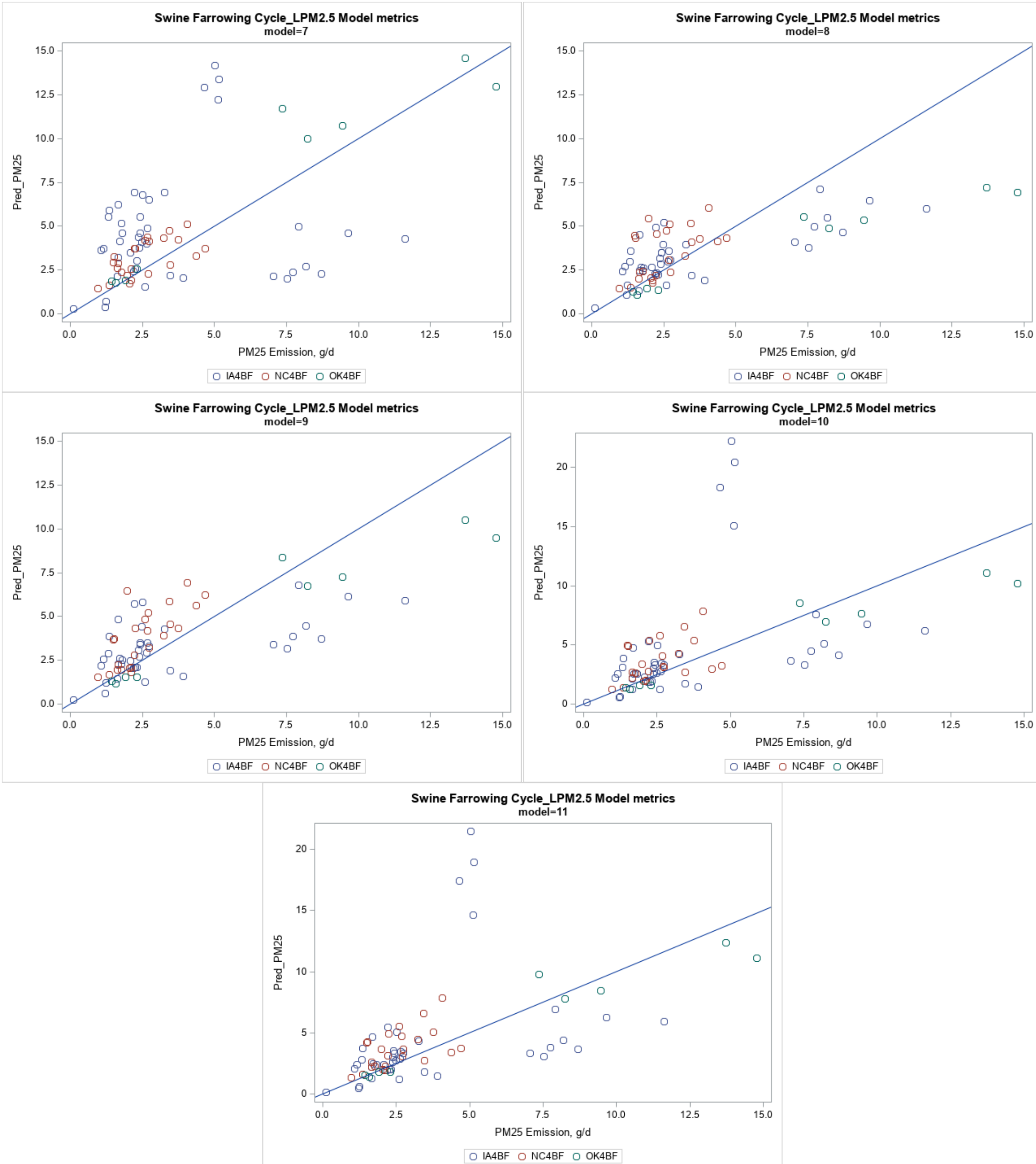


Figure F-114 Farrowing room $PM_{2.5}$ one-to-one plots for models 7 through 11.

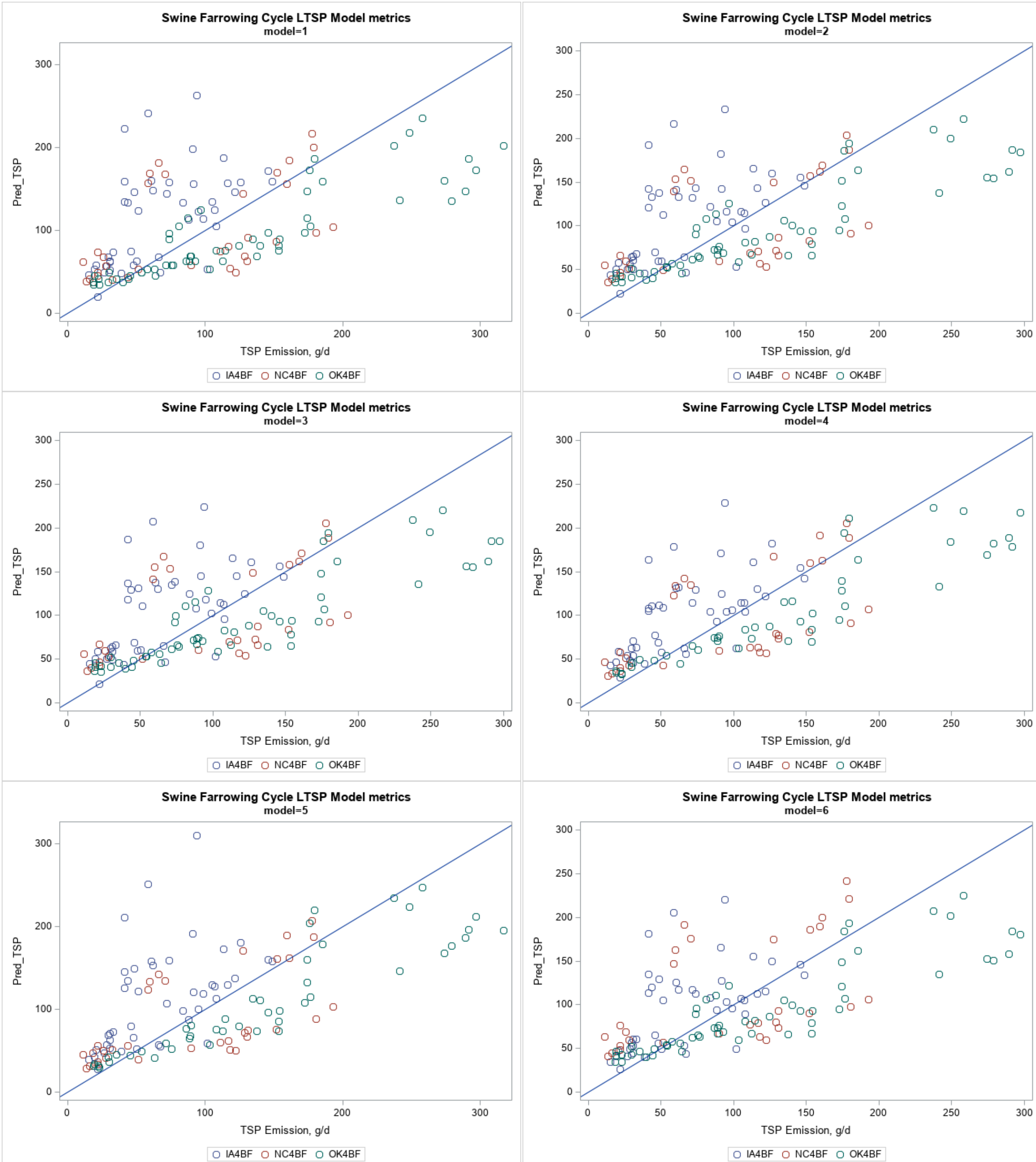


Figure F-115 Farrowing TSP one-to-one plots form models 1 through 6.

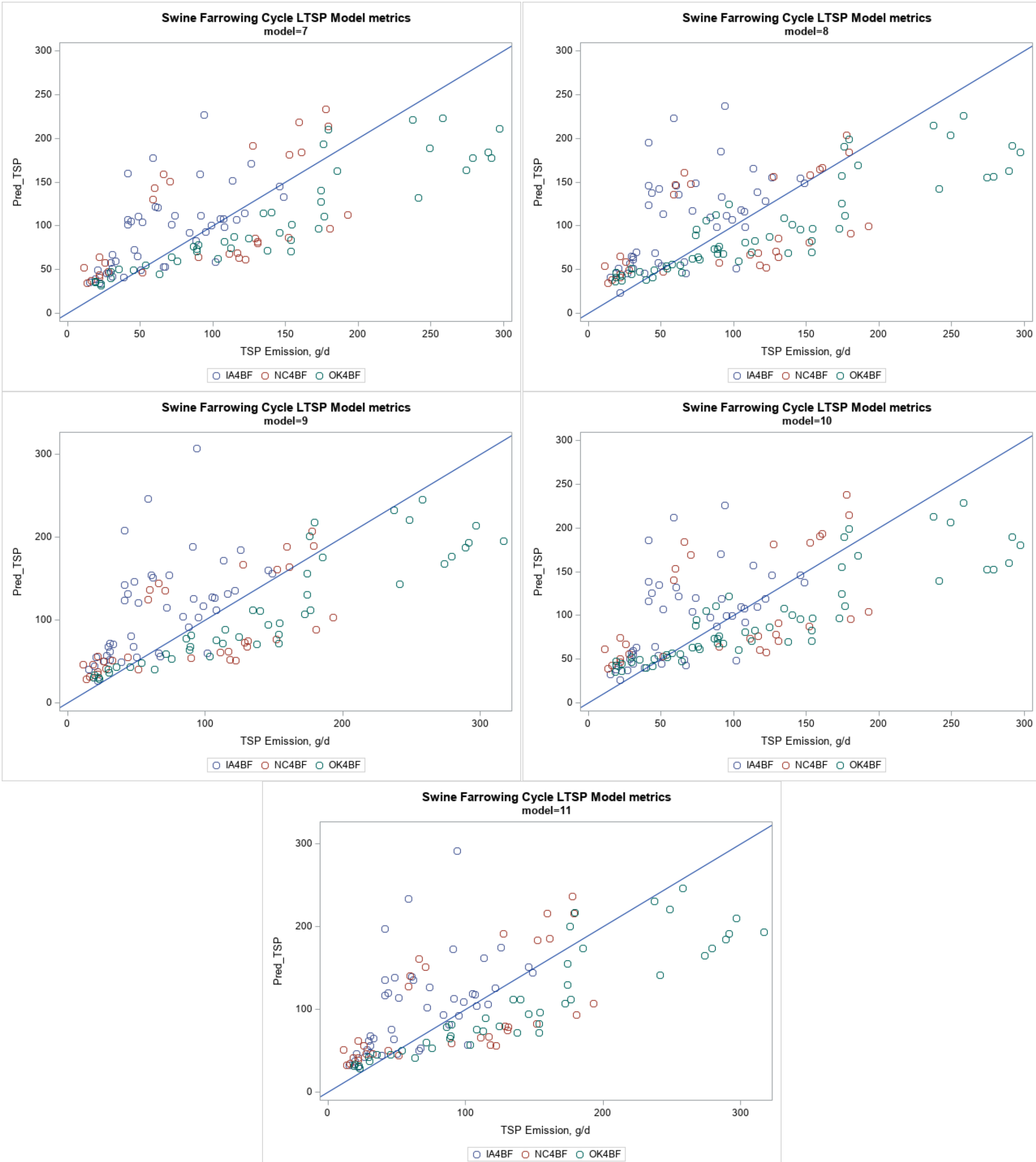


Figure F-116 Farrowing TSP one-to-one plots form models 7 through 11.

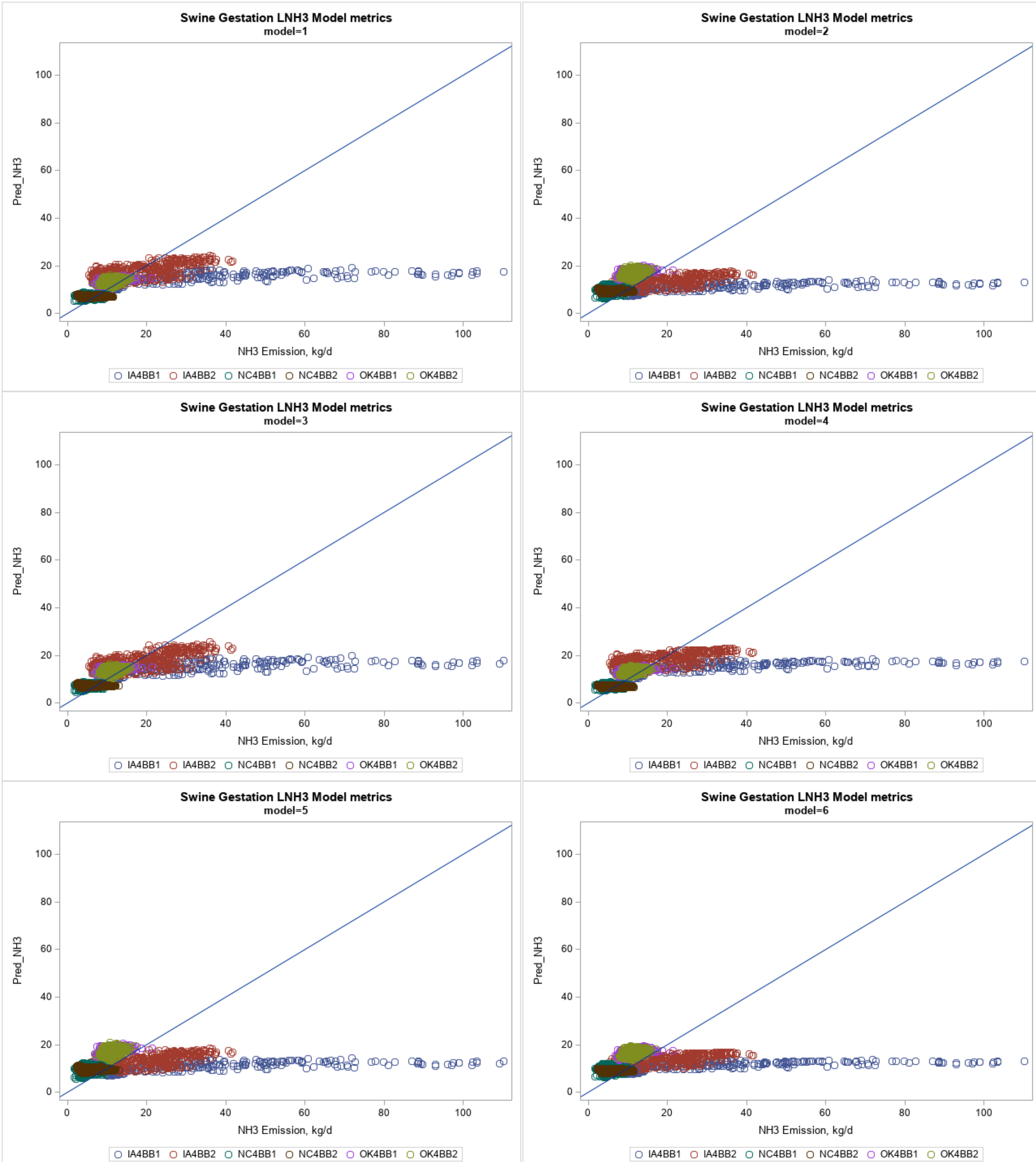


Figure F-117 Gestation NH_3 no pit model one-to-one plots.

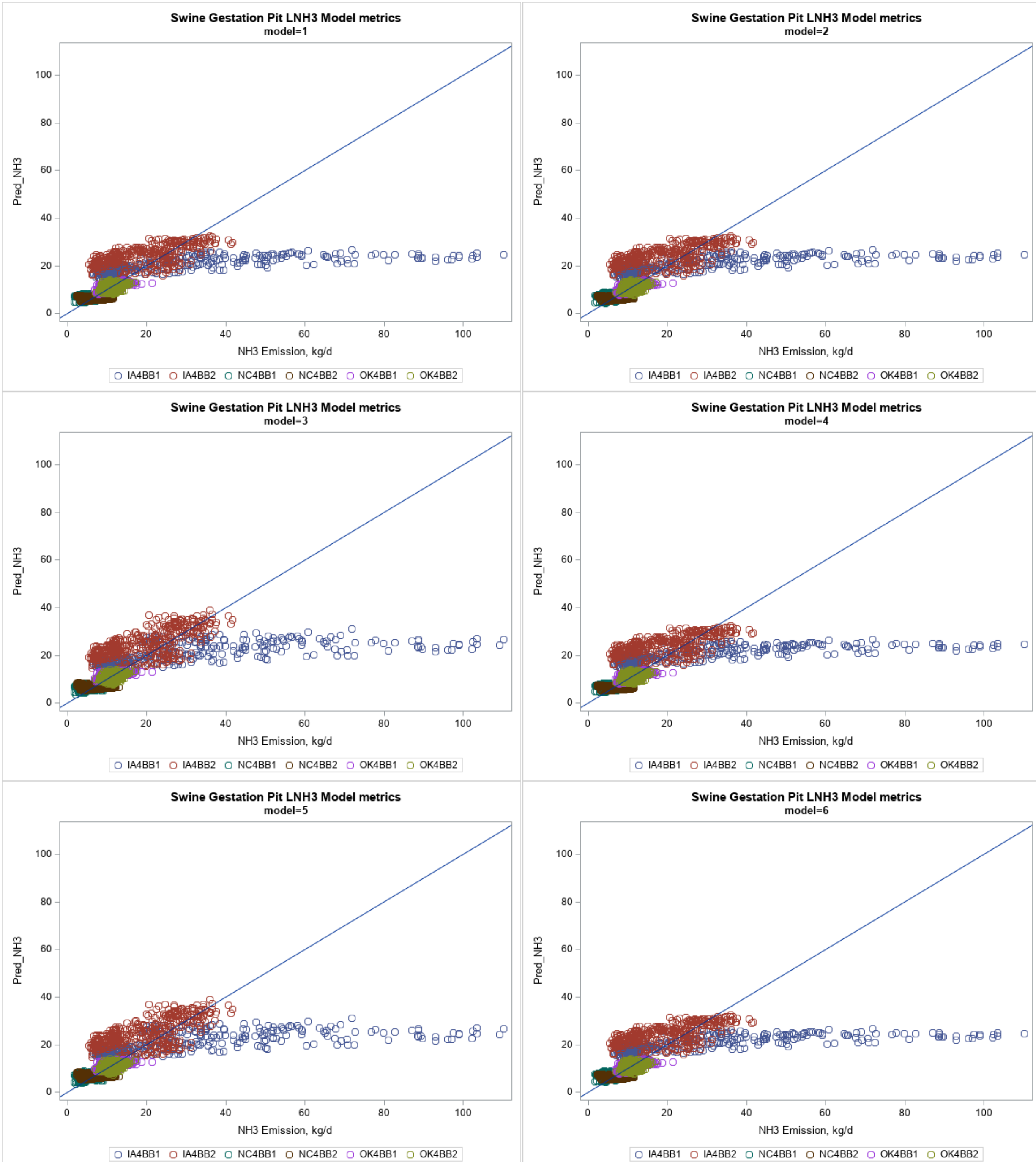


Figure F-118. Gestation NH_3 pit model one-to-one plots.

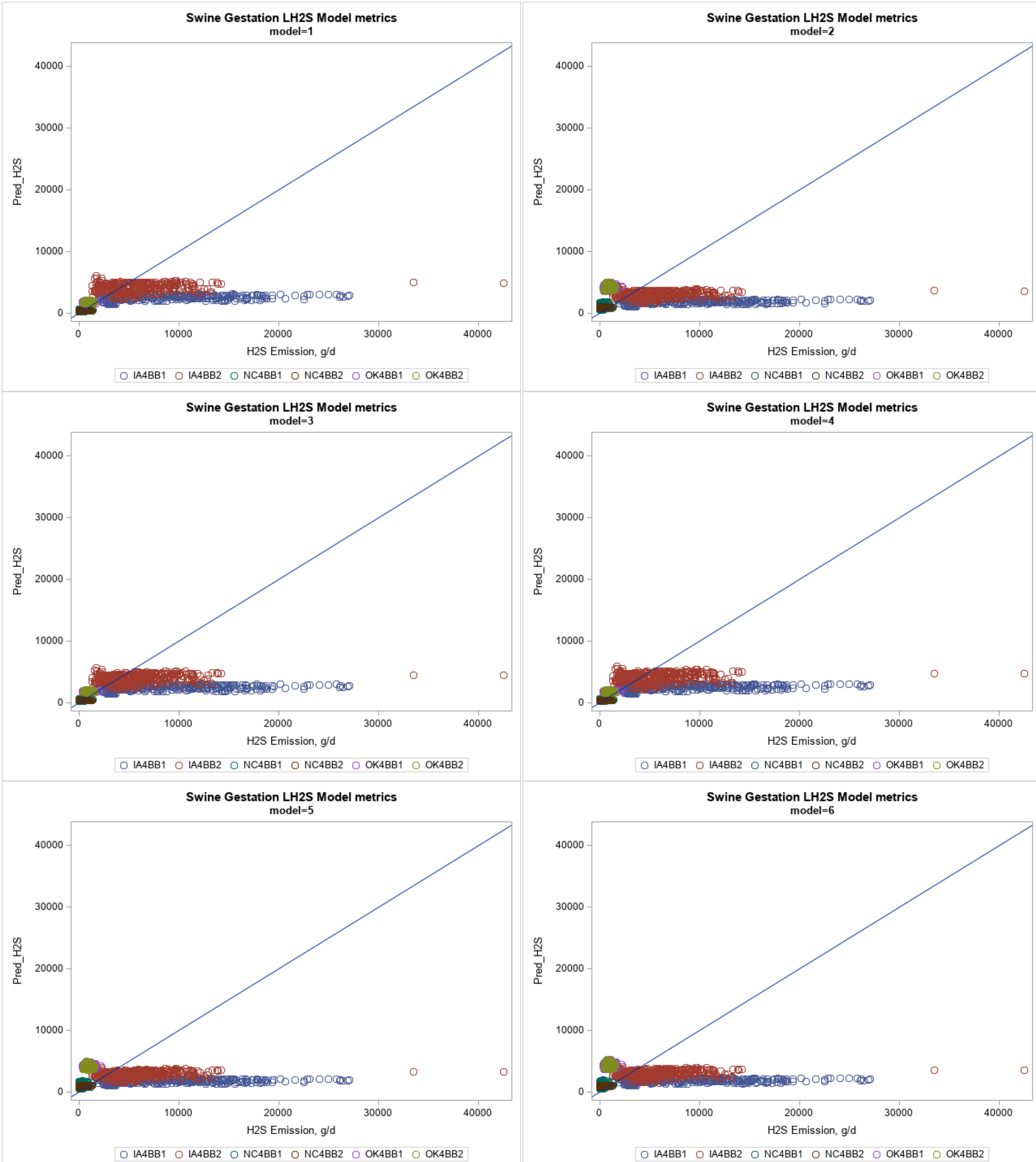


Figure F-119 Gestation H_2S no pit model one-to-one plots.

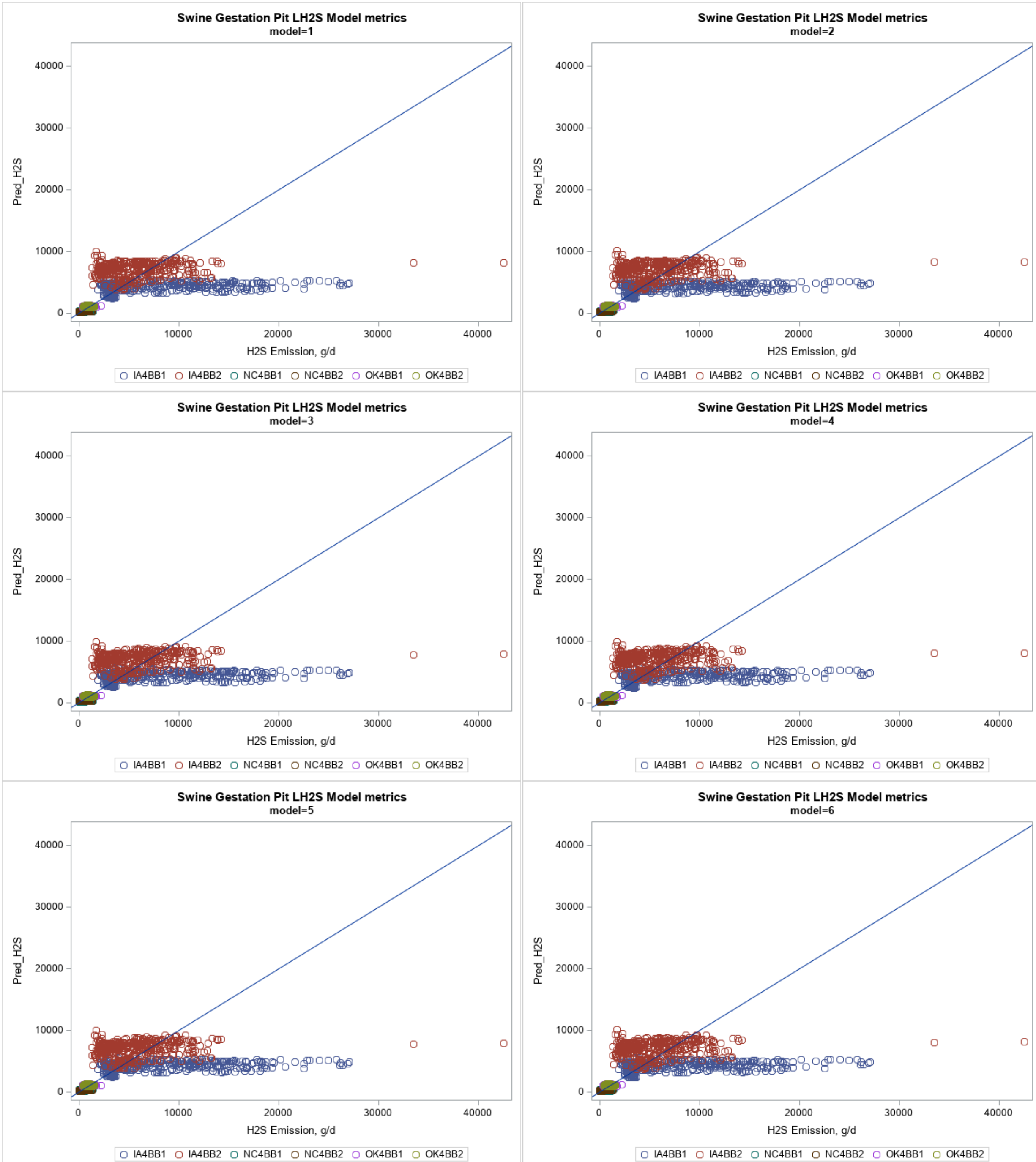


Figure F-120. Gestation H_2S pit model one-to-one plots.

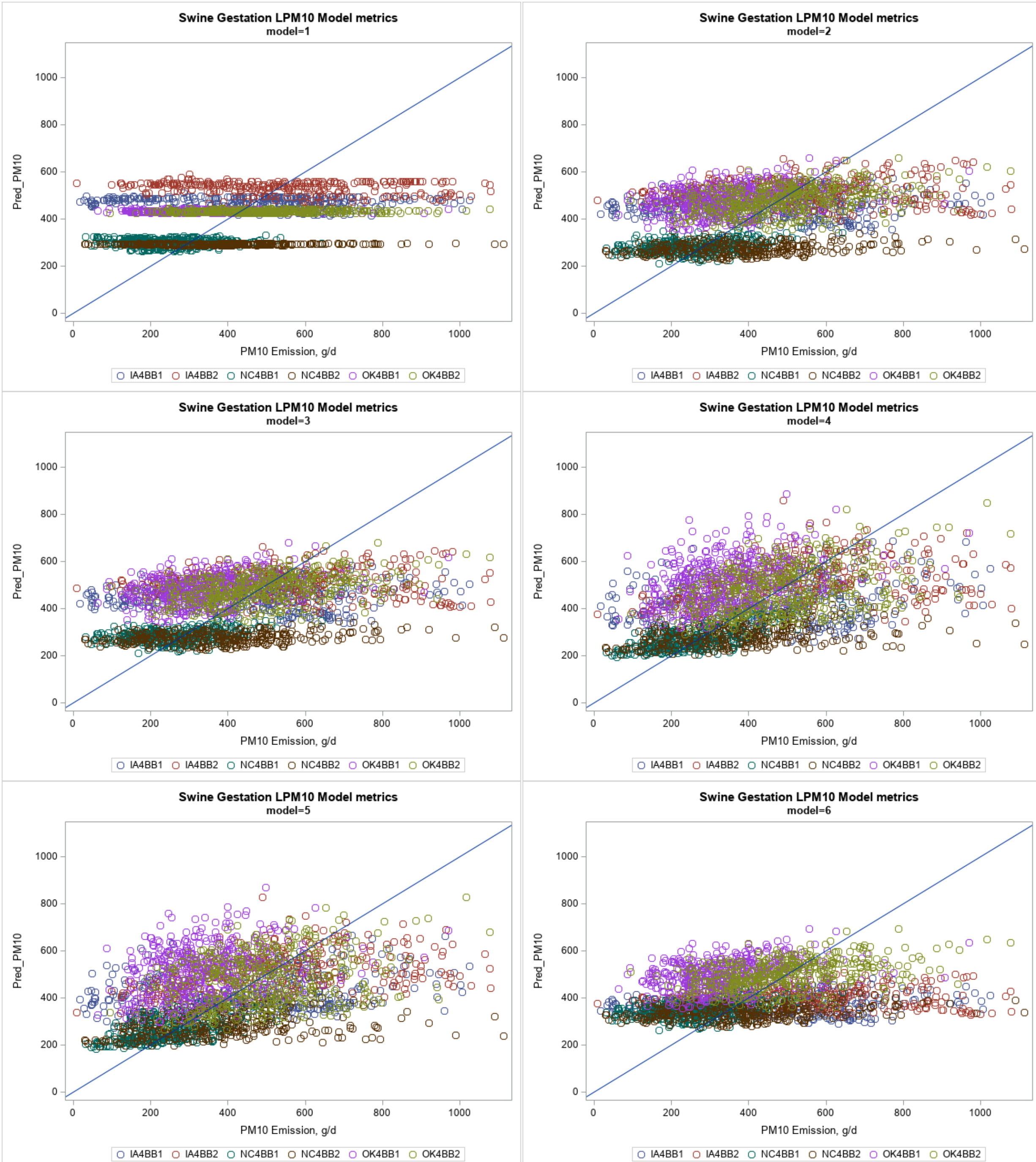


Figure F-121 Gestation PM_{10} one-to-one plots for models 1 through 6.

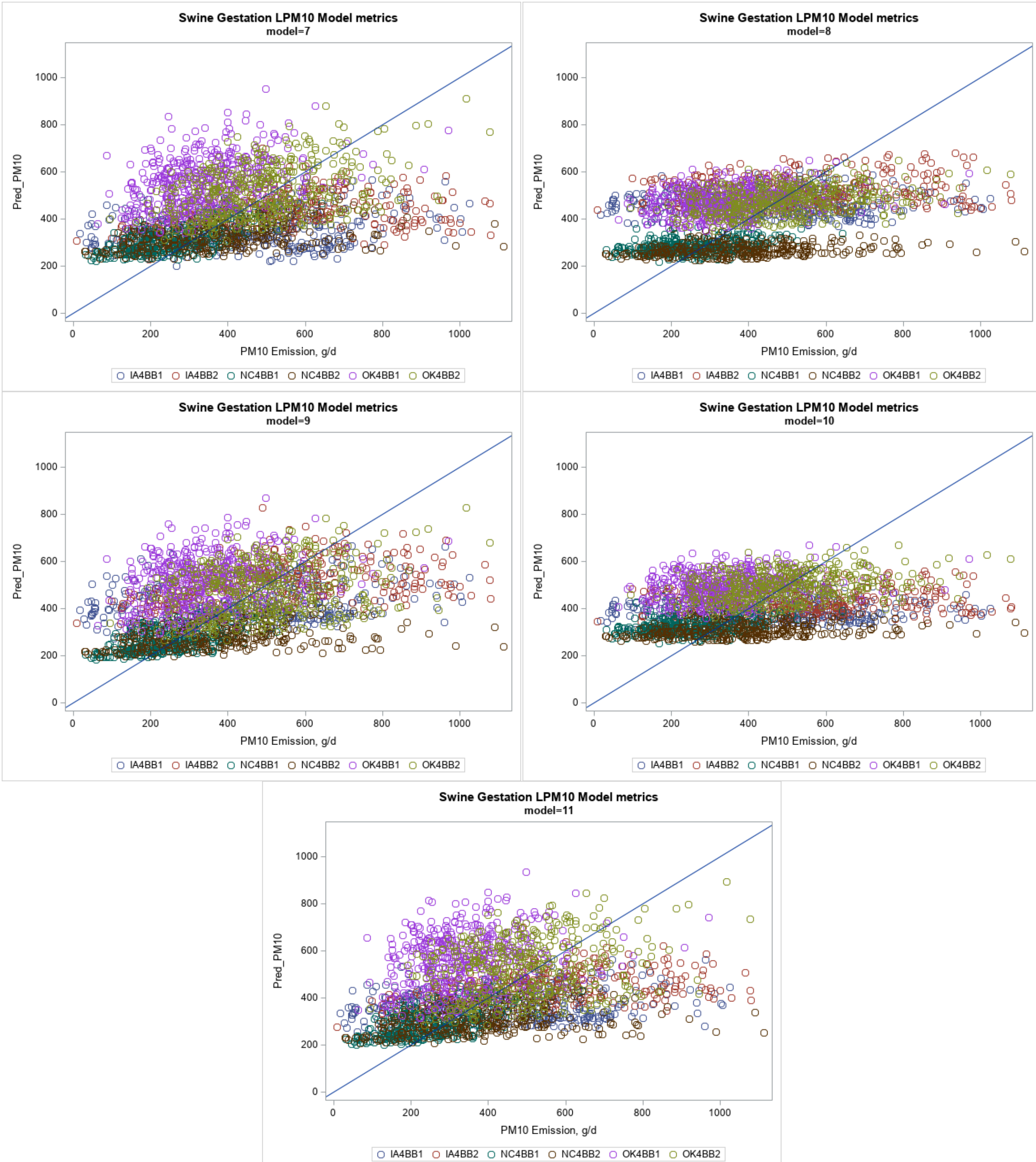


Figure F-122 Gestation PM_{10} one-to-one plots for models 7 through 11.

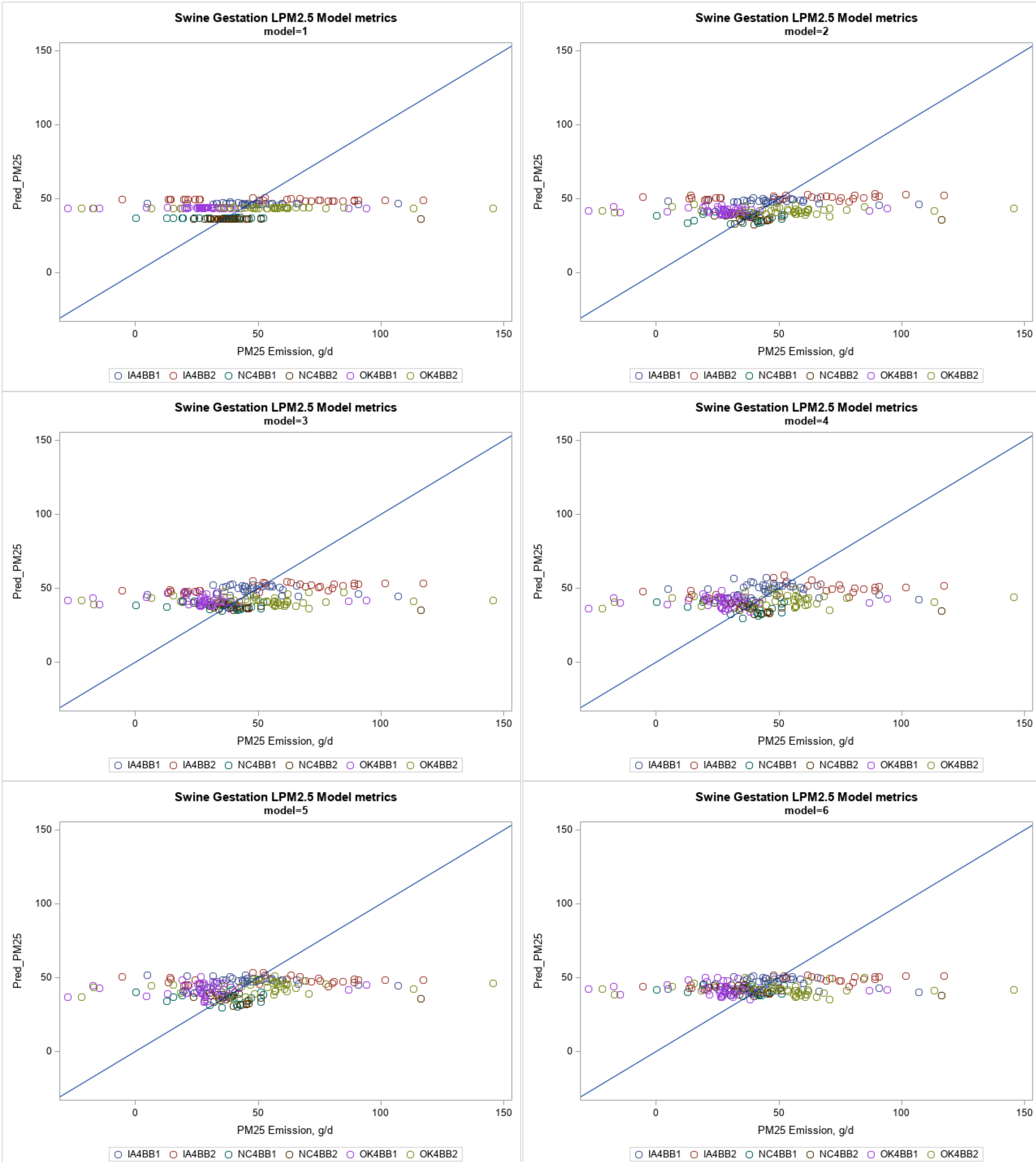


Figure F-123. Gestation $PM_{2.5}$ one-to-one plots form models 1 through 6.

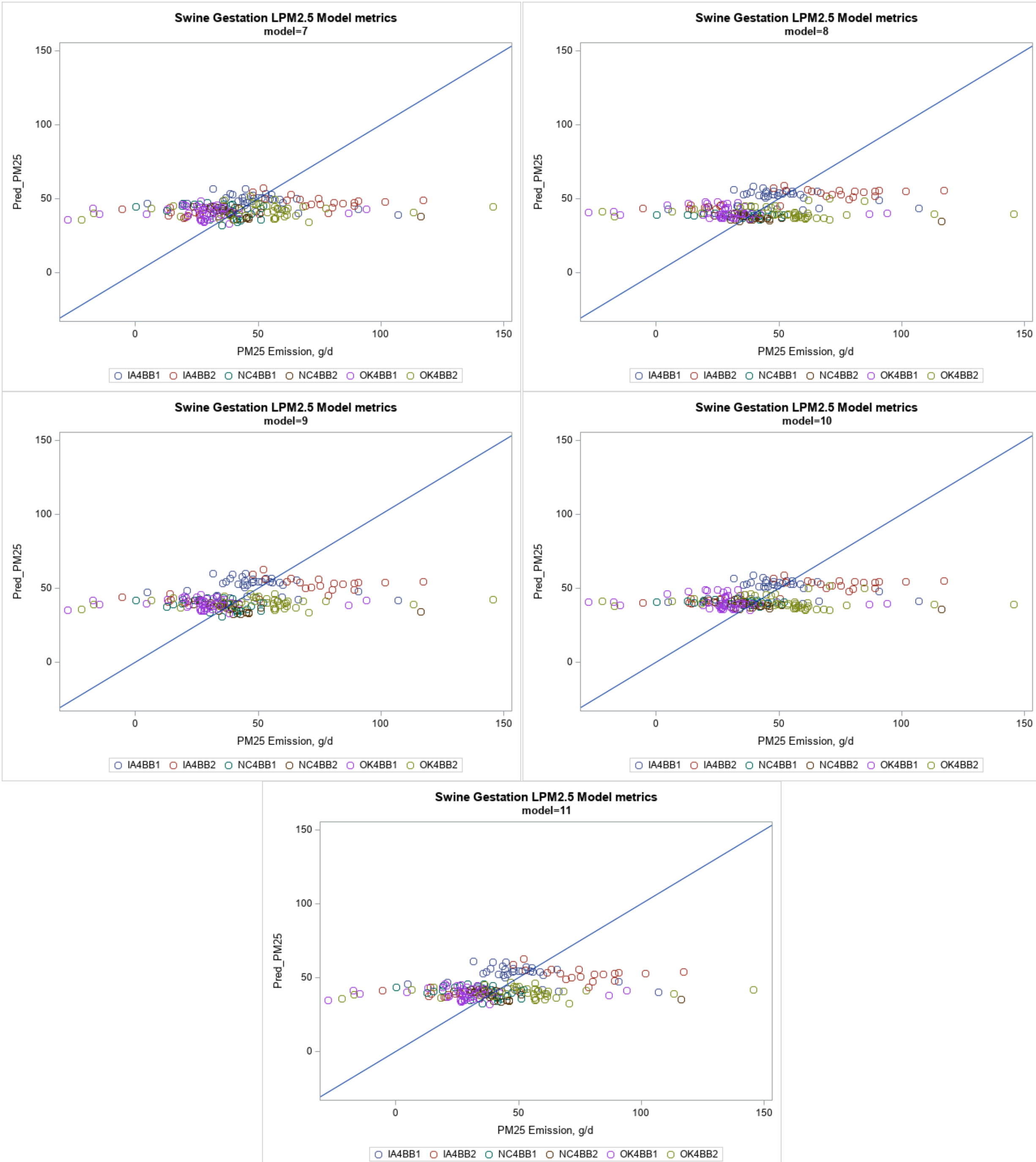


Figure F-124. Gestation $PM_{2.5}$ one-to-one plots form models 7 through 11.

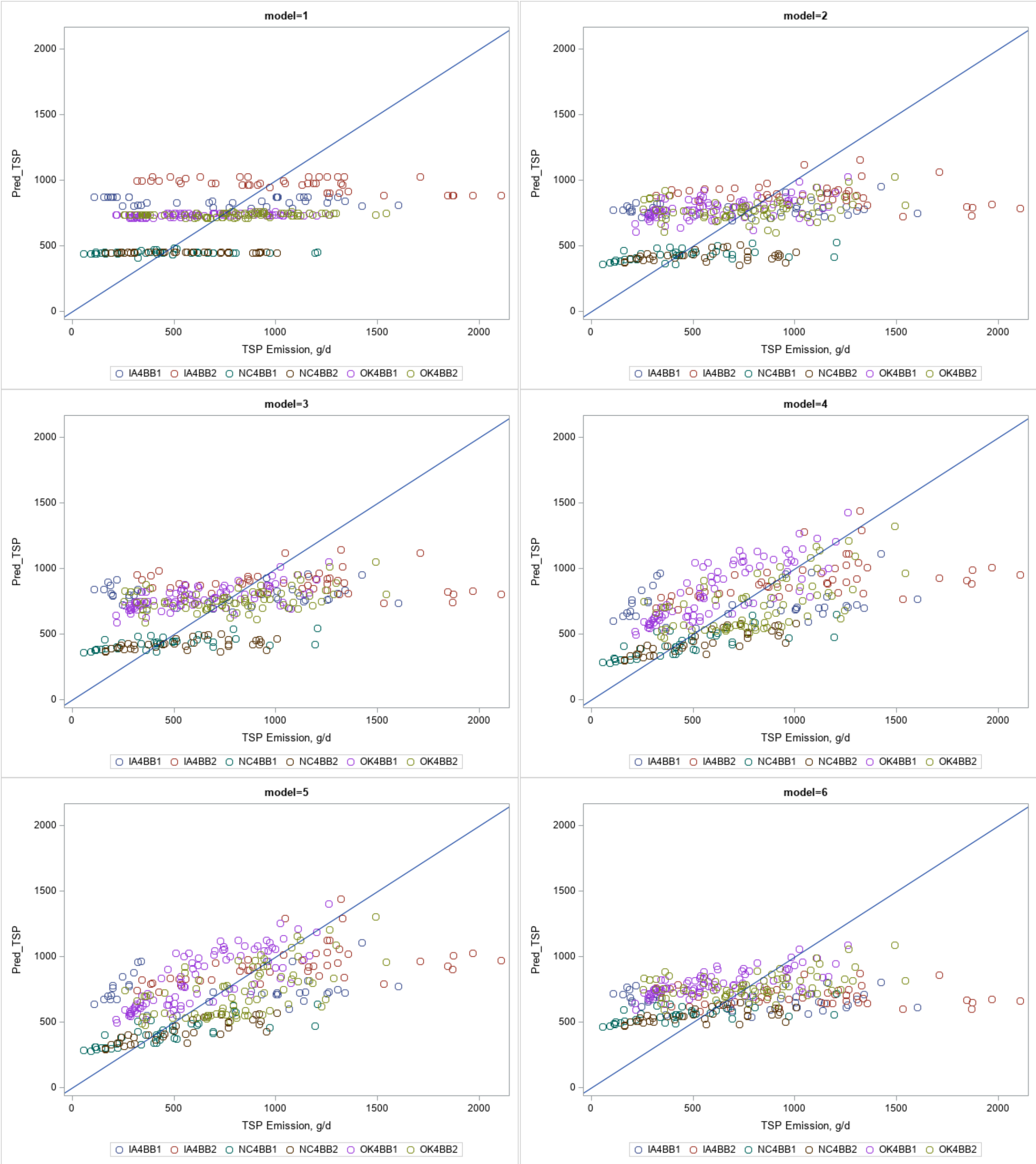


Figure F-125 Gestation TSP one-to-one plots form models 1 through 6.

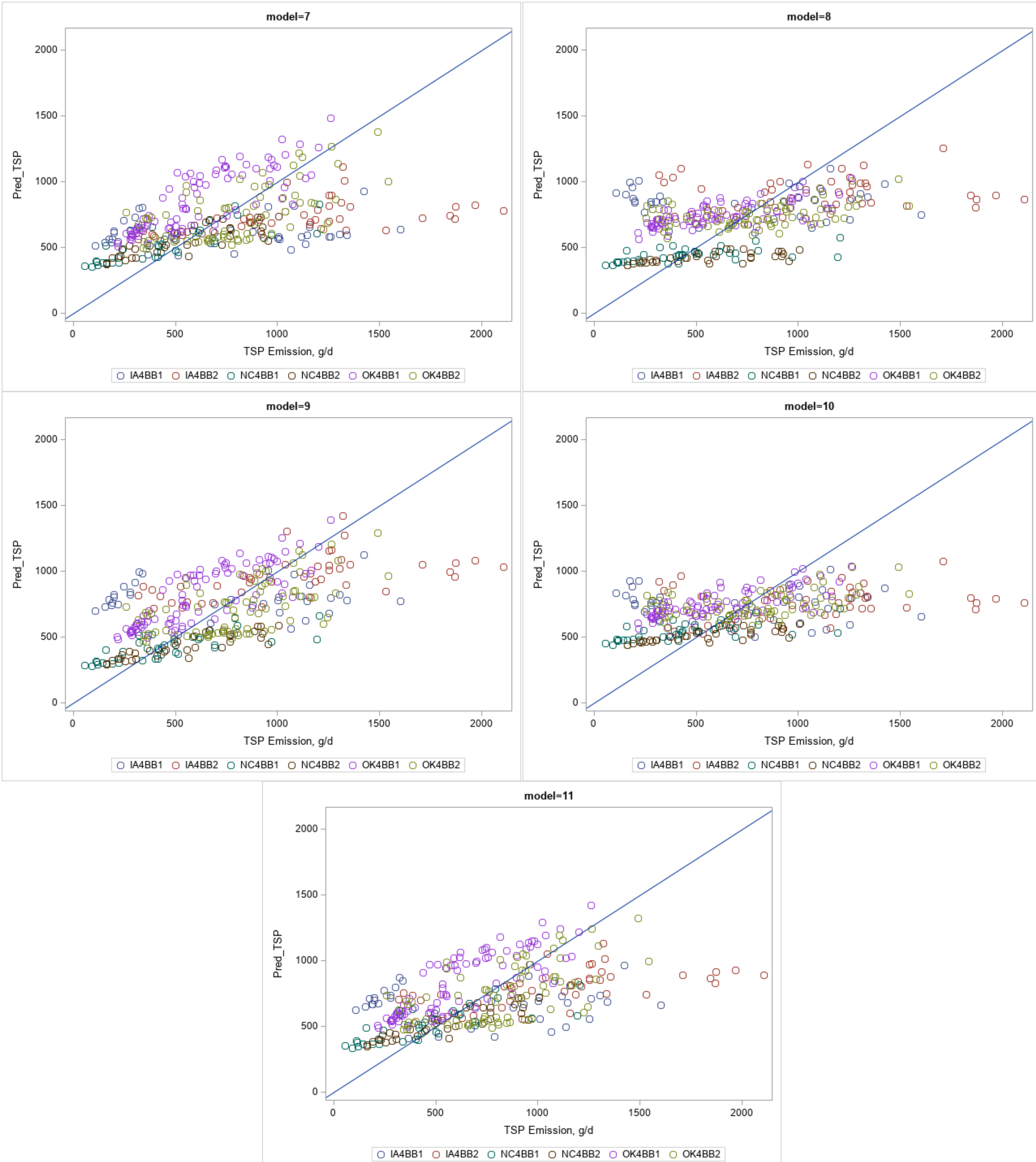


Figure F-126 Gestation TSP one-to-one plots form models 7 through 11.

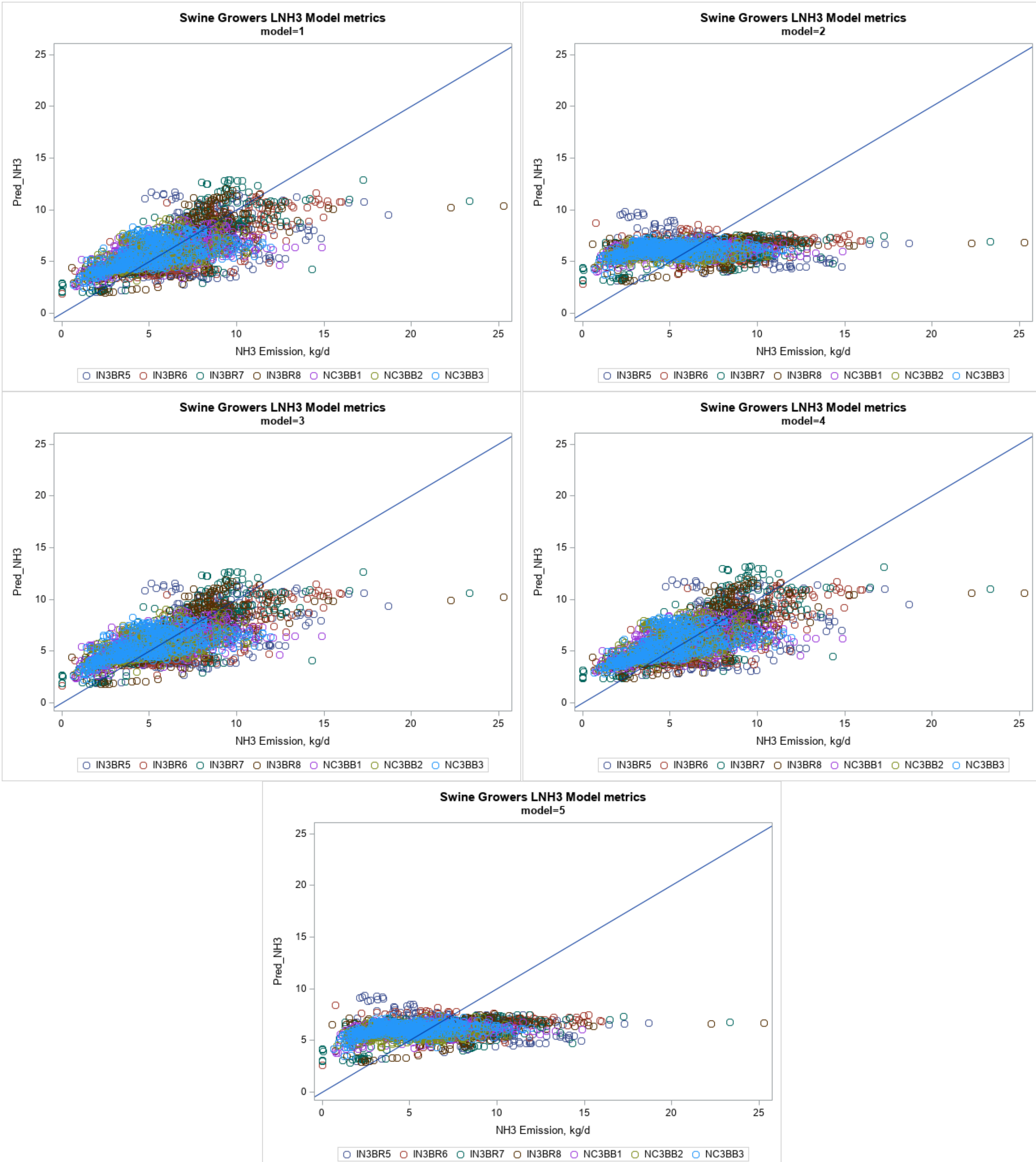


Figure F-127. Grow-finish NH_3 no pit model one-to-one plots.

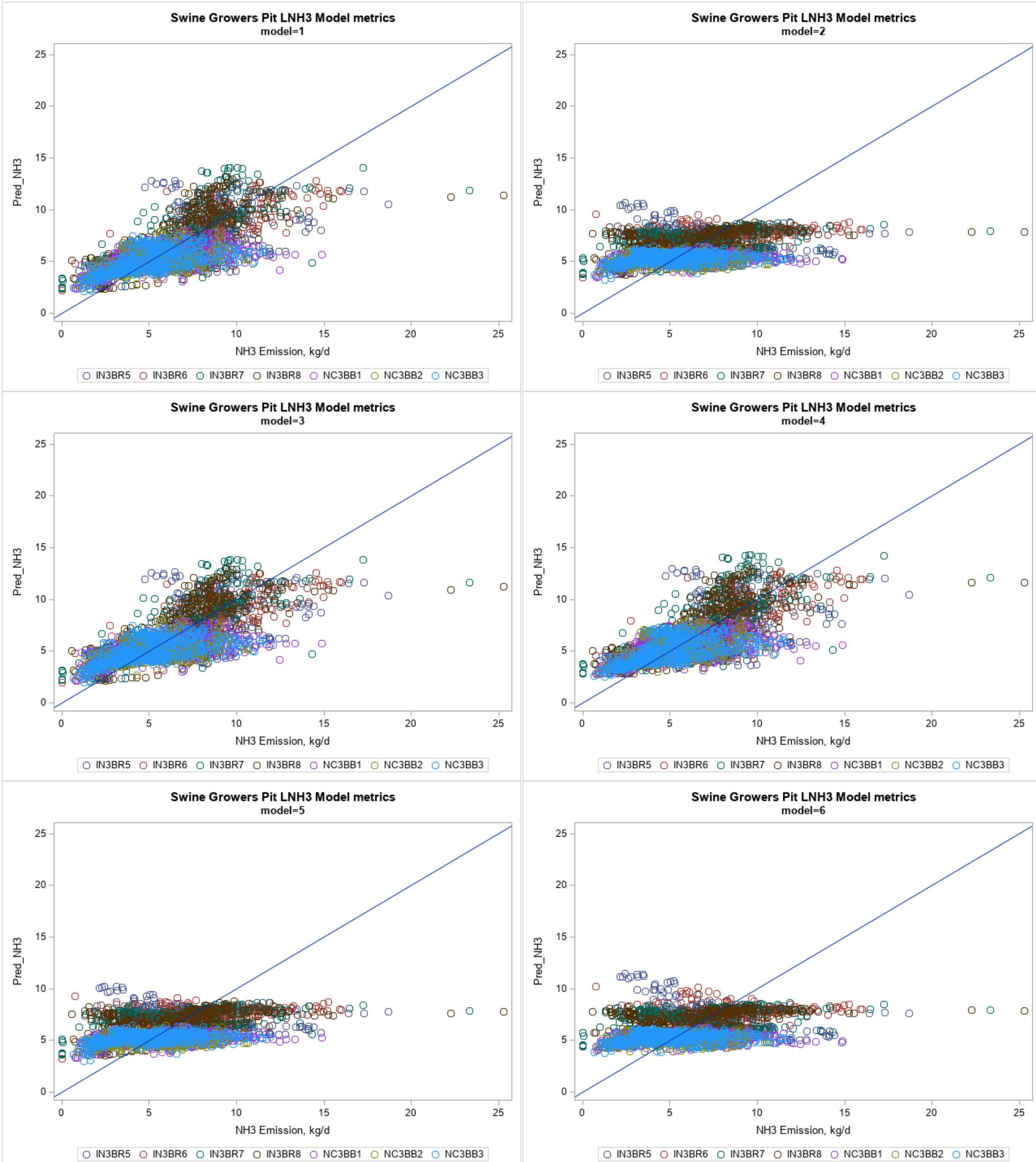


Figure F-128. Grow-finish NH_3 pit model one-to-one plots.

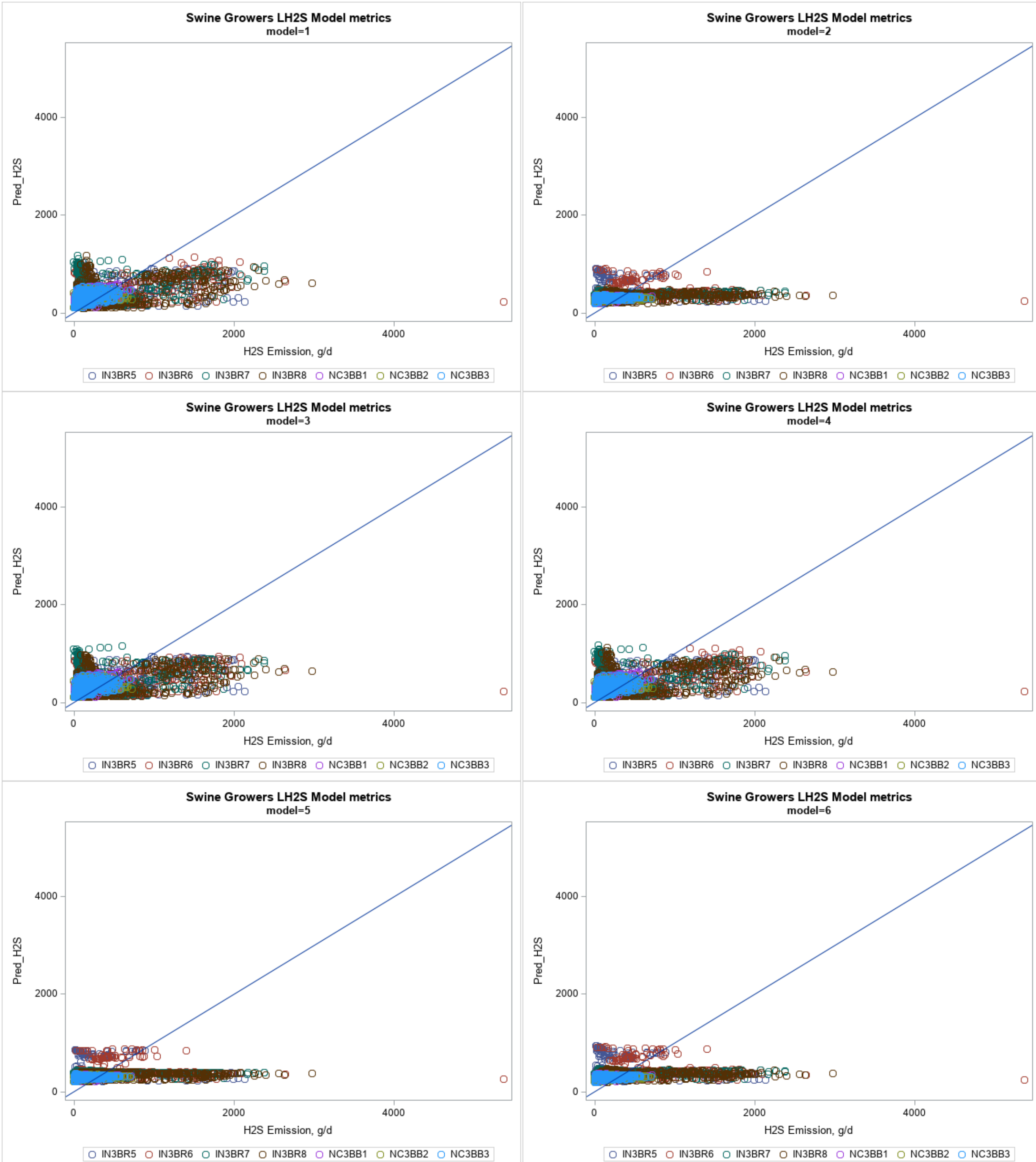


Figure F-129. Grow-finish H_2S no pit model one-to-one plots.

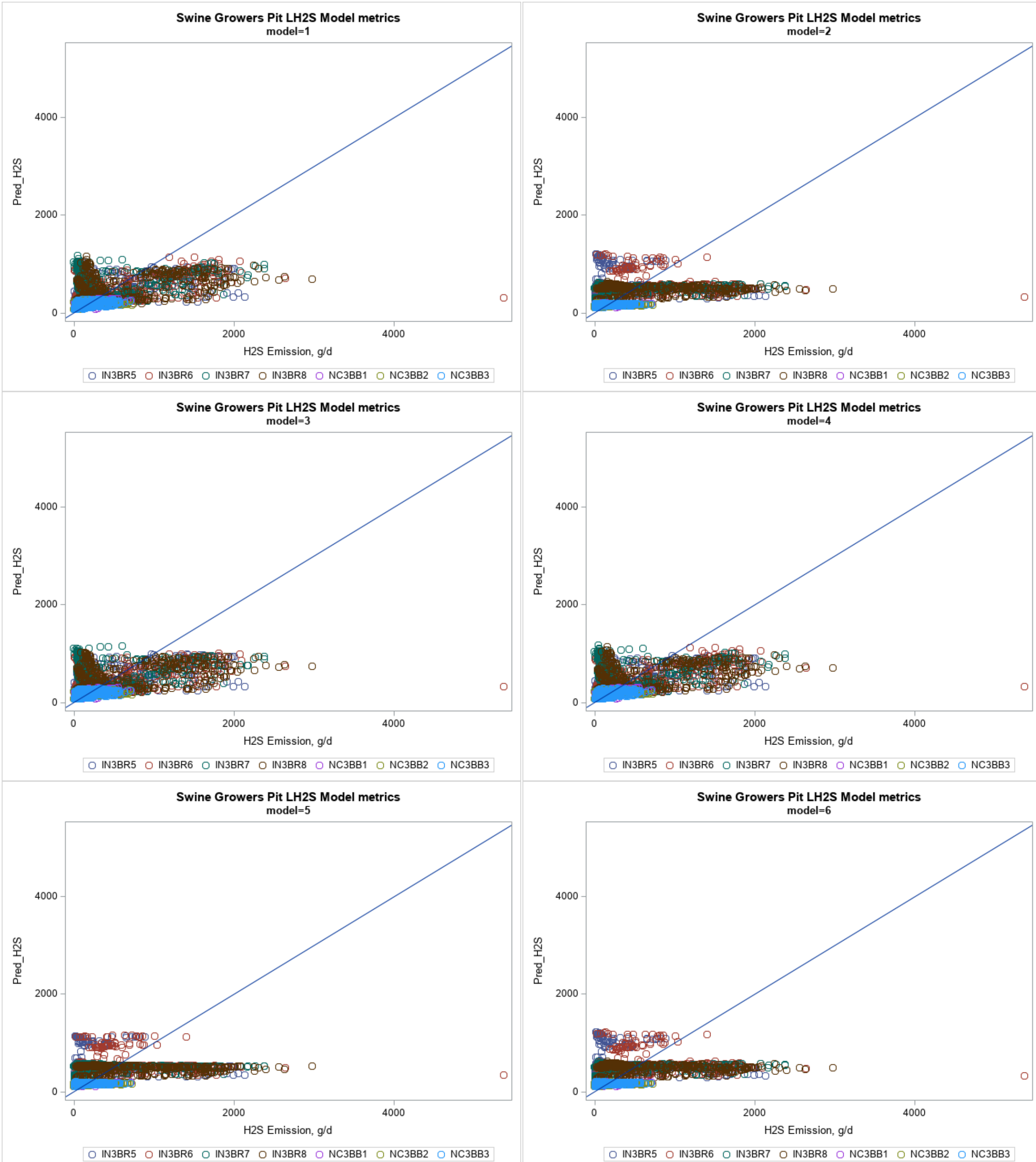


Figure F-130. Grow-finish H_2S pit model one-to-one plots.

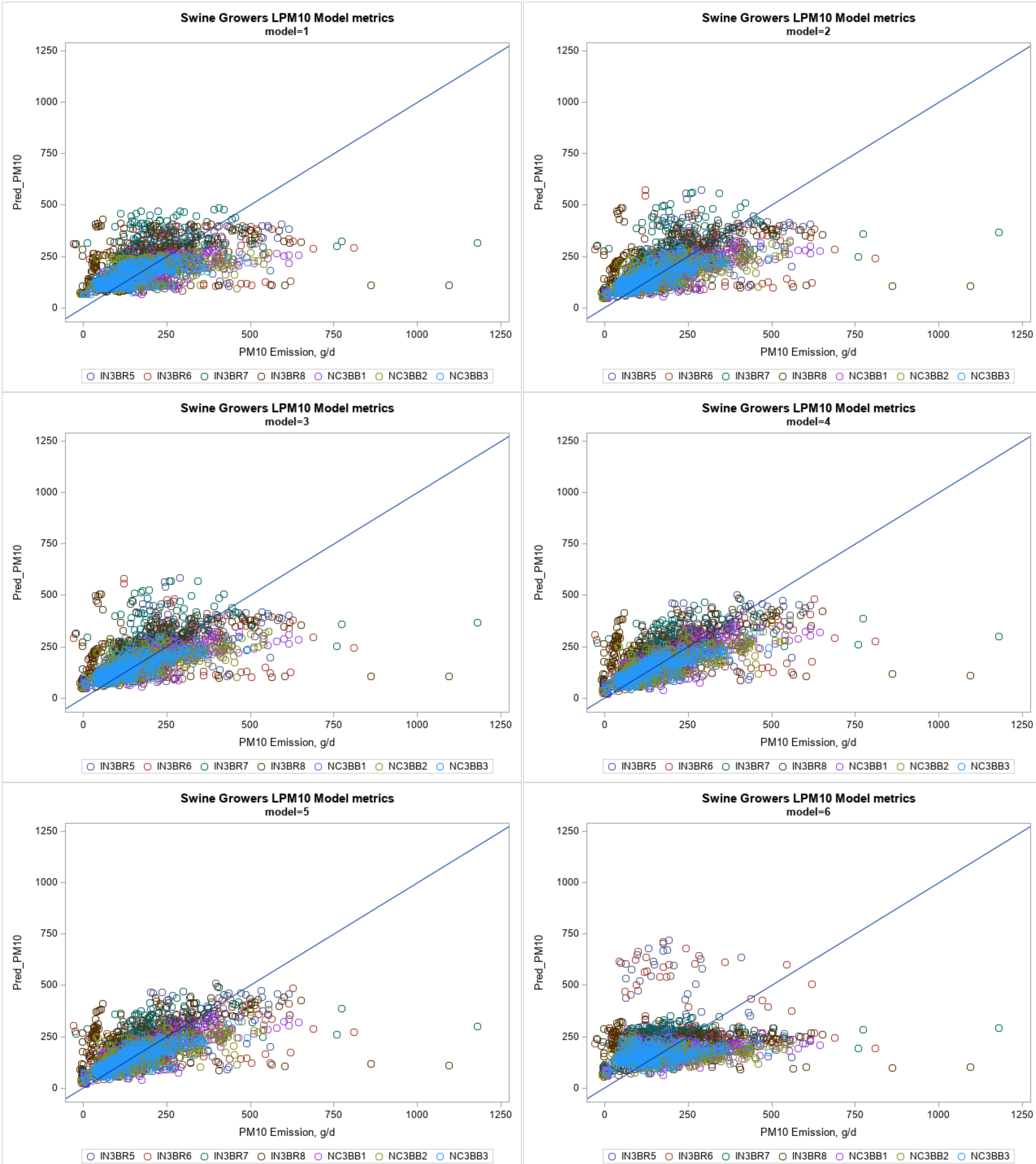


Figure F-131. Grow-finish PM_{10} one-to-one plots for models 1 through 6.

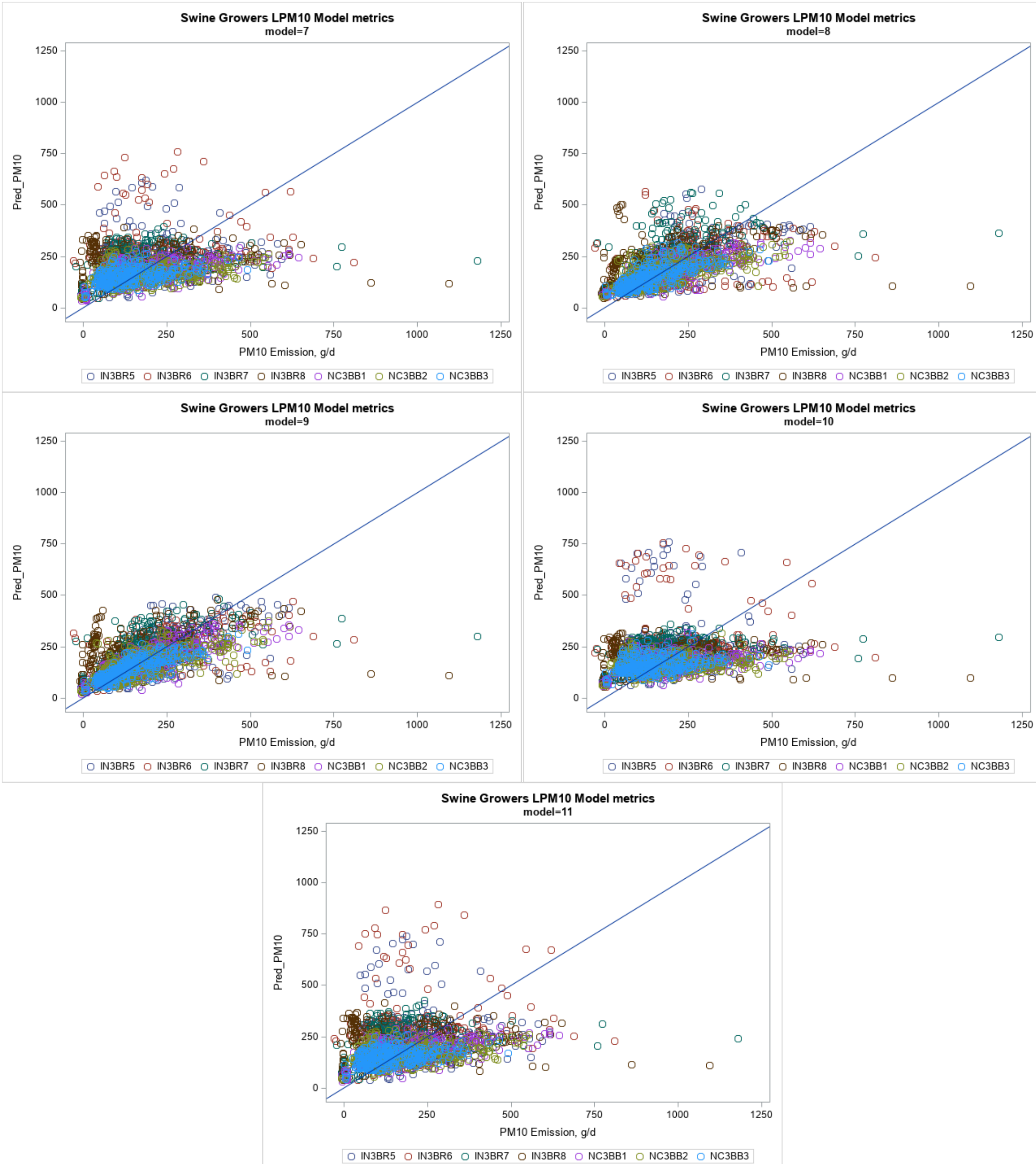


Figure F-132. Grow-finish PM_{10} one-to-one plots for models 7 through 11.

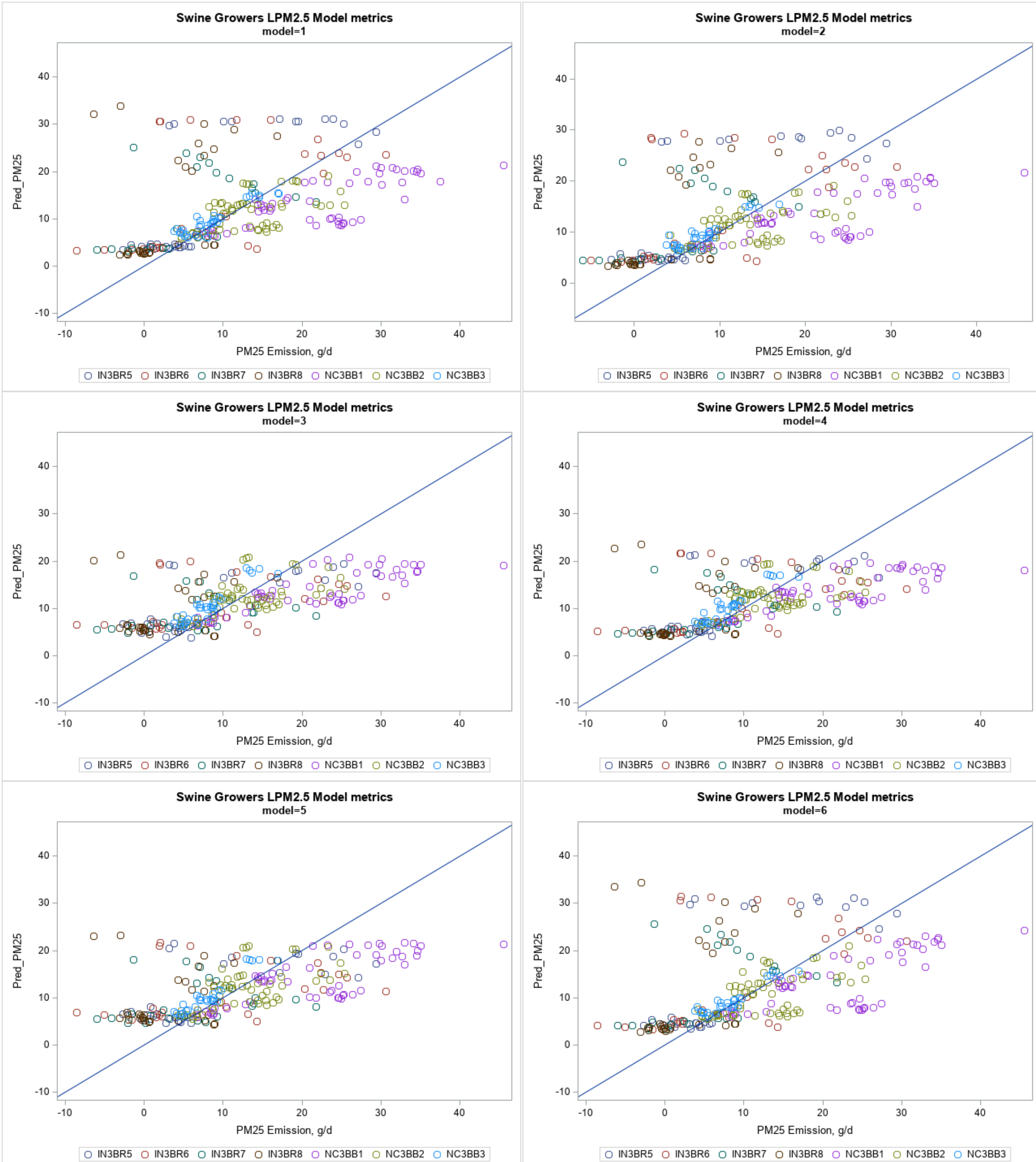
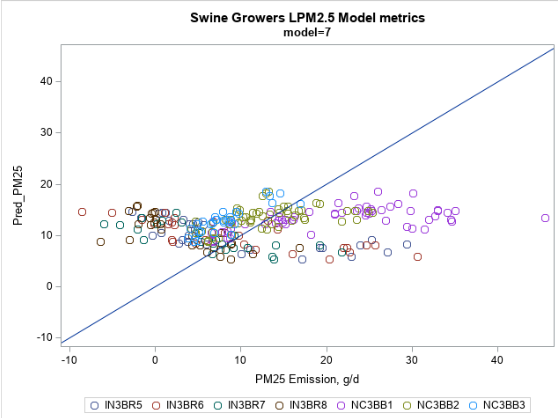
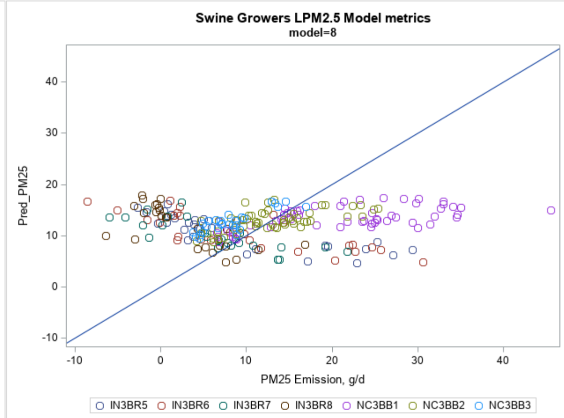
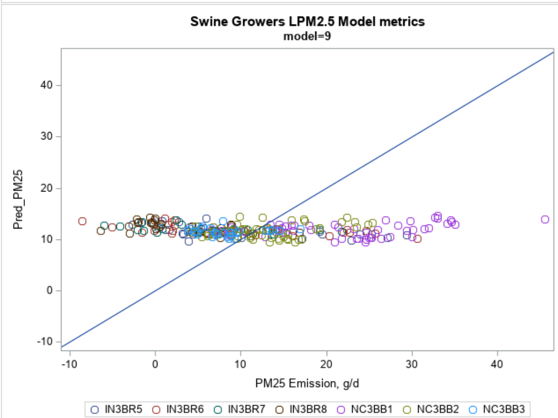
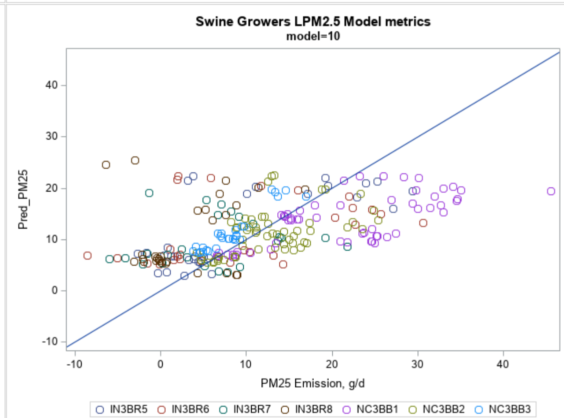


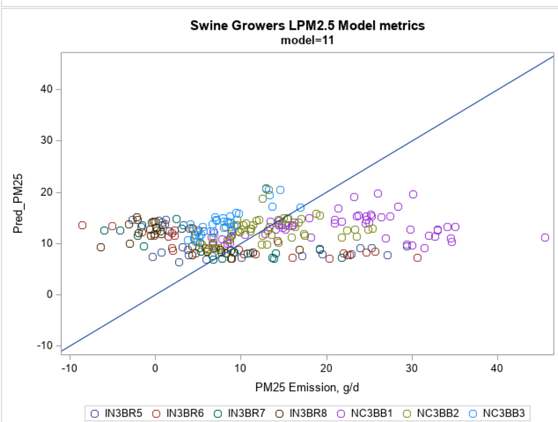
Figure F-133. Grow-finish $PM_{2.5}$ one-to-one plots for models 1 through 6.

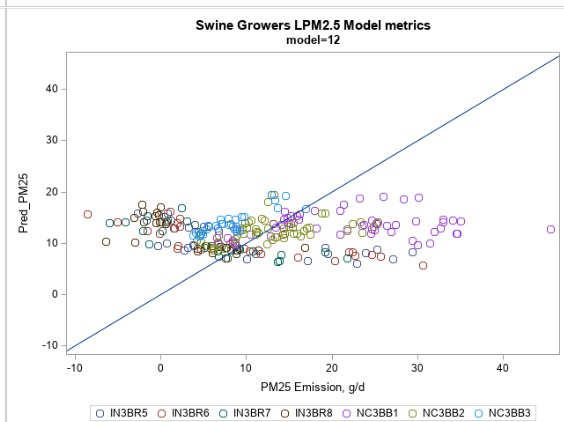

Swine Growers LPM2.5 Model metrics
model=7
Pred_PM25
PM25 Emission, g/d
-10
0
10
20
30
40
IN3BR5 IN3BR6 IN3BR7 IN3BR8 NC3BB1 NC3BB2 NC3BB3


Swine Growers LPM2.5 Model metrics
model=8
Pred_PM25
PM25 Emission, g/d
-10
0
10
20
30
40
IN3BR5 IN3BR6 IN3BR7 IN3BR8 NC3BB1 NC3BB2 NC3BB3


Swine Growers LPM2.5 Model metrics
model=9
Pred_PM25
PM25 Emission, g/d
-10
0
10
20
30
40
IN3BR5 IN3BR6 IN3BR7 IN3BR8 NC3BB1 NC3BB2 NC3BB3


Swine Growers LPM2.5 Model metrics
model=10
Pred_PM25
PM25 Emission, g/d
-10
0
10
20
30
40
IN3BR5 IN3BR6 IN3BR7 IN3BR8 NC3BB1 NC3BB2 NC3BB3


Swine Growers LPM2.5 Model metrics
model=11
Pred_PM25
PM25 Emission, g/d
-10
0
10
20
30
40
IN3BR5 IN3BR6 IN3BR7 IN3BR8 NC3BB1 NC3BB2 NC3BB3


Swine Growers LPM2.5 Model metrics
model=12
Pred_PM25
PM25 Emission, g/d
-10
0
10
20
30
40
IN3BR5 IN3BR6 IN3BR7 IN3BR8 NC3BB1 NC3BB2 NC3BB3

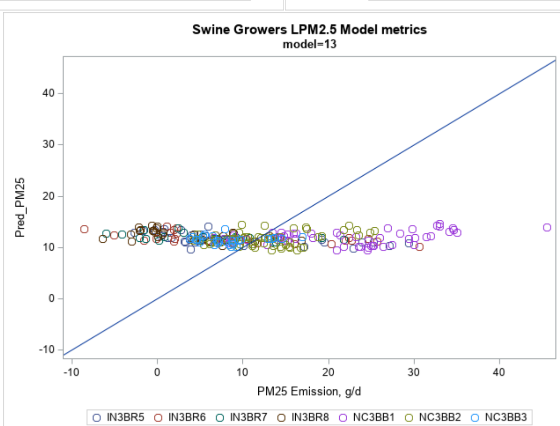

Swine Growers LPM2.5 Model metrics
model=13
Pred_PM25
PM25 Emission, g/d
-10
0
10
20
30
40
IN3BR5 IN3BR6 IN3BR7 IN3BR8 NC3BB1 NC3BB2 NC3BB3

Figure F-134. Grow-finish $PM_{2.5}$ one-to-one plots for models 7 through 13.

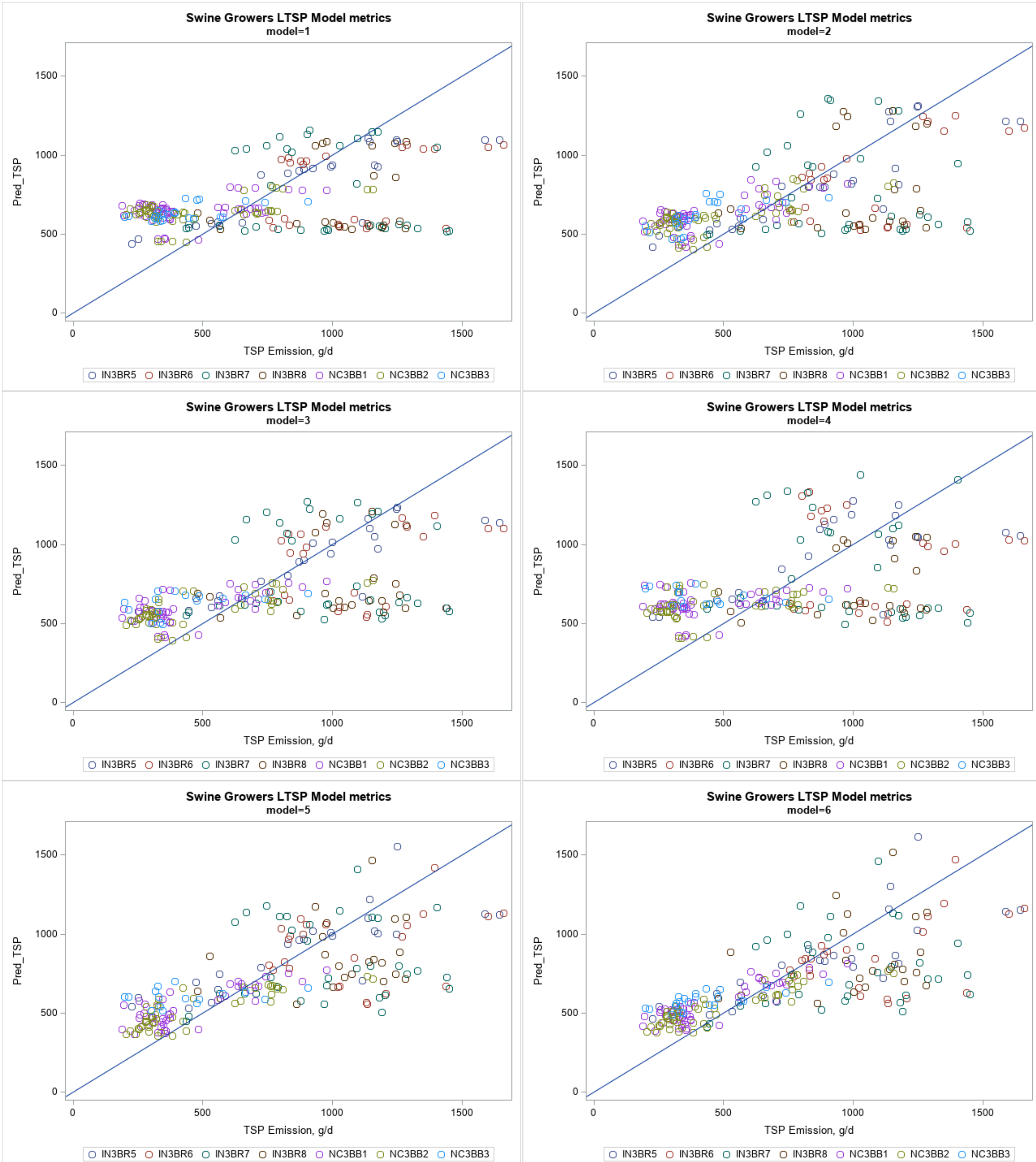
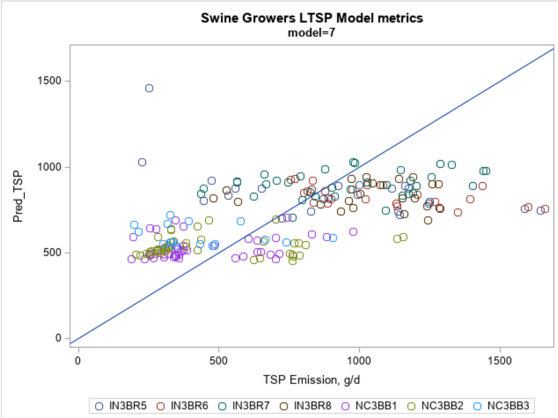
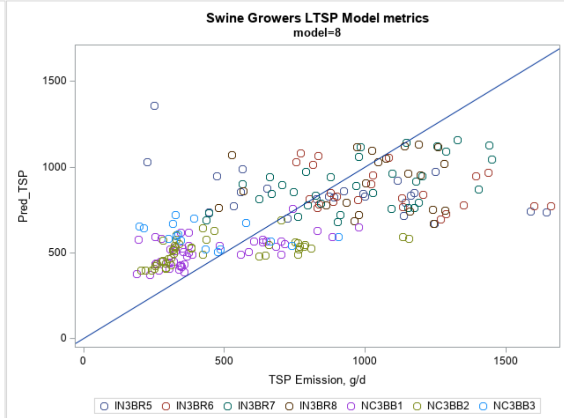
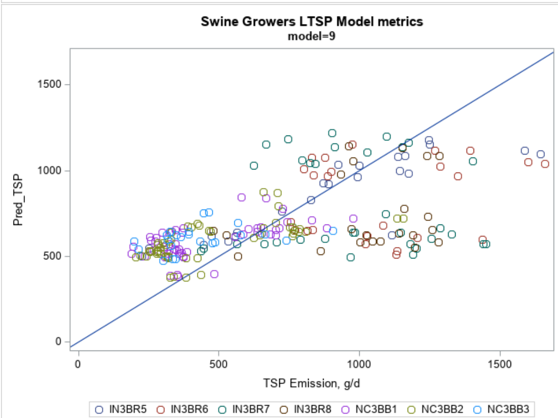
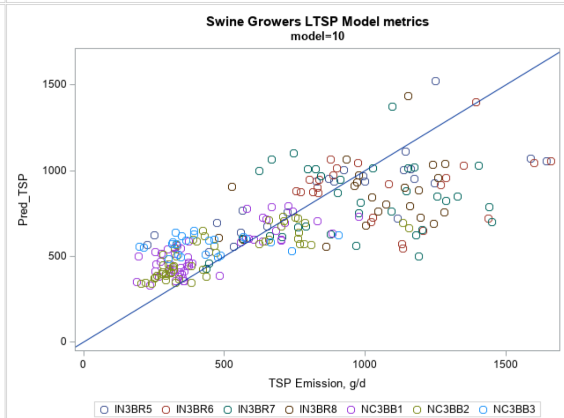


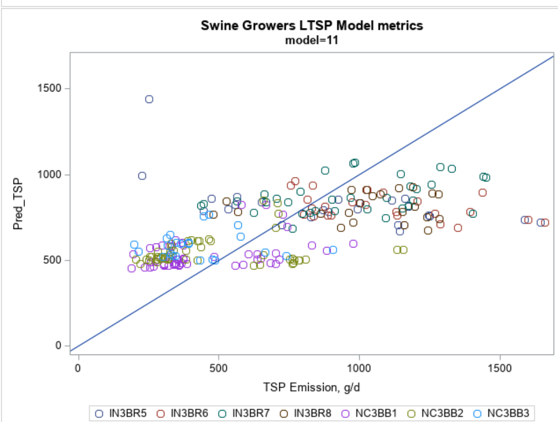
Figure F-135. Grow-finish TSP one-to-one plots for models 1 through 6.

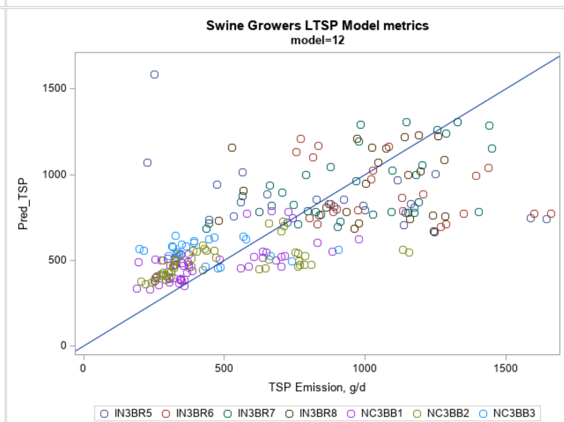

Swine Growers LTSP Model metrics
model=7
Pred_TSP
TSP Emission, g/d
0
500
1000
1500
IN3BR5 IN3BR6 IN3BR7 IN3BR8 NC3BB1 NC3BB2 NC3BB3


Swine Growers LTSP Model metrics
model=8
Pred_TSP
TSP Emission, g/d
0
500
1000
1500
IN3BR5 IN3BR6 IN3BR7 IN3BR8 NC3BB1 NC3BB2 NC3BB3


Swine Growers LTSP Model metrics
model=9
Pred_TSP
TSP Emission, g/d
0
500
1000
1500
IN3BR5 IN3BR6 IN3BR7 IN3BR8 NC3BB1 NC3BB2 NC3BB3


Swine Growers LTSP Model metrics
model=10
Pred_TSP
TSP Emission, g/d
0
500
1000
1500
IN3BR5 IN3BR6 IN3BR7 IN3BR8 NC3BB1 NC3BB2 NC3BB3


Swine Growers LTSP Model metrics
model=11
Pred_TSP
TSP Emission, g/d
0
500
1000
1500
IN3BR5 IN3BR6 IN3BR7 IN3BR8 NC3BB1 NC3BB2 NC3BB3


Swine Growers LTSP Model metrics
model=12
Pred_TSP
TSP Emission, g/d
0
500
1000
1500
IN3BR5 IN3BR6 IN3BR7 IN3BR8 NC3BB1 NC3BB2 NC3BB3

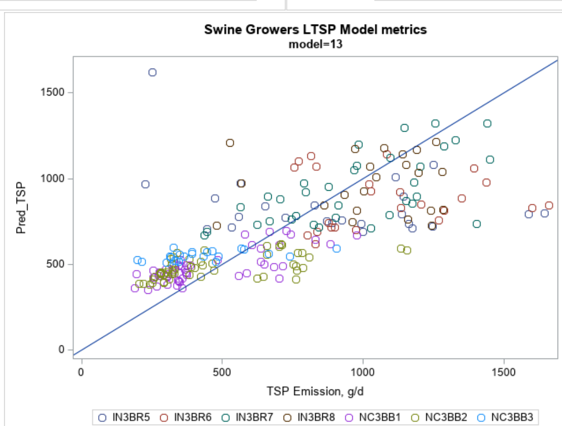

Swine Growers LTSP Model metrics
model=13
Pred_TSP
TSP Emission, g/d
0
500
1000
1500
IN3BR5 IN3BR6 IN3BR7 IN3BR8 NC3BB1 NC3BB2 NC3BB3

Figure F-136. Grow-finish TSP one-to-one plots for models 7 through 13.

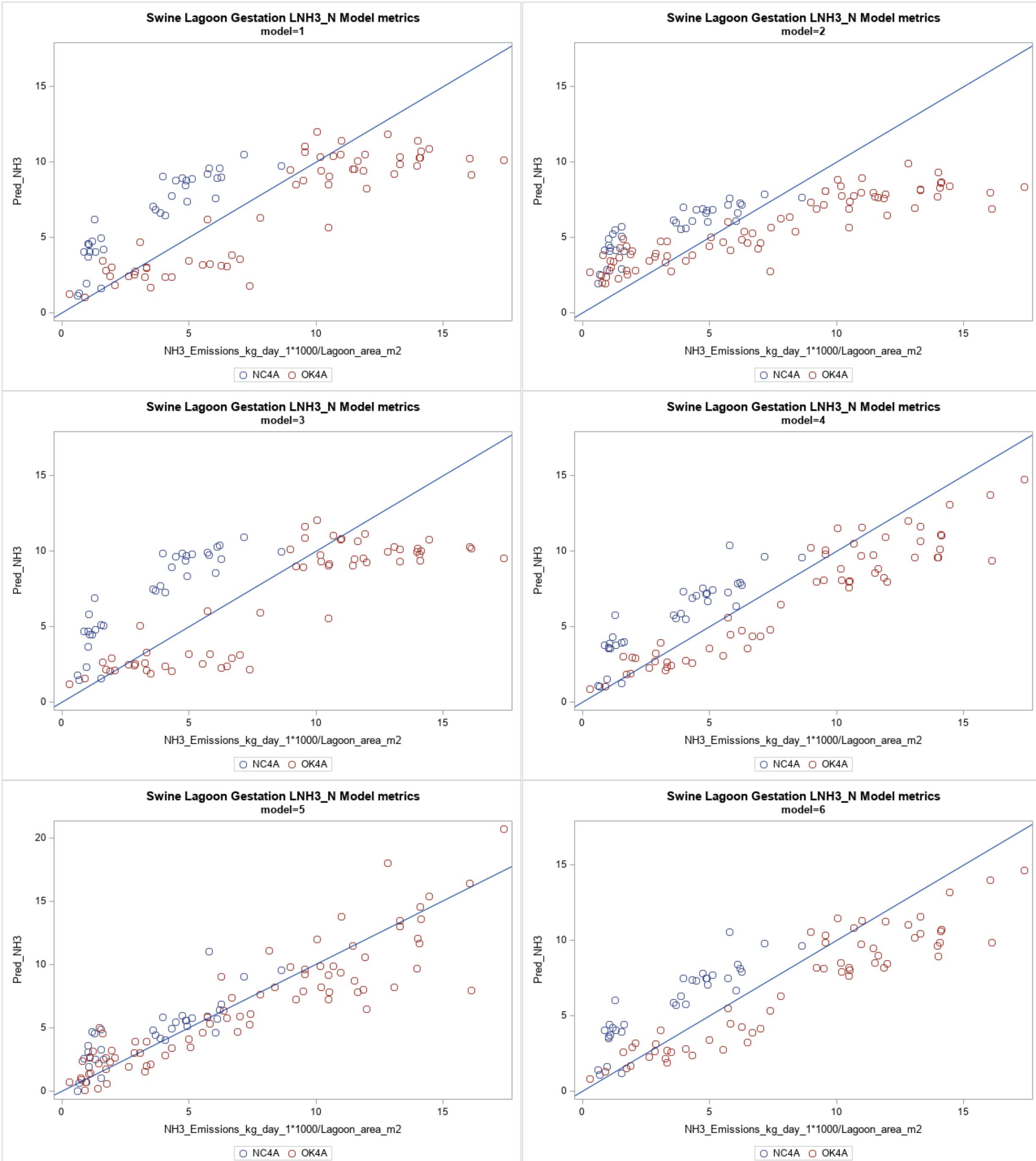


Figure F-137 Gestation lagoon NH_3 one-to-one plots for models 1 through 6.

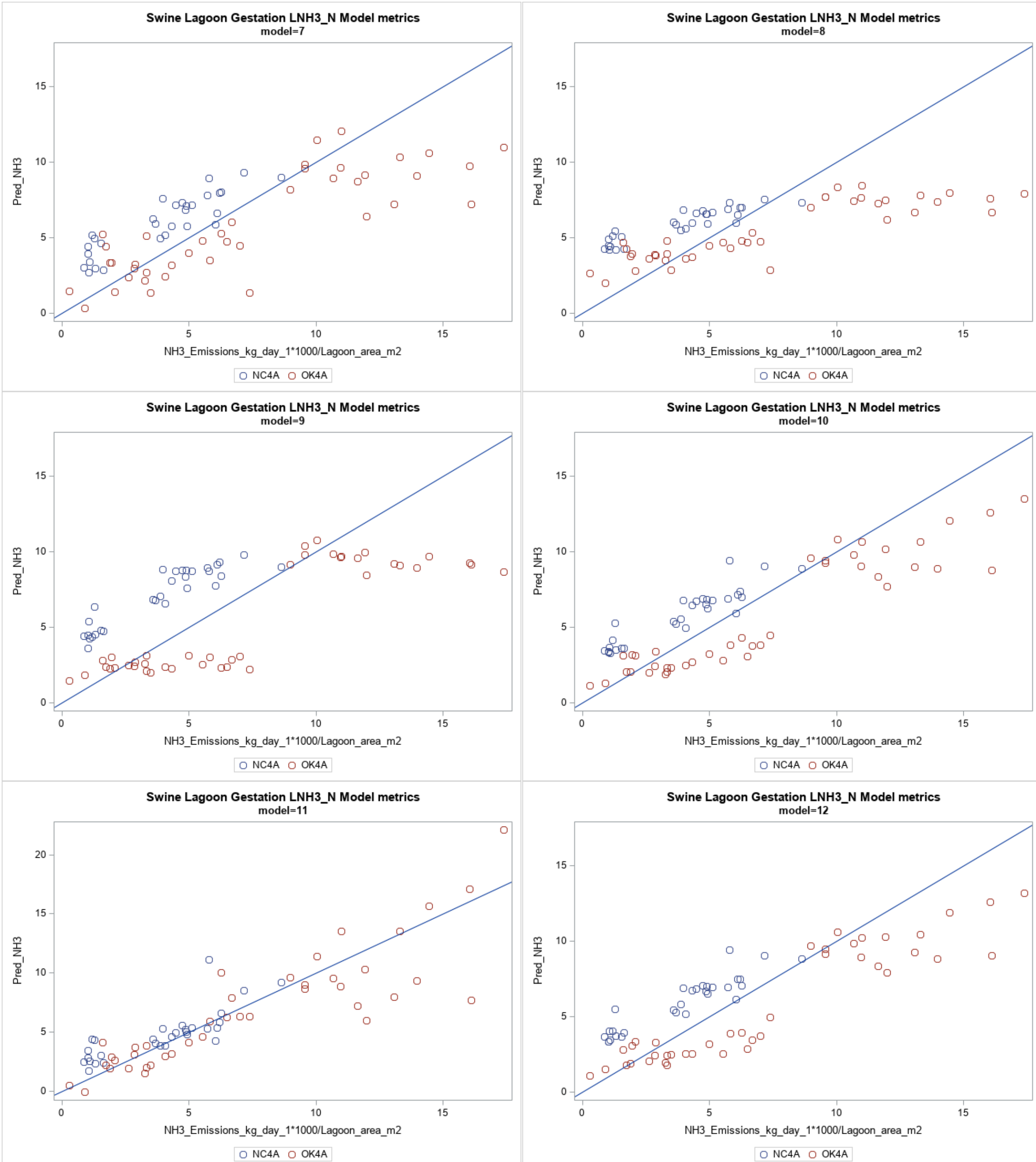


Figure F-138 Gestation lagoon NH_3 one-to-one plots for models 7 through 12.

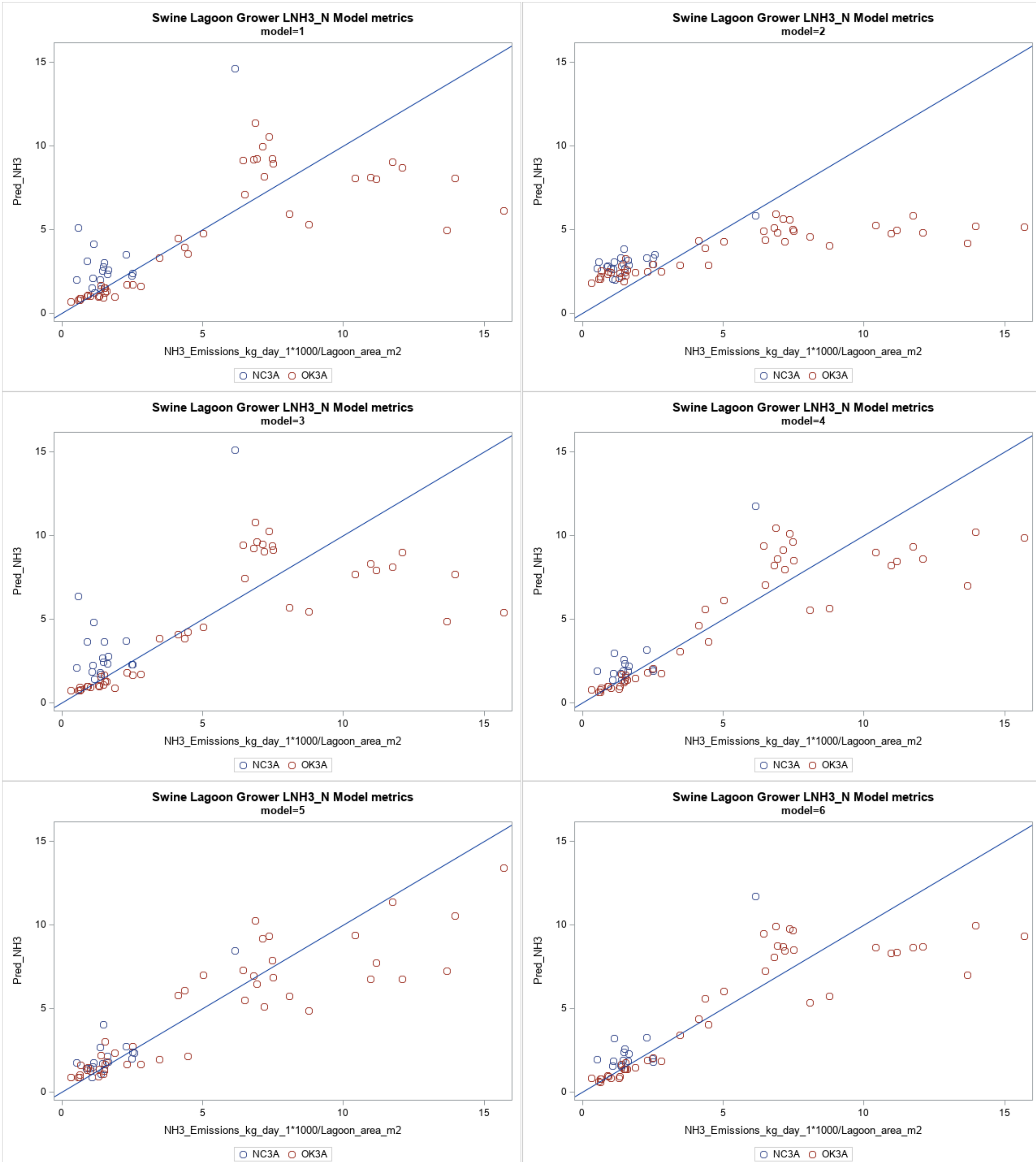


Figure F-139 Grower-finish lagoon NH_3 one-to-one plots for models 1 through 6.

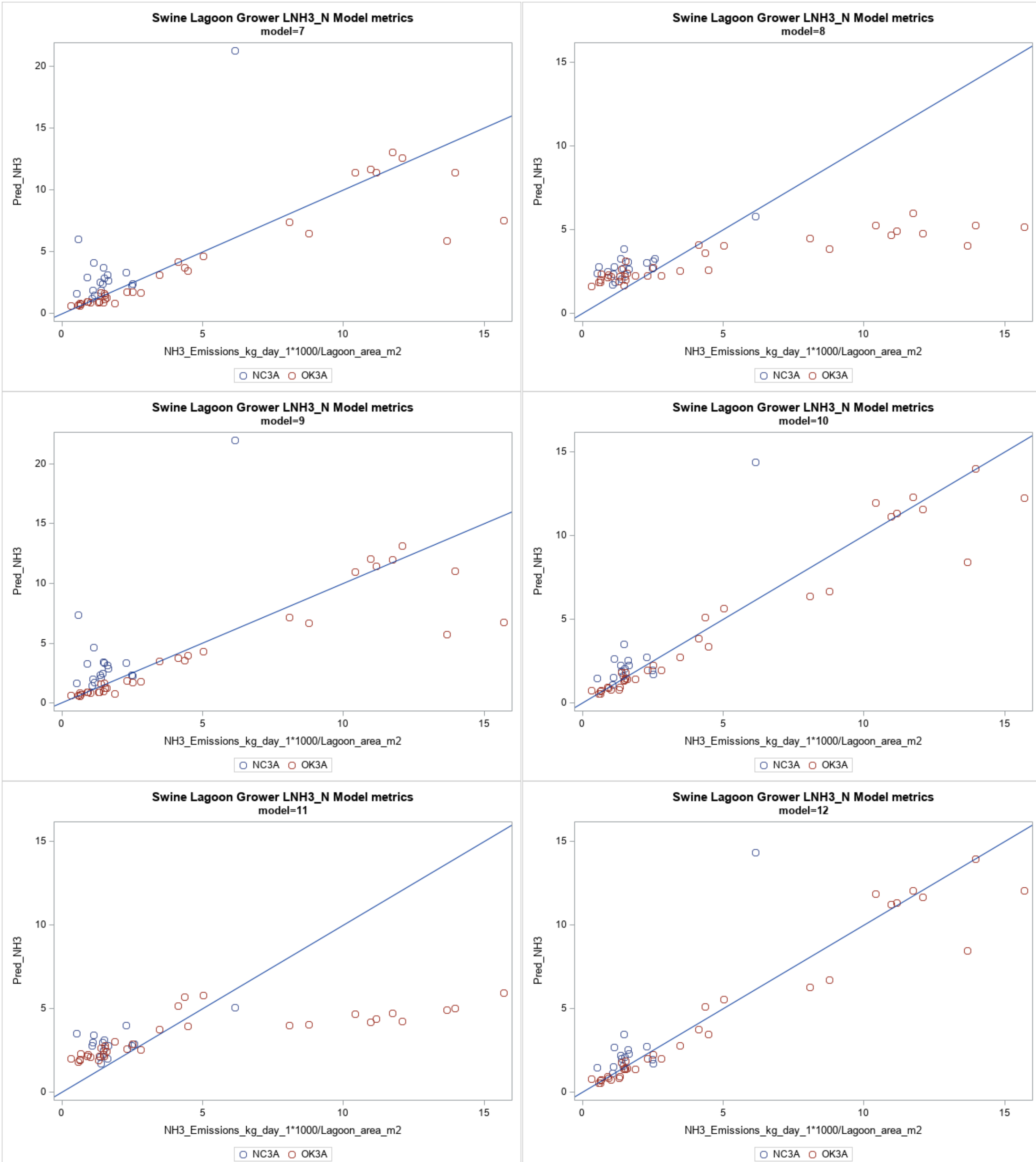


Figure F-140 Grower-finish lagoon NH_3 one-to-one plots for models 7 through 12.

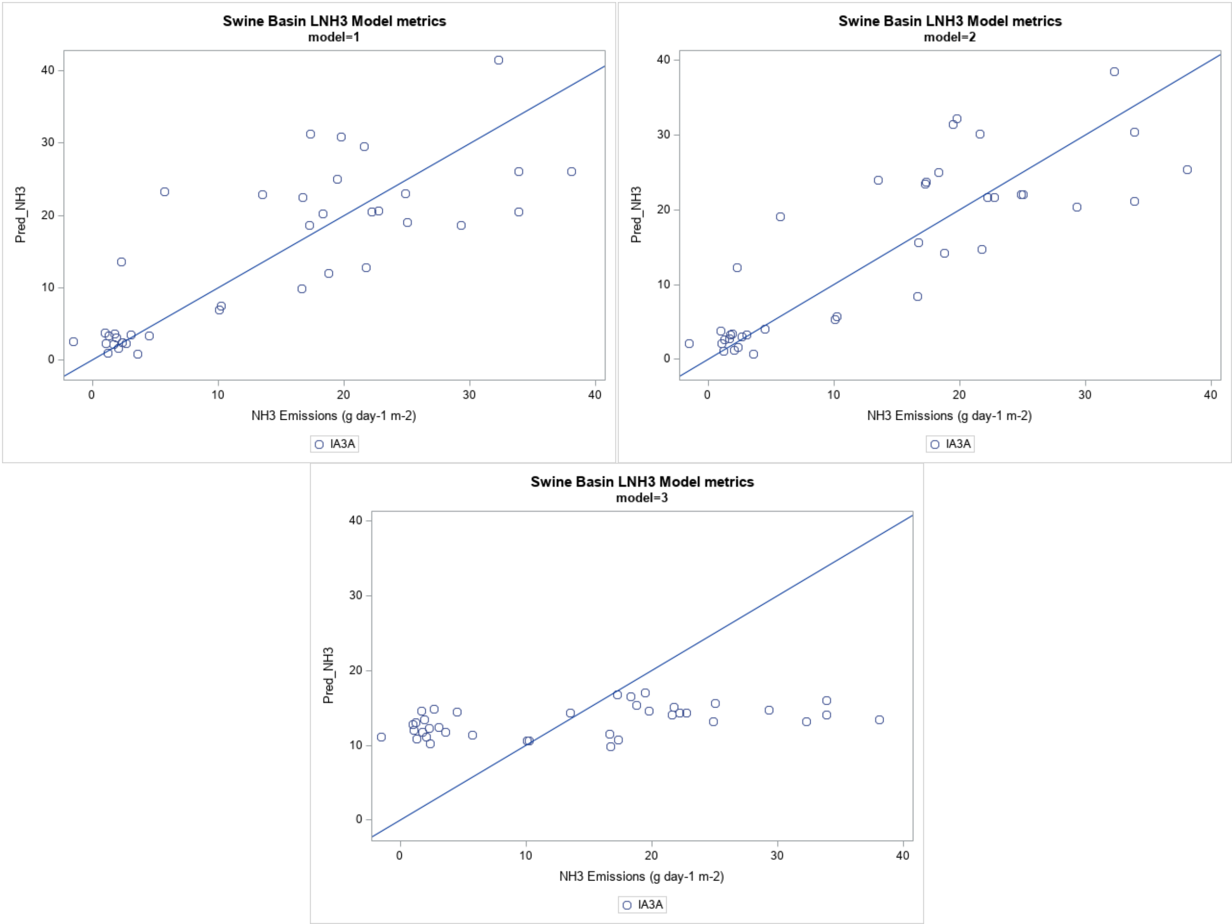


Figure F-141 Basin NH_3 model one-to-one plots.

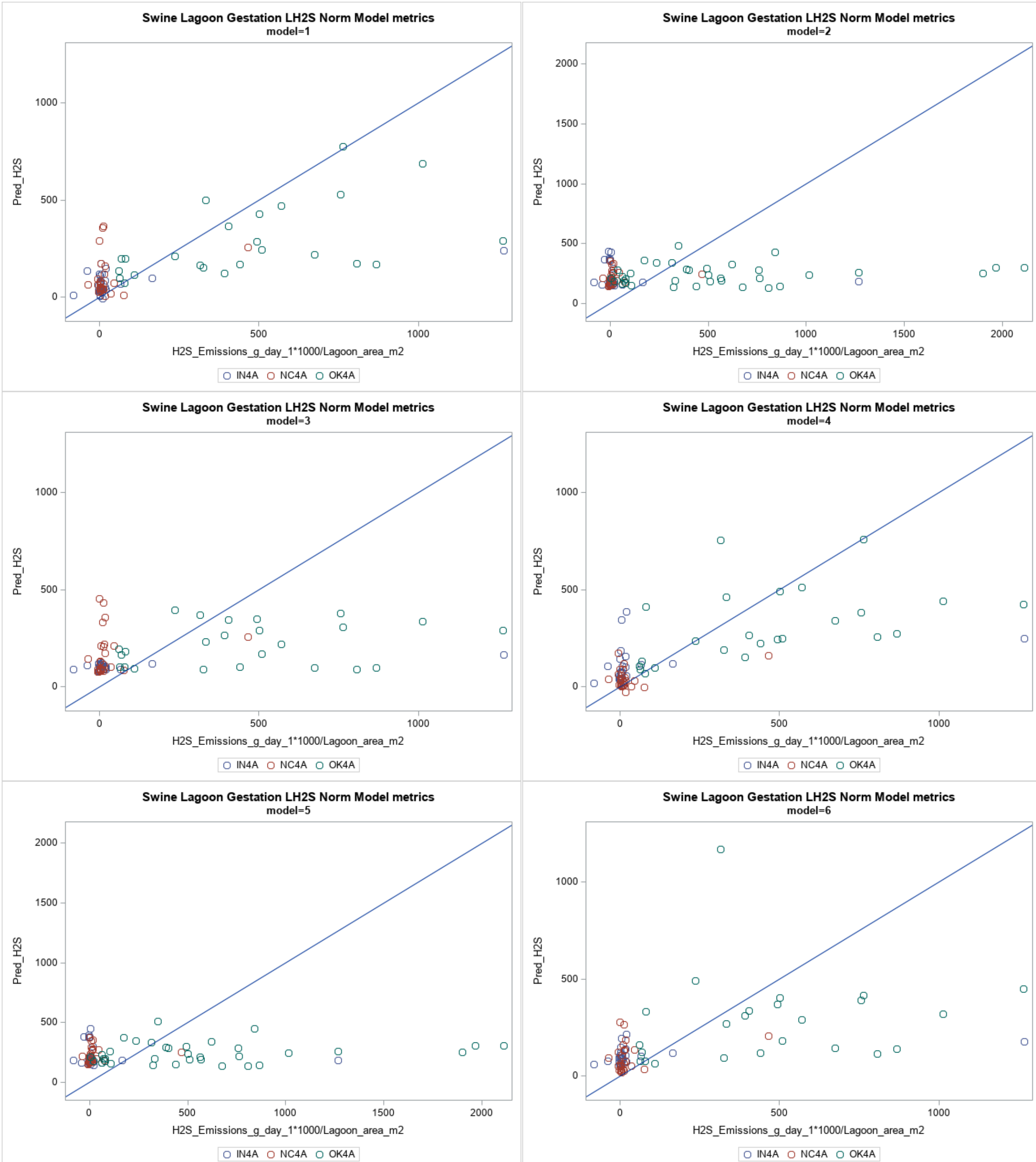
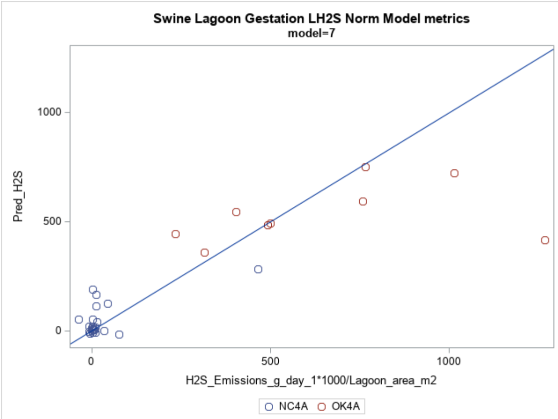
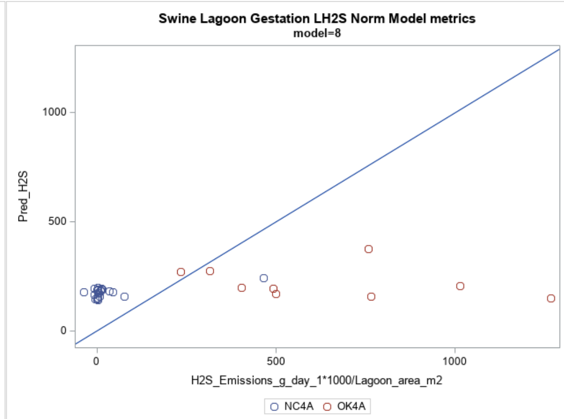
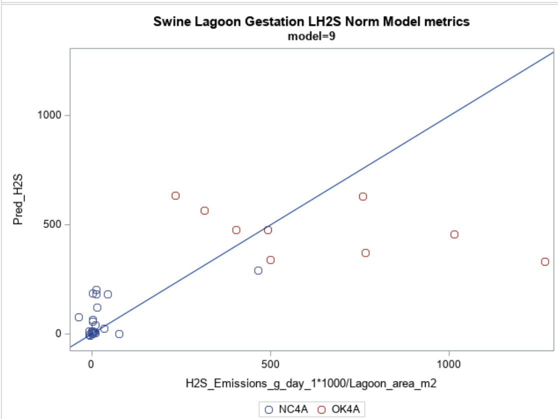
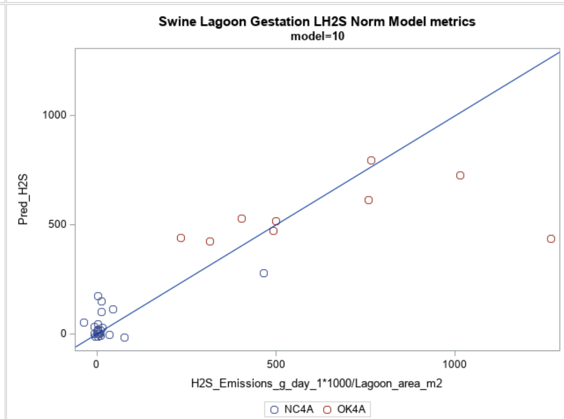


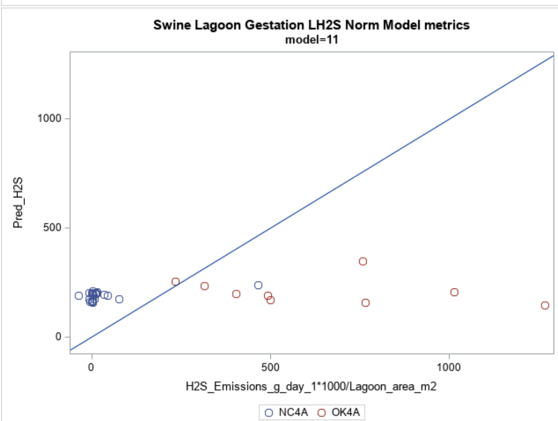
Figure F-142 Gestation Lagoon H_2S one-to-one plots for models 1 through 6.

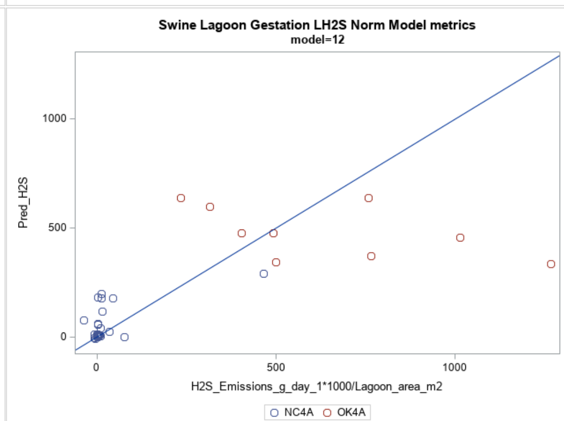

Swine Lagoon Gestation LH2S Norm Model metrics
model=7
Pred_H2S
0
500
1000
H2S_Emissions_g_day_1*1000/Lagoon_area_m2
NC4A
OK4A


Swine Lagoon Gestation LH2S Norm Model metrics
model=8
Pred_H2S
0
500
1000
H2S_Emissions_g_day_1*1000/Lagoon_area_m2
NC4A
OK4A


Swine Lagoon Gestation LH2S Norm Model metrics
model=9
Pred_H2S
0
500
1000
H2S_Emissions_g_day_1*1000/Lagoon_area_m2
NC4A
OK4A


Swine Lagoon Gestation LH2S Norm Model metrics
model=10
Pred_H2S
0
500
1000
H2S_Emissions_g_day_1*1000/Lagoon_area_m2
NC4A
OK4A


Swine Lagoon Gestation LH2S Norm Model metrics
model=11
Pred_H2S
0
500
1000
H2S_Emissions_g_day_1*1000/Lagoon_area_m2
NC4A
OK4A


Swine Lagoon Gestation LH2S Norm Model metrics
model=12
Pred_H2S
0
500
1000
H2S_Emissions_g_day_1*1000/Lagoon_area_m2
NC4A
OK4A

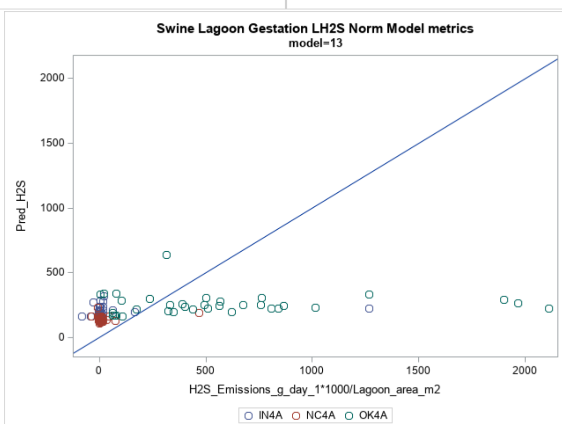

Swine Lagoon Gestation LH2S Norm Model metrics
model=13
Pred_H2S
0
500
1000
1500
2000
H2S_Emissions_g_day_1*1000/Lagoon_area_m2
IN4A
NC4A
OK4A

Figure F-143 Gestation Lagoon H_2S one-to-one plots for models 7 through 13.

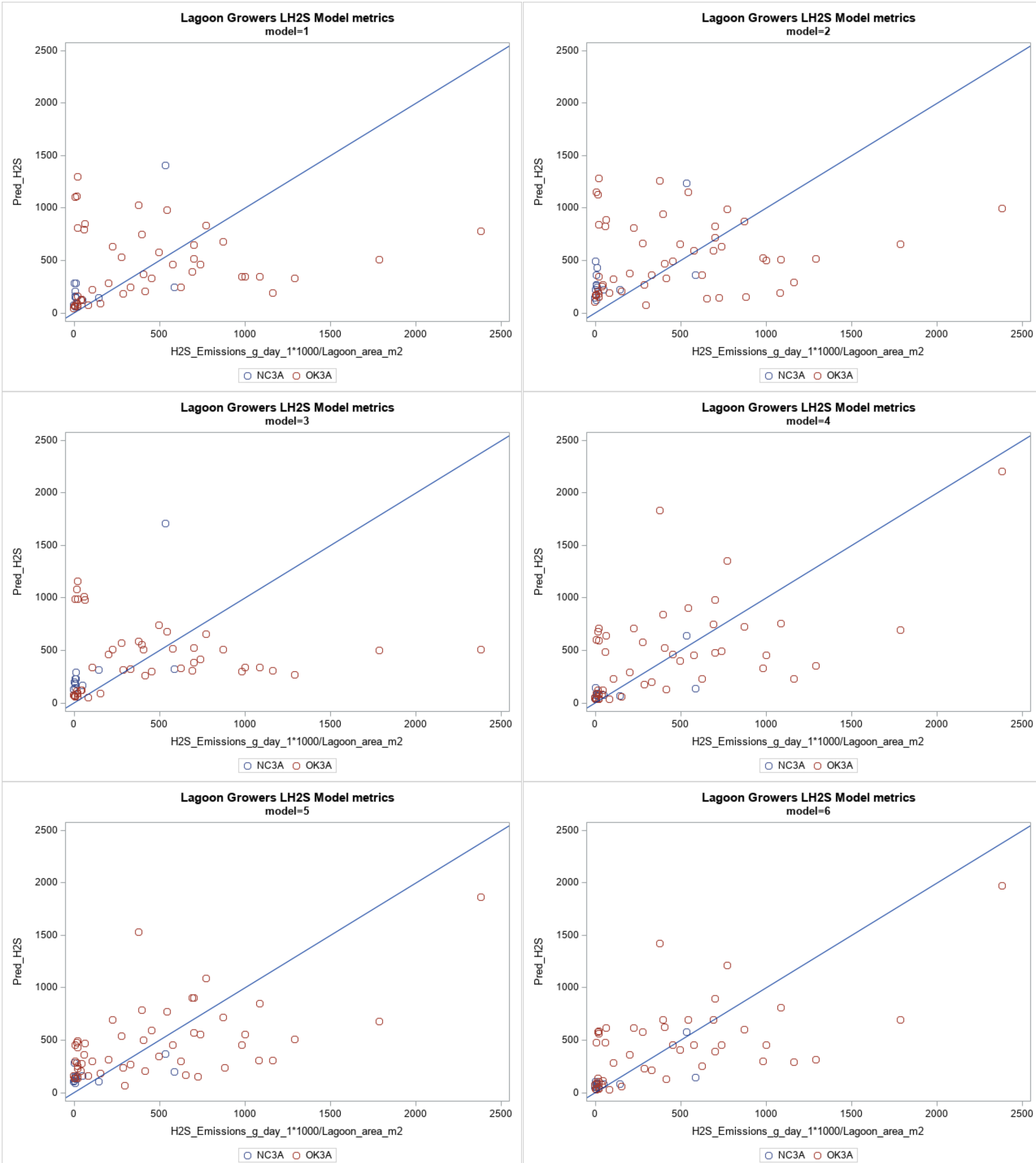
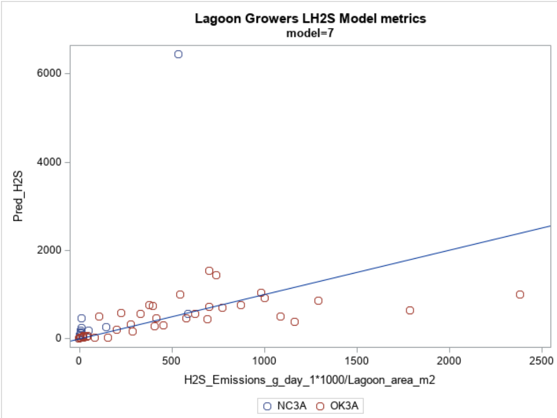
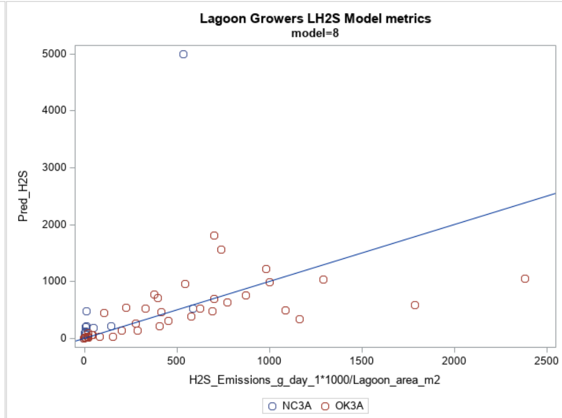
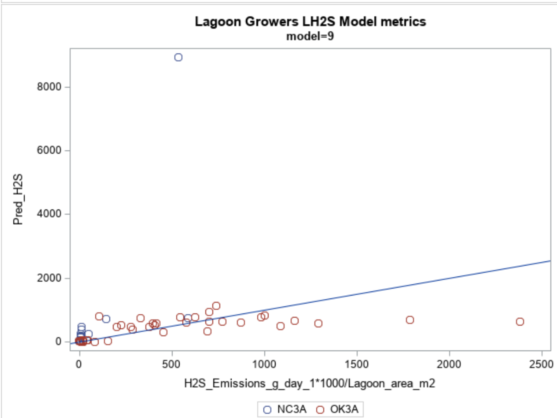
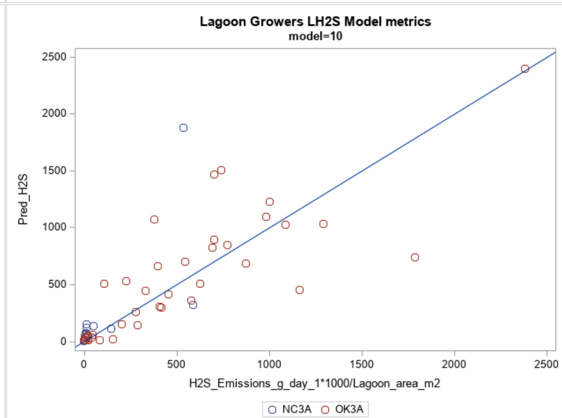


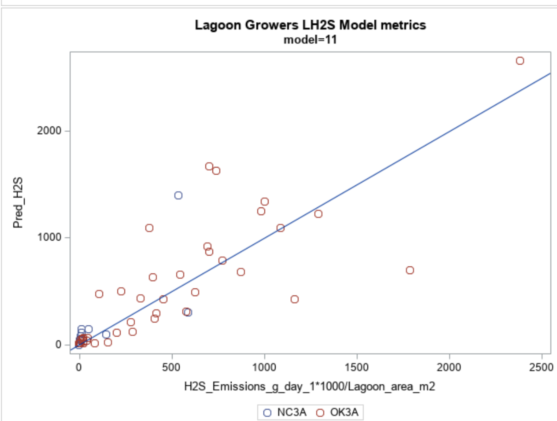
Figure F-144 Grow-finish Lagoon H_2S one-to-one plots for models 1 through 6.

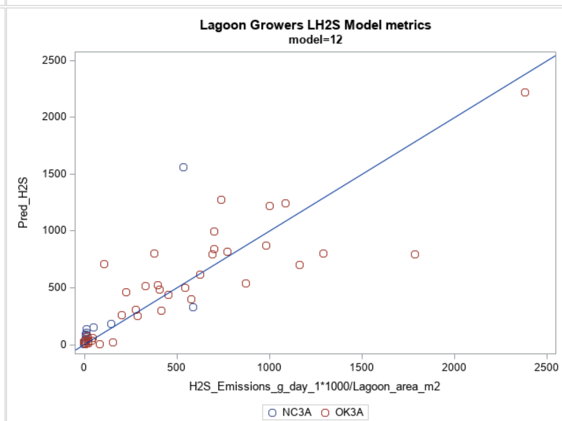

Lagoon Growers LH2S Model metrics
model=7
Pred_H2S
H2S_Emissions_g_day_1*1000/Lagoon_area_m2
NC3A OK3A


Lagoon Growers LH2S Model metrics
model=8
Pred_H2S
H2S_Emissions_g_day_1*1000/Lagoon_area_m2
NC3A OK3A


Lagoon Growers LH2S Model metrics
model=9
Pred_H2S
H2S_Emissions_g_day_1*1000/Lagoon_area_m2
NC3A OK3A


Lagoon Growers LH2S Model metrics
model=10
Pred_H2S
H2S_Emissions_g_day_1*1000/Lagoon_area_m2
NC3A OK3A


Lagoon Growers LH2S Model metrics
model=11
Pred_H2S
H2S_Emissions_g_day_1*1000/Lagoon_area_m2
NC3A OK3A


Lagoon Growers LH2S Model metrics
model=12
Pred_H2S
H2S_Emissions_g_day_1*1000/Lagoon_area_m2
NC3A OK3A

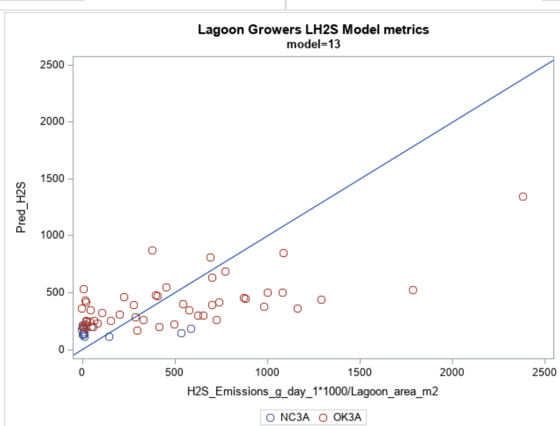

Lagoon Growers LH2S Model metrics
model=13
Pred_H2S
H2S_Emissions_g_day_1*1000/Lagoon_area_m2
NC3A OK3A

Figure F-145 Grow-finish Lagoon H_2S one-to-one plots for models 7 through 13.

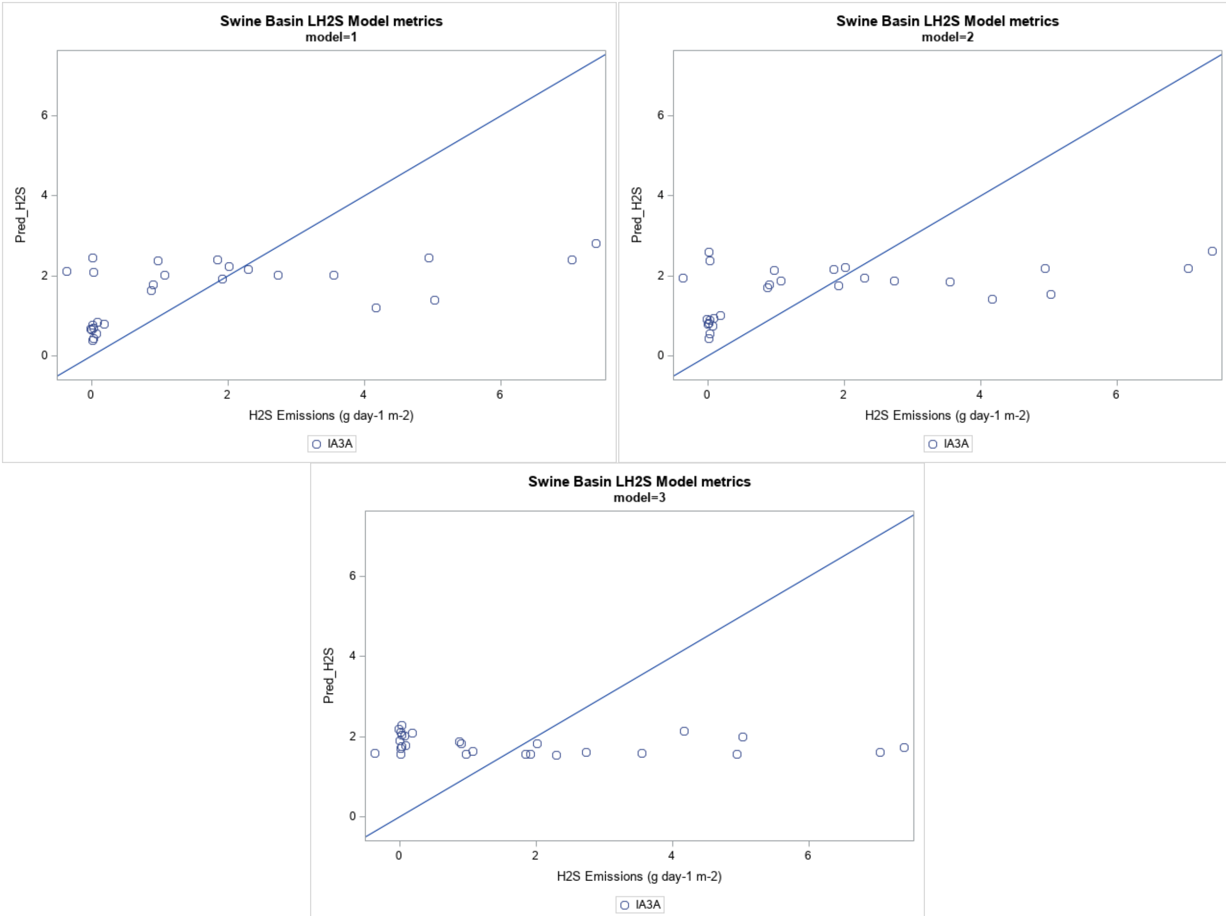


Figure F-146 Basin H_2S model one-to-one plots