

# Development of Emissions Estimating Methodologies for Animal Feeding Operations Volume 5: Dairy

Draft

Prepared by:

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

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## GLOSSARY / ACRONYMS

-2LogL	negative twice the likelihood
ADMs	average daily means
AFO	animal feeding operation
AIC	Akaike information criterion
AICc	adjusted Akaike information criterion
BIC	Schwarz Bayesian Information Criterion
FANS	Fan Assessment Numeration System
H <sub>2</sub> S	hydrogen sulfide
LAW	live animal weight
MB	mean bias
ME	mean error
NAEMS	National Air Emissions Monitoring Study
NH <sub>3</sub>	ammonia
NMB	normalized mean bias
NME	normalized mean error
PI	Principal Investigator
PM	particulate matter
PM <sub>10</sub>	particulate matter with aerodynamic diameters less than 10 micrometers
PM <sub>2.5</sub>	PM with aerodynamic diameters less than 2.5 micrometers
QAPP	quality assurance project plan
QC	quality control
TAN	total ammoniacal nitrogen
TEOM	tapered element oscillating microbalance
TKN	total Kjeldahl nitrogen
TSP	total suspended particulate
USDA	U.S. Department of Agriculture

# 1 INTRODUCTION

## 1.1 Confinement Site Descriptions

Five milk production facilities (dairy operations) had barns monitored under NAEMS. The locations were selected based on site-specific factors including representativeness of facility age, size, design and management, and herd diet and genetics. Three free stall and two open free stall dairy facilities were monitored as a part of NAEMS. Table 1-1 summarizes the sites and their characteristics.

**Table 1-1. Dairy confinement sites monitored under NAEMS.**

Site	Monitoring Period	Site Type	Ventilation Type	Number of Barns Measured	Manure Collection	Manure Storage <sup>4</sup>	Bedding Type <sup>5</sup>
NY5B	10/24/07 – 10/23/09	Free stall	Mechanically Ventilated	1 <sup>3</sup>	Scrape	Digester/SS/SSP	SDS
IN5B	8/24/07 – 8/23/09	Free stall	Mechanically Ventilated	2 <sup>3</sup>	Scrape	Digester/SS/Lagoon	SDS
WI5B <sup>1</sup>	9/12/07 – 10/31/09	Free stall	Mechanically Ventilated	2	Flush	SP/Lagoon	Mattress/shavings
CA5B	9/26/07 – 2/1/10	Open free stall <sup>2</sup>	Naturally Ventilated	2	Flush	SP/Lagoon	Soil/MS/Almond shells
WA5B <sup>1</sup>	9/28/07 – 9/27/09.	Open free stall <sup>2</sup>	Naturally Ventilated	2	Flush	SP/SS/SSP/Basin	MS

<sup>1</sup> Barn sites that also have measured area sources.

<sup>2</sup> Cows are free to walk from open free stall barn into dry lots between the barns.

<sup>3</sup> Monitored units include the milking center.

<sup>4</sup> Labeled consistent with the site reports, where: SP = Settling Pond; SS = solid separation; SSP= Solid Storage Pad

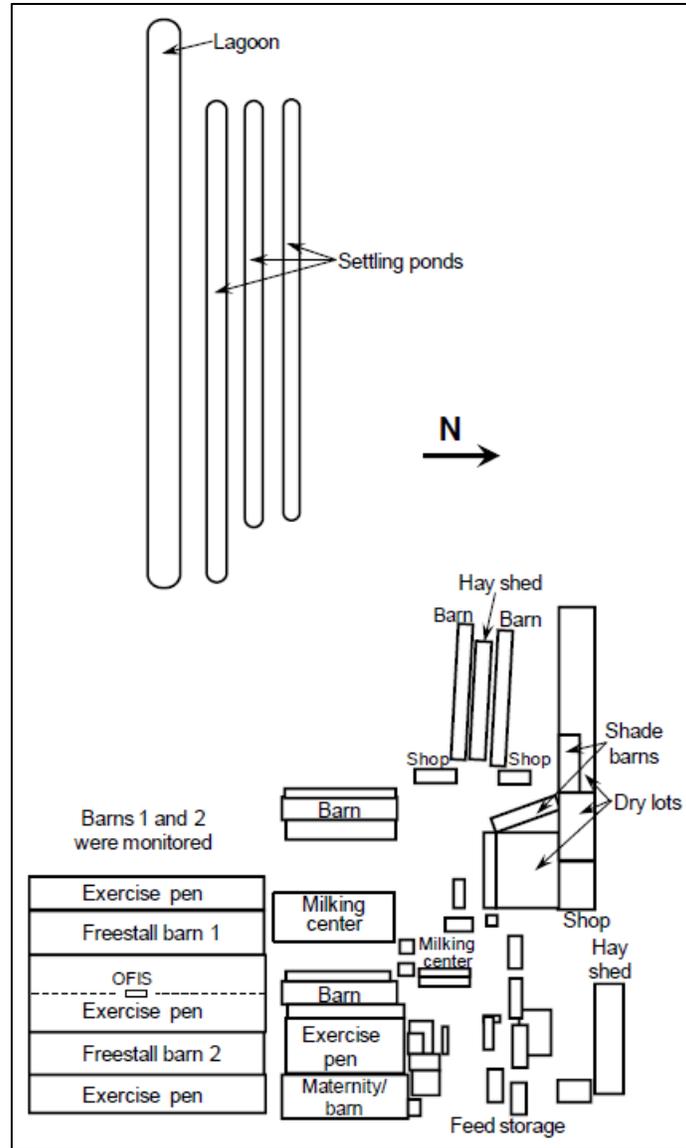
<sup>5</sup> MS = Manure solids; SDS = Separated digested solids

### 1.1.1 CA5B

In 2010, the California site (CA5B) was a 1,200-cow Holstein dairy farm. The farm has two naturally ventilated free stall barns, a milking center, and a lagoon and settling ponds (Figure 1-1). The farm also included exercise lots, which were located adjacent to each barn. Lactating cows were milked two times daily in the centrally located milking center. The on-site heifer program (i.e., activities to raise their own heifer calves until they can join the milking herd) was held on the north end of the farm, separated from the study area.

The two naturally ventilated free stall barns, barn 1 (B1) and barn 2 (B2), were monitored as part of NAEMS (Zhao, et al., 2010). Each barn had four free stall rows, two on each side of a central feed lane, housing 600 cows each. Barn 1 had the fresher cows (i.e., cows that recently gave birth) and served as the breeder barn, while barn 2 had pregnant lactating cows and the hard breeders (i.e., cows that have a hard time getting pregnant). The cows were generally inside the barns, particularly on hot days to provide shade.

The manure handling system included a barn flushing system, three settling ponds and a lagoon. Manure solids taken from the settling ponds were spread on nearby fields in the spring and fall.



**Figure 1-1. CA5B farm layout.**

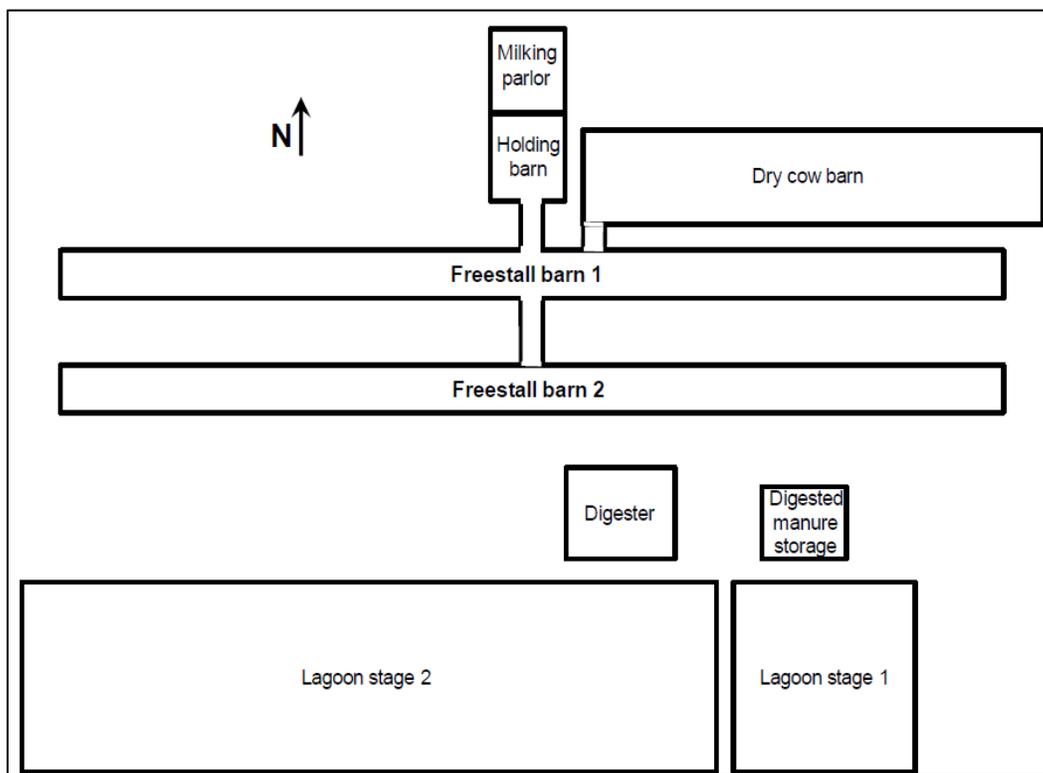
Source: Zhao, et al. (2010)

### 1.1.2 IN5B

The dairy farm in Indiana (IN5B) had 3,400-head capacity of Holstein cows. The dairy consisted of two free stall barns, a holding barn, milking parlor, and a dry cow barn (Figure 1-2). NAEMS gathered measurements from the two freestall barns, barn 1 (B1) and barn 2 (B2), and the milking center (MC), which consisted of the holding barn (area where cows waited approximately 45 minutes prior to milking) and milking parlor (Lim, et al., 2010). Each barn

used a bank of exhaust fans to pull air through the barns. Each barn typically housed up to 1,700 cows, with approximately 3,400 Holstein cows milked three times a day in the 72-stall rotary parlor. For the NAEMS, measurements of airflow and emissions focused on the western half of each of the barns.

The manure was removed from both freestall barns by scraper, while the manure from the holding barn and milking parlor was flushed. The manure removed from the freestall barn and milking center are held in a reception pit, and then directed to a digester that produced methane gas which was used in generators on the farm. Digester effluent was separated, with the digested solids moved to a storage area and the liquid stored in a two-stage pond/lagoon system. The liquid was then either irrigated onto or injected into land in the surrounding area. The separated digested solids were used as bedding in the free stall barns.



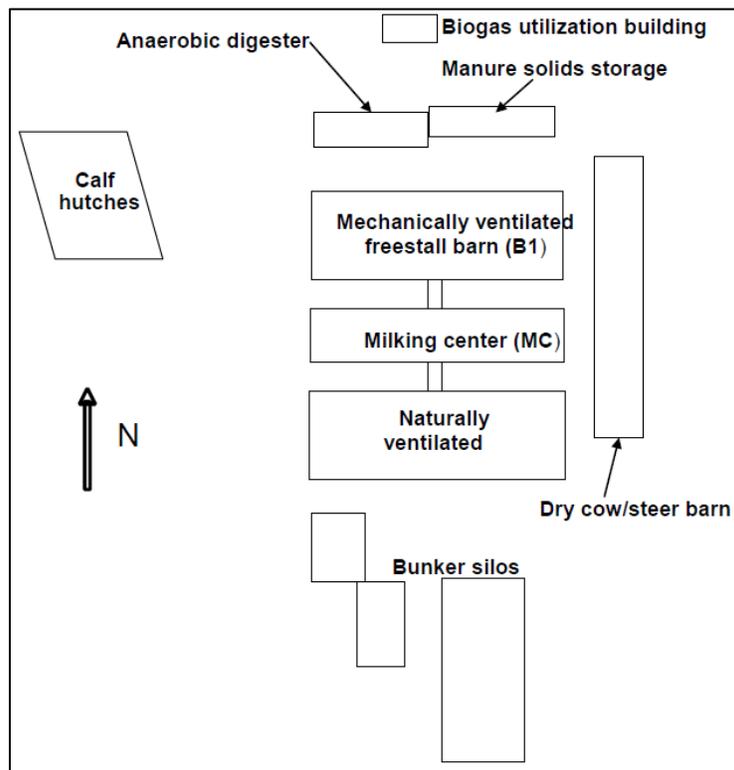
**Figure 1-2. IN5B farm layout.**  
Source: Lim et al. (2010)

### 1.1.3 NY5B

The dairy facility monitored in New York (NY5B) had a capacity of 1,000 Holstein cows and consisted of a mechanically ventilated free stall barn and a milking center, a naturally ventilated free stall barn, along with housing facilities for dry cows, steers, and calves on the same site (Figure 1-3). Measurements were collected from the mechanically ventilated 6 row free stall barn (barn 1 or B1) and the MC during the study (Bogan, et al., 2010). The MC included a

double-20 milking parlor, 31 free stalls and four bedded-pack box stalls for special-needs cows. Cows were brought in for milking three times per day.

The manure was removed from both the B1 and MC by scraper and deposited in a below-grade gravity flow channel that led to a centralized agitation and pumping station located in the covered connecting alley between the structures. From the alley, the manure was transferred to an anaerobic digester. The digester effluent was processed with a screw-press solid-liquid separator. The separated solids were stockpiled as bedding, land-applied to far-off fields, or sold. The liquid was pumped to long-term storage that was about 2.3 km away to the northeast.

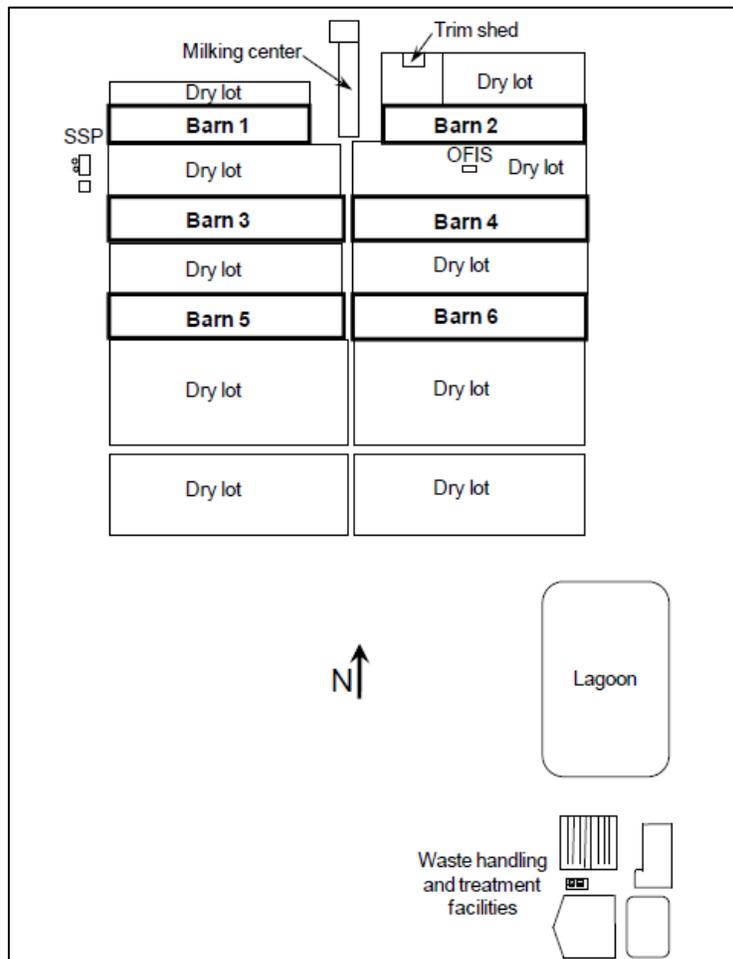


**Figure 1-3. NY5B farm layout.**  
Source: Bogan, et al. (2010)

#### 1.1.4 WA5B

The dairy facility located in Washington State (WA5B) was a 5,600-head Holstein dairy farm. The farm buildings included the milking parlor and six naturally ventilated symmetrically-distributed free stall barns (Figure 1-4). The farm also includes a total of ten corrals/exercise pens that are distributed around the barns. Two of the free stall barns, barn 2 (B2) and barn 4 (B4), were monitored as part of NAEMS (Ramirez-Dorransoro, et al., 2010). Barn 2 housed 600 cows in four rows of free stalls and Barn 4 housed 700 cows in six free stall rows.

Manure from the free stall barns was flushed automatically three times daily and scraped as needed. The effluent was directed, via pipes, to the waste handling and treatment system that included a sand separation pit, two primary settling ponds, a manure separation pad (which includes screen separators and centrifugal solid separators), and a pair of serpentine settling systems, in which each one had five sequential settling cells. Both serpentine cells then discharged into a central cell. The liquid effluent from the central cell was directed to the storage lagoon. The solid effluent from the sand separation pit, depending on the season and temperature, also was directed to two manure drying ponds, located south of the manure separator pad. The dried manure was used for bedding and land application, and the liquid was applied to surrounding fields. The site's lagoon was also monitored as a part of NAEMS (Section 1.2.3).

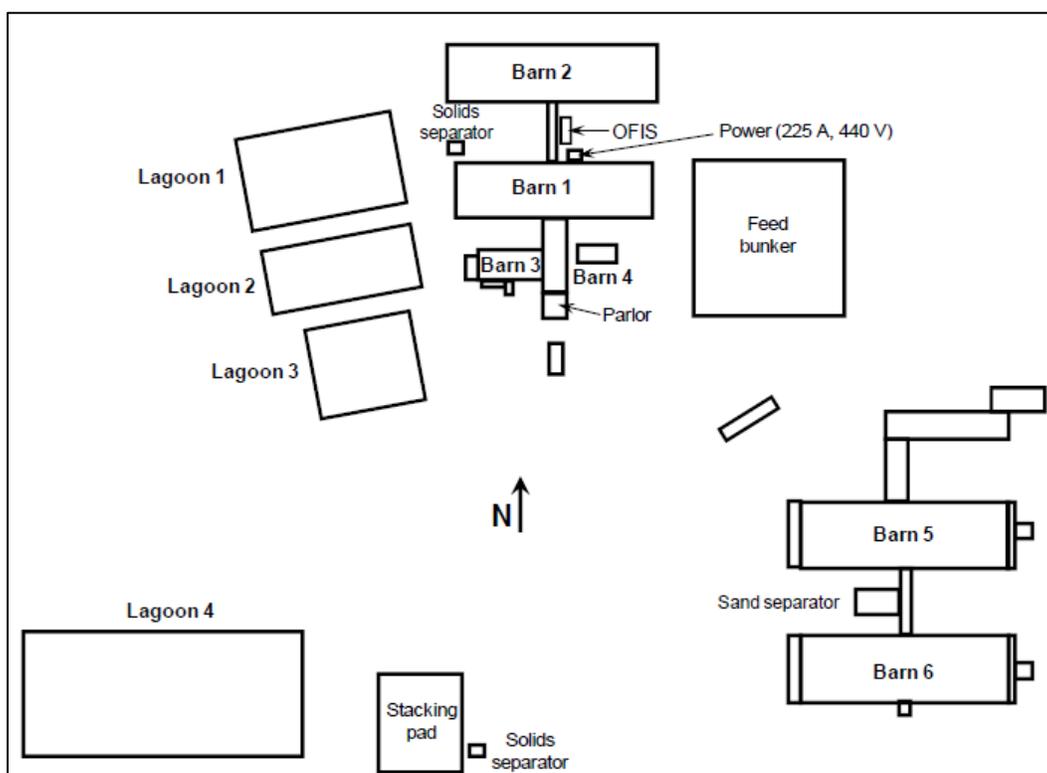


**Figure 1-4. WA5B farm layout.**  
 Source: Ramirez-Dorransoro, et al. (2010)

### 1.1.5 WI5B

The dairy facility monitored in Wisconsin (WI5B) had a total capacity of 1,700 Holstein dairy cows, and consisted of four free stall barns, a holding barn, and sixth barn that is divided into the calving pen for 2-year-olds and a hospital barn (Figure 1-5). Two of the free stall barns, barns 1 (B1) and 2 (B2), located on the north side of the farm, were monitored as a part of NAEMS (Cortus et al., 2010). Barn 1 (B1) had capacity of 275 cows in four rows of free stalls, and barn 2 (B2) had a capacity of 375 cows housed in five rows of free stalls.

Approximately halfway through the study, the manure removal system was changed in the barns. Initially, manure was removed by flushing three time per day. The manure flushed from the parlor, holding pens, and free stall barns was directed to a solid separator. Solids were directed to pads to wait for land application, while the liquid portion was pumped back into the vertical tanks to flush the barns. After September 19, 2008, the flush system was replaced with a tractor scrape system, which was already in use in barns 5 and 6.



**Figure 1-5. WI5B farm layout.**

Source: Cortus et al. (2010).

## 1.2 Open Source Site Descriptions

Three dairy lagoons and a dairy corral (TX5A) were monitored under NAEMS (Table 1-2). Sites were selected to capture different stages and manure practices typical of the industry. The sites selected also represent the broad geographical extent of dairy production to also

represent different climatological settings for farm and any regional differences in farm practices.

Dairy lagoon emissions were measured continuously at one farm (IN5A) for one year and for up to 21 days each season for two years at the two other farms (WA5A and WI5A). The dairy corral (TX5A) was also monitored for up to 21 days each season for two years.).

<sup>1</sup> Site that also had barn monitoring sites during NAEMS

<sup>2</sup> Lagoon can be single or double stage.

<sup>3</sup> SB= Settling Basin

**Table 1-2. Dairy open source sites monitored under NAEMS.**

Site	Source Monitored	Manure Collection	Manure Storage <sup>3</sup>
IN5A	Lagoon	Flush	Lagoon
WA5A <sup>1</sup>	Lagoon	Flush	Lagoon
WI5A <sup>1</sup>	Lagoon <sup>2</sup>	Flush	Lagoon
TX5A	Open Corral	Scrape	SB/Lagoon

<sup>1</sup> Site that also had barn monitoring sites during NAEMS

<sup>2</sup> Lagoon can be single or double stage.

<sup>3</sup> SB= Settling Basin

### 1.2.1 IN5A

The Indiana open source site consisted of three barns, a feed storage area, special needs barn, milking parlor, and an office and tool and repair shops (Figure 1-6). The facility had a capacity of 2,600 cows (Grant and Boehm, 2010a).

The monitored lagoon received effluent from the parlor and holding area. Manure was flushed from the holding area and milking parlor every half hour. A small fraction of waste was held in a slurry tank. The wastewater (flush) from the holding area and milking parlor was transferred to a settling basin before being transferred to the clay-lined lagoon. The clay-lined waste lagoon was 85m (280 ft) wide and 116m (380 ft) long, with a surface area of 9,884 m<sup>2</sup> (106,400 ft<sup>2</sup>). Sludge had never been removed from the lagoon (Grant and Boehm, 2010a).



**Figure 1-6. Aerial view of IN5A.**  
 Source: Grant and Boehm (2010a)

**1.2.2 TX5A**

The Texas dairy (TX5A) consisted of ten corrals, milking parlor, office, hay shed, commodities barn, calving/fresh cow barn and truck scale (Figure 1-7). The facility had a capacity of 3,400 Holstein cows (Grant and Boehm, 2010b). Wastewater from the dairy drains to two earthen sludge/settling basins before entering a retention/treatment structure. Runoff from the corrals drains to the larger of two retention structures which are connected in series.

Manure was scraped twice a week from the corral surface with some scrapings used as bedding and the remainder was pushed to the south into ditches, which drained into the runoff pond. Manure was vacuumed instead of scraped if persistent wet conditions occurred.



**Figure 1-7. Aerial view of TX5A.**  
 Source: Grant and Boehm (2010b)

### 1.2.3 WA5A

The Washington farm (WA5A) consisted of six barns, a milking parlor, and an office (Figure 1-8). The facility has a capacity of 4,400 milking cows and 1,200 dry cows in three units (Grant and Boehm, 2010c). The farm has free stall style barns, with automated flushing that occurred four times daily. Manure was transferred to an upper settling basin from a sand separation pit. Liquids were skim separated and then returned as flush to the barns. One lagoon was actively filled while the other was drying or sludge was being entirely removed. The settled solids (sludge) were completely removed within a year by front end loader. The settled solids (sludge) were removed annually by a front-end loader. These remaining solids were then strained through screens and centrifugal/screw presses, and the liquid transferred to large serpentine concrete basins for secondary settling. These solids are then dried for bedding. The water removed from the settled solids is stored in a large, clarified water storage basin for dilution of barn flush water from the lagoons.

The two upper lagoon/settling basins were measured as part of NAEMS, as well as two free stall barns described as in Section 1.1.4. Gaseous emissions occur both during lagoon filling and during sludge removal. The east lagoon was rectangular with dimensions of 183m (600 ft) by 72 m (235 ft). The west lagoon was five-sided with dimensions of approximately 183 m (600 ft) long and 83m (271 ft) wide with the southwest corner of the lagoon cut off. The east lagoon

was measured for gaseous emissions. At maximum capacity this lagoon had a liquid depth of 5 m (18 ft), surface area of 13,098 m<sup>2</sup> (141,000 ft<sup>2</sup>) and a volume of 186,300 m<sup>3</sup> (2,005,500 ft<sup>3</sup>).



**Figure 1-8. Aerial view of WA5A.**  
Source: Grant and Boehm (2010c)

#### **1.2.4 WI5A**

In 2010, the Wisconsin farm (WI5A) had a total of six barns, a milking parlor with holding pen, and a special needs area (Figure 1-9). The farm had a capacity of 1,700 Holstein cows (Grant and Boehm, 2010d). Manure from the free stall barns and the milking parlor complex was removed by flushing three times daily. The manure flushed from the parlor, holding pen, and free stall barns flows to a solids separator, from which the solids are removed and stacked on a pad until they are spread on fields. The liquid effluent from the solids separator was pumped back into vertical tanks for reuse to flush the barns. Once a week, enough water was removed from the third stage of the three-stage lagoon and added to the flush tanks to make up for water lost in the recycled flush system. The three-stage lagoon receives effluent from the two free stall barns measured by the barn component of NAEMS (Section 1.1.5), as well as the other barns and milking parlor. The lagoons are pumped out into trucks twice yearly. The first and second stages of the three-stage lagoon system were monitored, as well as two free stall barns as described in Section 1.1.5.

The first lagoon had a width of 52 m (170 ft) and a length of 82 m (270 ft). At maximum capacity, the first lagoon had a surface area of 4,264 m<sup>2</sup> (45,900 ft<sup>2</sup>) and a volume of 10,561 m<sup>3</sup> (373,000 ft<sup>3</sup>). The second lagoon had a width of 37 m (120 ft) and length of 79 m (260 ft). At maximum capacity, the second lagoon had a surface area of 2,898 m<sup>2</sup> (31,200 ft<sup>2</sup>) and a volume of 6,420 m<sup>3</sup> (226,700 ft<sup>3</sup>). Both lagoons had liquid depths of 3 m (11 ft) and sludge was last removed from the second lagoon in 2006.



**Figure 1-9. Aerial view of WI5A.**  
Source: Grant and Boehm (2010d)

### 1.3 Data Sampled

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

#### 1.3.1 Particulate Matter

At any one time, the sampled filterable PM size class was either equal to or less than a nominal aerodynamic diameter of 10 micrometers (PM<sub>10</sub>), and 2.5 micrometers (PM<sub>2.5</sub>) or total suspended particulate (TSP). Appendix A contains summary tables, which note the PM sampling

schedules for the confinement sites. Particulate matter emissions data were not collected for the open sources.

### **1.3.2 Animal Husbandry**

In general, the producer provided pen inventories and information about changes to site operational procedures like bedding, on a weekly basis. For NY5B, the producer also provided daily milk production.

### **1.3.3 Biomaterials Sampling Methods and Schedule**

All analyses of biomaterials were performed by an independent laboratory (Midwest Laboratories, Omaha, NE). Samples were collected based on procedures outlined in the QAPP (Heber, 2008). Specific sampling details for each site are summarized below. There were no lagoon samples collected for content analysis.

#### **1.3.3.1 CA5B**

Manure sampling was conducted approximately bimonthly during the second year of the study, with samples collected from the reception lane for the flushed manure in B1 and B2. The samples were analyzed for solids content, total nitrogen, ammoniacal nitrogen, and ash content to provide data for the nitrogen balance of the barns.

At the same time as manure sampling, samples of feed and fresh bedding (scraped soil and manure solids blended with almond shells or rice hulls) were taken from each barn. The samples were analyzed for solids content, total nitrogen, and ash. Sampling was added late in the study and only cover the second year of the study (Zhao, et al., 2010).

#### **1.3.3.2 IN5B**

Manure in the barns was sampled quarterly between 11/26/07 and 1/20/10. For each collection, at least four samples were collected from each of the two barns and analyzed for ammoniacal nitrogen, total nitrogen, pH, total solids, and ash (added later in the study). Samples of feed were also taken quarterly from each barn and analyzed for total nitrogen, total solids, and ash. Sampling was added late in the study and only cover the second year of the study (Lim, et al., 2010).

Bedding and milk tank samples were collected semiannually. Bedding samples were analyzed for total nitrogen and total solids, while the milk tank samples were only analyzed for total nitrogen.

#### **1.3.3.3 NY5B**

The daily volume of milk shipped (total milk less non-saleable milk) from the farm was copied manually from the yearly calendar where milk production was recorded daily by farm staff. Milk production data from B1 included the cows housed in the MC. Additionally, the farm reported milk urea nitrogen (MUN) and protein content nearly every day.

Bedding (post-digested separated manure solids) was sampled from each pen on approximately a monthly basis during the study's second year. The samples were analyzed for pH, solids content, total nitrogen, and ammoniacal nitrogen, and ash content. A single sample of the feed and water were taken at the end of the study. The feed was analyzed for solids content, total nitrogen, and ammoniacal nitrogen, and ash content, while the water sample was analyzed for total nitrogen, and ammoniacal nitrogen, and sulfur content.

Representative manure samples were collected in B1 from each the four pens, and the two manure alleys between the outside row of free stalls and the adjacent row of the head-to-head free stalls. Sampling was conducted approximately monthly during the second year. The samples were analyzed for pH, solids content, total nitrogen, and ammoniacal nitrogen.

#### **1.3.3.4 WA5B**

Sampling was conducted approximately bimonthly during the second year of the study. Samples of feed, bedding, and manure were taken from each barn. Bedding and feed samples were analyzed for total solids and total nitrogen content. Manure samples were analyzed for pH, total solids, total nitrogen, and ammonia (NH<sub>3</sub>) content. Milk samples were taken from the holding tank and analyzed for total nitrogen only.

#### **1.3.3.5 WI5B**

Manure in the barns was sampled quarterly for the last year of the study. Each collection was composed of four samples from each of the two barns. Samples were analyzed for ammoniacal nitrogen, pH, and total solids.

## **2 REVISIONS TO DATA SET AND EMISSIONS DATA SUMMARY**

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

### **2.1 Revisions to the 2010 Data Set**

As described in Section 4.2 of the Overview report, the NAEMS monitoring data were submitted to EPA in 2010, with revisions submitted in 2015. Revisions included modifying the approach used to determine the inlet concentrations of NH<sub>3</sub> and hydrogen sulfide (H<sub>2</sub>S) to align time used to determine valid concentrations at the barn inlet and outlet, using a 10day running average of inlet concentrations rather than interpolation, and invalidating air flow rates for periods when the ventilation system was not operating. Corrections were submitted for IN5B, NY5B, WA5B, and WI5B. A revised file for CA5B was not submitted by the NAEMS principal investigator (PI).

In addition to the revisions submitted by the PI, EPA reviewed the validity of negative emissions values present in the data set. Negative calculated emissions values can occur in the NAEMS data set due to a range of different scenarios as described in the SAB review of the 2012 emissions estimating methodologies (EEMs) developed by EPA (U.S. EPA SAB, 2013). These different negative emissions scenarios include calculation biases for emissions values that were close to the instrument's detection limit, biases due to lack of lag time corrections, or from outdoor events that increased pollutant concentration outside of the barns. EPA developed a procedure for removing negative emissions values that resulted from elevated background concentrations. For this procedure, EPA determined the median emissions value for each pollutant, then excluded negative emissions values that fell outside of a range based on uncertainty range established in the QAPP for each pollutant. Appendix B describes this process in more detail. The negative emissions removed accounted for between 2% (NH<sub>3</sub> and TSP) and 26% (PM<sub>2.5</sub>) of the total number of average daily emission values available for the pollutant. Appendix B provides a summary of the number of values removed due to this process by barn for each pollutant.

The 2010 data sets for dairy open sources (lagoons, basins, and corrals) were provided to EPA by the NAEMS PI. The datasets contain 30-minute NH<sub>3</sub> values obtained using the backward Lagrangian Stochastics (bLS) model and vertical radial plume mapping (VRPM), and H<sub>2</sub>S emissions obtained using the bLS model. The extensive data sets also include fields used to determine the quality and validity of the emissions data. Based on a literature review of papers published since NAEMS (Grant and Boehm 2020, Grant et al., 2020, Grant and Boehm 2015,

Grant et al., 2013a), EPA revised the acceptance criteria for the 30-minute data. Overall, the number of valid 30-minute bLS NH<sub>3</sub> values for lagoons increased and H<sub>2</sub>S decreased. The opposite occurred for the corral site, TX5A, as the number of bLS measure estimates NH<sub>3</sub> and H<sub>2</sub>S decreased and increased, respectively. Appendix B summarizes the changes in data acceptance criteria and the effects they had on the number of 30-minute values available for each site.

Literature (Grant et al., 2013a) also suggested bLS measurements could be adjusted to be comparable to VRPM results. To prepare the 2012 NAEMS data sets of 30-minute values for use in calculating daily averages, the bLS NH<sub>3</sub> values for sites IN5A and WI5A were adjusted by multiplying the emissions values by 1.19 (Grant and Boehm 2020) and 1.13 (Grant and Boehm 2020), respectively. After the adjustment, the bLS and VRPM data were used together to determine which day had more than 24 half hour values to meet the revised 52% completeness criteria days. In cases where 30-minute emissions flux values were available for both the bLS model and VRPM, the average of the bLS and VRPM values were used. A practical example of the calculation is provided in Appendix B. Table B-23 presents example calculations for two days at site IN5A (one day with both bLS and VRPM data, and one day with only bLS data).

## **2.2 Comparison between the 2010 and Revised Barn Data Sets**

The influence of the previously described corrections on the revised data sets can be observed by comparing the summary statistics of all the valid emissions values (at 75% data completeness) between the 2010 dataset, as summarized in the final site reports, and the revised data set. The following sections summarize the differences between the 2010 data set and revised data set for each of the barn types for a set of standard summary statistics (e.g., mean, standard deviation, count (N), minimum, maximum, and number less than 0 (N<0)) of the average daily emissions. For summary tables presented, the percentage difference was calculated as the revised data set minus the 2010 version of the data set, divided by the 2010 version of the data set (e.g., % Diff = (Revised - Data<sub>2010</sub>)/Data<sub>2010</sub> \* 100). This calculation yielded negative values when decreases were seen in the revised version of the dataset.

### **2.2.1 Mechanically Ventilated Barns**

In general, the 2010 and revised data set vary less than 10% for the barns at IN2B for NH<sub>3</sub> (Table 2-1) and H<sub>2</sub>S (Table 2-2), while the data sets for the PM size fractions (Table 2-3) were not changed. The exceptions are the increase in the number of H<sub>2</sub>S values less than zero (N<0) at IN2B (Table 2-2). There was more of a difference in the data sets for NY5B, particularly with the minimum value of H<sub>2</sub>S (Table 2-2), which was revised from a very large negative value (-226 g/d) to a small positive value (34.05 g/d). NY5B was the only site that had changes to the PM data set (Table 2-3), most notable of which was a decrease in the number of

negative values for PM<sub>10</sub>. The WI5B site saw some of the biggest differences in NH<sub>3</sub> data, largely due to the increase in the number of valid average daily means (ADM) available for NH<sub>3</sub> after the revisions. The WI5B data sets for PM<sub>10</sub>, PM<sub>2.5</sub>, and TSP were unchanged.

**Table 2-1. Percentage difference in NH<sub>3</sub> summary statistics between the 2010 and revised dataset (at 75% data completeness).**

Parameter	IN5B B1	IN5B B2	NY5B B1	WI5B B1	WI5B B2
Mean	3%	3%	6%	-4%	-3%
Standard Deviation	5%	5%	5%	-11%	-3%
N	0%	0%	-12%	19%	20%
Minimum	-6%	-6%	-1%	25%	-26%
Maximum	4%	9%	7%	-2%	-2%
N<0	0%	0%	0%	0%	0%

**Table 2-2. Percentage difference in H<sub>2</sub>S summary statistics between the 2010 and revised dataset (at 75% data completeness).**

Parameter	IN5B B1	IN5B B2	NY5B B1	WI5B B1	WI5B B2
Mean	1%	-2%	10%	0%	0%
Standard Deviation	0%	1%	3%	0%	-3%
N	2%	4%	-12%	-3%	-2%
Minimum	2%	2%	764%	0%	0%
Maximum	-2%	8%	-3%	4%	-5%
N<0	47%	67%	0%	33%	-88%

**Table 2-3. Percentage difference in PM summary statistics between the 2010 and revised dataset (at 75% data completeness).**

Parameter	NY5B B1, PM <sub>10</sub>	NY5B B1, PM <sub>2.5</sub>	NY5B B1, TSP	IN5B, PM	WI5B, PM
Mean	5%	2%	2%	No difference	No difference
Standard Deviation	5%	1%	0%	No difference	No difference
N	0%	2%	0%	No difference	No difference
Minimum	0%	0%	0%	No difference	No difference
Maximum	7%	1%	1%	No difference	No difference
N<0	-50%	13%	0%	No difference	No difference

### 2.2.2 Naturally Ventilated Barns

For the naturally ventilated barns, there were no changes in the CA5B datasets for any pollutant and no changes in the WA5B datasets for NH<sub>3</sub>, H<sub>2</sub>S, or PM<sub>2.5</sub>. For PM<sub>10</sub> (Table 2-4), both WA5B barns saw an increase in the number of valid ADM, including new maximums more than 50% larger than in the 2010 data set. The TSP data set (Table 2-5) also changed, most notably there was an 18% decrease in the number of valid ADM at both barns and an increase in the minimum value for barn 2.

**Table 2-4. Percentage difference in PM<sub>10</sub> summary statistics between the 2010 and revised dataset (at 75% data completeness).**

Parameter	CA5B B1	CA5B B2	WA5B B1	WA5B B2
Mean	No difference	No difference	20%	12%
Standard Deviation	No difference	No difference	63%	38%
N	No difference	No difference	1%	1%
Minimum	No difference	No difference	0%	0%
Maximum	No difference	No difference	83%	68%
N<0	No difference	No difference	0%	0%

**Table 2-5. Percentage difference in TSP summary statistics between the 2010 and revised dataset (at 75% data completeness).**

Parameter	CA5B B1	CA5B B2	WA5B B1	WA5B B2
Mean	No difference	No difference	3%	1%
Standard Deviation	No difference	No difference	5%	6%
N	No difference	No difference	-18%	-18%
Minimum	No difference	No difference	522%	0%
Maximum	No difference	No difference	0%	0%
N<0	No difference	No difference	0%	0%

### **2.2.3 Milking Centers**

For the IN5B MC, most changes were minor for NH<sub>3</sub> (Table 2-6) and H<sub>2</sub>S (Table 2-7). The most notable change is the increase in the number of negative ADM for both gaseous pollutants due to the changes in emission calculation. There were no measurements of PM<sub>10</sub>, PM<sub>2.5</sub> or TSP made at the IN5B milking center.

The NY5B MC had minor changes to the NH<sub>3</sub> dataset and mostly minor changes to the H<sub>2</sub>S data set. One of the largest changes was an increase in the minimum value for H<sub>2</sub>S (Table 2-7), which was the result of the removal of a large negative ADM. The data sets for the PM size fractions (Table 2-8) generally saw minor changes. The notable exception is the 33% decrease in the number of negative values for ADM. This statistic is a little misleading, as there were only four values, and one of which was dropped during the revision.

**Table 2-6. Percentage difference in NH<sub>3</sub> summary statistics between the 2010 and revised dataset (at 75% data completeness).**

Parameter	IN5B	NY5B
Mean	7%	0%
Standard Deviation	8%	0%
N	0%	-7%
Minimum	0%	15%
Maximum	4%	-2%
N<0	8%	0%

**Table 2-7. Percentage difference in H<sub>2</sub>S summary statistics between the 2010 and revised dataset (at 75% data completeness).**

Parameter	IN5B	NY5B
Mean	2%	-2%
Standard Deviation	-4%	0%
N	1%	1%
Minimum	0%	764%
Maximum	-12%	-2%
N<0	39%	0%

**Table 2-8. Percentage difference in NY5B MC PM summary statistics between the 2010 and revised dataset (at 75% data completeness).**

Parameter	PM <sub>10</sub>	PM <sub>2.5</sub>	TSP
Mean	-1%	2%	1%
Standard Deviation	11%	1%	0%
N	8%	0%	0%
Minimum	0%	11%	0%
Maximum	0%	1%	1%
N<0	-33%	0%	0%

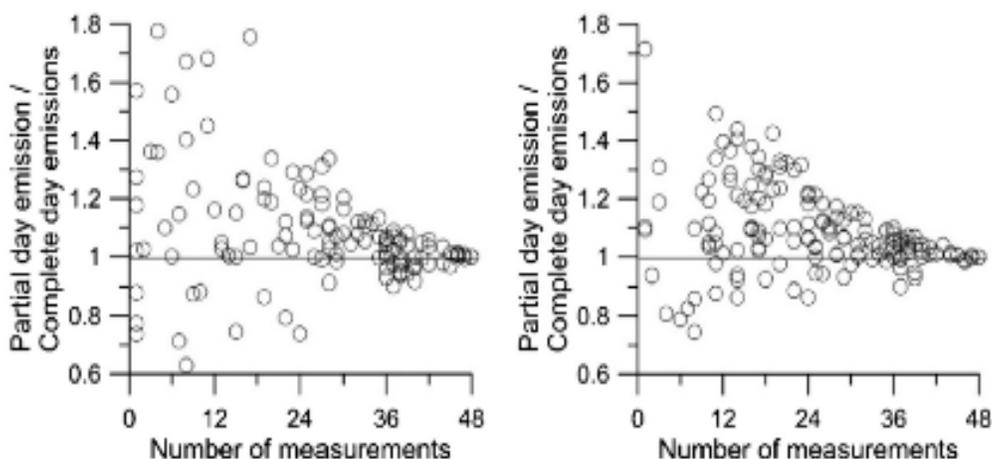
### 2.3 Data Completeness Criteria for the Revised Data Set

The appropriate data completeness criteria to use in a study depends on the size of the dataset and the accuracy needed. A study by Grant et al. (2013b), in which NH<sub>3</sub> emissions were modeled from swine lagoons based on NAEMS data, investigated data completeness and associated accuracy. The swine lagoon NH<sub>3</sub> emissions dataset had limited data availability at a data completeness of 75%. Grant et al. (2013b) explored how much the data completeness criteria could be relaxed but still result in data with acceptable error. The study suggested an error of  $\pm 25\%$  to be acceptable and determined that a daily data completeness of 52% (or 25 out of 48 30-minute periods) gave less than  $\pm 25\%$  error (see Figure 2-1). Using this revised daily completeness criteria resulted in a substantial increase in the size of the dataset.

Based on Figure 2-1 from the Grant et al. (2013b) 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. (2013b) study is representative of other NAEMS datasets, the effect of relaxed data completeness criteria can be investigated for other NAEMS sources.

The NAEMS PI provided EPA with additional analysis that examined the effect of different completeness criteria by comparing the number of valid ADM. EPA reviewed these data for the barn data site and retained the 75% completeness criterion. For the open source sites, EPA review found that adjusting the daily data completeness to 52% provided significantly more data and justified the increase in the error. The full analysis can be found in Appendix C.



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

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

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

A simple comparison of the summary statistics presented in these papers and the summary statistics of the revised dataset is presented in the following sections. Overall, the dataset used for model development and presented in the papers are different due to differences in data screening methods. For  $\text{NH}_3$  and  $\text{H}_2\text{S}$  at naturally ventilated barns, the model development dataset contains at least twice the number of observations than were used in the article due to different choices in processing the data. Similarly, the revisions to the acceptance

criteria for open sources noted in Section 2.1 also resulted in differences between the published data set and the modeling data set. For the open sources, the acceptance criteria used by EPA are the culmination of several published papers aiming to improve the data quality and go beyond what was discussed in the compared work. Overall, the comparison highlights that EPA has done extensive analysis and review of the dairy data sets to obtain a robust data set for model development.

#### 2.4.1 Naturally Ventilated Barns

Despite no difference between NH<sub>3</sub> and H<sub>2</sub>S in the revised data set and the submitted 2010 data set (Section 2.2.2) for WA5B, the published data has different maximum, minimum, and average values for both (Table 2-9 and Table 2-10). A closer examination of Joo et al. (2015) reveals a more extensive outlier removal process, whereby anything outside 1.5 times the interquartile range were designated as outliers. The article also only reports on data collected in the second year of the study (November 2008 to October 2009) since there were “more and longer trouble-free periods” (Joo et al., 2015). The article further truncates the data by focusing on one-week data sets of continuously collected measurements selected every two months, for a total of 7 weeks (49 days) of data. The model data set contains at least twice as many days as the published data set, which quickly explains the differences seen.

**Table 2-9. Comparison of naturally ventilated NH<sub>3</sub> emissions in the model dataset to published datasets.**

Site	Emissions Units	Statistic	Model Dataset	Published Studies	Study
WA5B B2	kg day <sup>-1</sup>	Mean	26.6	14.1	Joo et al., 2015
WA5B B2	kg day <sup>-1</sup>	Minimum	-156.4	10.8	Joo et al., 2015
WA5B B2	kg day <sup>-1</sup>	Maximum	96.6	19.7	Joo et al., 2015
WA5B B4	kg day <sup>-1</sup>	Mean	54.7	19.4	Joo et al., 2015
WA5B B4	kg day <sup>-1</sup>	Minimum	9.0	17.2	Joo et al., 2015
WA5B B4	kg day <sup>-1</sup>	Max	170.9	21.2	Joo et al., 2015

**Table 2-10. Comparison of naturally ventilated H<sub>2</sub>S emissions in the model dataset to published datasets.**

Site	Emissions Units	Statistic	Model Dataset	Published Studies	Study
WA5B B2	g day <sup>-1</sup>	Mean	555.6	397.4	Joo et al., 2015
WA5B B2	g day <sup>-1</sup>	Minimum	-5,400.9	123.5	Joo et al., 2015
WA5B B2	g day <sup>-1</sup>	Maximum	6,513.6	542.4	Joo et al., 2015
WA5B B4	g day <sup>-1</sup>	Mean	1,130.9	627.7	Joo et al., 2015
WA5B B4	g day <sup>-1</sup>	Minimum	-11,640.1	0.0	Joo et al., 2015
WA5B B4	g day <sup>-1</sup>	Max	17,960.3	1711.8	Joo et al., 2015

## 2.4.2 Open sources

Section 2.1 and Appendix B outline how EPA altered the acceptance criteria for the open sources. The changes were culled from several peer reviewed journal articles (Grant and Boehm 2020, Grant et al., 2020, Grant and Boehm 2015, Grant et al., 2013a) published since the 2010 receipt of the NAEMS data. While each of the articles referenced typically focus on one site, EPA developed a list of revisions to be applied to each site that represent the state of the science for the method. As such, the lagoon NH<sub>3</sub> values (Table 2-11) differ from the values published in Grant and Boehm (2020) due to difference in the acceptance criteria.

**Table 2-11. Comparison of lagoon and basin NH<sub>3</sub> emissions in the model dataset to published datasets.**

Site	Emissions Units	Statistic	Model Dataset	Published Studies	Study
IN5A	g s <sup>-1</sup>	Mean	0.23	0.27	Grant and Boehm, 2020
IN5A	g s <sup>-1</sup>	Minimum	-0.14	0.17	Grant and Boehm, 2020
IN5A	g s <sup>-1</sup>	Maximum	1.07	0.39	Grant and Boehm, 2020
WI5A	g s <sup>-1</sup>	Mean	0.07	0.22	Grant and Boehm, 2020
WI5A	g s <sup>-1</sup>	Minimum	-0.04	0.07	Grant and Boehm, 2020
WI5A	g s <sup>-1</sup>	Maximum	0.91	0.42	Grant and Boehm, 2020

Similarly, NH<sub>3</sub> emissions from dairy corrals varied from the published work due to revisions to the acceptance criteria that EPA implemented. These revisions resulted in 6 additional daily average emissions values from the Grant publication (Table 2-12). These additional days shift the average of the daily means higher than in the published work and increased the variability, as shown by the increase in the standard deviation. As noted previously, the acceptance criteria used by EPA are an attempt to apply the revisions from several published papers aiming to improve the data quality and go beyond what was discussed in the compared work. Overall, the comparison highlights that EPA has done extensive analysis and review of the dairy sets to obtain a robust data set for model development.

**Table 2-12. Comparison of corral (TX5A) NH<sub>3</sub> emissions in the model dataset to published datasets.**

Source	N	Mean (kg d <sup>-1</sup> )	Standard Deviation
Revised	73	755.0	317.5
Grant et al., 2020	67	287.6	144.7

### **3 RELATIONSHIPS ESTABLISHED IN LITERATURE**

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

#### **3.1 NH<sub>3</sub> and H<sub>2</sub>S from Confinement Sources**

Emissions from barns originate from the nitrogen and sulfur content in urine and manure deposited in pits or on the floor along with any bedding material present in the barn. The amount of NH<sub>3</sub> and H<sub>2</sub>S emitted depend on the amount of manure produced and its characteristics, that is the total ammoniacal nitrogen (TAN) and sulfur content, (Sanchis, Calvet, del Prado, and Estelles (2019)). Multiple factors influence the generation and release of NH<sub>3</sub> and H<sub>2</sub>S emissions, such as the type of building and its volume, flooring type, housing density, manure management, livestock management practices, milk yield, diet, animal behavior, and factors affecting the microclimate within the buildings (e.g., temperature, humidity, and airflow) (Bjerg et al., 2013, Bougouin et al. 2016, Herbut and Angrecka 2014). The following section outlines the relationship between these specific parameters and emission rates, as well as whether the parameter, or suitable proxy, is available in the NAEMS data set.

Manure volume is a key factor influencing NH<sub>3</sub> and H<sub>2</sub>S emissions in both mechanically ventilated and naturally ventilated barns. That is, the more manure and urine there is, the more precursor material there is for NH<sub>3</sub> and H<sub>2</sub>S emissions. No estimates or measurements on the amount of manure generated were taken at any of the dairy sites. However, other parameters, such as inventory and live animal weight (LAW), can be used as proxies for fresh waste generation as more or larger animals produce more waste. Both inventory and LAW were determined daily at each site and were selected for further investigation.

Second to volume, the compositional characteristics—that is nitrogen, NH<sub>3</sub>, and sulfur content of the waste—provide information on the amount of NH<sub>3</sub> and H<sub>2</sub>S than can form and be emitted by the barn. As noted in Section 2.3, sampling for total ammoniacal nitrogen content (TAN), total Kjeldahl nitrogen (TKN), and sulfur content occurred for various components of the barn, including bedding material and the waste collected from the floor. However, a limited number of samples were taken over the course of the study. Including them in the regression analysis would limit the number of days available for model development, and thereby the variability of other factors included in the model. EPA has looked at interpolating the data between samplings to extend the data to more days, however, this does require assumptions

about the behavior of nitrogen and sulfur content in the manure between samples. Knowing the incoming nitrogen and sulfur content of the feed, water, and bedding would inform the interpolation process, leading to better assumptions as this would indicate the maximum amount of nitrogen and sulfur introduced into the system, allowing for mass balance checks. However, data on feed and water were not provided by the producers. As such, the limited data available on waste characteristics (i.e., TAN, TKN, sulfur content) were excluded from the model development dataset.

Manure pH has a strong correlation with both  $\text{NH}_3$  and  $\text{H}_2\text{S}$  emissions (Rotz et al. 2014, Montes et al., 2009). The  $\text{NH}_3$  fraction of TAN is partly a function of pH, so pH would provide an indication of  $\text{NH}_3$  available in the manure (Montes et al., 2009). For  $\text{H}_2\text{S}$ , water with an acidic pH has an increased concentration of molecular  $\text{H}_2\text{S}$ , which increases the potential for  $\text{H}_2\text{S}$  emissions. However, like TAN and TKN measurements, only limited pH data were collected during NAEMS. As such, the limited data available were excluded from the model development dataset.

The Sanchis et al. (2019) review overwhelmingly found air temperature in the barn had a positive relationship with  $\text{NH}_3$  emissions for both mechanically and naturally ventilated barns. The higher temperatures increase  $\text{NH}_3$  losses by decreasing the solubility of  $\text{NH}_3$  and increasing the proportion of TAN as  $\text{NH}_3$  gas (Meisinger and Jokela, 2000). For a similar reason, manure temperature is highly correlated to  $\text{NH}_3$  emissions. NAEMS collected barn exhaust temperature and ambient temperature at all sites and these factors were selected for further investigation. Ambient temperature was chosen for further investigation, as it is related to barn conditions and would provide an alternative to barn-based temperature monitoring for operators.

The studies cited by Sanchis et al. (2019) found, in some cases, the relationship between temperature was affected by the floor type (e.g., slatted versus solid flooring) and manure handling system. EPA investigated the type of manure management system (i.e., flush or scrape) for the mechanical barns for further analysis. A similar analysis was not included for the naturally ventilated barns, as both sites used flush systems. Bedding type was also considered, however the study data only indicated in general the type of bedding used in the barns. In the case of CA5B, the operator used several bedding types as they were available (Zhao et al., 2010) with no reliable indication of when those changes occur or what the percentage of each bedding type was on any given day.

Schmithausen et al. (2018) also noted permanent under floor storage of slurry potentially contributed to higher  $\text{NH}_3$  emissions. The site description of two mechanically ventilated sites, IN5B and NY5B, suggest that they utilize a reception pit to hold scraped material as part of their manure management system. While the NY5B site report notes the deep reception pit is in the

connecting alley between the freestall barn and milking center, the location of the pit at IN5B was not documented. It was noted that the material in the reception pits, at both sites, were transferred to a digester on a regular basis. Because the material was transferred on a regular basis and was not long term, a variable to account for under floor storage was not included at this time.

The ventilation rate of mechanically ventilated barns has been shown as having a positive correlation to  $\text{NH}_3$  emissions across several studies (Kavolelis, 2003; Philippe, et al., 2011; Samer et al., 2012). Ventilation rates are typically driven by the temperature inside the barn, which is affected by the outside temperature. For modeling purposes, this suggests that temperature, either barn or ambient, might make a good proxy for ventilation rate.

For naturally ventilated barns, the ventilation or air flow through the barn is driven by the wind. Many studies (Arogo et al., 1999; Bjerg et al. 2013, Wu et al. 2012; Schrade et al., 2012; and Herbut and Angrecka, 2014) have found a strong correlation between emissions and wind speed, and occasionally wind direction (Feidler and Müller, 2011). However, Saha et al. (2014) did not find the clear relationship between wind speed and emissions. Saha et al. (2014) suggested that the effects of wind speed might be masked by other environmental parameters, such as temperature and relative humidity, or the presence of other buildings and slurry tanks that might influence wind entering the building. Bjerg et al. (2013) noted that the more important component to release was air velocity over the manure, which is not necessarily correlated to wind speed in the barn, as air movement could be affected by numerous things, such as animals and other obstructions in the barn. For modeling purposes, wind speed was selected for further study for naturally ventilated barns.

The literature review did not find references showing a correlation between either  $\text{NH}_3$  or  $\text{H}_2\text{S}$  emissions in mechanically ventilated barns and relative humidity. Sanchis et al. (2019) suggests that there are no significant effects due to the high variability of relative humidity in the barn environment. However, Sanchis et al. (2019) noted studies of naturally ventilated barns showed that higher relative air humidity leads to reduced  $\text{NH}_3$  emissions rates. In general, higher air humidity values are expected to yield reduced  $\text{NH}_3$  concentrations, since  $\text{NH}_3$  is highly water-soluble and would be absorbed by the water vapor in the air and less gaseous  $\text{NH}_3$  would be measured. However, this is only true within a certain temperature range and the management strategies would also affect this relationship. Saha et al. (2014) also noted that the effect of relative humidity might be related to the changes in animal activity and performance in response to heat stress. Because of the potential relationship between  $\text{NH}_3$  and moisture, relative humidity was selected for further study for both mechanically and naturally ventilated barns.

Animal and management activities, such as feeding and milking, can affect emissions rates (Ngwabie, et al. 2011, Hempel 2016). There was no specific daily information on management activities recorded by NAEMS.

### **3.2 Particulate Matter from Barns**

The release of PM<sub>10</sub>, TSP, and PM<sub>2.5</sub> (collectively referred to as PM) into the air of dairy barns is caused by the physical suspension of a range of different materials in the barns including feed, manure, bedding, and skin or hair (Cambra-Lopez et al., 2011). Accordingly, the EPA chose LAW and inventory as predictor variables, as they are related to the amount of source material. One study, Garcia et al. (2013), found an inverse relationship between milking center capacity and PM<sub>2.5</sub> concentration on the farm, which was attributed to the larger dairies being newer and more efficiently operated. This suggests there are different management practices at newer barns that can affect particulate emissions, likely making the use of inventory more nuanced than with other animal types.

Physical suspension of PM from barn surfaces can be caused by air flow, animal activity, and human activity (Aarnink and Ellen, 2007); however, EPA did not receive barn activity measurements and could not explore the influence of this variable further. Airflow, or ventilation rate, was recorded for all barn sources. As mentioned in the previous section, mechanical ventilation rates are related to ambient and barn temperature, thus meaning that temperature could be a potential surrogate variable that represents airflow. For naturally ventilated buildings wind speeds may have an influence on the air flow, which in turn could potentially affect the PM emissions from the buildings. Accordingly, EPA selected the airflow for further review, as well as wind speed from naturally ventilated barns. Temperature was selected for both mechanically ventilated barns, due to the correlation with airflow, and naturally ventilated barns. While Takai et al. (1998) did not find seasonal variation with PM emissions from naturally ventilated barns, Mostafa et al. (2016) did see greater emissions in summer and lower values in winter. The longer observation periods of PM during NAEMS showed some seasonality, with the highest values occurring in the summer.

Physical suspension may also be influenced by moisture conditions and relative humidity (Cambra-Lopez et al., 2010). A study by Takai et al. (1998) examined PM emissions from a variety of livestock types including dairy cattle and reported that relative humidity greater than 70% contributed to particles aggregating together and thus reducing emissions. Accordingly, for dairy barns, the variables ambient relative humidity and barn relative humidity were selected for further investigation.

### 3.3 NH<sub>3</sub> and H<sub>2</sub>S from Open Sources

The release of NH<sub>3</sub> and H<sub>2</sub>S from open sources follows similar mechanics as release from waste in the barns. That is, the amount of NH<sub>3</sub> and H<sub>2</sub>S emitted will depend on some of the same factors as the barn, such as the compositional characteristics. With lagoons and basins, the amount of waste can be characterized by the lagoon surface area in addition to farm level inventory and LAW. For open source model development, EPA used the lagoon surface area to normalize emissions, as it represents the amount of the manure that can exchange gas with the atmosphere. For corrals, the area of the corrals was selected along with the inventory for the farm since the emissions measurements covered a wider area. As with barn sources, TAN, TKN, and sulfide content of the manure has a major influence on dairy open source NH<sub>3</sub> and H<sub>2</sub>S emissions (see section 3.1 for details). For NAEMS open source sites, there were no measurements of TAN, TKN, or sulfide at the three sites. As a result, EPA could not investigate these parameters further.

Like barn sources, NH<sub>3</sub> and H<sub>2</sub>S emissions are a function of the pH, specifically the pH at the surface of the manure, and temperature as both parameters affect the chemistry associated with the generation and release of the pollutants (Arogo et al., 2006, Rotz et al., 2014). Ambient temperature, along with turbulence, typically represented by wind speed, affect the diffusion and dispersion of the gases released from the lagoon surface (Arogo et al., 2006, Sommer et al., 2013). There were continuous measurements of lagoon temperature, lagoon pH for lagoon/basin sites, and air temperature and wind speed for all NAEMS open sources. Accordingly, these four variables were selected for further analysis for lagoon/basin sources and air temperature and wind speed were selected for corral sources.

Like manure in barns, moisture levels can affect the volatilization of NH<sub>3</sub> and H<sub>2</sub>S. In drier environments, evaporation and volatilization are going to occur more rapidly. In a lagoon, where waste is held as a slurry, it is likely less of a factor than in a corral where manure is often mixed into the soil creating a drier environment. Grant et al. (2020) suggested that the vapor pressure deficit might be a more compelling parameter than relative humidity to represent the potential for volatilization from the manure and soil mixture present in corrals. The vapor pressure deficit is the difference between how much moisture the air can hold when saturated and the actual amount of moisture in the air. Unlike relative humidity, the vapor pressure deficit is not a function of temperature, which also allows for a more consistent comparison between days. EPA chose to include both relative humidity and vapor pressure deficit to further investigate their relationship with emissions from the corral.

The presence of a crust or cover on a lagoon or basin will inhibit the transfer of NH<sub>3</sub> 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 EEMs 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 SITE COMPARISON, TRENDS, AND ANALYSIS

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

Based on the analysis described in Section 3.0, EPA identified the key environmental and manure parameters that potentially affect emissions from dairy barns and associated open sources. Parameters of particular interest included inventory, barn conditions (exhaust temperature, exhaust relative humidity, and airflow), ambient temperature, ambient relative humidity, and wind speed.

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

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

A summary of this analysis for environmental parameters is discussed in Section 4.2. Appendix D contains summary statistics, Appendix E contains the relevant time series plots, and Appendix F contains the least squares regression analyses between the identified parameters and emissions.

**Table 4-1. Relationship classification based on R<sup>2</sup> values.**

Range of R <sup>2</sup>	Relationship Strength
R <sup>2</sup> ≤ 0.001	None
0.001 < R <sup>2</sup> ≤ 0.2	Slight or weak
0.2 < R <sup>2</sup> ≤ 0.4	Modest
0.4 < R <sup>2</sup> ≤ 0.6	Moderate
0.6 < R <sup>2</sup> ≤ 0.8	Moderately strong
R <sup>2</sup> > 0.8	Strong

#### **4.1 Mechanically Ventilated Dairy Barns (IN5B-B1, IN5B-B2, NY5-B1, WI5B-B1, and WI5B-B2)**

##### **4.1.1 Emissions data**

Tables D-1 and D-2 of Appendix D present the summary statistics for daily average emissions of NH<sub>3</sub> for the mechanically ventilated sites in kilograms per day and grams per day per head (kg d<sup>-1</sup> and g d<sup>-1</sup> hd<sup>-1</sup>), respectively. Based on Table D-1, the emissions appear to vary across sites. However, when presented on a per head basis, as in Appendix D, Table D-2, the emissions are consistent across sites with average daily emissions ranging from 31.35 kg d<sup>-1</sup> hd<sup>-1</sup> at WIB5-B2 to 48.28 kg d<sup>-1</sup> hd<sup>-1</sup> at IN5B-B1. Appendix E, Figure E-1 showed that the emissions follow a seasonal cycle, with greater emissions typically occurring in the summer and decreasing to lows in winter months. Emissions from the WI5B site have a more muted seasonal cycle in the first year, with slightly increased values in the second year of the study. This appears to correlate changing from a flush system to a scrape system in September of 2008. As noted in Section 3, manure management systems can affect the emissions generated in the barn. Appendix E, Figure E-1 suggests it is worth pursuing modeling options that account for the manure management system.

The summary statistics for daily average H<sub>2</sub>S emissions are presented in Appendix D, Table D-3 and D-4 for g d<sup>-1</sup> and mg d<sup>-1</sup> hd<sup>-1</sup>, respectively. Unlike NH<sub>3</sub>, the per head values in Table D-4 show emissions values 2 to 4 times greater at the WI5B barns than the other sites. Appendix E, Figure E-2 showed the time series plot for H<sub>2</sub>S emissions. The plot showed a seasonal trend in H<sub>2</sub>S emissions for the IN5B and NY5B site, with emissions trending higher in warmer months. However, the WI5B barns show a very different trend. The H<sub>2</sub>S emissions for both barns are quite high and variable for the first half of the plot, and then fall to lower levels. Like the shift with the NH<sub>3</sub> emissions, this change corresponds to the switch to a scrape system in the barns.

Appendix D, Table D-5 and D-6 presents the summary statistics in g d<sup>-1</sup> and mg d<sup>-1</sup> hd<sup>-1</sup>, respectively, for the daily average emissions of PM<sub>10</sub> for the mechanically ventilated sites. There were variations in emissions between sites, both in the total for the day and when normalized on

a per head basis. The average daily emissions ranged from 9.73 g d<sup>-1</sup> (12.49 mg d<sup>-1</sup> hd<sup>-1</sup>) at site IN5B-B1 to 562.91 g d<sup>-1</sup> (1,571.90 mg d<sup>-1</sup> hd<sup>-1</sup>) at WI5B-B2. The time series plot (Appendix E, E-3) showed readings hovering between 0 and 500 g d<sup>-1</sup>, with greater spikes typically occurring in the summer months. WI5B does experience maximum values that are twice as high as the other sites. These peaks occur both in the summer of 2008 and 2009, suggesting the change to a scrape manure management system did not contribute to the highest emissions days. The dataset used for the exploratory data analysis has several negative values, which were further reviewed during the data review process described in Section 2.

Like PM<sub>10</sub>, the PM<sub>2.5</sub> average daily emissions vary substantially across sites. The average daily emissions summarized in Appendix D, Table D-7, indicate that WI5B emissions are much greater than the other barns. The emissions across all sites range from 21.18 g d<sup>-1</sup> at IN5B-B1 up to 186.75 g d<sup>-1</sup> at WI5B-B2. When accounting for inventory difference (Appendix D, Table D-8), the WI5B are still more than twice any other mechanically ventilated barn monitored during NAEMS, with an average value of 662.17 mg d<sup>-1</sup> hd<sup>-1</sup> at WI5B-B1 compared to 25.89 mg d<sup>-1</sup> hd<sup>-1</sup> at IN5B-B1. Appendix E, Figure E-4 showed the temporal variability of the PM<sub>2.5</sub> emissions. The plot for IN5B does show some rather large negative numbers in the exploratory data analysis, which were further reviewed during the data set review process described in Section 2. The inclusion of these points is likely the reason for the lower average values at IN5B compared to the other sites. The sparse temporal nature of the daily PM<sub>2.5</sub> values, due to a rotating monitoring schedule for the PM size fractions at the NAEMS sites, makes it hard to determine if there is a seasonal trend to the data. The number of negative daily averages from the sites varied greatly. The barns at IN2B had the least negative values with 28 and 29 at B1 and B2, respectively. The remaining sites had nearly twice as many negative values; NY5B-B1 had 53, while WI5B had 53 and 45 at B1 and B2, respectively.

The daily average TSP emissions followed a similar trend to PM<sub>10</sub> and PM<sub>2.5</sub>. That is WI5B had average emissions substantially greater than the other two sites (Appendix D, Table D-9), even after accounting for difference in inventory levels (Appendix D, Table D-10). Like PM<sub>2.5</sub>, the sparse temporal nature of the daily TSP values makes it hard to determine if there is a seasonal trend to the data. The plot of WI5B does suggest some seasonality, with slightly greater emissions in the summer. However, a similar pattern is not obvious at the other sites. There were fewer negative daily TSP values, with all sites reporting less than 10 negative values.

#### **4.1.2 Environmental data**

The statistical summary of the environmental parameters associated with mechanically ventilated barns are presented in Appendix D, Table D-11. The inventory varied across the sites, ranging from an average of 211 head at WI5B-B1 to 864 head at IN5B-B2. Appendix E, Figure

E-6 showed that the number of cows present over the course of NAEMS was consistent, with any one barn varying by less than 112 cows over the study duration. Of note, the first-year inventory data from WI5B appears to be based on average inventory of the barn and not actual inventory levels. Appendix F, Figures F-1 through F-5 show the scatter plots of inventory versus each pollutant. A summary of the findings is provided in Table 4-2. In general, there is a weak relationship with inventory across all pollutants, except that NH<sub>3</sub> has a moderate positive relationship. Of note, all the PM size fractions show a weak negative linear relationship with inventory, as the smaller barns have greater emissions. Further investigation showed the barns with greater inventory are newer, which is consistent with the finding from the literature review that newer barns had lower PM emissions. As noted in Section 3.2, the difference between the newer facilities is likely a management practice applied in the newer construction. It is currently unknown what leads to the decrease in emissions for larger newer farms. A possibility to somehow account for this unknown factor is to consider the age of the facility in modeling; however, the limited range in ages (Table 4-1) makes it difficult to incorporate at this time. EPA will continue to pursue identifying the physical or chemical property driving this decrease in Pm emissions in newer barns, and a way to incorporate this into the modeling.

**Table 4-2. Year mechanically ventilated barns were constructed.**

Barn	Year Constructed
WI5B B1	1990
WI5B B2	1994
NY5B B1	1998
IN5B B1	2004
IN5B B2	2004

Average animal weight for the IN5B and WI5B barns were reported as a constant value. For NY5B, the daily value reported only vary by less than 5 kg (576 to 580 kg). This limited range of daily average animal weight is apparent in the time series (Appendix E, Figure E-7). The regression analyses in Appendix F, Figures F-6 through F-10, summarized in Table 4-2, showed only a slight or weak relationship between average animal weight and each pollutant. Trends in LAW (i.e., inventory \* average animal weight) do not vary dramatically over the monitoring period (Appendix E, Figure E-8). The regression analyses in Appendix F, Figures F-11 through F-15 showed similar relationships as inventory, which is the most variable component of LAW.

Exhaust temperatures were comparable across all the sites, ranging from an average of 10.55 °C at WI5B-B2 to 12.89 °C at NY5B-B1. The time series in Appendix E, Figure E-9 show the typical seasonal trend, where temperatures peak in the summer, decrease to minimums around the new year, and then trend upwards during the spring. The linear regression analyses

(Appendix F, Figures F-16 through F-20) only shows a weak to modest positive relationship to temperature. However, the figure for IN5B suggests a nonlinear relationship with temperature, which might be reducing the overall strength of the correlation. The shift in manure management system at WI5B affected the strength of the relationship for those barns. A summary of the findings is provided in Table 4-3.

A review of the exhaust relative humidity summary (Appendix D, Table D-11), were comparable across all the sites, ranging from an average of 66.8% at WI5B-B2 to 75.4% at NY5B-B1. The time series (Appendix E, Figure E-10) show the relative humidity is variable, as there is a spread in the data for any time of the year. The plots suggest dips in humidity for the spring, with IN5B also suggesting a dip in the fall. When regressed with the emissions (Figures F-21 through F-25), there are only slight or weak relationships, which are positive for gaseous pollutants and negative with PM daily emissions (kg/d).

The measured airflow through the barn was comparable across sites and ranged from 131. dry standard cubic meter per second ( $\text{dsm}^3\text{s}^{-1}$ ) at WI5B-B1 to 210.  $\text{dsm}^3\text{s}^{-1}$  at IN5B-B1. The time series (Appendix E, Figure E-11) showed a seasonal pattern, as ventilation rates would increase to maintain barn temperatures during warm months. The regression analyses (Appendix F, Figures F-26 through F-30) showed weak to modest positive relationships with emissions, which is supported by literature.

**Table 4-3. Mechanically ventilated barn environmental parameter regression analyses.**

Pollutant	Parameter	R	R <sup>2</sup>	Strength	Figure
NH <sub>3</sub>	Inventory	0.660	0.435	Moderate	Appendix F, F-1
H <sub>2</sub> S	Inventory	0.002	< 0.001	Slight or weak	Appendix F, F-2
PM <sub>10</sub>	Inventory	-0.292	0.085	Slight or weak	Appendix F, F-3
PM <sub>2.5</sub>	Inventory	-0.319	0.102	Slight or weak	Appendix F, F-4
TSP	Inventory	-0.327	0.107	Slight or weak	Appendix F, F-5
NH <sub>3</sub>	Average animal weight	-0.423	0.179	Slight or weak	Appendix F, F-6
H <sub>2</sub> S	Average animal weight	0.114	0.013	Slight or weak	Appendix F, F-7
PM <sub>10</sub>	Average animal weight	0.240	0.058	Slight or weak	Appendix F, F-8
PM <sub>2.5</sub>	Average animal weight	0.384	0.148	Slight or weak	Appendix F, F-9
TSP	Average animal weight	0.384	0.147	Slight or weak	Appendix F, F-10
NH <sub>3</sub>	LAW	0.653	0.426	Moderate	Appendix F, F-11
H <sub>2</sub> S	LAW	0.014	< 0.001	Slight or weak	Appendix F, F-12
PM <sub>10</sub>	LAW	-0.278	0.077	Slight or weak	Appendix F, F-13
PM <sub>2.5</sub>	LAW	-0.283	0.080	Slight or weak	Appendix F, F-14
TSP	LAW	-0.307	0.094	Slight or weak	Appendix F, F-15
NH <sub>3</sub>	Exhaust temperature	0.493	0.243	Modest	Appendix F, F-16
H <sub>2</sub> S	Exhaust temperature	0.323	0.104	Slight or weak	Appendix F, F-17
PM <sub>10</sub>	Exhaust temperature	0.410	0.168	Slight or weak	Appendix F, F-18
PM <sub>2.5</sub>	Exhaust temperature	0.484	0.234	Modest	Appendix F, F-19

Pollutant	Parameter	R	R <sup>2</sup>	Strength	Figure
TSP	Exhaust temperature	0.406	0.165	Slight or weak	Appendix F, F-20
NH <sub>3</sub>	Exhaust relative humidity	0.390	0.152	Slight or weak	Appendix F, F-21
H <sub>2</sub> S	Exhaust relative humidity	0.193	0.037	Slight or weak	Appendix F, F-22
PM <sub>10</sub>	Exhaust relative humidity	-0.269	0.072	Slight or weak	Appendix F, F-23
PM <sub>2.5</sub>	Exhaust relative humidity	-0.414	0.171	Slight or weak	Appendix F, F-24
TSP	Exhaust relative humidity	-0.322	0.104	Slight or weak	Appendix F, F-25
NH <sub>3</sub>	Airflow	0.536	0.287	Modest	Appendix F, F-26
H <sub>2</sub> S	Airflow	0.232	0.054	Slight or weak	Appendix F, F-27
PM <sub>10</sub>	Airflow	0.425	0.180	Slight or weak	Appendix F, F-28
PM <sub>2.5</sub>	Airflow	0.449	0.202	Modest	Appendix F, F-29
TSP	Airflow	0.376	0.141	Slight or weak	Appendix F, F-30

#### 4.1.3 Ambient Data

The statistical summary of the ambient parameters associated with mechanically ventilated barns are presented in Appendix D, Table D-12. The average daily temperatures were cooler at WI5B at 7.2 °C, compared to 12.2 °C at IN5B. The time series in Appendix E, Figure E-12 show the typical seasonal pattern to temperatures (i.e., maximum in summer and minimum in winter). Of note, data is missing starting in January 2008 at IN5B. No reason for the data loss was provided in the final site report. With the inclusion of three sites, there are ample measurements of emissions at the anticipated temperature range for model development. The scatter plots of ambient temperature (Appendix F, Figures F-31 through F-35), summarized in Table 4-4, show weak-to-modest positive relationships with emissions. The NH<sub>3</sub> plots (Appendix F, Figures F-31) indicate emissions increased more rapidly with temperature at IN5B than the remaining sites.

Ambient relative humidity is similar between sites, ranging from an average value of 67.8% at NY5B to 68.4% at WI5B. The time series (Appendix E, Figure E-13) show the values vary by at least 20% for any given time of the year. Like the exhaust relative humidity, there is an indication that minimum values are more likely in both spring and fall, though the scatter to the data makes a seasonal pattern hard to discern. The regression analyses (Appendix F, Figures F-36 through F-40) indicate slight or weak negative relationships between ambient relative humidity and emissions, even when looking at sites individually.

**Table 4-4. Mechanically ventilated barn ambient parameter regression analyses.**

Pollutant	Parameter	R	R <sup>2</sup>	Strength	Figure
NH <sub>3</sub>	Ambient temperature	0.537	0.289	Modest	Appendix F, F-31
H <sub>2</sub> S	Ambient temperature	0.257	0.066	Slight or weak	Appendix F, F-32
PM <sub>10</sub>	Ambient temperature	0.370	0.137	Slight or weak	Appendix F, F-33
PM <sub>2.5</sub>	Ambient temperature	0.398	0.159	Slight or weak	Appendix F, F-34
TSP	Ambient temperature	0.348	0.121	Slight or weak	Appendix F, F-35
NH <sub>3</sub>	Ambient relative humidity	-0.110	0.012	Slight or weak	Appendix F, F-36
H <sub>2</sub> S	Ambient relative humidity	<0.001	<0.001	Slight or weak	Appendix F, F-37

Pollutant	Parameter	R	R <sup>2</sup>	Strength	Figure
PM <sub>10</sub>	Ambient relative humidity	-0.129	0.017	Slight or weak	Appendix F, F-38
PM <sub>2.5</sub>	Ambient relative humidity	-0.331	0.109	Slight or weak	Appendix F, F-39
TSP	Ambient relative humidity	-0.155	0.024	Slight or weak	Appendix F, F-40

## 4.2 Milking Centers (IN5B-MC and NY5B-MC)

### 4.2.1 Emissions Data

Appendix D, Table D-13 and Table D-14 presents the summary statistics, in kg d<sup>-1</sup> and g d<sup>-1</sup> hd<sup>-1</sup>, for daily average emissions of NH<sub>3</sub> for the MCs monitored during NAEMS. The total emissions (kg d<sup>-1</sup>) are relatively similar between the barns, though IN5B has a larger standard deviation. When scaled for the capacity of the MC (Appendix D, Table D-14), NY5B, at 30.3 g d<sup>-1</sup> hd<sup>-1</sup>, was nearly double the average emissions of 15.7 g d<sup>-1</sup> hd<sup>-1</sup> at IN5B. The time series plot of NH<sub>3</sub> emissions (Appendix E, Figure E-14) showed some seasonality in the data. The plots for IN5B suggest greater emissions in the warmer months, particularly in the summers of 2008 and 2009. The data at NY5B does not have as strong of a seasonal pattern as IN5B.

In a reversal of what was seen with the NH<sub>3</sub> statistics, IN5B had greater overall H<sub>2</sub>S emissions (Appendix D, Table D-15) than NY5B and greater scaled emissions (Appendix D, Table D-16). Average emissions at IN5B were 1,207 g d<sup>-1</sup> (2,148 mg d<sup>-1</sup> hd<sup>-1</sup>) compared to 129 g d<sup>-1</sup> (2,681 mg d<sup>-1</sup> hd<sup>-1</sup>). The time series plot of H<sub>2</sub>S emissions (Appendix E, Figure E-15) suggests some seasonality to the data, with higher readings in the summer months, which may be related to ventilation rates, and indirectly related to ambient temperature. The peaks at IN5B were much greater than NY5B, suggesting an additional difference in the site. Further review showed that IN5B used a flush system and NY5B used a scrape system for manure removal. Like the emissions shift seen at WI5B, it is possible that the manure management system is influencing the emissions levels.

Particulate matter emissions observations were only taken at NY5B. Appendix, Table D-17 provides the statistical summary in g d<sup>-1</sup> and Appendix D, Table D-18 provide them in mg d<sup>-1</sup> hd<sup>-1</sup>. Appendix E, Figure E-16 shows the time series of PM<sub>10</sub> emissions estimates. The plot suggests some seasonality to the data, with higher readings in the summer months, which may relate to ventilation rates. The time series of PM<sub>2.5</sub> emissions is in Appendix E, Figure E-17, while Appendix E, Figure E-18 showed the time series for TSP. The sparse nature of the PM<sub>2.5</sub> and TSP data makes it hard to determine if there is any seasonality to the data.

### 4.2.2 Environmental data

The statistical summary of the environmental parameters associated with MCs is presented in Appendix D, Table D-19. Daily inventory numbers were not reported for the MCs. The capacity of the milking center was used to represent the inventory levels. This is evident in the time series (Appendix E, Figure E-19) and the scatter plots (Appendix F, Figures F-41

through F-45). Average animal weight for the IN5B MC was reported as a constant value. For NY5B, the daily value reported only vary by less than 5 kg (576 to 580 kg), like the mechanically ventilated barn. This limited range of daily average animal weight is apparent in the time series (Appendix E, Figure E-20). The regression analyses in Appendix F, Figures F-46 through F-50, summarized in Table 4-5, showed only a slight or weak relationship between average animal weight and each pollutant. Because of the constant inventory and near constant average animal weight, trends in LAW (i.e., capacity \* average animal weight) do not vary dramatically over the monitoring period (Appendix E, Figure E-21). The regression analyses in Appendix F, Figures F-51 through F-55 showed only slight relationships with emissions. To include size of the operation in the models as a proxy for volume of manure produced, EPA opted to test models where the emissions were normalized by the capacity of the MC. The models will yield an estimate of emissions per head capacity of the MC.

Exhaust temperature was comparable between sites (Appendix E, Figure E-22), with average daily means of 12.8 °C at NY5B and 13.2 °C at IN5B. The regression analyses (Appendix F, Figures F-56 through F-60) showed a weak-to-modest correlation between exhaust temperature and emissions, like the mechanically ventilated barns. Exhaust relative humidity was also comparable between sites (Appendix E, Figure E-23), with average daily values of 74.2% and 73.8% at IN5B and NY5B, respectively. Like with mechanically ventilated barns, there is a tendency for the lowest values to occur in the spring and fall. However, the wide scatter of values for any time of the year makes any strong seasonal pattern hard to discern. The regression analyses (Appendix F, Figures F-61 through F-65) only showed slight-to-weak positive correlation with emissions.

Airflow rates were much lower at NY5B than IN5B, which is clearly demonstrated in the time series plot (Appendix E, Figure E-24). Average airflow rates were 39.90  $\text{dsm}^3\text{s}^{-1}$  at NY5B and 183.33  $\text{dsm}^3\text{s}^{-1}$  at IN5B. The MC at IN5B is connected to Barn 1 at the site (see Figure 1-2 in Section 1), while the MC at NY5B is connected to both Barn 1 and a naturally ventilated barn (see Figure 1-3 in Section 1). It is possible that the connection to the naturally ventilated barn reduced the ventilation needs at the MC. The regression analyses (Appendix F, Figures F-66 through F-70) showed only a slight to weak correlation with emissions, except for  $\text{PM}_{10}$ , which has a modest correlation.

**Table 4-5. Milking center environmental parameter regression analyses.**

Pollutant	Parameter	R	R <sup>2</sup>	Strength	Figure
NH <sub>3</sub>	Inventory (MC Capacity)	0.279	0.078	Slight or weak	Appendix F, F-41
H <sub>2</sub> S	Inventory (MC Capacity)	0.360	0.130	Slight or weak	Appendix F, F-42
PM <sub>10</sub>	Inventory (MC Capacity)	-	-	None	Appendix F, F-43
PM <sub>2.5</sub>	Inventory (MC Capacity)	-	-	None	Appendix F, F-44
TSP	Inventory (MC Capacity)	-	-	None	Appendix F, F-45
NH <sub>3</sub>	Average animal weight	0.279	0.078	Slight or weak	Appendix F, F-46
H <sub>2</sub> S	Average animal weight	0.360	0.130	Slight or weak	Appendix F, F-47
PM <sub>10</sub>	Average animal weight	-0.005	< 0.001	Slight or weak	Appendix F, F-48
PM <sub>2.5</sub>	Average animal weight	-0.161	0.026	Slight or weak	Appendix F, F-49
TSP	Average animal weight	0.154	0.024	Slight or weak	Appendix F, F-50
NH <sub>3</sub>	LAW	0.279	0.078	Slight or weak	Appendix F, F-51
H <sub>2</sub> S	LAW	0.360	0.130	Slight or weak	Appendix F, F-52
PM <sub>10</sub>	LAW	-0.005	< 0.001	Slight or weak	Appendix F, F-53
PM <sub>2.5</sub>	LAW	-0.161	0.026	Slight or weak	Appendix F, F-54
TSP	LAW	0.154	0.024	Slight or weak	Appendix F, F-55
NH <sub>3</sub>	Exhaust temperature	0.518	0.268	Modest	Appendix F, F-56
H <sub>2</sub> S	Exhaust temperature	0.322	0.104	Slight or weak	Appendix F, F-57
PM <sub>10</sub>	Exhaust temperature	0.550	0.303	Modest	Appendix F, F-58
PM <sub>2.5</sub>	Exhaust temperature	0.401	0.160	Slight or weak	Appendix F, F-59
TSP	Exhaust temperature	0.348	0.121	Slight or weak	Appendix F, F-60
NH <sub>3</sub>	Exhaust relative humidity	-0.188	0.035	Slight or weak	Appendix F, F-61
H <sub>2</sub> S	Exhaust relative humidity	-0.378	0.143	Slight or weak	Appendix F, F-62
PM <sub>10</sub>	Exhaust relative humidity	-0.111	0.012	Slight or weak	Appendix F, F-63
PM <sub>2.5</sub>	Exhaust relative humidity	-0.241	0.058	Slight or weak	Appendix F, F-64
TSP	Exhaust relative humidity	0.184	0.034	Slight or weak	Appendix F, F-65
NH <sub>3</sub>	Airflow	0.381	0.146	Slight or weak	Appendix F, F-66
H <sub>2</sub> S	Airflow	0.332	0.110	Slight or weak	Appendix F, F-67
PM <sub>10</sub>	Airflow	-0.458	0.210	Modest	Appendix F, F-68
PM <sub>2.5</sub>	Airflow	-0.009	< 0.001	Slight or weak	Appendix F, F-69
TSP	Airflow	0.106	0.011	Slight or weak	Appendix F, F-70

#### 4.2.3 Ambient Data

The statistical summary of the ambient parameters associated with MCs are presented in Appendix D, Table D-20. The summary statistics indicate the ambient temperatures are similar for both sites, with daily means of 11.13 °C at NY5B and 12.20 °C at IN5B. Ambient temperature trends (Appendix E, Figure E-27) follow seasonal patterns, as expected, and the time series reiterates the similarity in temperatures at both sites. The regression analyses (Appendix F, Figures F-71 through F-75) summarized in Table 4-6, showed weak-to-modest positive correlation with emissions.

Ambient relative humidity was also similar between the sites with daily means of 67.81% at NY5B and 67.90% at IN5B. The time series (Appendix E, Figure E-28) showed variability in average daily humidity values, with the lowest values occurring in the spring. The regression

analyses (Appendix F, Figures F-76 through F-80), summarized in Table 4-6, showed only a slight-to-weak correlation with emissions.

**Table 4-6. Milking center ambient parameters regression analyses.**

Pollutant	Parameter	R	R <sup>2</sup>	Strength	Figure
NH <sub>3</sub>	Ambient temperature	0.495	0.245	Modest	Appendix F, F-71
H <sub>2</sub> S	Ambient temperature	0.296	0.088	Slight or weak	Appendix F, F-72
PM <sub>10</sub>	Ambient temperature	0.568	0.323	Modest	Appendix F, F-73
PM <sub>2.5</sub>	Ambient temperature	0.399	0.159	Slight or weak	Appendix F, F-74
TSP	Ambient temperature	0.348	0.121	Slight or weak	Appendix F, F-75
NH <sub>3</sub>	Ambient relative humidity	-0.043	0.002	Slight or weak	Appendix F, F-76
H <sub>2</sub> S	Ambient relative humidity	0.039	0.002	Slight or weak	Appendix F, F-77
PM <sub>10</sub>	Ambient relative humidity	-0.421	0.178	Slight or weak	Appendix F, F-78
PM <sub>2.5</sub>	Ambient relative humidity	0.043	0.002	Slight or weak	Appendix F, F-79
TSP	Ambient relative humidity	0.066	0.004	Slight or weak	Appendix F, F-80

### 4.3 Naturally Ventilated Barns (CA5B-B1, CA5B-B2, WA5B-B2, and WA5B-B4)

#### 4.3.1 Emissions Data

Appendix D, Table D-21 and Table D-22 presents the summary statistics, in kg d<sup>-1</sup> and g d<sup>-1</sup> hd<sup>-1</sup>, for daily average emissions of NH<sub>3</sub> for the naturally ventilated sites. The average daily emissions rate is substantially different between the sites, ranging from 2.76 kg d<sup>-1</sup> (4.98 g d<sup>-1</sup> hd<sup>-1</sup>) at CA5B-B1 to 54.65 kg d<sup>-1</sup> (56.51 g d<sup>-1</sup> hd<sup>-1</sup>) at WA5B-B4. The time series plot (Appendix E, Figure E-29) showed the highest emissions at WA5B occurring in late spring to early summer of 2008. After a break in observations, the emissions levels mostly drop to lower levels, though it is still greater than CA5B. CA5B does have quite a few negative days, 37 at B1 and 42 at B2, which are contributing to the lower overall average compared to WA5B. These negative numbers were further reviewed during the data set review process described in Section 2, prior to inclusion in the model development dataset. Appendix E, Figure E-29 also showed the emissions are variable across the year with no obvious seasonal pattern.

The summary statistics for daily average H<sub>2</sub>S emissions are presented in Appendix D, Table D-23 and D-24 for g d<sup>-1</sup> and mg d<sup>-1</sup> hd<sup>-1</sup>, respectively. Unlike the NH<sub>3</sub> emissions, the average of the daily emissions are more comparable across the sites. However, reviewing the time series plot (Appendix E, Figure E-30) showed more variability at WA5B, including a few very high values and extreme negative values. There were several negative values at each barn, ranging from 18 values at CA5B-B2 to 45 values at WA5B-B2. Some of the negative numbers were quite large, -609.00 g d<sup>-1</sup> at CA5B-B2 to -11,640.14 g d<sup>-1</sup> at WA5B-B2. These negative numbers were further reviewed during the dataset review process described in Section 2, prior to inclusion in the model development dataset. Appendix E Figure E-30 also showed the emissions are variable across the year with no obvious seasonal pattern.

The summary statistics for PM<sub>10</sub> are presented in Appendix D, Table D-25 and D-26 for g d<sup>-1</sup> and mg d<sup>-1</sup> hd<sup>-1</sup>, respectively. Like NH<sub>3</sub>, the PM<sub>10</sub> emissions vary between the barns, even when accounting for the differences in inventory. Average daily emissions range from -325.80 g d<sup>-1</sup> (-636.79 mg d<sup>-1</sup> hd<sup>-1</sup>) at CA5B-B1 to 11,391.71 g d<sup>-1</sup> (11,794.47 mg d<sup>-1</sup> hd<sup>-1</sup>) at WA5B-B4. CA5B has quite a few negative days, 372 at B1 and 221 at B2, which are contributing to the lower overall average compared to WA5B, and the overall negative average for CA5B-B1. These negative numbers were further reviewed during the dataset review process described in Section 2, prior to inclusion in the model development dataset. The time series plot (Appendix E, Figure E-31) showed the frequency of the negatives at CA5B, as well as the extremely high values seen at WA5B.

PM<sub>2.5</sub> was like PM<sub>10</sub> in that there is a substantial number of negative daily emissions values at CA5B (Appendix D, D-27, and D-28). Specifically, at B1, 44 of the 47 values are negative and 40 of 54 are negative at B2. This results in a negative overall average value for CA5B barns. The WA5B site has fewer negative values, 0 at WA5B-B2 and 6 at WA5B-B4. These negative numbers were further reviewed during the dataset review process described in Section 2, prior to inclusion in the model development dataset. The time series plot (Appendix E, Figure E-32) showed the frequency of the negatives at CA5B, as well as the spread in values seen in at WA5B. No seasonal pattern was apparent.

Regarding the TSP summary statistics (Appendix D, D-29, and D-30), the two sites have different daily average values despite fewer negative daily emissions values for CA5B than the other PM size fractions. Average TSP daily emissions ranged from 4,766 g d<sup>-1</sup> (9,113 mg d<sup>-1</sup> hd<sup>-1</sup>) at CA5B-B1 to 47,389 g d<sup>-1</sup> (49,099 mg d<sup>-1</sup> hd<sup>-1</sup>) at WA5B-B4. The time series plot (Appendix E, Figure E-33) showed a lot of variability in measurements, which makes a seasonal pattern hard to discern.

#### **4.3.2 Environmental Data**

The statistical summary of the environmental parameters associated with naturally ventilated barns are presented in Appendix D, Table D-31. The average inventory for most of the barns is between 514 at WA5B-B2 to 558 at WA5B-B2. WA5B-B4 is the exception, with an average inventory almost double the other barn of 963.20 head. The time series (Appendix E, Figure E-34) showed there is some variability in the inventory at the site, with most only varying by 100 head from the average. The regression analyses (Appendix F, Figures F-81 through F-85), summarized in Table 4-7, generally showed only slight or weak linear relationship with emissions, except for NH<sub>3</sub>, which had a moderate positive linear relationship.

Average animal mass was provided as a single value and not reported daily. The summary table (Appendix D, Table D-31) and the time series (Appendix E, Figure E-35)

reiterate the single value. With constant values, the regression analyses (Appendix F, Figures F-86 through F-90) showed only slight or weak relationship with emissions. Combining inventory and average weight into LAW produces a size variable with trends (Appendix E, Figure E-36), like inventory. Like the inventory regression analyses, Appendix F, Figures F-91 through F-95 showed a light or weak relationship with all pollutants except NH<sub>3</sub>, which had a moderate positive relationship.

The average daily mean exhaust temperatures were slightly higher at CA5B. The means ranged from 11.41 °C at WA5B-B2 to 18.75 °C at CA5B-B1. The time series (Appendix E, Figure E-37) show similar trends and ranges between the sites, with lower values at the WA5B barns. The regression analyses (Appendix F, Figures F-96 through F-100) indicated modest positive relationships with NH<sub>3</sub> and PM<sub>10</sub> emissions and slight or weak relationships with other pollutants.

The average daily exhaust relative humidity values are also slightly higher at CA5B. The mean values ranged from 45.16% at WA5B-B4 to 58.49% at CA5B-B1. The time series (Appendix E, Figure E-38) show the highest levels in the winter and lower values in the summer at both sites. There is a lack of variability at the WA5B barns around January 2008 which will be further investigated prior to finalizing the models. The regression analyses (Appendix F, Figures F-101 through F-105) showed only slight to weak relationships with emissions, which were positive for the gaseous pollutants and negative for the all the PM size fractions.

Estimated airflows at the naturally ventilated barns were comparable and ranged from 882.65 dsm<sup>3</sup>s<sup>-1</sup> to 1,151.61 dsm<sup>3</sup>s<sup>-1</sup> at CA5B. The time series (Appendix E, Figure E-39) show variability across the year, with slightly enhanced airflow during the summer. However, peak values can occur at any time of year. The regression analyses (Appendix F, Figures F-106 through F-110) showed modest positive linear relationship with NH<sub>3</sub> and PM<sub>2.5</sub> emissions. All other pollutants had a slightly positive relationship with airflow.

**Table 4-7. Naturally ventilated barn environmental parameter regression analyses.**

Pollutant	Parameter	R	R <sup>2</sup>	Strength	Figure
NH <sub>3</sub>	Inventory	0.660	0.435	Moderate	Appendix F, F-81
H <sub>2</sub> S	Inventory	0.002	< 0.001	Slight or weak	Appendix F, F-82
PM <sub>10</sub>	Inventory	-0.292	0.085	Slight or weak	Appendix F, F-83
PM <sub>2.5</sub>	Inventory	-0.319	0.102	Slight or weak	Appendix F, F-84
TSP	Inventory	-0.327	0.107	Slight or weak	Appendix F, F-85
NH <sub>3</sub>	Average animal weight	-0.423	0.179	Slight or weak	Appendix F, F-86
H <sub>2</sub> S	Average animal weight	0.114	0.013	Slight or weak	Appendix F, F-87
PM <sub>10</sub>	Average animal weight	0.240	0.058	Slight or weak	Appendix F, F-88
PM <sub>2.5</sub>	Average animal weight	0.384	0.148	Slight or weak	Appendix F, F-89
TSP	Average animal weight	0.384	0.147	Slight or weak	Appendix F, F-90

Pollutant	Parameter	R	R <sup>2</sup>	Strength	Figure
NH <sub>3</sub>	LAW	0.653	0.426	Moderate	Appendix F, F-91
H <sub>2</sub> S	LAW	0.014	< 0.001	Slight or weak	Appendix F, F-92
PM <sub>10</sub>	LAW	-0.278	0.077	Slight or weak	Appendix F, F-93
PM <sub>2.5</sub>	LAW	-0.283	0.080	Slight or weak	Appendix F, F-94
TSP	LAW	-0.307	0.094	Slight or weak	Appendix F, F-95
NH <sub>3</sub>	Exhaust temperature	0.493	0.243	Modest	Appendix F, F-96
H <sub>2</sub> S	Exhaust temperature	0.323	0.104	Slight or weak	Appendix F, F-97
PM <sub>10</sub>	Exhaust temperature	0.410	0.168	Slight or weak	Appendix F, F-98
PM <sub>2.5</sub>	Exhaust temperature	0.484	0.234	Modest	Appendix F, F-99
TSP	Exhaust temperature	0.406	0.165	Slight or weak	Appendix F, F-100
NH <sub>3</sub>	Exhaust relative humidity	0.390	0.152	Slight or weak	Appendix F, F-101
H <sub>2</sub> S	Exhaust relative humidity	0.193	0.037	Slight or weak	Appendix F, F-102
PM <sub>10</sub>	Exhaust relative humidity	-0.269	0.072	Slight or weak	Appendix F, F-103
PM <sub>2.5</sub>	Exhaust relative humidity	-0.414	0.171	Slight or weak	Appendix F, F-104
TSP	Exhaust relative humidity	-0.322	0.104	Slight or weak	Appendix F, F-105
NH <sub>3</sub>	Airflow	0.536	0.287	Modest	Appendix F, F-106
H <sub>2</sub> S	Airflow	0.232	0.054	Slight or weak	Appendix F, F-107
PM <sub>10</sub>	Airflow	0.425	0.180	Slight or weak	Appendix F, F-108
PM <sub>2.5</sub>	Airflow	0.449	0.202	Modest	Appendix F, F-109
TSP	Airflow	0.376	0.141	Slight or weak	Appendix F, F-110

### 4.3.3 Ambient Data

The statistical summary of the ambient parameters associated with naturally ventilated barns are presented in Appendix D, Table D-32. Ambient temperatures were generally higher at CA5B leading to an average of the daily mean of 16.34 °C compared to 10.07 °C at WA5B. The time series (Appendix E, Figure E-40) showed the typical seasonal trend. Of note, the temperatures in summer 2008 were substantially lower than summer 2009. The site report noted the temperature sensor produced a “noisy signal” from late October 2007 to March of 2008. The average of the sonic anemometers was used as a substitute after analysis to confirm agreement with the remaining dates (Ramirez-Dorronsoro et al., 2010). The regression analyses (Appendix F, Figures F-111 through F-115), summarized in Table 4-8, showed a modest positive relationship with temperature and weak positive correlations with all other pollutants.

On average, the ambient relative humidity was lower at WA5B (45.81%) than CA5B (62.01%). The time series (Appendix E, Figure E-41) showed a muted peak around January 2008 for WA5B, like the exhaust relative humidity for the site. The site report offered no explanation for the plateau to the values. The regression analyses (Appendix F, Figures F-116 through F-120) showed slight or weak negative relationships with the emissions value. The negative relationship between NH<sub>3</sub> emissions and relative humidity is consistent with Sanchis et al. (2019).

Wind speeds averaged slightly higher at WA5B (2.59 ms<sup>-1</sup>) than CA5B (1.97ms<sup>-1</sup>). The time series (Appendix E, Figure E-42) showed no distinct seasonal trends, as peak and minimum

values occurred throughout the year. The regression analyses (Appendix F, Figures F-121 through F-125) showed a modest positive relationship with NH<sub>3</sub> emissions, and weak positive relationships with all other pollutants.

**Table 4-8. Naturally ventilated barn ambient parameters regression analyses.**

Pollutant	Parameter	R	R <sup>2</sup>	Strength	Figure
NH <sub>3</sub>	Ambient temperature	0.537	0.289	Modest	Appendix F, F-111
H <sub>2</sub> S	Ambient temperature	0.257	0.066	Slight or weak	Appendix F, F-112
PM <sub>10</sub>	Ambient temperature	0.370	0.137	Slight or weak	Appendix F, F-113
PM <sub>2.5</sub>	Ambient temperature	0.398	0.159	Slight or weak	Appendix F, F-114
TSP	Ambient temperature	0.348	0.121	Slight or weak	Appendix F, F-115
NH <sub>3</sub>	Ambient relative humidity	-0.110	0.012	Slight or weak	Appendix F, F-116
H <sub>2</sub> S	Ambient relative humidity	< 0.001	< 0.001	None	Appendix F, F-117
PM <sub>10</sub>	Ambient relative humidity	-0.129	0.017	Slight or weak	Appendix F, F-118
PM <sub>2.5</sub>	Ambient relative humidity	-0.331	0.109	Slight or weak	Appendix F, F-119
TSP	Ambient relative humidity	-0.155	0.024	Slight or weak	Appendix F, F-120
NH <sub>3</sub>	Wind speed	0.537	0.289	Modest	Appendix F, F-121
H <sub>2</sub> S	Wind speed	0.257	0.066	Slight or weak	Appendix F, F-122
PM <sub>10</sub>	Wind speed	0.370	0.137	Slight or weak	Appendix F, F-123
PM <sub>2.5</sub>	Wind speed	0.398	0.159	Slight or weak	Appendix F, F-124
TSP	Wind speed	0.348	0.121	Slight or weak	Appendix F, F-125

#### 4.4 Open Sources (IN5A, WI5A, and TX5A)

##### 4.4.1 Emissions Data

Appendix D, Table D-33 presents the summary statistics for daily average emissions of NH<sub>3</sub> for the open source sites, including corrals. Appendix D, Table D-34 presents the emissions per square meter of surface area. The emissions from the sites with lagoons, IN5A and WI5A, were comparable, with emissions ranging from 19.83 kg d<sup>-1</sup> (2.01 g d<sup>-1</sup> m<sup>-2</sup>) at IN5A to 11.45 kg d<sup>-1</sup> (1.61 g d<sup>-1</sup> m<sup>-2</sup>) at WI5A. The time series (Appendix E, Figures E-43 and E-45) showed the observations from IN5A in the same year and showed a seasonal pattern. The observations from WI5B are more spread out over the two-year monitoring period and showed a subtle seasonal pattern. The NH<sub>3</sub> emissions for corrals was higher than for the lagoons on a per day basis with average emissions of 754.97 kg d<sup>-1</sup> (222.1 g d<sup>-1</sup> hd<sup>-1</sup>). However, when normalized for the surface area, it was slightly greater at 3.12 g d<sup>-1</sup> m<sup>-2</sup>. The time series for the corral site (TX5A) is available in Appendix E, Figure E-52. There are not many summertime observations, so seasonality is hard to discern.

Appendix D, Table D-35 presents the summary statistics for daily average emissions of NH<sub>3</sub> for the open source sites, including corrals. Appendix D, Table D-36 presents the emissions per square meter of surface area. The average H<sub>2</sub>S emissions from the lagoon sites showed more of a difference, with emissions ranging from to 0.42 g d<sup>-1</sup> (0.06 g d<sup>-1</sup> m<sup>-2</sup>) at WI5A to 9.39 g d<sup>-1</sup> (0.95 g d<sup>-1</sup> m<sup>-2</sup>) at IN5A. The time series (Appendix E, Figures E-44 and E-46) showed the

observations from IN5A in the same year and showed a seasonal pattern. The observations from WI5B are more spread out over the two-year monitoring period and showed a subtle seasonal pattern. The H<sub>2</sub>S emissions for the corral was greater than for the lagoons at 10.69 g d<sup>-1</sup> (3.14 g d<sup>-1</sup> hd<sup>-1</sup>) but was much less when normalized by area (44.18 mg d<sup>-1</sup> m<sup>-2</sup>). The time series for the corral site is available in Appendix E, Figure E-53. No seasonal pattern was apparent.

#### 4.4.2 Environmental Data

The statistical summary of the environmental parameters associated with dairy lagoons are presented in Appendix D, Table D-37. Lagoon temperatures were colder at WI5A, which had an average daily temperature of 18.35 °C compared to 21.57 °C at IN5A. The time series (Appendix E, Figure E-47) shows the sparse nature of the observations but does suggest the expected trend of lagoon temperatures following seasonal temperature patterns. The regression analyses (Appendix F, Figures F-126 through F-127; summarized in Table 4-9) shows moderate relationships with daily emissions (kg/d).

Lagoon pH was consistent between the sites, with average daily mean values at 7.02 and 7.43 for WI5A and IN5A, respectively. The time series (Appendix E, Figure E-48) shows values typically between 7.0 and 7.5 for most of the observations. There is a small cluster of readings for IN5A above 8.0 for Fall 2008. The regression analyses (Appendix F, Figures F-128 through F-129), summarized in Table 4-9, showed only slight or weak relationships with daily emissions (kg/d).

**Table 4-9. Open source environmental parameter regression analyses.**

Pollutant	Parameter	R	R <sup>2</sup>	Strength	Figure
NH <sub>3</sub>	Lagoon temperature	0.66	0.436	Moderate	Appendix F, F-126
H <sub>2</sub> S	Lagoon temperature	-0.68	0.462	Moderate	Appendix F, F-127
NH <sub>3</sub>	Lagoon pH	-0.2	0.040	Slight or weak	Appendix F, F-128
H <sub>2</sub> S	Lagoon pH	0.4	0.160	Slight or weak	Appendix F, F-129

#### 4.4.3 Ambient Data

The statistical summary of the ambient parameters associated with dairy lagoons are presented in Appendix D, Table D-38. The average ambient temperature observed during monitoring periods for WI5A (-3.41 °C) was much lower than IN5A (6.25 °C). The time series (Appendix E, Figure E-49) show the expected seasonal trend in temperatures. The regression analyses (Appendix F, Figures F-130 through F-131), summarized in Table 4-10, show modest and moderately strong positive relationships with H<sub>2</sub>S and NH<sub>3</sub> daily emissions (kg/d), respectively.

Observed ambient relative humidity were comparable between sites, with average daily means ranging from 71.53% at WI5A to 72.02% at IN5A. The time series (Appendix E, Figure

E-50) show the relative humidity values vary throughout the year with no seasonal pattern. The regression analyses (Appendix F, Figures F-132 through F-133) shows a slight negative relationship with daily emissions (kg/d) of both NH<sub>3</sub> and H<sub>2</sub>S.

Wind speeds were also comparable between sites and ranged from 3.28 m s<sup>-1</sup> at IN5A to 3.45 m s<sup>-1</sup> at WI5A. The time series (Appendix E, Figure E-51) average daily wind speeds were equally variable throughout the year at both sites. The regression analyses (Appendix F, Figures F-134 through F-135) showed only slight correlation with daily emissions (kg/d), which was negative for NH<sub>3</sub> and positive for H<sub>2</sub>S.

**Table 4-10. Open source ambient parameters regression analyses.**

Pollutant	Parameter	R	R <sup>2</sup>	Strength	Figure
NH <sub>3</sub>	Ambient temperature	0.84	0.706	Moderately strong	Appendix F, F-130
H <sub>2</sub> S	Ambient temperature	0.59	0.348	Modest	Appendix F, F-131
NH <sub>3</sub>	Ambient relative humidity	-0.34	0.116	Slight or weak	Appendix F, F-132
H <sub>2</sub> S	Ambient relative humidity	-0.18	0.032	Slight or weak	Appendix F, F-133
NH <sub>3</sub>	Wind speed	-0.25	0.063	Slight or weak	Appendix F, F-134
H <sub>2</sub> S	Wind speed	0.1	0.010	Slight or weak	Appendix F, F-135

The statistical summary of the ambient parameters associated with the monitored dairy corral are presented in Appendix D, Table D-39. Observations of ambient temperature ranged from -5.64 °C to 27.50 °C, and followed expected seasonal trends (Appendix E, Figure E-54). The regression analyses (Appendix F, Figures F-136 through F-137; summarized in Table 4-11) showed a slight positive relationship between temperature and emissions.

Average daily ambient relative humidity values ranged from 22.3% to 78.54% over the study at TX5A. The time series (Appendix E, Figure E-55) do not suggest any seasonal trends. The regression analyses (Appendix F, Figures F-138 through F-139) shows slightly positive relationships with emissions. Average daily wind speeds ranged from 2.35 to 6.79 ms<sup>-1</sup> and showed no trends in the time series (Appendix E, Figure E-56). The time series did show a peak value in late winter to spring of 2009. The regression analyses (Appendix F, Figures F-140 through F-141) do not show a relationship between wind speed and emissions.

Water vapor deficit estimates ranged from 2.09 to 26.88 hectopascal (hPa) and showed some tendency for higher values in the summer and fall (Appendix E, Figure E-57). The regression analyses (Appendix F, Figures F-142 through F-143) summarized in Table 4-11 indicated a slight relationship between emissions that was positive for NH<sub>3</sub> and negative for H<sub>2</sub>S.

**Table 4-11. Corral ambient parameters regression analyses.**

<b>Pollutant</b>	<b>Parameter</b>	<b>R</b>	<b>R<sup>2</sup></b>	<b>Strength</b>	<b>Figure</b>
NH <sub>3</sub>	Ambient temperature	0.17	0.029	Slight or weak	Appendix F, F-136
H <sub>2</sub> S	Ambient temperature	0.003	< 0.001	Slight or weak	Appendix F, F-137
NH <sub>3</sub>	Ambient relative humidity	0.17	0.029	Slight or weak	Appendix F, F-138
H <sub>2</sub> S	Ambient relative humidity	0.15	0.023	Slight or weak	Appendix F, F-139
NH <sub>3</sub>	Wind speed	0.002	< 0.001	Slight or weak	Appendix F, F-140
H <sub>2</sub> S	Wind speed	0.003	< 0.001	Slight or weak	Appendix F, F-141
NH <sub>3</sub>	Water vapor deficit	0.32	0.102	Slight or weak	Appendix F, F-142
H <sub>2</sub> S	Water vapor deficit	-0.16	0.026	Slight or weak	Appendix F, F-143

## 5 DEVELOPMENT AND SELECTION OF MODELS FOR DAILY EMISSIONS

### 5.1 Mechanically Ventilated Barns

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

The various combinations of these parameters were used in test models. For NH<sub>3</sub> and H<sub>2</sub>S, 9 different combinations were evaluated as potential models (Table 5-1). There were 17 models (Table 5-2) evaluated for PM emissions, which had variations to predict the emissions normalized by inventory.

**Table 5-1. Parameter combinations evaluated as mechanically ventilated barn models for NH<sub>3</sub> and H<sub>2</sub>S emissions.**

Model	Parameters
MV-G1	Inventory, manure management system (Flush, Scrape)
MV-G2	Inventory, exhaust temperature, Exhaust relative humidity, manure management system (Flush, Scrape)
MV-G3	Inventory, exhaust temperature, manure management system (Flush, Scrape)
MV-G4	Inventory, exhaust relative humidity, manure management system (Flush, Scrape)
MV-G5	Inventory, ambient relative humidity, ambient temperature, manure management system (Flush, Scrape)
MV-G6	Inventory, ambient temperature, manure management system (Flush, Scrape)
MV-G7	Inventory, ambient relative humidity, manure management system (Flush, Scrape)
MV-G8	Inventory, ambient temperature, exhaust relative humidity, manure management system (Flush, Scrape)
MV-G9	Inventory, exhaust temperature, ambient relative humidity, manure management system (Flush, Scrape)

**Table 5-2. Parameter combinations evaluated as mechanically ventilated barn models for PM<sub>10</sub>, PM<sub>2.5</sub>, and TSP emissions.**

Model	Parameters
MV-P1	Intercept, inventory
MV-P2	Intercept, inventory, exhaust temperature, exhaust relative humidity
MV-P3	Intercept, inventory, exhaust temperature
MV-P4	Intercept, inventory, exhaust relative humidity
MV-P5	Intercept, inventory, ambient relative humidity, ambient temperature
MV-P6	Intercept, inventory, ambient temperature

Model	Parameters
MV-P7	Intercept, inventory, ambient relative humidity
MV-P8	Intercept, inventory, ambient temperature, exhaust relative humidity
MV-P9	Intercept, inventory, exhaust temperature, ambient relative humidity
MV-P10	Intercept, exhaust temperature, exhaust relative humidity (Emissions normalized by inventory)
MV-P11	Intercept, exhaust temperature (emissions normalized by inventory)
MV-P12	Intercept, exhaust relative humidity (emissions normalized by inventory)
MV-P13	Intercept, ambient temperature, ambient relative humidity (Emissions normalized by inventory)
MV-P14	Intercept, ambient temperature (emissions normalized by inventory)
MV-P15	Intercept, ambient relative humidity (emissions normalized by inventory)
MV-P16	Intercept, ambient temperature, exhaust relative humidity (Emissions normalized by inventory)
MV-P17	Intercept, ambient relative humidity, exhaust temperature (Emissions normalized by inventory)

For both NH<sub>3</sub> (Appendix G, Table G-3) and H<sub>2</sub>S (Appendix G, Table G-5), models MV-G5 and MV-G7 had terms that were not statistically significant ( $p > 0.05$ ) for both pollutants and were removed from further consideration. For H<sub>2</sub>S, model MV-G4 and G9 had insignificant terms. The model fit (-2 log likelihood, AIC, AICc, and BIC) and evaluation statistics (ME, NME, MB, NMB) for NH<sub>3</sub> (Appendix G, Table G-4) and H<sub>2</sub>S (Appendix G, Table G-5) indicate the remaining models had comparable performance, which suggested that using ambient parameters was as effective as models that included barn specific parameters. As noted in the Process Overview report, the model selection process also looked at how easily obtainable the parameters are as not to create an undue burden on the operators. Generally, ambient parameters were preferred since ambient meteorological data is actively recorded across the country and representative site data is accessible through the National Centers for Environmental Information (NCEI) website.

Therefore, considering ambient temperature is a suitable proxy for barn airflow as exhaust temperature and representative ambient temperature data is accessible, the EPA concluded that a model using ambient temperature and relative humidity would be preferable to one with exhaust temperature and relative humidity. Of the remaining models that used ambient parameters (MV-G1 and G6), EPA selected model MV-G6 (including the parameters: inventory, ambient temperature, and manure management system) for further analysis for both NH<sub>3</sub> and H<sub>2</sub>S as it had the best normalized mean bias of the remaining models. The final form of these models is presented in Table 5-3.

**Table 5-3. Selected daily models for mechanically ventilated barns.**

Pollutant	Formula	Units	Equation Number
NH <sub>3</sub> , Flush	$\ln(NH_3) = 1.746585 + 1.773832 * Inventory + 0.029586 * Amb_T$	kg/d	Equation 1
NH <sub>3</sub> , Scrape	$\ln(NH_3) = 1.864935 + 1.773832 * Inventory + 0.029586 * Amb_T$	kg/d	Equation 2
H <sub>2</sub> S, Flush	$\ln(H_2S) = 7.406887 + 0.86173 * Inventory + 0.012786 * Amb_T$	g/d	Equation 3
H <sub>2</sub> S, Scrape	$\ln(H_2S) = 6.287004 + 0.86173 * Inventory + 0.012786 * Amb_T$	g/d	Equation 4
PM <sub>10</sub>	$\ln(PM_{10}) = 8.130759 + 0.01083 * Amb_T - 0.00432 * Amb_{RH}$	mg/d-hd	Equation 5
PM <sub>2.5</sub>	$\ln(PM_{10}) = 6.76777 + 0.00474 * Amb_T - 0.00055 * Amb_{RH}$	mg/d-hd	Equation 6
TSP	$\ln(PM_{10}) = 8.434953 + 0.01277 * Amb_T - 0.01342 * Amb_{RH}$	mg/d-hd	Equation 7

For PM<sub>10</sub> models (Appendix G, Table G-7), models MVP-1 through MVP-9 include inventory as a proxy for volume of manure produced. While all model terms were statistically significant ( $p > 0.05$ ), coefficients for inventory were negative which suggests that emissions decrease as inventory increases. The negative coefficients for inventory are also seen in models MVP-1 through MVP-9 for PM<sub>2.5</sub> (Appendix G, Table G-9) and TSP (Appendix G, Table G-11). As noted in Section 3.2, Garcia et al. (2012) found a similar inverse relationship with PM<sub>2.5</sub> concentrations and inventory for MCs, which was attributed to the larger dairies being newer and more efficiently operated. Based on the site reports, the older barns have the lowest average inventory (Table 5-4), which lines up with Garcia et al. (2012). Still unknown is the management practice in the newer barns contributing to the reduced emissions and how to account for that practice in the model. The age of the barn and construction year were discussed as a possible parameter; however, there is not enough variability in construction year available in the NAEMS data for model construction.

**Table 5-4. Summary of barn construction dates for mechanically ventilated barns.**

Barn	Year Constructed	Average Inventory
IN5B-B1	2004	833
IN5B-B2	2004	864
NY5B-B1	1998	467
WI5B-B1	1990	211
WI5B-B2	1994	355

EPA evaluated a set of models that normalized emissions by inventory, MVP-10 through MVP-17, which use the same environmental and barn parameters as models MVP-2 through MVP-9. The goal was to determine if these models could be predictive based on the other environmental and ambient parameters alone. The model performance statistics (i.e., ME, NME, MB, NMB) did increase for these models (Appendix G, Tables G-8, G-10, and G-12). As a result, we selected model MV-13 for this effort. Efforts will continue to discern a viable parameter to include to account for the reduced emissions in newer barns.

## 5.2 Milking Centers

The literature review (Section 3) and exploratory data analysis (Section 4) suggested that EPA should consider ambient temperature, exhaust temperature, ambient relative humidity, exhaust relative humidity, milk production, and inventory in the development of the emissions models for MCs. Barn airflow, or ventilation rate, can have a substantial influence on the emissions rate, but was not included in the parameter list as it may not be easily obtained at all farms. Since ventilation rate is essentially driven by the temperature (i.e., the higher ambient temperature, the higher the ventilation rate), the ambient temperature provides an indication of airflow in the models evaluated. EPA evaluated 24 combinations of these parameters as potential models (Table 5-5), including which had variations to predict the emissions normalized by inventory (MC-25 through MC-32). The models to predict normalized emissions were added to incorporate a barn size into the model, as the relatively consistent inventory of the MCs could reduce the significance if inventory was used as a predictive parameter. This is demonstrated with the NH<sub>3</sub> modeling results (Appendix G, Table G-13), as inventory is insignificant in models MC-10 through MC-16.

Milk production values were only available for NY5B, and when combined with a static value for barn inventory, as in models MC-1 through MC-8, inventory was dropped from the model, making the result equivalent to models MC-17 through MC-24 for all pollutants. Therefore, the summary presented in this section will focus on models MC-8 through MC-32. Results for all models is summarized in Appendix G.

**Table 5-5. Parameter combinations evaluated as milking center models.**

Model	Parameters
MC-1	Intercept, inventory, milk production, exhaust temperature, exhaust relative humidity
MC-2	Intercept, inventory, milk production, exhaust temperature
MC-3	Intercept, inventory, milk production, exhaust relative humidity
MC-4	Intercept, inventory, milk production, ambient relative humidity, ambient temperature
MC-5	Intercept, inventory, milk production, ambient temperature
MC-6	Intercept, inventory, milk production, ambient relative humidity
MC-7	Intercept, inventory, milk production, ambient temperature, exhaust relative humidity
MC-8	Intercept, inventory, milk production, exhaust temperature, ambient relative humidity
MC-9	Intercept, inventory, exhaust temperature, exhaust relative humidity
MC-10	Intercept, inventory, exhaust temperature
MC-11	Intercept, inventory, exhaust relative humidity
MC-12	Intercept, inventory, ambient relative humidity, ambient temperature
MC-13	Intercept, inventory, ambient temperature
MC-14	Intercept, inventory, ambient relative humidity
MC-15	Intercept, inventory, ambient temperature, exhaust relative humidity
MC-16	Intercept, inventory, exhaust temperature, ambient relative humidity
MC-17	Intercept, milk production, exhaust temperature, exhaust relative humidity

Model	Parameters
MC-18	Intercept, milk production, exhaust temperature
MC-19	Intercept, milk production, exhaust relative humidity
MC-20	Intercept, milk production, ambient relative humidity, ambient temperature
MC-21	Intercept, milk production, ambient temperature
MC-22	Intercept, milk production, ambient relative humidity
MC-23	Intercept, milk production, ambient temperature, exhaust relative humidity
MC-24	Intercept, milk production, exhaust temperature, ambient relative humidity
MC-25	Intercept, exhaust temperature, exhaust relative humidity (Emissions normalized by inventory)
MC-26	Intercept, exhaust temperature (emissions normalized by inventory)
MC-27	Intercept, exhaust relative humidity (emissions normalized by inventory)
MC-28	Intercept, ambient temperature, ambient relative humidity (Emissions normalized by inventory)
MC-29	Intercept, ambient temperature (emissions normalized by inventory)
MC-30	Intercept, ambient relative humidity (emissions normalized by inventory)
MC-31	Intercept, ambient temperature, exhaust relative humidity (Emissions normalized by inventory)
MC-32	Intercept, ambient relative humidity, exhaust temperature (Emissions normalized by inventory)

For NH<sub>3</sub> (Appendix G, Table G-13) models MC-1 through MC-24 had terms that were not statistically significant ( $p > 0.05$ ). All the models predicting NH<sub>3</sub> emissions per head (MC-25 through MC-32) were comprised of significant parameters. The model fit (-2 log likelihood, AIC, AICc, and BIC) and evaluation statistics (ME, NME, MB, NMB) for these models are presented in Appendix G, Table G-14. The ambient parameter models performed comparably to their barn parameter counterparts, suggesting selecting the models with the easier to obtain ambient parameter would be as effective. Therefore, EPA concluded that a model using ambient temperature and relative humidity would be preferable to one with exhaust temperature and relative humidity. Of the remaining models that used ambient parameters (MC-28, MC-29, and MC-30), the NME and ME are comparable for the models. Model MC-30 has a substantially lower MB and NMB. However, this model only includes relative humidity and not temperature. The literature search (Section 3) noted that temperature is strongly linked to NH<sub>3</sub> emissions and should be included in the selected model. The model performance plots (Appendix G, Figures G-20 and G-24) also show better scatter across the one-to-one (1:1) for models MC-28, MC-29, indicating better predictive performance than model MC-30. Therefore, EPA selected model MC-29 (including ambient temperature as the predictive parameter) for further analysis for NH<sub>3</sub> as it had the best NMB of the remaining models. The final form of these models is presented in Table 5-6.

In addition to the models predicting normalized emissions, models MC-9, MC-10, MC-11, MC-13, MC-15, MC-18, and MC-21 were comprised of significant parameters for H<sub>2</sub>S

(Appendix G, Table G-15). Of the seven additional models, all but MC-11 contained either exhaust temperature or ambient temperature, as well as models MC-25 through MC-32. Comparing the model fit and evaluation statistics (Appendix G, Table G-16) the ambient parameter models performed comparably to their barn parameter counterparts, suggesting models utilizing the easier to obtain ambient parameter would be as effective. Therefore, EPA concluded that a model using ambient temperature and ambient relative humidity would be preferable to one with exhaust temperature and relative humidity. Of the remaining models that used ambient parameters (MC-13, MC-21, MC-28, MC-29, and MC-30), the error statistics (NME and ME) are lower for models MC-13 and MC-21, while the bias statistics (MB and NMB) are lower for MC-21 and MC-30, with other models being comparable. The scatter plots of observed versus predicted (Appendix G, Figures G-26 through G-32) for model MC-21 has more variability in the scatter across the 1:1 line, indicating a slightly better fit. However, this model includes milk production values, which are only available for one site. For this study, it is preferred to include multiple sites in the model development dataset to represent variability across the country. Therefore, EPA selected model MC-29 (including ambient temperature as the predictive parameter) for further analysis for H<sub>2</sub>S as it had the best NMB of the remaining models (i.e., MC-13, MC-30). The final form of these models is presented in Table 5-6.

For the PM size fractions, only NY5B reported emissions. With the dataset dropping to one site with a constant value for MC capacity, the coefficient of inventory in models MC-9 through MC-16 is estimated at zero and eliminates a size estimate from the model. The focus for the PM model narrowed to just models MC-17 through MC-32. For PM<sub>10</sub>, models MC-17, MC-18, MC-19, MC-20, MC-21, and MC-23 have parameters that are statistically insignificant (Appendix G, Table G-17). The model fit and evaluation statistics (Appendix G, Table G-18) for models with ambient parameters performed comparably to their barn parameter counterparts, suggesting models utilizing the easier to obtain ambient parameter would be as effective. Of the remaining models that used ambient parameters (MC-28, MC-29, and MC-30), the NME and ME are slightly lower for Model 28, and the bias parameters are similar. EPA selected model MC-28 (including ambient temperature and ambient relative humidity as the predictive parameter) for further analysis for PM<sub>10</sub> as it had the best NMB of the remaining models. The final form of these models is presented in Table 5-6.

As noted in Section 6.4 of the Overview report, the PM model selection starts with PM<sub>10</sub> due to the greater quantity of emissions data. The PM<sub>10</sub> models had between 315 and 436 records available depending on the completeness of the various predictive parameters. For PM<sub>2.5</sub> and TSP, the number of records available ranged between 40 to 44 for PM<sub>2.5</sub> and 29 to 40 for TSP. This is substantially less data than were available for PM<sub>10</sub> and does not necessarily cover the breadth of conditions that the PM<sub>10</sub> data does. Therefore, the models generated with these

smaller datasets were examined mainly for consistency with the PM<sub>10</sub> results to build confidence in using the same model form for all the PM species.

Compared to the PM<sub>10</sub> models, more of the PM<sub>2.5</sub> and TSP models have insignificant terms. For both PM<sub>2.5</sub> (Appendix G, Table G-19) and TSP (Appendix G, Table G-21), only models MC-26 and MC-29 are comprised of significant parameters. Despite the insignificance of the parameters for most of the models, the relationships were consistent with the PM<sub>10</sub> models and literature. The model performance statistics for PM<sub>2.5</sub> (Appendix G, Table G-20) and the model performance plots (Appendix G, Figures G-41 through G-48) were consistent, with slightly lower bias metric for model MC-29. For TSP, the performance metrics (Appendix G, Table G-22) and plots (Appendix G, Figures G-49 through G-56) were comparable. Therefore, EPA selected model MC-29 for PM<sub>2.5</sub> (including ambient temperature as the predictive parameter) and model MC-28 (including ambient temperature and ambient relative humidity as the predictive parameter) for TSP to conduct further evaluation and analysis as an emissions estimation method. The full forms of the models are presented in Table 5-6.

**Table 5-6. Selected daily models for milking centers.**

Pollutant	Formula	Units	Equation Number
NH <sub>3</sub>	$\ln(NH_3) = 2.505637 + 0.046434 * Amb_T$	g/d-hd	Equation 8
H <sub>2</sub> S	$\ln(H_2S) = 6.898188 + 0.024053 * Amb_T$	mg/d-hd	Equation 9
PM <sub>10</sub>	$\ln(PM_{10}) = 8.042215 + 0.006791 * Amb_T - 0.003552 * Amb_{RH}$	mg/d-hd	Equation 10
PM <sub>2.5</sub>	$\ln(PM_{2.5}) = 6.58377 + 0.006698 * Amb_T$	mg/d-hd	Equation 11
TSP	$\ln(TSP) = 7.457268 + 0.010997 * Amb_T - 0.003639 * Amb_{RH}$	mg/d-hd	Equation 12

### 5.3 Naturally Ventilated Barns

The literature review (Section 3) and exploratory data analysis (Section 4) suggested that EPA should consider ambient temperature, ambient relative humidity, exhaust relative humidity, wind speed, and inventory in the development of the emissions models for naturally ventilated barns. EPA evaluated 8 combinations of these parameters as potential models (Table 5-7). Models predicting emissions normalized by inventory were not pursued at this time. However, based on the initial results of MCs, normalized inventory models may be considered for the final models.

**Table 5-7. Parameter combinations evaluated as naturally ventilated barns models.**

Model	Parameters
NV-1	Intercept, inventory

Model	Parameters
NV-2	Intercept, inventory, ambient temperature, ambient relative humidity, wind speed
NV-3	Intercept, inventory, ambient temperature
NV-4	Intercept, inventory, ambient relative humidity
NV-5	Intercept, inventory, wind speed
NV-6	Intercept, inventory, ambient temperature, ambient relative humidity
NV-7	Intercept, inventory, ambient relative humidity, wind speed
NV-8	Intercept, inventory ambient temperature, wind speed

For the gaseous species, models NV-3 and NV-8 had terms that were not statistically significant ( $p > 0.05$ ) for  $\text{NH}_3$  (Appendix G, Table G-24), and models NV-2, NV-3, NV-4, NV-6, NV-7, and NV-8 had insignificant terms for  $\text{H}_2\text{S}$  (Appendix G, Table G-26). The model fit (-2 log likelihood, AIC, AICc, and BIC) and evaluation statistics (ME, NME, MB, NMB) for these models are presented in Appendix G, Table G-25, and Table G-27 for  $\text{NH}_3$  and  $\text{H}_2\text{S}$ , respectively. For both pollutants, the statistics for the models were comparable. Therefore, EPA selected model NV-5 (including as the predictive parameters: inventory and wind speed) for further analysis for  $\text{NH}_3$  and  $\text{H}_2\text{S}$  as it had the best NMB of the remaining models. The final form of these models is presented in Table 5-8.

For  $\text{PM}_{10}$ , all models were comprised of statistically significant parameters (Appendix G, Table G-28). The model fit and evaluation statistics (Appendix G, Table G-29) suggested comparable performance across all models, with model NV-2 having slightly better error metrics. EPA selected model NV-2 (including the predictive parameters: inventory, ambient temperature, ambient relative humidity, and wind speed) for further analysis. The final form of the model is presented in Table 5-8.

As noted in Section 6.4 of the Overview report and with the MC model selection, the PM model selection starts with the  $\text{PM}_{10}$  due to the greater quantity of emissions data. For naturally ventilated barns, the  $\text{PM}_{10}$  models had between 1,457 and 1,469 records available depending on the completeness of the various predictive parameters. For  $\text{PM}_{2.5}$  and TSP, the number of records available was 93 for  $\text{PM}_{2.5}$  and 205 for TSP. The  $\text{PM}_{2.5}$  models (Appendix G, Table G-30) all have insignificant parameters. The relationship generally follows the expected trend from literature (e.g., negative relationship with relative humidity). However, inventory has a negative coefficient in each model. For TSP (Appendix G, Table G-32), all models are comprised entirely of significant parameters and the predictive parameters have the same relationships as with  $\text{PM}_{10}$ . Model NV-2 had reasonable performance for both  $\text{PM}_{2.5}$  (Appendix G, Table G-31) and TSP (Appendix G, Table G-33) and would be consistent with the  $\text{PM}_{10}$  formulation that was developed from a much larger dataset. Therefore, EPA selected model NV-2 (including the predictive parameters: inventory, ambient temperature, ambient relative humidity, and wind

speed) for further analysis. The final form of the models for PM<sub>2.5</sub> and TSP are presented in Table 5-8.

**Table 5-8. Selected daily models for naturally ventilated barns.**

Pollutant	Formula	Units	Equation Number
NH <sub>3</sub>	$\ln(NH_3) = 0.188357 + 3.451939 * Inventory + 0.048153 * WindSpeed$	kg/d	Equation 13
H <sub>2</sub> S	$\ln(H_2S) = 6.541057 + 0.587702 * Inventory + 0.062678 * WindSpeed$	g/d	Equation 14
PM <sub>10</sub>	$\ln(PM_{10}) = 7.64258 + 1.525009 * Inventory + 0.011864 * Amb_T - 0.01521 * Amb_{RH} + 0.173698 * WindSpeed$	g/d	Equation 15
PM <sub>2.5</sub>	$\ln(PM_{2.5}) = 7.068797 - 0.220453 * Inventory + 0.01121 * Amb_T - 0.003808 * Amb_{RH} + 0.218968 * WindSpeed$	g/d	Equation 16
TSP	$\ln(TSP) = 7.868847 + 2.953893 * Inventory + 0.034508 * Amb_T - 0.033997 * Amb_{RH} + 0.248191 * WindSpeed$	g/d	Equation 17

#### 5.4 Open Sources

The literature review (Section 3) and exploratory data analysis (Section 4) suggested that EPA should consider lagoon pH, lagoon temperature, ambient temperature, and wind speed in the development of the emissions models for open sources. EPA evaluated 15 combinations of these parameters as potential models (Table 5-9). Models were developed to predict daily emissions per meter squared (m<sup>2</sup>) of surface area of the open source.

**Table 5-9. Parameter combinations evaluated as open source models for NH<sub>3</sub> and H<sub>2</sub>S emissions.**

Model	Parameters
LB-1	Lagoon pH, lagoon temperature
LB-2	Lagoon pH
LB-3	Lagoon temperature
LB-4	Ambient temperature, wind speed
LB-5	Ambient temperature
LB-6	Wind speed
LB-7	Lagoon pH, lagoon temperature, ambient temperature, wind speed
LB-8	Lagoon pH, lagoon temperature, ambient temperature
LB-9	Lagoon pH, lagoon temperature, wind speed
LB-10	Lagoon pH, ambient temperature, wind speed
LB-11	Lagoon temperature, ambient temperature, wind speed
LB-12	Lagoon pH, ambient temperature
LB-13	Lagoon pH, wind speed
LB-14	Lagoon temperature, ambient temperature
LB-15	Lagoon temperature, wind speed

For NH<sub>3</sub>, of the 15 models evaluated, only LB-3, LB-5, LB-6, and LB-15 were comprised of significant parameters (Appendix G, Table G-34). The model fit (-2 log likelihood, AIC,

AICc, and BIC) and evaluation statistics (ME, NME, MB, NMB) for these models are presented in Appendix G, Table G-35, and were consistent across the models with significant terms. This suggests that models with ambient temperature (model LB-5) perform as well as models with lagoon specific parameters (LB-3 and LB-15). Therefore, EPA selected model NV-5 (including ambient temperature as the predictive parameter) for further analysis for NH<sub>3</sub>. The final form of this model is presented in Table 5-10.

For H<sub>2</sub>S, of the 15 models evaluated, only LB-3, LB-5, and LB-6 were comprised entirely of significant parameters (Appendix G, Table G-36). The model fit and evaluation statistics (Appendix G, Table G-37), and were consistent across the models with significant terms. This suggests that models with ambient temperature (model LB-5) perform as well as models with lagoon specific parameters (LB-3). Therefore, EPA selected model NV-5 (including ambient temperature as the predictive parameter) for further analysis for H<sub>2</sub>S. The final form of this model is presented in Table 5-10.

**Table 5-10. Selected daily models for lagoons sources.**

Pollutant	Formula	Units	Equation Number
NH <sub>3</sub>	$\ln(NH_3) = 1.396734 + 0.027201 * Amb_T$	g/d-m <sup>2</sup>	Equation 18
H <sub>2</sub> S	$\ln(H_2S) = 1.189272 + 0.010557 * Amb_T$	g/d-m <sup>2</sup>	Equation 19

## 5.5 Corrals

The literature review (Section 3) and exploratory data analysis (Section 4) suggested that EPA should consider ambient temperature, ambient relative humidity, water vapor deficit, and wind speed in the development of the emissions models for corrals. EPA evaluated 15 combinations of these parameters as potential models (Table 5-11). Models were developed to predict daily emissions per meter squared (g/d-m<sup>2</sup>) of corral surface area, as well as emissions per m<sup>2</sup> per 1,000 head (g/d-m<sup>2</sup>-1,000 hd), to account for the stock density of the corral. In total, 30 models were evaluated to account for the 15 different parameter combinations and two forms of the emissions.

**Table 5-11. Parameter combinations evaluated as corral models for NH<sub>3</sub> and H<sub>2</sub>S emissions.**

Model	Emissions	Parameters
CR-1a	g/d-m <sup>2</sup>	Ambient temperature, ambient relative humidity, wind speed, water vapor deficit
CR-2a	g/d-m <sup>2</sup>	Ambient temperature, ambient relative humidity, water vapor deficit
CR-3a	g/d-m <sup>2</sup>	Ambient temperature, ambient relative humidity, wind speed
CR-4a	g/d-m <sup>2</sup>	Ambient relative humidity, wind speed, water vapor deficit
CR-5a	g/d-m <sup>2</sup>	Ambient temperature, wind speed, water vapor deficit
CR-6a	g/d-m <sup>2</sup>	Ambient temperature, ambient relative humidity
CR-7a	g/d-m <sup>2</sup>	Ambient temperature, water vapor deficit

Model	Emissions	Parameters
CR-8a	g/d-m <sup>2</sup>	Ambient relative humidity, water vapor deficit
CR-9a	g/d-m <sup>2</sup>	Ambient temperature, wind speed
CR-10a	g/d-m <sup>2</sup>	Ambient relative humidity, wind speed
CR-11a	g/d-m <sup>2</sup>	Wind speed, water vapor deficit
CR-12a	g/d-m <sup>2</sup>	Ambient temperature
CR-13a	g/d-m <sup>2</sup>	Ambient relative humidity
CR-14a	g/d-m <sup>2</sup>	Water vapor deficit
CR-15a	g/d-m <sup>2</sup>	Wind speed
CR-1b	g/d-m <sup>2</sup> - 1,000 hd	Ambient temperature, ambient relative humidity, wind speed, water vapor deficit
CR-2b	g/d-m <sup>2</sup> - 1,000 hd	Ambient temperature, ambient relative humidity, water vapor deficit
CR-3b	g/d-m <sup>2</sup> - 1,000 hd	Ambient temperature, ambient relative humidity, wind speed
CR-4b	g/d-m <sup>2</sup> - 1,000 hd	Ambient relative humidity, wind speed, water vapor deficit
CR-5b	g/d-m <sup>2</sup> - 1,000 hd	Ambient temperature, wind speed, water vapor deficit
CR-6b	g/d-m <sup>2</sup> - 1,000 hd	Ambient temperature, ambient relative humidity
CR-7b	g/d-m <sup>2</sup> - 1,000 hd	Ambient temperature, water vapor deficit
CR-8b	g/d-m <sup>2</sup> - 1,000 hd	Ambient relative humidity, water vapor deficit
CR-9b	g/d-m <sup>2</sup> - 1,000 hd	Ambient temperature, wind speed
CR-10b	g/d-m <sup>2</sup> - 1,000 hd	Ambient relative humidity, wind speed
CR-11b	g/d-m <sup>2</sup> - 1,000 hd	Wind speed, water vapor deficit
CR-12b	g/d-m <sup>2</sup> - 1,000 hd	Ambient temperature
CR-13b	g/d-m <sup>2</sup> - 1,000 hd	Ambient relative humidity
CR-14b	g/d-m <sup>2</sup> - 1,000 hd	Water vapor deficit
CR-15b	g/d-m <sup>2</sup> - 1,000 hd	Wind speed

Models CR-3a, CR-4a, CR-6a, CR-8a, CR-12a, CR-13a, CR-14a, CR-4b, CR-6b, CR-8b, CR-12b, CR-13b, CR-14b, CR-15b were comprised of significant parameters for NH<sub>3</sub> (Appendix G, Table G-38). The model fit (-2 log likelihood, AIC, AICc, and BIC) and evaluation statistics (ME, NME, MB, NMB) for these models are presented in Appendix G, Table G-39, and were consistent across all the models. The models predicting the emissions in mg/d-m<sup>2</sup>-hd have lower

mean bias and mean error values than their counterpart predicting emissions as g/d-m<sup>2</sup>. EPA selected model CR-3b (including the predictive parameters: ambient temperature, ambient relative humidity, and wind speed) for further analysis for NH<sub>3</sub>. The final form of this model is presented in Table 5-12.

For H<sub>2</sub>S, only model CR-13a was comprised entirely of statistically significant parameters (Appendix G, Table G-40). Like NH<sub>3</sub>, the model fit and evaluation statistics (Appendix G, Table G-41) for the version of the model predicting emissions as μg/d-m<sup>2</sup>-hd (i.e., CR-13b) has slightly lower mean bias and mean error values. EPA selected model CR-13b (including the predictive parameter ambient relative humidity) for further analysis for corral H<sub>2</sub>S emissions. The final form of this model is presented in Table 5-12.

**Table 5-12. Selected daily models for corrals.**

<b>Pollutant</b>	<b>Formula</b>	<b>Units</b>	<b>Equation Number</b>
NH <sub>3</sub>	$ln(NH_3) = 1.053805 + 0.00499 * Amb_T + 0.0031 * Amb_{RH} + 0.017832 * WindSpeed$	mg/d-m <sup>2</sup> -hd	Equation 20
H <sub>2</sub> S	$ln(H_2S) = 2.404792 + 0.007177 * Amb_{RH}$	μg/d-m <sup>2</sup> -hd	Equation 21

## 6 MODEL COEFFICIENT EVALUATION

To ensure reliable prediction of the emissions, the model coefficients were evaluated with the jackknife method (Christensen et al., 2016; Leeden et al., 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 lagoons are the mutually exclusive independent sample units. EPA then determined the associated parameter estimates for the selected model based on this dataset. This was repeated for each of the sample units. These results were then compared to the model coefficients based on the full dataset (full model). For each jackknife model, the ME, NME, MB, and NMB were calculated, based on the equations outlined in Section 6 of the Overview report, to facilitate comparison.

EPA also prepared plots showing the variation in coefficients and standard errors for the selected models and compared the plots to each of the jackknife models. EPA interpreted these plots similar to 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  $\pm 1$  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 removed from analysis, and other potential remediation measures considered.

### 6.1 Mechanically Ventilated Barn Models

#### 6.1.1 *NH<sub>3</sub> Model Evaluation*

Table 6-1 and Figure 6-1 show the variation in coefficients and standard errors for the selected model (“None”) and each of the jackknife models. The model coefficients from the jackknife approach were comparable across the withheld sets (Table 6-1) and remained significant (p-value <0.05) across all models. The plots in Figure 6-1 show that the results for all jackknife models overlap the full model estimate  $\pm 1$  standard error, except for ambient temperature. In comparison to the full model, that is where the barn removed is “None”, the maximum percentage differences for parameter estimates across the three models were 7%, 23%, 3%, and 4% for inventory, ambient temperature, intercept for the flush barns, and intercept for scrape barns, respectively. Across all models, the difference in NME and NMB (Table 6-2) in comparison to the selected model were minor. For NME the values differed by less than 8%. For NMB the values varied by less than 34%. The largest difference was seen when WI5B B1 was withheld from the dataset, which decreased the NME and NMB by 8% and 34%, respectively.

**Table 6-1. Model coefficients developed using the jackknife approach for NH<sub>3</sub> emissions from mechanically ventilated barns.**

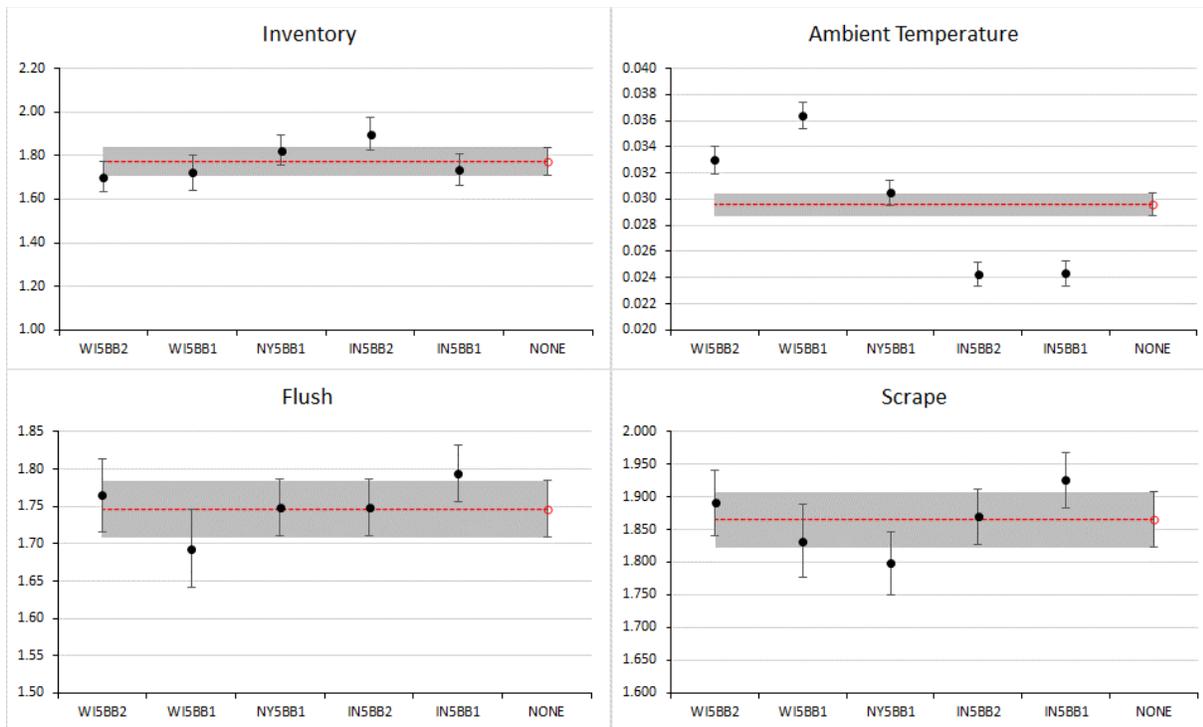
Barn Out	Effect	Estimate	Standard Error	p-value
None	Inventory	1.773832	0.06477	<.0001
None	Ambient Temperature	0.029586	0.00088	<.0001
None	Flush	1.746585	0.03789	<.0001
None	Scrape	1.864935	0.04253	<.0001
IN5BB1	Inventory	1.736301	0.07221	<.0001
IN5BB1	Ambient Temperature	0.024312	0.00093	<.0001
IN5BB1	Flush	1.793836	0.03772	<.0001
IN5BB1	Scrape	1.925841	0.04232	<.0001
IN5BB2	Inventory	1.898712	0.07457	<.0001
IN5BB2	Ambient Temperature	0.024229	0.00091	<.0001
IN5BB2	Flush	1.748491	0.03749	<.0001
IN5BB2	Scrape	1.869675	0.0425	<.0001
NY5BB1	Inventory	1.824003	0.06932	<.0001
NY5BB1	Ambient Temperature	0.030506	0.00095	<.0001
NY5BB1	Flush	1.72461	0.03966	<.0001
NY5BB1	Scrape	1.798078	0.04787	<.0001
WI5BB1	Inventory	1.722238	0.07977	<.0001
WI5BB1	Ambient Temperature	0.036382	0.00101	<.0001
WI5BB1	Flush	1.693687	0.05244	<.0001
WI5BB1	Scrape	1.832478	0.05634	<.0001
WI5BB2	Inventory	1.703501	0.07134	<.0001
WI5BB2	Ambient Temperature	0.032999	0.00105	<.0001
WI5BB2	Flush	1.765095	0.04896	<.0001
WI5BB2	Scrape	1.891018	0.05005	<.0001

**Table 6-2. Model fit statistics for the mechanically ventilated barns NH<sub>3</sub> jackknife.**

Barn Out	n	LNME <sup>a</sup> (%)	NME <sup>b</sup> (%)	ME <sup>b</sup> (kg day <sup>-1</sup> )	MB <sup>b</sup> (kg day <sup>-1</sup> )	NMB <sup>b</sup> (%)	Corr.
None	2,192	7.322	24.573	5.959	-0.583	-2.404	0.917
IN5BB1	1,771	7.213	25.072	5.003	-0.542	-2.717	0.911
IN5BB2	1,762	7.148	25.329	5.042	-0.472	-2.372	0.905
NY5BB1	1,846	7.403	24.716	6.115	-0.701	-2.835	0.924
WI5BB1	1,676	6.866	22.488	6.538	-0.459	-1.579	0.918
WI5BB2	1,713	7.212	23.375	6.523	-0.547	-1.961	0.919

<sup>a</sup> Based on transformed data (i.e., ln(NH<sub>3</sub>)).

<sup>b</sup> Based on back-transformed data.



**Figure 6-1. Comparison of variation in coefficients and standard errors for NH<sub>3</sub> emissions from mechanically ventilated barn model.**

Variation in coefficients and standard errors (black closed circle and  $\pm$  SE bar) for each jackknife model with the selected NH<sub>3</sub> mechanically ventilated model coefficient (“None”, gray band for  $\pm$  SE) for each model parameter.

### 6.1.2 H<sub>2</sub>S Model Evaluation

The variation in coefficients and standard errors for the selected model (“None”) and each of the H<sub>2</sub>S jackknife models is shown in Table 6-3 and Figure 6-2. The model coefficients from the jackknife approach were comparable across the withheld sets (Table 6-3) and remained significant (p-value <0.05) across all models. The plots in Figure 6-2 show that the results for all jackknife models overlap the full model estimate  $\pm$  1 standard error, except for WI5B B1 for ambient temperature. In comparison to the full model, where the barn removed is “None”, the maximum percentage differences for parameter estimates across the three models were 14%, 26%, 2%, and 1% for inventory, ambient temperature, intercept for the flush barns, and intercept for scrape barns, respectively. Across all models, the difference in NME and NMB (Table 6-4) in comparison to the selected model were minor for NME (< 8%) and more substantial for NMB (<32%).

**Table 6-3. Model coefficients developed using the jackknife approach for H<sub>2</sub>S emissions from mechanically ventilated barns.**

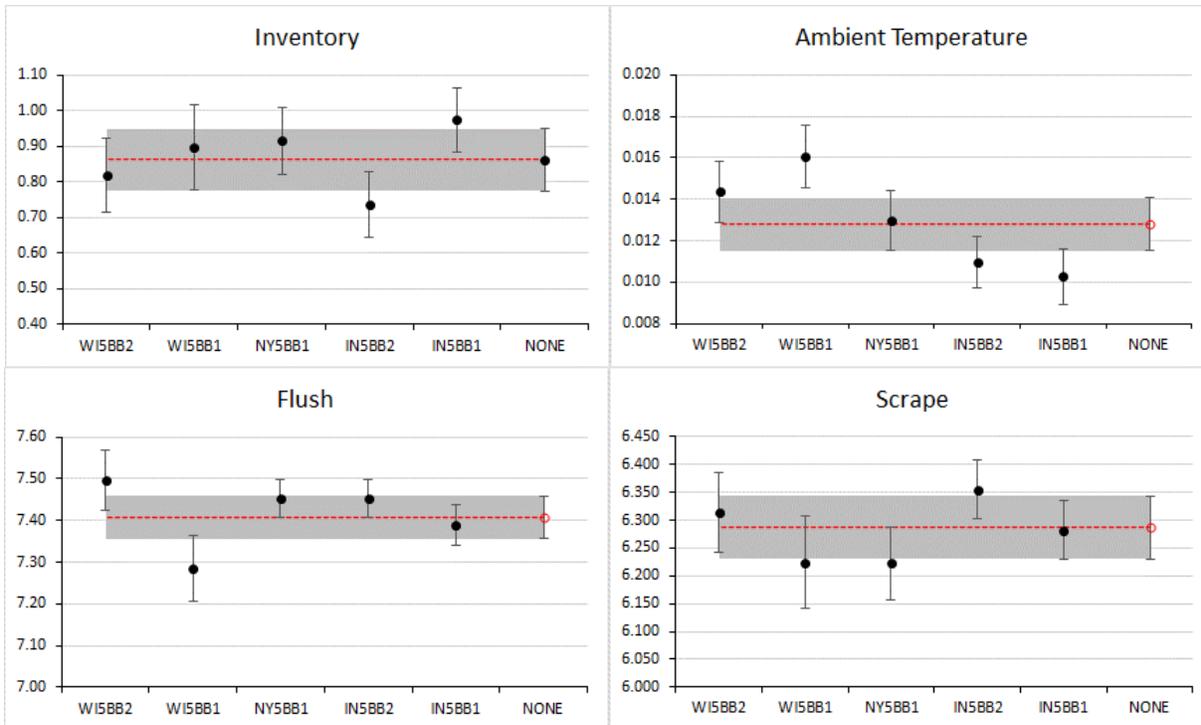
Barn Out	Effect	Estimate	Standard Error	p-value
None	Inventory	0.86173	0.08664	<.0001
None	Ambient Temperature	0.012786	0.00127	<.0001
None	Flush	7.406887	0.05129	<.0001
None	Scrape	6.287004	0.05691	<.0001
IN5BB1	Inventory	0.974345	0.08989	<.0001
IN5BB1	Ambient Temperature	0.010264	0.00134	<.0001
IN5BB1	Flush	7.389176	0.04755	<.0001
IN5BB1	Scrape	6.282462	0.053	<.0001
IN5BB2	Inventory	0.73697	0.09126	<.0001
IN5BB2	Ambient Temperature	0.010959	0.00124	<.0001
IN5BB2	Flush	7.453061	0.04624	<.0001
IN5BB2	Scrape	6.355244	0.0521	<.0001
NY5BB1	Inventory	0.915728	0.09384	<.0001
NY5BB1	Ambient Temperature	0.012973	0.00147	<.0001
NY5BB1	Flush	7.389581	0.05383	<.0001
NY5BB1	Scrape	6.222805	0.06537	<.0001
WI5BB1	Inventory	0.897494	0.11836	<.0001
WI5BB1	Ambient Temperature	0.016059	0.00149	<.0001
WI5BB1	Flush	7.285544	0.07955	<.0001
WI5BB1	Scrape	6.224063	0.08308	<.0001
WI5BB2	Inventory	0.817846	0.10259	<.0001
WI5BB2	Ambient Temperature	0.014378	0.00148	<.0001
WI5BB2	Flush	7.495271	0.07179	<.0001
WI5BB2	Scrape	6.313356	0.07154	<.0001

**Table 6-4. Model fit statistics for the mechanically ventilated barns H<sub>2</sub>S jackknife.**

Barn Out	n	LNME <sup>a</sup> (%)	NME <sup>b</sup> (%)	ME <sup>b</sup> (g day <sup>-1</sup> )	MB <sup>b</sup> (g day <sup>-1</sup> )	NMB <sup>b</sup> (%)	Corr.
None	2,454	4.46	64.308	553.14	-38.66	-4.495	0.58
IN5BB1	1,993	4.088	61.644	533.71	-34.72	-4.01	0.592
IN5BB2	1,954	3.911	59.42	464	-25.36	-3.248	0.677
NY5BB1	1,992	4.736	65.587	615.71	-39.17	-4.173	0.565
WI5BB1	1,920	4.696	66.693	561.9	-47.91	-5.686	0.543
WI5BB2	1,957	4.653	64.785	564.15	-51.6	-5.925	0.582

<sup>a</sup> Based on transformed data (i.e., ln(H<sub>2</sub>S)).

<sup>b</sup> Based on back-transformed data.



**Figure 6-2. Comparison of variation in coefficients and standard errors for H<sub>2</sub>S mechanically ventilated barn model.**

Variation in coefficients and standard errors (black closed circle and  $\pm$  SE bar) for each jackknife model with the selected H<sub>2</sub>S mechanically ventilated barn model coefficient (“None”, gray band for  $\pm$  SE) for each model parameter.

### 6.1.3 PM<sub>10</sub> Model evaluation

The variation in coefficients and standard errors for the selected model (“None”) and each of the PM<sub>10</sub> jackknife models is shown in Table 6-5 and Figure 6-3. The model coefficients from the jackknife approach were mostly comparable across the withheld sets (Table 6-3) and remained significant ( $p$ -value  $< 0.05$ ) across all models. The plots in Figure 6-2 show that the results for all jackknife models overlap the full model estimate  $\pm 1$  standard error, except for W15B B1 for all parameters and W15B B1 for ambient temperature. In comparison to the full model, where the barn removed is “None”, the maximum percentage differences for parameter estimates across the three models were 2%, 32%, and 37% for the intercept, ambient temperature, and relative humidity, respectively. Across all models, the difference in NME and NMB (Table 6-6) in comparison to the selected model were minor for NME ( $< 23\%$ ) and more substantial for NMB ( $< 31\%$ ).

**Table 6-5. Model coefficients developed using the jackknife approach for PM<sub>10</sub> emissions from mechanically ventilated barns.**

Barn Out	Effect	Estimate	Standard Error	p-value
None	Intercept	8.130759	0.04588	$< .0001$
None	Ambient Temperature	0.01083	0.00117	$< .0001$

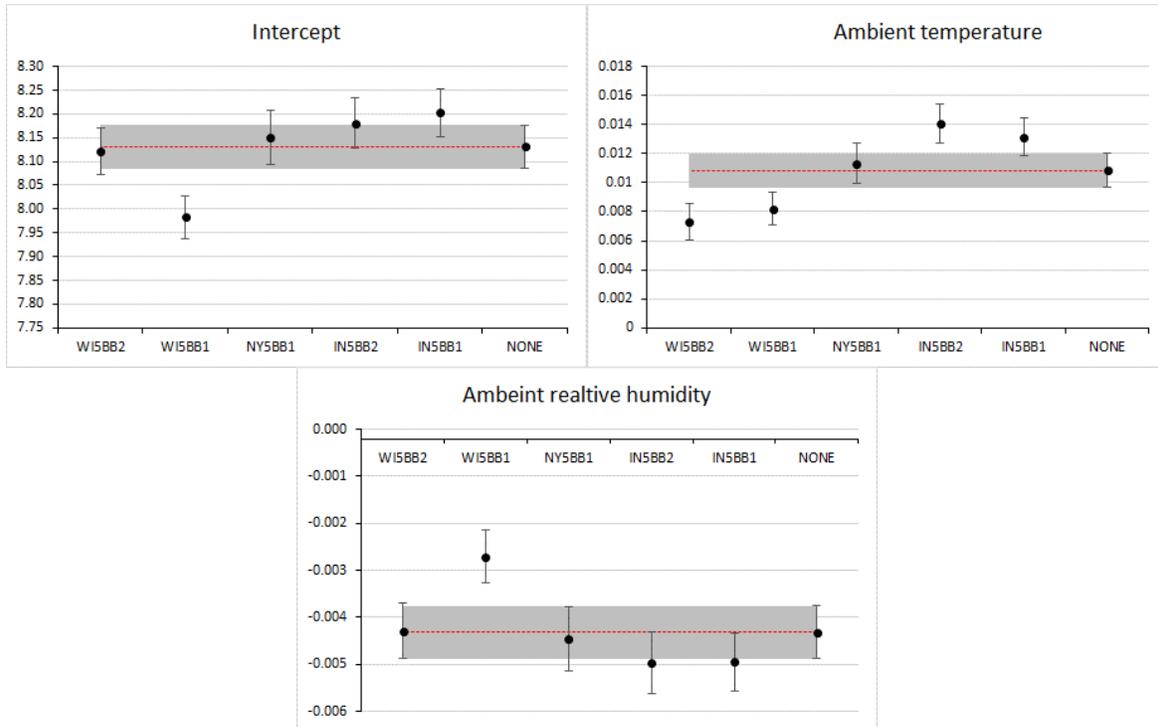
Barn Out	Effect	Estimate	Standard Error	p-value
None	Ambient Relative Humidity	-0.004322	0.00056	<.0001
IN5BB1	Intercept	8.202657	0.05056	<.0001
IN5BB1	Ambient Temperature	0.013151	0.0013	<.0001
IN5BB1	Ambient Relative Humidity	-0.004953	0.00062	<.0001
IN5BB2	Intercept	8.180828	0.05239	<.0001
IN5BB2	Ambient Temperature	0.014081	0.00135	<.0001
IN5BB2	Ambient Relative Humidity	-0.004971	0.00065	<.0001
NY5BB1	Intercept	8.150673	0.05578	<.0001
NY5BB1	Ambient Temperature	0.011303	0.00139	<.0001
NY5BB1	Ambient Relative Humidity	-0.004464	0.00068	<.0001
WI5BB1	Intercept	7.983117	0.04467	<.0001
WI5BB1	Ambient Temperature	0.008207	0.00115	<.0001
WI5BB1	Ambient Relative Humidity	-0.002713	0.00056	<.0001
WI5BB2	Intercept	8.122029	0.0495	<.0001
WI5BB2	Ambient Temperature	0.007319	0.00125	<.0001
WI5BB2	Ambient Relative Humidity	-0.00429	0.00059	<.0001

**Table 6-6. Model fit statistics for the mechanically ventilated barns PM<sub>10</sub> jackknife.**

Barn Out	n	LNME <sup>a</sup> (%)	NME <sup>b</sup> (%)	ME <sup>b</sup> (g day <sup>-1</sup> )	MB <sup>b</sup> (g day <sup>-1</sup> )	NMB <sup>b</sup> (%)	Corr.
None	1,529	2.78	102.84	951.81	-45.14	-4.877	0.423
IN5BB1	1,303	2.937	95.858	1,016.3	-61.6	-5.81	0.482
IN5BB2	1,241	2.994	96.362	1,050	-65.32	-5.994	0.492
NY5BB1	1,222	3.093	105.97	1,092.3	-51.87	-5.033	0.422
WI5BB1	1,159	2.137	101.71	666.2	-21.96	-3.352	0.382
WI5BB2	1,191	2.444	107.63	820.34	-28.62	-3.755	0.348

<sup>a</sup> Based on transformed data (i.e., ln(H<sub>2</sub>S)).

<sup>b</sup> Based on back-transformed data.



**Figure 6-3. Comparison of variation in coefficients and standard errors for PM<sub>10</sub> mechanically ventilated barn model.**

Variation in coefficients and standard errors (black closed circle and  $\pm$  SE bar) for each jackknife model with the selected PM<sub>10</sub> mechanically ventilated barn model coefficient (“None”, gray band for  $\pm$  SE) for each model parameter.

#### 6.1.4 PM<sub>2.5</sub> Model evaluation

The variation in coefficients and standard errors for the selected model (“None”) and each of the PM<sub>2.5</sub> jackknife models is shown in Table 6-7 and Figure 6-4. The model coefficients from the jackknife approach were comparable across the withheld sets (Table 6-7) however, they were not always significant ( $p$ -value  $< 0.05$ ) across all models. The plots in Figure 6-4 show that the results for all jackknife models overlap the full model estimate  $\pm 1$  standard error. In comparison to the full model, where the barn removed is “None”, the maximum percentage differences for parameter estimates across the three models were 2%, 51%, and 203% for the intercept, ambient temperature, and ambient relative humidity, respectively. Across all models, the difference in NME and NMB (Table 6-8) in comparison to the selected model were more substantial, with NME ( $< 44\%$ ) and NMB ( $< 65\%$ ). As noted previously, the PM<sub>2.5</sub> dataset is small, and larger error were anticipated.

**Table 6-7. Model coefficients developed using the jackknife approach for PM<sub>2.5</sub> emissions from mechanically ventilated barns.**

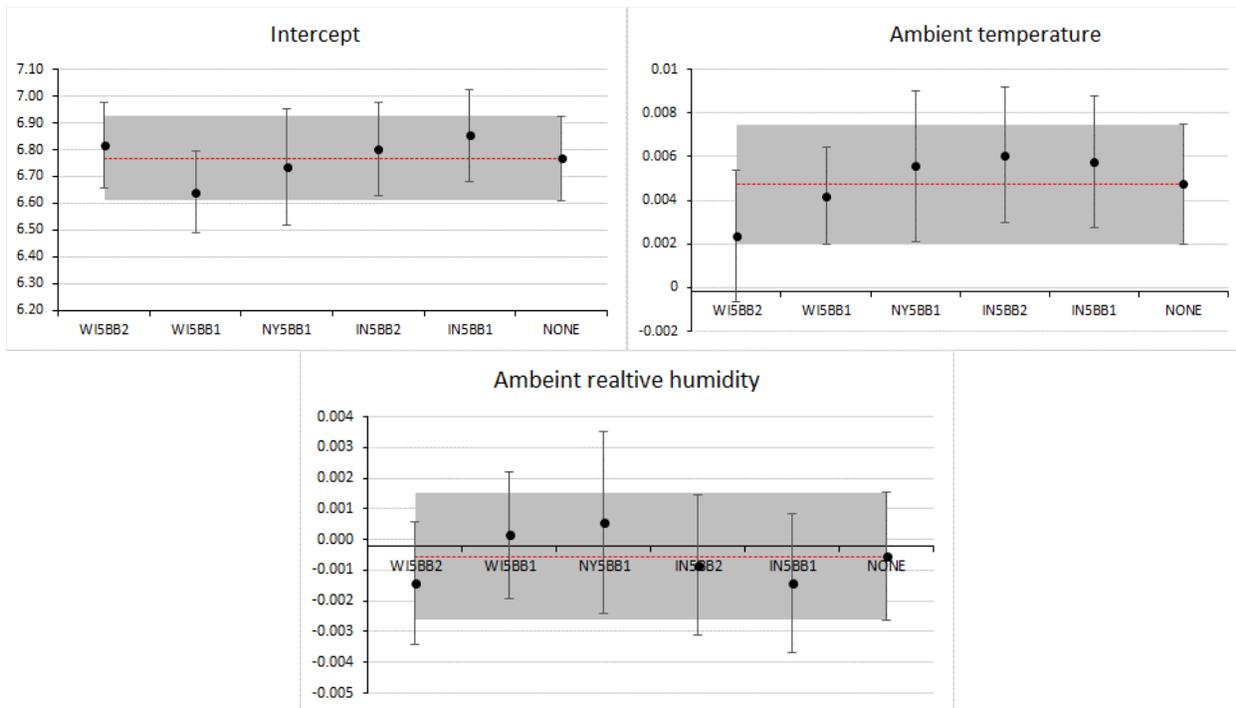
Barn Out	Effect	Estimate	Standard Error	p-value
None	Intercept	6.76777	0.15722	<.0001
None	Ambient Temperature	0.00474	0.00273	0.0872
None	Ambient Relative Humidity	-0.000547	0.00207	0.7919
IN5BB1	Intercept	6.853684	0.17231	<.0001
IN5BB1	Ambient Temperature	0.005778	0.00302	0.0608
IN5BB1	Ambient Relative Humidity	-0.001429	0.00225	0.5272
IN5BB2	Intercept	6.803117	0.1748	<.0001
IN5BB2	Ambient Temperature	0.006067	0.00309	0.0542
IN5BB2	Ambient Relative Humidity	-0.000833	0.00229	0.7161
NY5BB1	Intercept	6.736309	0.21788	<.0001
NY5BB1	Ambient Temperature	0.005557	0.00344	0.1135
NY5BB1	Ambient Relative Humidity	0.000565	0.00296	0.849
WI5BB1	Intercept	6.642277	0.15065	<.0001
WI5BB1	Ambient Temperature	0.004204	0.00222	0.0662
WI5BB1	Ambient Relative Humidity	0.000146	0.00205	0.9434
WI5BB2	Intercept	6.817705	0.16064	<.0001
WI5BB2	Ambient Temperature	0.002344	0.00302	0.4396
WI5BB2	Ambient Relative Humidity	-0.001419	0.00201	0.4828

**Table 6-8. Model fit statistics for the mechanically ventilated barns PM<sub>2.5</sub> jackknife.**

Barn Out	n	LNME <sup>a</sup> (%)	NME <sup>b</sup> (%)	ME <sup>b</sup> (g day <sup>-1</sup> )	MB <sup>b</sup> (g day <sup>-1</sup> )	NMB <sup>b</sup> (%)	Corr.
None	166	3.229	101.8	257.99	-4.866	-1.92	0.31
IN5BB1	146	3.499	100.29	276.55	-7.344	-2.663	0.369
IN5BB2	145	3.612	104.07	282.86	-6.381	-2.348	0.343
NY5BB1	113	3.752	96.571	324.38	-8.665	-2.58	0.369
WI5BB1	126	1.82	78.635	120.8	-1.025	-0.667	0.289
WI5BB2	134	2.933	105.61	246.63	-3.748	-1.605	0.314

<sup>a</sup> Based on transformed data (i.e., ln(PM<sub>2.5</sub>)).

<sup>b</sup> Based on back-transformed data.



**Figure 6-4. Comparison of variation in coefficients and standard errors for PM<sub>2.5</sub> mechanically ventilated barn model.**

Variation in coefficients and standard errors (black closed circle and ± SE bar) for each jackknife model with the selected PM<sub>2.5</sub> mechanically ventilated barn model coefficient (“None”, gray band for ± SE) for each model parameter.

### 6.1.5 TSP Model evaluation

The variation in coefficients and standard errors for the selected model (“None”) and each of the TSP jackknife models is shown in Table 6-9 and Figure 6-5. The model coefficients from the jackknife approach were comparable across the withheld sets (Table 6-9) and generally remained significant ( $p$ -value  $< 0.05$ ) across all models. The plots in Figure 6-5 show that the results for all jackknife models overlap the full model estimate  $\pm 1$  standard error, except for W15B B1 for ambient relative humidity and the intercept. In comparison to the full model, where the barn removed is “None”, the maximum percentage differences for parameter estimates across the three models were 5%, 69%, and 38% for the intercept, ambient temperature, and ambient relative humidity, respectively. Across all models, the difference in NME and NMB (Table 6-10) in comparison to the selected model were substantial for NME ( $< 28\%$ ) and more substantial for NMB ( $< 33\%$ ).

**Table 6-9. Model coefficients developed using the jackknife approach for TSP emissions from mechanically ventilated barns.**

Barn Out	Effect	Estimate	Standard Error	p-value
None	Intercept	8.434953	0.17254	<.0001
None	Ambient Temperature	0.01277	0.00439	0.004
None	Ambient Relative Humidity	-0.013417	0.0023	<.0001

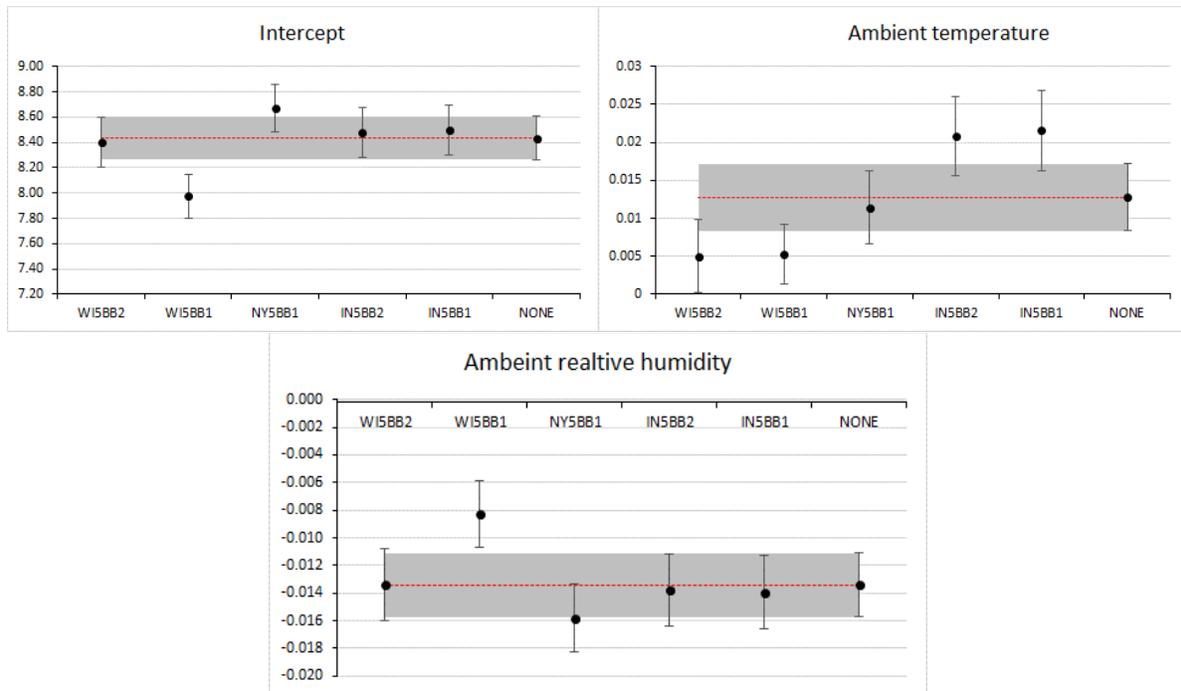
Barn Out	Effect	Estimate	Standard Error	p-value
IN5BB1	Intercept	8.497608	0.19819	<.0001
IN5BB1	Ambient Temperature	0.02156	0.00525	<.0001
IN5BB1	Ambient Relative Humidity	-0.013954	0.00267	<.0001
IN5BB2	Intercept	8.478918	0.19551	<.0001
IN5BB2	Ambient Temperature	0.020788	0.0052	0.0001
IN5BB2	Ambient Relative Humidity	-0.013785	0.00262	<.0001
NY5BB1	Intercept	8.672509	0.18816	<.0001
NY5BB1	Ambient Temperature	0.011443	0.00474	0.0166
NY5BB1	Ambient Relative Humidity	-0.015823	0.00246	<.0001
WI5BB1	Intercept	7.97449	0.17335	<.0001
WI5BB1	Ambient Temperature	0.005286	0.00398	0.1863
WI5BB1	Ambient Relative Humidity	-0.008276	0.00238	0.0006
WI5BB2	Intercept	8.404181	0.19578	<.0001
WI5BB2	Ambient Temperature	0.005024	0.00484	0.3
WI5BB2	Ambient Relative Humidity	-0.013388	0.00257	<.0001

**Table 6-10. Model fit statistics for the mechanically ventilated barns TSP jackknife.**

Barn Out	n	LNME <sup>a</sup> (%)	NME <sup>b</sup> (%)	ME <sup>b</sup> (g day <sup>-1</sup> )	MB <sup>b</sup> (g day <sup>-1</sup> )	NMB <sup>b</sup> (%)	Corr.
None	1529	2.78	102.84	951.81	-45.14	-4.877	0.423
IN5BB1	1303	2.937	95.858	1016.3	-61.6	-5.81	0.482
IN5BB2	1241	2.994	96.362	1050	-65.32	-5.994	0.492
NY5BB1	1222	3.093	105.97	1092.3	-51.87	-5.033	0.422
WI5BB1	1159	2.137	101.71	666.2	-21.96	-3.352	0.382
WI5BB2	1191	2.444	107.63	820.34	-28.62	-3.755	0.348

<sup>a</sup> Based on transformed data (i.e., ln(TSP)).

<sup>b</sup> Based on back-transformed data.



**Figure 6-5. Comparison of variation in coefficients and standard errors for TSP mechanically ventilated barn model.**

Variation in coefficients and standard errors (black closed circle and  $\pm$  SE bar) for each jackknife model with the selected TSP mechanically ventilated barn model coefficient (“None”, gray band for  $\pm$  SE) for each model parameter.

## 6.2 Milking Center Models

### 6.2.1 $NH_3$ Model Evaluation

Table 6-11 and Figure 6-6 show the variation in coefficients and standard errors for the selected model (“None”) and each of the jackknife models. The model coefficients from the jackknife approach were comparable across the withheld sets (Table 6-11) and remained significant ( $p$ -value  $< 0.05$ ) across all models. The plots in Figure 6-6 show that the results for all jackknife models do not overlap the full model estimate  $\pm 1$  standard error. The standard error was very small for the full model, where the Barn removed is “None”, which prevented the overlap. In comparison to the full model, the maximum percentage differences for parameter estimates across the two models were 29% and 44% for the intercept and ambient temperature, respectively. Across all models, the difference in NME and NMB (Table 6-12) in comparison to the selected model were substantial for NME and NMB, with values differing by up to 44% and 104%, respectively. Upon further review, it was determined that the MCs utilize different manure handling techniques. Specifically, IN5B used a flush system while NY5B used a scrape system. Additional models using this distinction will be evaluated for the final report.

**Table 6-11. Model coefficients developed using the jackknife approach for NH<sub>3</sub> emissions from milking centers.**

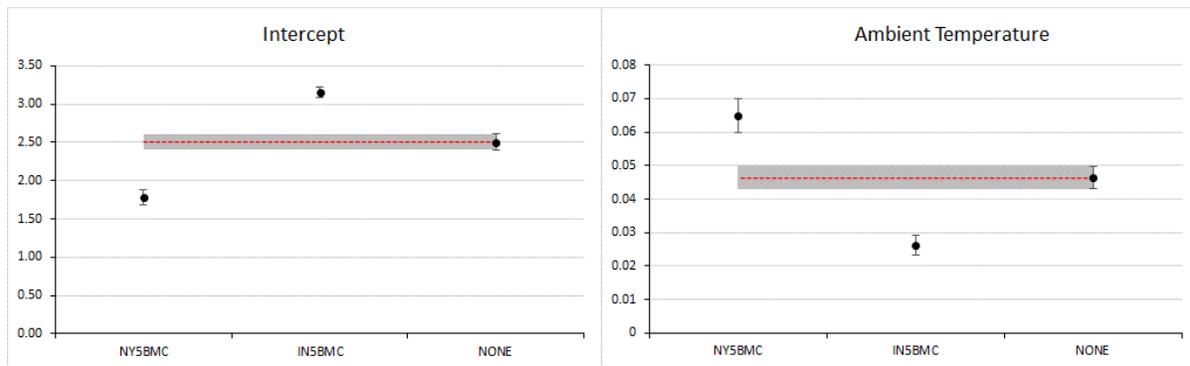
Site Out	Effect	Estimate	Standard Error	p-value
None	Intercept	2.505637	0.10119	<.0001
None	Ambient Temperature	0.046434	0.00335	<.0001
IN5BMC	Intercept	3.155214	0.06261	<.0001
IN5BMC	Ambient Temperature	0.026195	0.00297	<.0001
NY5BMC	Intercept	1.783938	0.09766	<.0001
NY5BMC	Ambient Temperature	0.064815	0.0051	<.0001

**Table 6-12. Model fit statistics for the milking center NH<sub>3</sub> jackknife.**

Site Out	n	LNME <sup>a</sup> (%)	NME <sup>b</sup> (%)	ME <sup>b</sup> (kg day <sup>-1</sup> )	MB <sup>b</sup> (kg day <sup>-1</sup> )	NMB <sup>b</sup> (%)	Corr.
NONE	713	18.245	54.184	12.63	3.017	12.941	0.364
IN5BMC	376	8.032	30.564	9.232	1.475	4.884	0.264
NY5BMC	337	16.728	43.666	6.819	-0.088	-0.561	0.706

<sup>a</sup> Based on transformed data (i.e., ln(NH<sub>3</sub>)).

<sup>b</sup> Based on back-transformed data.



**Figure 6-6. Comparison of variation in coefficients and standard errors for NH<sub>3</sub> milking center model.**

Variation in coefficients and standard errors (black closed circle and  $\pm$  SE bar) for each jackknife model with the selected NH<sub>3</sub> for milking center model coefficient (“None”, gray band for  $\pm$  SE) for each model parameter.

### 6.2.2 H<sub>2</sub>S Model Evaluation

Table 6-13 and Figure 6-7 show the variation in coefficients and standard errors for the selected H<sub>2</sub>S MC model (“None”) and each of the jackknife models. The model coefficients from the jackknife approach were comparable across the withheld sets (Table 6-13) and remained significant ( $p$ -value <0.05) across all models. The plots in Figure 6-7 show that the results for all jackknife models do not overlap the full model estimate  $\pm$  1 standard error, except the intercept for the IN5B withheld model. Like the NH<sub>3</sub> model, the standard error was very small for the full model, where the Barn removed is “None”, which prevented the overlap. In comparison to the full model, the maximum percentage differences for parameter estimates across the two models were 4% and 120% for the intercept and ambient temperature, respectively. Across all models,

the difference in NME and NMB (Table 6-14) in comparison to the selected model were substantial for NME and NMB, with values differing by less than 32% and 79%, respectively. As with the NH<sub>3</sub> models, adding a parameter for manure management system may account for the variability between sites. Additional models using this distinction will be evaluated for the final report.

**Table 6-13. Model coefficients developed using the jackknife approach for H<sub>2</sub>S emissions from milking centers.**

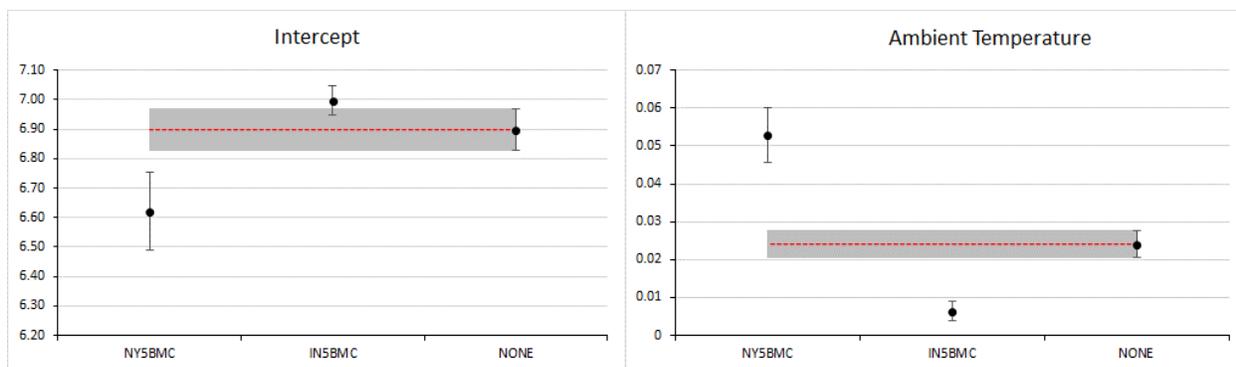
Site Out	Effect	Estimate	Standard Error	p-value
None	Intercept	6.898188	0.07052	<.0001
None	Ambient Temperature	0.024053	0.00361	<.0001
IN5BMC	Intercept	6.99747	0.05042	<.0001
IN5BMC	Ambient Temperature	0.006415	0.0025	0.011
NY5BMC	Intercept	6.621331	0.13313	<.0001
NY5BMC	Ambient Temperature	0.052894	0.00711	<.0001

**Table 6-14. Model fit statistics for the milking center H<sub>2</sub>S jackknife.**

Site Out	n	LNME <sup>a</sup> (%)	NME <sup>b</sup> (%)	ME <sup>b</sup> (g day <sup>-1</sup> )	MB <sup>b</sup> (g day <sup>-1</sup> )	NMB <sup>b</sup> (%)	Corr.
None	926	6.611	90.97	1204.3	-113.5	-8.571	0.347
IN5BMC	540	4.099	61.55	413.65	-12.28	-1.827	0.466
NY5BMC	386	8.707	84.8	1895.8	-284.9	-12.74	0.448

<sup>a</sup> Based on transformed data (i.e., ln(H<sub>2</sub>S)).

<sup>b</sup> Based on back-transformed data.



**Figure 6-7. Comparison of variation in coefficients and standard errors for H<sub>2</sub>S milking center model.**

Variation in coefficients and standard errors (black closed circle and ± SE bar) for each jackknife model with the selected H<sub>2</sub>S milking center model coefficient (“None”, gray band for ± SE) for each model parameter.

### 6.2.3 Particulate Matter Model Evaluation

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

obtaining additional data that would allow for further model testing and evaluation and an improved emissions model.

### 6.3 Naturally Ventilated Barn Models

A theme across all the results presented below is that withholding WA4B B4 from the data set produces the largest differences across the models. This is likely due to WA4B B4 having an average daily inventory almost twice the other three barns included in NAEMS. Removing this barn greatly reduced the variability of inventory values in the data set that the model must capture.

#### 6.3.1 NH<sub>3</sub> Model Evaluation

Table 6-15 and Figure 6-8 show the variation in coefficients and standard errors for the selected NH<sub>3</sub> naturally ventilated barn model (“None”) and each of the jackknife models. The model coefficients from the jackknife approach had some differences, most notable in the models with WA5B barns withheld (Table 6-15). For the models where WA4B B2 and B4 were withheld, one or both parameters were insignificant (p-value >0.05). The plots in Figure 6-8 show that the coefficients for these models also fall outside the full model estimate ± 1 standard error, except for wind speed. In comparison to the full model, where the barn removed is “None”, the maximum percentage differences for parameter estimates across the models were 2,292%, 235%, and 23% for the intercept, inventory, and wind speed, respectively. These largest differences all occurred for the model where WA5B B4 was removed. Across all models, the difference in NME and NMB (Table 6-16) in comparison to the selected model were the largest when WA5B B4 was withheld from the dataset, which increased the NME by 32% and decreased NMB by 174%. This is likely due to the reduced variability in inventory values caused by withholding WA4B B4.

**Table 6-15. Model coefficients developed using the jackknife approach for NH<sub>3</sub> emissions from naturally ventilated barns.**

Site Out	Effect	Estimate	Standard Error	p-value
None	Intercept	0.188357	0.2678	0.484
None	Inventory	3.451939	0.4106	<.0001
None	Wind Speed	0.048153	0.01837	0.009
CA5BB1	Intercept	0.734625	0.34491	0.0385
CA5BB1	Inventory	2.885717	0.49667	<.0001
CA5BB1	Wind Speed	0.043071	0.01873	0.022
CA5BB2	Intercept	0.730143	0.31533	0.0253
CA5BB2	Inventory	2.985909	0.45768	<.0001
CA5BB2	Wind Speed	0.040555	0.01847	0.0288
WA5BB2	Intercept	-0.84424	0.13064	<.0001
WA5BB2	Inventory	4.709923	0.19931	<.0001
WA5BB2	Wind Speed	0.019312	0.02201	0.3808

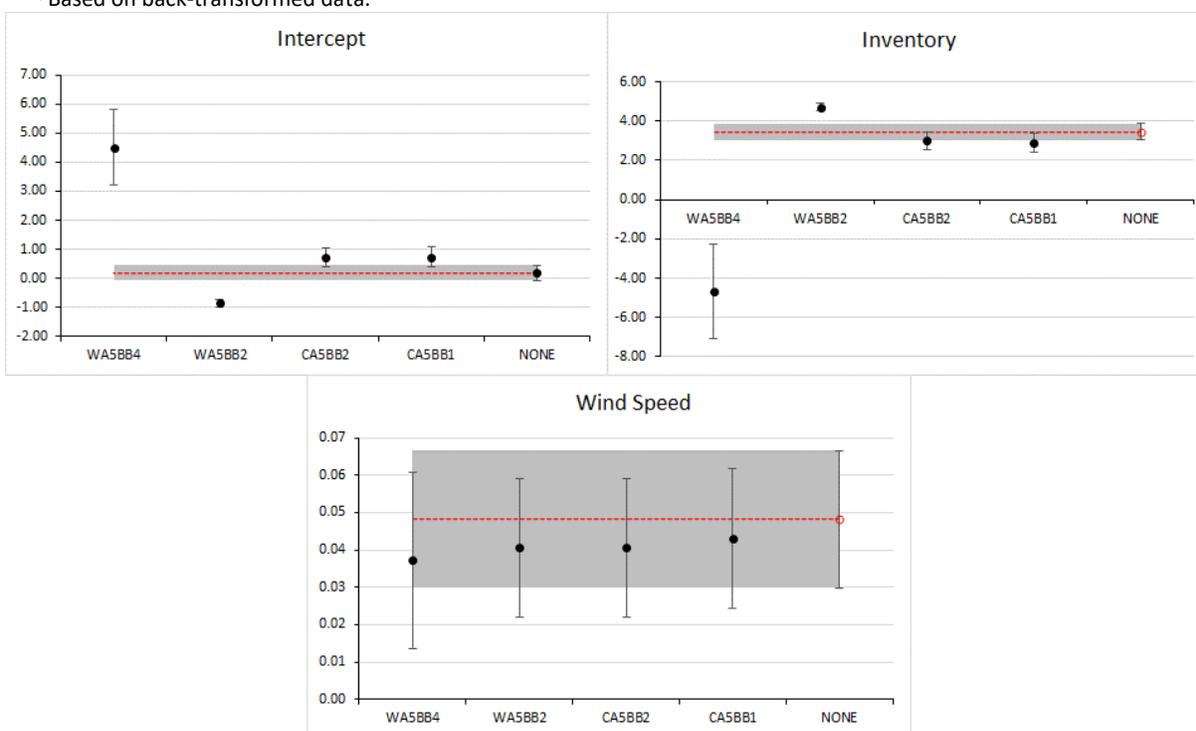
Site Out	Effect	Estimate	Standard Error	p-value
WA5BB4	Intercept	4.505901	1.29423	0.0009
WA5BB4	Inventory	-4.658465	2.41694	0.0582
WA5BB4	Wind Speed	0.037293	0.02361	0.1149

**Table 6-16. Model fit statistics for the naturally ventilated barns NH<sub>3</sub> jackknife.**

Site Out	n	LNME <sup>a</sup> (%)	NME <sup>b</sup> (%)	ME <sup>b</sup> (kg day <sup>-1</sup> )	MB <sup>b</sup> (kg day <sup>-1</sup> )	NMB <sup>b</sup> (%)	Corr.
NONE	605	27.084	75.233	12.818	0.828	4.862	0.636
CA5BB1	431	27.885	72.445	16.265	0.754	3.36	0.601
CA5BB2	396	25.139	69.96	16.995	1.728	7.114	0.599
WA5BB2	482	20.19	51.412	7.179	-0.504	-3.611	0.793
WA5BB4	506	32.404	98.929	9.575	-0.249	-2.571	0.207

<sup>a</sup> Based on transformed data (i.e., ln(NH<sub>3</sub>)).

<sup>b</sup> Based on back-transformed data.



**Figure 6-8. Comparison of variation in coefficients and standard errors for NH<sub>3</sub> naturally ventilated barn model.**

Variation in coefficients and standard errors (black closed circle and  $\pm$  SE bar) for each jackknife model with the selected NH<sub>3</sub> naturally ventilated barn model coefficient (“None”, gray band for  $\pm$  SE) for each model parameter.

### 6.3.2 H<sub>2</sub>S Model Evaluation

Table 6-17 and Figure 6-9 show the variation in coefficients and standard errors for the selected H<sub>2</sub>S naturally ventilated barn model (“None”) and each of the jackknife models. The model coefficients from the jackknife approach had some differences, most notable the coefficient for inventory switched to negative in the model with WA5B B4 withheld (Table

6-17) and was insignificant (p-value >0.05). For the models where CA4B B1 and B2 were withheld, the coefficient from wind speed became insignificant. The plots in Figure 6-9 show that the coefficients for the model where WA5B B4 was withheld fall outside the full model estimate  $\pm 1$  standard error, except for wind speed. In comparison to the full model, where the barn removed is “None”, the maximum percentage differences for parameter estimates across the models occurred when WA5B was withheld and were 12%, 307%, and 75% for the intercept, inventory, and wind speed, respectively. Across all models, the difference in NME and NMB (Table 6-18) in comparison to the selected model were the largest when WA5B B4 was withheld from the dataset, which increased the NME by 17% and decreased NMB by 92%. Withholding WA4B B4 from the dataset reduced variability in inventory, which changed the significance of inventory as a predictive parameter and lowered the bias seen in the model.

**Table 6-17. Model coefficients developed using the jackknife approach for H<sub>2</sub>S emissions from naturally ventilated barns.**

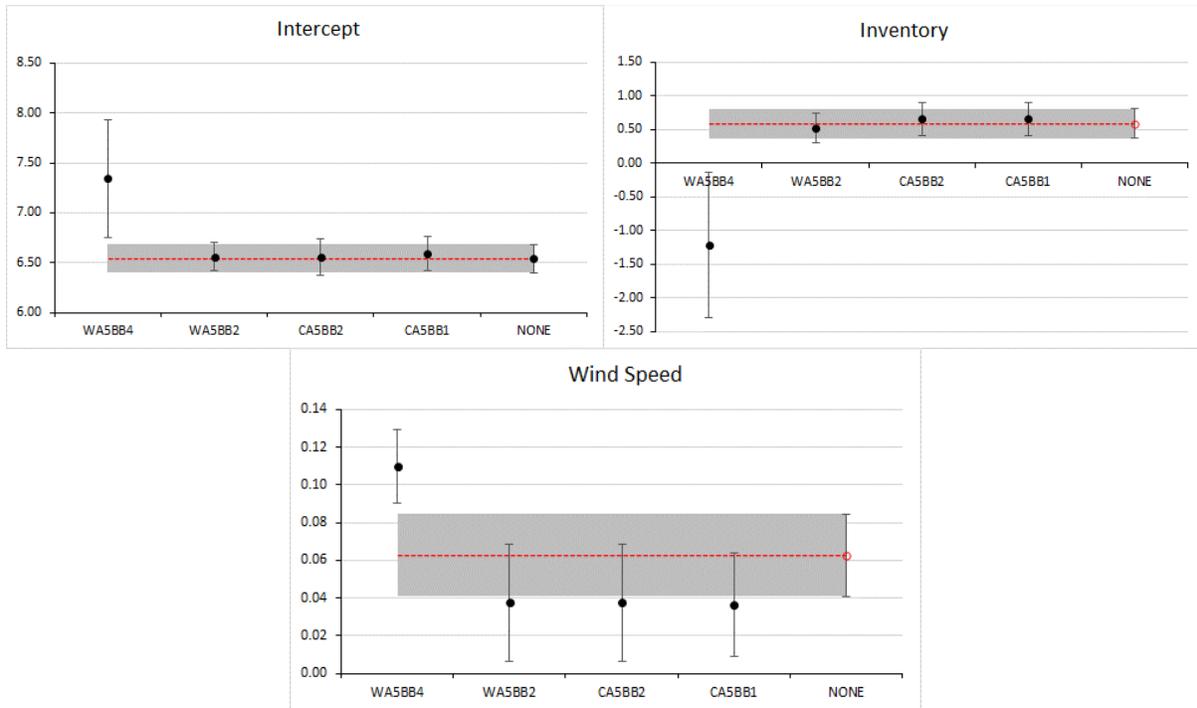
Site Out	Effect	Estimate	Standard Error	p-value
None	Intercept	6.541057	0.14434	<.0001
None	Inventory	0.587702	0.21921	0.008
None	Wind Speed	0.062678	0.02193	0.0044
CA5BB1	Intercept	6.593149	0.17451	<.0001
CA5BB1	Inventory	0.661236	0.24717	0.0083
CA5BB1	Wind Speed	0.036373	0.02762	0.1886
CA5BB2	Intercept	6.557214	0.18007	<.0001
CA5BB2	Inventory	0.6616	0.24813	0.0085
CA5BB2	Wind Speed	0.03755	0.03114	0.2288
WA5BB2	Intercept	6.559682	0.14376	<.0001
WA5BB2	Inventory	0.520217	0.21815	0.0182
WA5BB2	Wind Speed	0.075574	0.02381	0.0016
WA5BB4	Intercept	7.344257	0.58948	<.0001
WA5BB4	Inventory	-1.214405	1.08122	0.2645
WA5BB4	Wind Speed	0.109848	0.01931	<.0001

**Table 6-18. Model fit statistics for the naturally ventilated barns H<sub>2</sub>S jackknife.**

Site Out	n	LNME <sup>a</sup> (%)	NME <sup>b</sup> (%)	ME <sup>b</sup> (g day <sup>-1</sup> )	MB <sup>b</sup> (kg day <sup>-1</sup> )	NMB <sup>b</sup> (%)	Corr.
None	647	6.461	77.092	677.49	-29.02	-3.302	0.33
CA5BB1	449	6.937	80.862	807.4	-34.82	-3.487	0.326
CA5BB2	380	7.784	89.878	915.9	-39.6	-3.886	0.32
WA5BB2	550	5.832	69.934	603.45	-36.4	-4.218	0.371
WA5BB4	562	5.662	69.734	490.88	-1.791	-0.254	0.249

<sup>a</sup> Based on transformed data (i.e., ln(H<sub>2</sub>S)).

<sup>b</sup> Based on back-transformed data.



**Figure 6-9. Comparison of variation in coefficients and standard errors for H<sub>2</sub>S naturally ventilated barn model.**

Variation in coefficients and standard errors (black closed circle and  $\pm$  SE bar) for each jackknife model with the selected H<sub>2</sub>S naturally ventilated barns model coefficient (“None”, gray band for  $\pm$  SE) for each model parameter.

### 6.3.3 PM<sub>10</sub> Model Evaluation

Table 6-19 and Figure 6-10 show the variation in coefficients and standard errors for the selected PM<sub>10</sub> naturally ventilated barn model (“None”) and each of the jackknife models. The model coefficients from the jackknife approach had some differences, most notably the coefficient for inventory switched to negative in the model with WA5B B4 withheld (Table 6-19) and became insignificant. For the models where WA4B4 was withheld, the coefficient for ambient temperature also became insignificant ( $p$ -value  $>0.05$ ). The plots in Figure 6-10 show that the coefficients for the model where WA5B B4 fall outside the full model estimate  $\pm 1$  standard error, except for ambient relative humidity. In comparison to the full model, where the barn removed is “None”, the maximum percentage differences for parameter estimates across the three models were 15%, 138%, 80%, 24%, and 20% for the intercept, inventory, ambient temperature, ambient relative humidity, and wind speed, respectively. Across all models, the difference in NME and NMB (Table 6-20) in comparison to the selected model were the largest when WA5B B4 was withheld from the dataset, which increased the NME by 16% and decreased NMB by 37%.

**Table 6-19. Model coefficients developed using the jackknife approach for PM<sub>10</sub> emissions from naturally ventilated barns.**

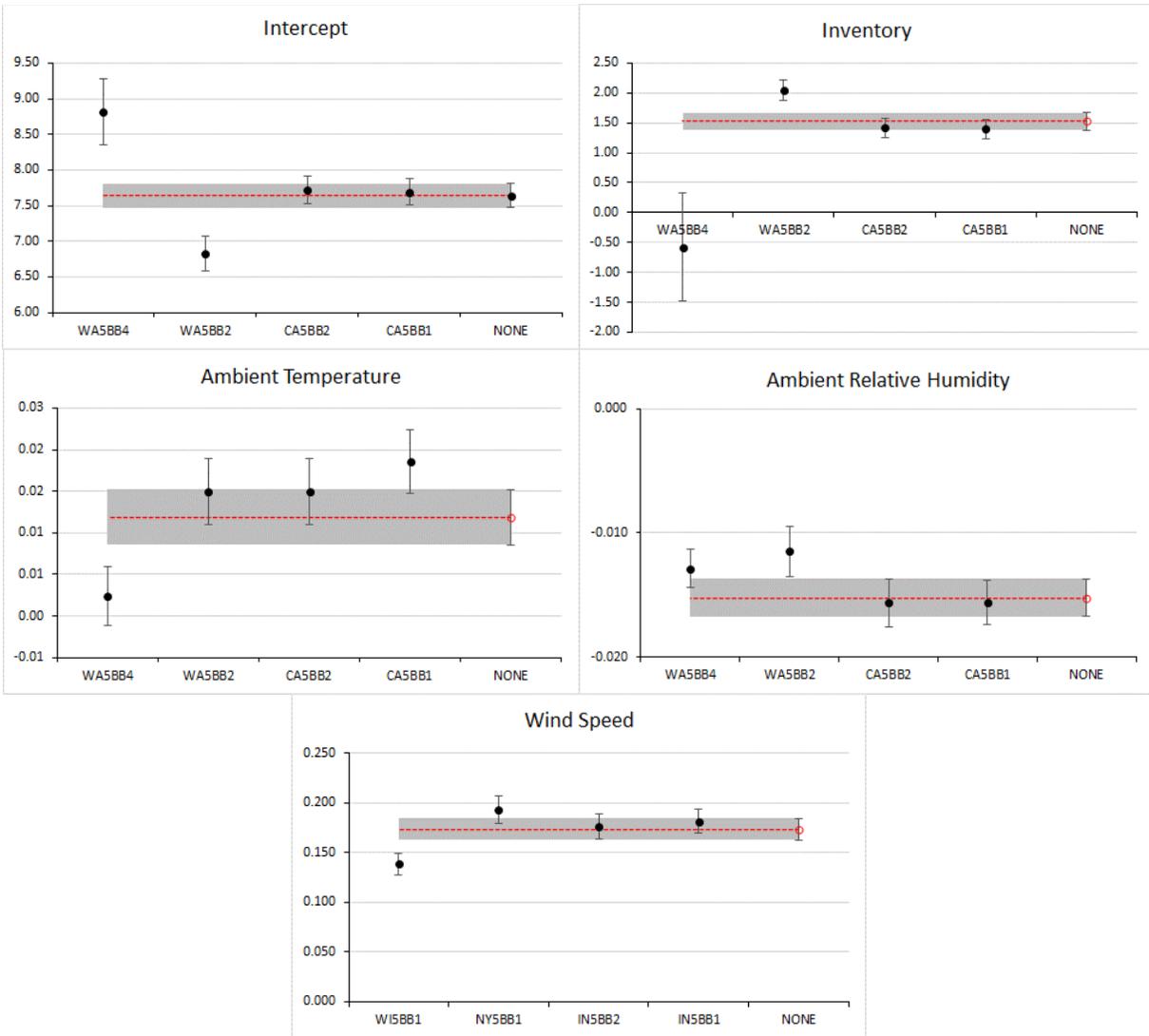
Site Out	Effect	Estimate	Standard Error	p-value
None	Intercept	7.64258	0.16783	<.0001
None	Inventory	1.525009	0.14917	<.0001
None	Ambient Temperature	0.011864	0.00333	0.0004
None	Ambient Relative Humidity	-0.01521	0.00154	<.0001
None	Wind Speed	0.173698	0.01064	<.0001
CA5BB1	Intercept	7.695149	0.18357	<.0001
CA5BB1	Inventory	1.399494	0.16322	<.0001
CA5BB1	Ambient Temperature	0.018588	0.00384	<.0001
CA5BB1	Ambient Relative Humidity	-0.01564	0.00178	<.0001
CA5BB1	Wind Speed	0.181527	0.0118	<.0001
CA5BB2	Intercept	7.726456	0.19289	<.0001
CA5BB2	Inventory	1.420078	0.16427	<.0001
CA5BB2	Ambient Temperature	0.014917	0.00397	0.0002
CA5BB2	Ambient Relative Humidity	-0.015634	0.00196	<.0001
CA5BB2	Wind Speed	0.175816	0.01265	<.0001
WA5BB2	Intercept	6.831711	0.24796	<.0001
WA5BB2	Inventory	2.045075	0.17514	<.0001
WA5BB2	Ambient Temperature	0.020629	0.00419	<.0001
WA5BB2	Ambient Relative Humidity	-0.0115	0.00199	<.0001
WA5BB2	Wind Speed	0.192966	0.01355	<.0001
WA5BB4	Intercept	8.81874	0.46389	<.0001
WA5BB4	Inventory	-0.576586	0.90282	0.5241
WA5BB4	Ambient Temperature	0.002425	0.00354	0.494
WA5BB4	Ambient Relative Humidity	-0.012854	0.00154	<.0001
WA5BB4	Wind Speed	0.138497	0.01071	<.0001

**Table 6-20. Model fit statistics for the naturally ventilated barns PM<sub>10</sub> jackknife.**

Site Out	N	LNME <sup>a</sup> (%)	NME <sup>b</sup> (%)	ME <sup>b</sup> (g day <sup>-1</sup> )	MB <sup>b</sup> (kg day <sup>-1</sup> )	NMB <sup>b</sup> (%)	Corr.
CA5BB1	1,214	5.102	79.404	4,772.9	-701.9	-11.68	0.372
CA5BB2	1,088	5.412	81.443	5,265.9	-688.8	-10.65	0.358
None	1,457	4.896	82.575	4,195.9	-668.8	-13.16	0.374
WA5BB2	1,024	4.537	76.692	3,944.7	-926.4	-18.01	0.462
WA5BB4	1,045	4.156	95.397	2,384	-277.5	-11.1	0.208

<sup>a</sup> Based on transformed data (i.e., ln(PM<sub>10</sub>)).

<sup>b</sup> Based on back-transformed data.



**Figure 6-10. Comparison of variation in coefficients and standard errors for PM<sub>10</sub> naturally ventilated barn model.**

Variation in coefficients and standard errors (black closed circle and  $\pm$  SE bar) for each jackknife model with the selected PM<sub>10</sub> naturally ventilated barns model coefficient (“None”, gray band for  $\pm$  SE) for each model parameter.

#### 6.3.4 PM<sub>2.5</sub> Model Evaluation

The analysis for the PM<sub>2.5</sub> naturally ventilated barns was a departure from the other evaluations, more of the models have coefficients that vary and are insignificant (Table 6-21). When compared to the full model, the coefficients vary up to 125%, 4,370%, 406%, 21,410%, and 25% for the intercept, inventory, ambient temperature, ambient relative humidity, and wind speed, respectively, and the large differences are not limited to the model with WA5B B4 withheld. Table 6-21 and Figure 6-11 show the variation in coefficients and standard errors for the selected PM<sub>2.5</sub> naturally ventilated barn model (“None”) and each of the jackknife models. The plots in Figure 6-11 show that most of the coefficients for the models overlapped the full

model estimate  $\pm 1$  standard error. The models for the WA5B barn both fell outside for the intercept and inventory, and the WA5B B1 model fell outside for ambient relative humidity. The difference in NME and NMB (Table 6-22) across the models with a barn withheld compared to the selected model changed by as much as 40% for NME and 1,566% for NMB.

**Table 6-21. Model coefficients developed using the jackknife approach for PM<sub>2.5</sub> emissions from naturally ventilated barns.**

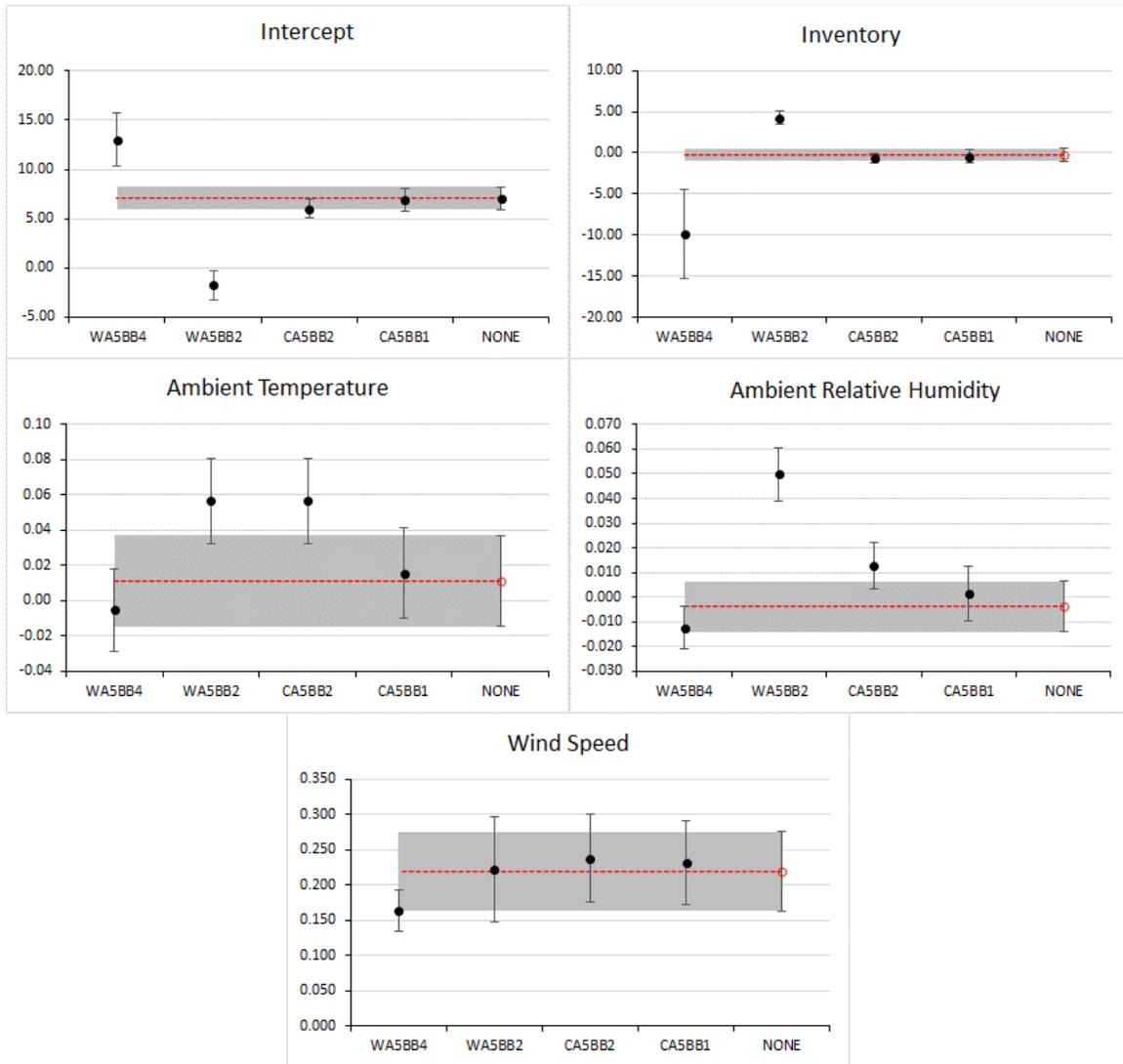
Site Out	Effect	Estimate	Standard Error	p-value
None	Intercept	7.068797	1.15954	<.0001
None	Inventory	-0.220453	0.75959	0.7753
None	Ambient Temperature	0.01121	0.02585	0.6681
None	Ambient Relative Humidity	-0.003808	0.01023	0.7125
None	Wind Speed	0.218968	0.0563	0.0002
CA5BB1	Intercept	6.922323	1.15234	<.0001
CA5BB1	Inventory	-0.432386	0.76218	0.579
CA5BB1	Ambient Temperature	0.015697	0.02584	0.5493
CA5BB1	Ambient Relative Humidity	0.001448	0.01082	0.8946
CA5BB1	Wind Speed	0.232037	0.05911	0.0002
CA5BB2	Intercept	5.999344	0.97451	<.0001
CA5BB2	Inventory	-0.637279	0.60064	0.3062
CA5BB2	Ambient Temperature	0.056741	0.02418	0.0293
CA5BB2	Ambient Relative Humidity	0.012843	0.00944	0.1876
CA5BB2	Wind Speed	0.237943	0.06181	0.0002
WA5BB2	Intercept	-1.742952	1.50484	0.2592
WA5BB2	Inventory	4.220142	0.79698	<.0001
WA5BB2	Ambient Temperature	0.135315	0.02619	<.0001
WA5BB2	Ambient Relative Humidity	0.049877	0.01071	0.0001
WA5BB2	Wind Speed	0.221498	0.0743	0.0044
WA5BB4	Intercept	13.01778	2.71873	0.0035
WA5BB4	Inventory	-9.854431	5.35402	0.1099
WA5BB4	Ambient Temperature	-0.005191	0.0234	0.8255
WA5BB4	Ambient Relative Humidity	-0.012329	0.00844	0.1545
WA5BB4	Wind Speed	0.163688	0.02852	<.0001

**Table 6-22. Model fit statistics for the naturally ventilated barns PM<sub>2.5</sub> jackknife.**

Site Out	n	LNME <sup>a</sup> (%)	NME <sup>b</sup> (%)	ME <sup>b</sup> (g day <sup>-1</sup> )	MB <sup>b</sup> (kg day <sup>-1</sup> )	NMB <sup>b</sup> (%)	Corr.
CA5BB1	89	8.295	59.345	1,154	9.362	0.481	0.651
CA5BB2	78	6.288	37.718	820.71	50.306	2.312	0.821
None	93	8.789	62.65	1,167	-19.48	-1.046	0.665
WA5BB2	56	5.461	48.197	625.08	198.89	15.335	0.901
WA5BB4	56	5.877	54.701	1,018.8	-91.41	-4.908	0.718

<sup>a</sup> Based on transformed data (i.e., ln(NH<sub>3</sub>)).

<sup>b</sup> Based on back-transformed data.



**Figure 6-11. Comparison of variation in coefficients and standard errors for PM<sub>2.5</sub> naturally ventilated barn model.**

Variation in coefficients and standard errors (black closed circle and  $\pm$  SE bar) for each jackknife model with the selected PM<sub>2.5</sub> naturally ventilated barn model coefficient (“None”, gray band for  $\pm$  SE) for each model parameter.

### 6.3.5 TSP Model Evaluation

Table 6-23 and Figure 6-12 show the variation in coefficients and standard errors for the selected TSP naturally ventilated barn model (“None”) and each of the jackknife models. The model coefficients from the jackknife approach were comparable across the withheld sets (Table 6-23) and remained significant (p-value <0.05) across all models, except for ambient temperature in the model where WA5BB4 was removed. The plots in Figure 6-12 show that all the coefficients overlap the full model estimate  $\pm$  1 standard error, except for inventory for the model where WA5BB4 was removed. In comparison to the full model, that is where the barn removed is “None”, the maximum percentage differences for parameter estimates across the three models

were 17%, 141%, 56%, 25%, and 18% for the intercept, inventory, ambient temperature, ambient relative humidity, and wind speed, respectively. Across all models, the difference in NME and NMB (Table 6-24) in comparison to the selected model changed by as much as 16% for NME and 160% for NMB.

**Table 6-23. Model coefficients developed using the jackknife approach for TSP emissions from naturally ventilated barns.**

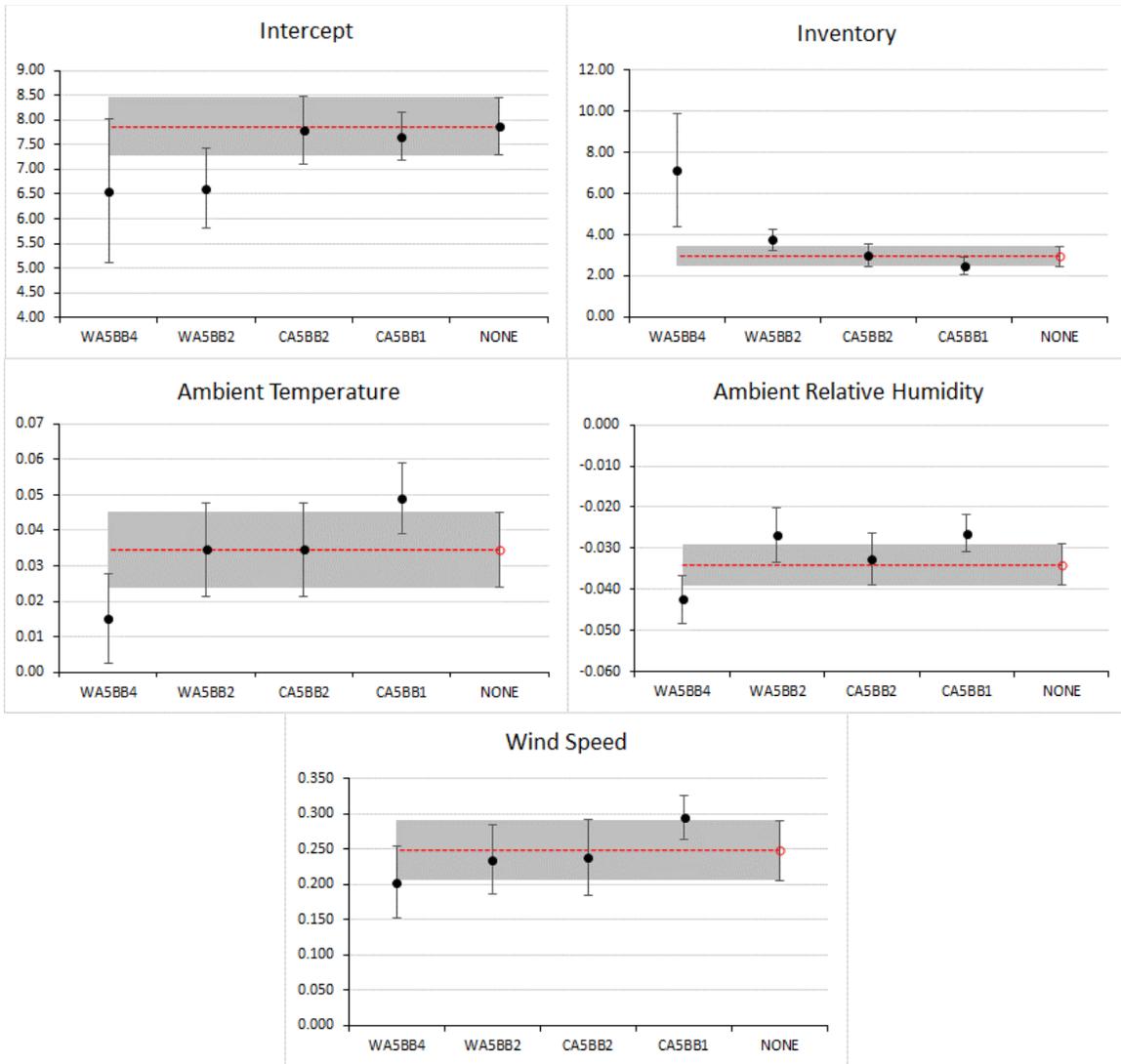
Site Out	Effect	Estimate	Standard Error	p-value
None	Intercept	7.868847	0.58294	<.0001
None	Inventory	2.953893	0.48928	<.0001
None	Ambient Temperature	0.034508	0.01069	0.0021
None	Ambient Relative Humidity	-0.033997	0.00508	<.0001
None	Wind Speed	0.248191	0.04211	<.0001
CA5BB1	Intercept	7.667585	0.48937	<.0001
CA5BB1	Inventory	2.477977	0.44054	<.0001
CA5BB1	Ambient Temperature	0.048926	0.01002	<.0001
CA5BB1	Ambient Relative Humidity	-0.026332	0.00445	<.0001
CA5BB1	Wind Speed	0.294612	0.03075	<.0001
CA5BB2	Intercept	7.786063	0.68673	<.0001
CA5BB2	Inventory	2.998098	0.56151	<.0001
CA5BB2	Ambient Temperature	0.034621	0.01325	0.0127
CA5BB2	Ambient Relative Humidity	-0.032651	0.00638	<.0001
CA5BB2	Wind Speed	0.238451	0.05294	<.0001
WA5BB2	Intercept	6.616785	0.81649	<.0001
WA5BB2	Inventory	3.762081	0.52641	<.0001
WA5BB2	Ambient Temperature	0.048947	0.01322	0.0005
WA5BB2	Ambient Relative Humidity	-0.026808	0.00659	0.0001
WA5BB2	Wind Speed	0.235277	0.04912	<.0001
WA5BB4	Intercept	6.558937	1.4622	<.0001
WA5BB4	Inventory	7.12147	2.73945	0.0131
WA5BB4	Ambient Temperature	0.0151	0.01245	0.2317
WA5BB4	Ambient Relative Humidity	-0.042411	0.0058	<.0001
WA5BB4	Wind Speed	0.203451	0.05134	0.0001

**Table 6-24. Model fit statistics for the naturally ventilated barns TSP jackknife.**

Site Out	n	LNME <sup>a</sup> (%)	NME <sup>b</sup> (%)	ME <sup>b</sup> (g day <sup>-1</sup> )	MB <sup>b</sup> (kg day <sup>-1</sup> )	NMB <sup>b</sup> (%)	Corr.
CA5BB1	135	4.902	44.574	9,954.9	-1381	-6.185	0.875
CA5BB2	146	6.598	55.473	1,0927	-932.6	-4.734	0.799
None	205	6.07	52.783	8,639.5	-492.6	-3.009	0.807
WA5BB2	167	5.659	49.037	7,695.7	-297.8	-1.898	0.821
WA5BB4	167	6.446	57.093	5,315	12.023	0.129	0.666

<sup>a</sup> Based on transformed data (i.e., ln(TSP)).

<sup>b</sup> Based on back-transformed data.



**Figure 6-12. Comparison of variation in coefficients and standard errors for TSP naturally ventilated barn model.**

Variation in coefficients and standard errors (black closed circle and  $\pm$  SE bar) for each jackknife model with the selected TSP naturally ventilated barn model coefficient (“None”, gray band for  $\pm$  SE) for each model parameter.

## 6.4 Open Source Models

For the corral models, we did not complete jackknife analysis because there was only one site in the dataset. We also did not pursue a model evaluation using a k-fold cross validation technique based on previous SAB comments (SAB, 2013) recommending against using this method to select data for temporally correlated data. Future EPA efforts will look into obtaining additional data that would allow for further model testing and evaluation and an improved emissions model.

### 6.4.1 NH<sub>3</sub> Model Evaluation

Table 6-25 and Figure 6-13 show the variation in coefficients and standard errors for the selected NH<sub>3</sub> open source model (“None”) and each of the jackknife models. The model coefficients from the jackknife approach were comparable across the withheld sets (Table 6-25) and remained significant (p-value <0.05) across all models. The plots in Figure 6-13 show that the results for all jackknife models do not overlap the full model estimate ± 1 standard error, except the model where IN5A was withheld for ambient temperature. In comparison to the full model, the maximum percentage differences for parameter estimates across the two models were 13% and 24% for the intercept and ambient temperature, respectively. Across all models, the difference in NME and NMB (Table 6-26) in comparison to the selected model were substantial for NME and NMB, with values differing by up to 38% and 77%, respectively.

**Table 6-25. Model coefficients developed using the jackknife approach for NH<sub>3</sub> emissions from open sources.**

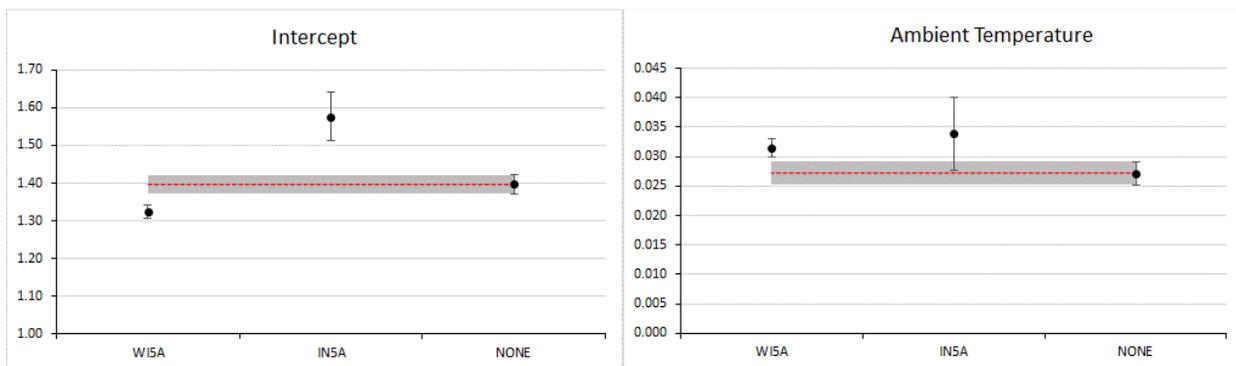
Site Out	Effect	Estimate	Standard Error	p-value
None	Intercept	1.396734	0.0248	<.0001
None	Ambient Temperature	0.027201	0.00195	<.0001
IN5A	Intercept	1.576653	0.06521	<.0001
IN5A	Ambient Temperature	0.033848	0.00616	<.0001
W15A	Intercept	1.323888	0.01843	<.0001
W15A	Ambient Temperature	0.031531	0.00152	<.0001

**Table 6-26. Model fit statistics for the open sources NH<sub>3</sub> jackknife.**

Site Out	n	LNME <sup>a</sup> (%)	NME <sup>b</sup> (%)	ME <sup>b</sup> (g day <sup>-1</sup> )	MB <sup>b</sup> (kg day <sup>-1</sup> )	NMB <sup>b</sup> (%)	Corr.
IN5A	28	12.225	53.586	0.865	-0.048	-2.958	0.84
NONE	157	9.709	38.766	0.712	-0.034	-1.859	0.821
W15A	129	8.159	31.915	0.601	-0.008	-0.433	0.887

<sup>a</sup> Based on transformed data (i.e., ln(NH<sub>3</sub>)).

<sup>b</sup> Based on back-transformed data.



**Figure 6-13. Comparison of variation in coefficients and standard errors for NH<sub>3</sub> open source model.**

Variation in coefficients and standard errors (black closed circle and  $\pm$  SE bar) for each jackknife model with the selected NH<sub>3</sub> open source model coefficient (“None”, gray band for  $\pm$  SE) for each model parameter.

#### 6.4.2 H<sub>2</sub>S Model Evaluation

Table 6-27 and Figure 6-14 show the variation in coefficients and standard errors for the selected H<sub>2</sub>S open source model (“None”) and each of the jackknife models. The model coefficients from the jackknife approach were comparable across the withheld sets (Table 6-27) and remained significant (p-value <0.05) across all models. The plots in Figure 6-14 show that the results for all jackknife models do not overlap the full model estimate  $\pm$  1 standard error, except the model where IN5A was withheld. In comparison to the full model, the maximum percentage differences for parameter estimates across the two models were 7% and 68% for the intercept and ambient temperature, respectively. Across all models, the difference in NME and NMB (Table 6-28) in comparison to the selected model were substantial for NME and NMB, with values differing by up to 20% and 98%, respectively.

**Table 6-27. Model coefficients developed using the jackknife approach for H<sub>2</sub>S emissions from open sources.**

Site Out	Effect	Estimate	Standard Error	p-value
None	Intercept	1.189272	0.03163	<.0001
None	Ambient Temperature	0.010557	0.0022	<.0001
IN5A	Intercept	1.109037	0.01639	<.0001
IN5A	Ambient Temperature	0.003382	0.00127	0.0203
WA5A	Intercept	1.189558	0.03019	<.0001
WA5A	Ambient Temperature	0.011581	0.00218	<.0001
W15A	Intercept	1.226774	0.04029	<.0001
W15A	Ambient Temperature	0.009725	0.00256	0.0005

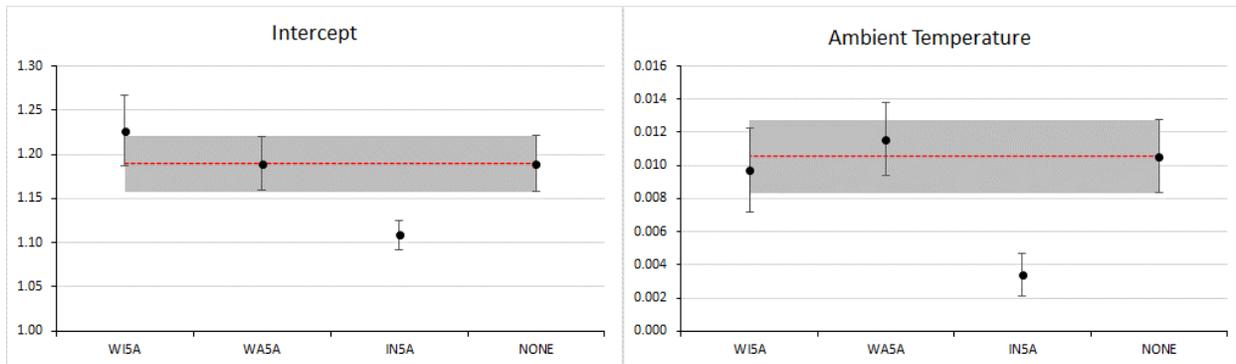
**Table 6-28. Model fit statistics for the open source H<sub>2</sub>S jackknife.**

Site Out	n	LNME <sup>a</sup> (%)	NME <sup>b</sup> (%)	ME <sup>b</sup> (g day <sup>-1</sup> )	MB <sup>b</sup> (kg day <sup>-1</sup> )	NMB <sup>b</sup> (%)	Corr.
None	70	9.258	63.688	0.499	-0.011	-1.403	0.587
IN5A	13	1.475	76.161	0.052	0	-0.032	0.782

Site Out	n	LNME <sup>a</sup> (%)	NME <sup>b</sup> (%)	ME <sup>b</sup> (g day <sup>-1</sup> )	MB <sup>b</sup> (kg day <sup>-1</sup> )	NMB <sup>b</sup> (%)	Corr.
WA5A	69	8.922	61.188	0.484	-0.01	-1.321	0.615
W15A	58	9.575	58.078	0.542	-0.009	-0.914	0.525

<sup>a</sup>Based on transformed data (i.e.,  $\ln(\text{H}_2\text{S})$ ).

<sup>b</sup>Based on back-transformed data.



**Figure 6-14. Comparison of variation in coefficients and standard errors for  $\text{H}_2\text{S}$  open source model.**

Variation in coefficients and standard errors (black closed circle and  $\pm$  SE bar) for each jackknife model with the selected  $\text{H}_2\text{S}$  open source model coefficient (“None”, gray band for  $\pm$  SE) for each model parameter.

## 7 ANNUAL EMISSIONS ESTIMATES AND MODEL UNCERTAINTY

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

As noted in Section 6 of the Overview report, the model results are transformed values of the emissions. To convert to the native emissions units (e.g., kg or g), the back transformation equation (Equation from Section 6 of the Overview report) is applied using the values of  $\bar{E}_i$  and C provided in Table 7-1 for each emissions model. Section 8 contains examples of this calculation.

**Table 7-1. Back transformation parameters.**

Animal Type	Pollutant	$\bar{E}_i$	C	Resulting Units
Mechanically Ventilated barn	NH <sub>3</sub>	1.03966	3	kg/d
Mechanically Ventilated barn	H <sub>2</sub> S	1.11434	628	g/d
Mechanically Ventilated barn	PM <sub>10</sub>	a	a	a
Mechanically Ventilated barn	PM <sub>2.5</sub>	a	a	a
Mechanically Ventilated barn	TSP	a	a	a
Milking Center	NH <sub>3</sub>	1.21693	3	g/d-hd
Milking Center	H <sub>2</sub> S	1.30119	628	mg/d-hd
Milking Center	PM <sub>10</sub>	1.0057	2200	mg/d-hd
Milking Center	PM <sub>2.5</sub>	1.00796	680	mg/d-hd
Milking Center	TSP	1.0311	978	mg/d-hd
Naturally Ventilated barn	NH <sub>3</sub>	1.46499	3	kg/d
Naturally Ventilated barn	H <sub>2</sub> S	1.23366	628	g/d
Naturally Ventilated barn	PM <sub>10</sub>	1.27211	2200	g/d
Naturally Ventilated barn	PM <sub>2.5</sub>	1.33005	680	g/d
Naturally Ventilated barn	TSP	1.25126	978	g/d
Lagoon/basin	NH <sub>3</sub>	1.0079	3	g/d-m <sup>2</sup>
Lagoon/basin	H <sub>2</sub> S	1.03006	3	g/d-m <sup>2</sup>
Corral	NH <sub>3</sub>	1.0066	3	mg/d-m <sup>2</sup> -hd
Corral	H <sub>2</sub> S	1.00007	3	µg/d-m <sup>2</sup> -hd

<sup>a</sup> Annual models were not calculated to allow time to optimize the daily models.

EPA also developed an estimate of uncertainty for total annual emissions, characterized by the random error in the model prediction, based on parametric principles, using the Gaussian

error of propagation. Under this approach, the annual standard deviation ( $S_{an}$ ) for n days can be determined using the following equation:

$$S_{an} = \sqrt{(S_{r1})^2 + (S_{r2})^2 + \dots + (S_{rn})^2} \quad \text{Equation 19}$$

where  $S_r$  is the standard deviation of the daily residual values (i.e., the difference between model-predicted and observed or measured emissions). If  $S_r$  is the same value for each day (i.e.,  $S_{r1} = S_{r2} = \dots = S_{rn}$ ), Equation 19 simplifies to:

$$S_{an} = S_r n^{0.5} \quad \text{Equation 20}$$

Table 7-2 lists the  $S_r$  values for swine barns and open sources by pollutant. EPA considered a 95-percent residual distribution (i.e., the range was the difference between the 97.5 and 2.5 percentiles) or equivalently 1.96 standard deviations; therefore, the annual uncertainty ( $U_{an}$ ) can be approximated as:

$$U_{an} \approx 1.96 S_{an} \quad \text{Equation 21}$$

Combining Equations 20 and 21 with an n value of 365 (representing the number of days in the annual uncertainty calculation) yields:

$$U_{an} \approx 1.96 S_{an} \approx 1.96 S_r n^{0.5} \approx 1.96 S_r (365)^{0.5} \approx 37.45 S_r \quad \text{Equation 22}$$

**Table 7-2. Daily residual standard deviation values for dairy barns, milking centers, and open sources.**

Process	Pollutant	$S_r$	Emissions Units
Mechanically ventilated barn - Flush	NH <sub>3</sub>	9.393	kg/d
Mechanically ventilated barn - Scrape	NH <sub>3</sub>	9.393	kg/d
Mechanically ventilated barn - Flush	H <sub>2</sub> S	921.07	g/d
Mechanically ventilated barn - Scrape	H <sub>2</sub> S	921.07	g/d
Mechanically ventilated barn	PM <sub>10</sub>	473.12	g/d
Mechanically ventilated barn	PM <sub>2.5</sub>	866.66	g/d
Mechanically ventilated barn	TSP	5,798.5	g/d
Milking Center	NH <sub>3</sub>	14.823	g/d-hd
Milking Center	H <sub>2</sub> S	2,507.8	mg/d-hd
Milking Center	PM <sub>10</sub>	289.09	mg/d-hd
Milking Center	PM <sub>2.5</sub>	132.7	mg/d-hd
Milking Center	TSP	416.02	mg/d-hd
Naturally ventilated barn	NH <sub>3</sub>	19.759	kg/d
Naturally ventilated barn	H <sub>2</sub> S	1,331.3	g/d
Naturally ventilated barn	PM <sub>10</sub>	15,938	g/d
Naturally ventilated barn	PM <sub>2.5</sub>	1,382.2	g/d
Naturally ventilated barn	TSP	22,252	g/d

Process	Pollutant	S <sub>r</sub>	Emissions Units
Lagoon/basin	NH <sub>3</sub>	0.001	g/d-m <sup>2</sup>
Lagoon/basin	H <sub>2</sub> S	0.700	g/d-m <sup>2</sup>
Corral	NH <sub>3</sub>	1.276	mg/d-m <sup>2</sup> -hd
Corral	H <sub>2</sub> S	18.451	µg/d-m <sup>2</sup> -hd

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

$$\text{Total farm uncertainty} = \sqrt{(U_{B1})^2 + \dots + (U_{Bi})^2 + (U_{L1})^2 + \dots + (U_{Lj})^2} \quad \text{Equation 22}$$

Where:

*Total farm uncertainty* = total uncertainty for the total emissions from all farm sources.

*UBi* = the resulting uncertainty for barns, with i representing the total number of barns on the farm,

*ULj* = the resulting uncertainty for manure sheds, with j representing the total number of open sources on the farm.

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

## 8 MODEL APPLICATION AND ADDITIONAL TESTING

Key to the development of any model is the demonstration of the use and practical examples of how the model behaves and replicates independent data. This section provides a series of example calculations to demonstrate the application of the models (Section 8.1), the sensitivity of the models to their inputs (Section 8.2), a comparison of the models developed to literature (Section 8.3), and a test of model performance against an independent data set (Section 8.4). Finally, this section wraps up with a discussion of data limitations that could be driving sensitivity or performance issues.

### 8.1 Model Application Example

The following sections demonstrate how the daily emissions models from Section 5 and the annual uncertainty from Section 7 are used to calculate emissions for an example farm for each structure type. Details about the use of the emissions models to demonstrate compliance with Clean Air Act permitting thresholds will be addressed in a forthcoming implementation document. These example calculations demonstrate how to use the system of equations to estimate emissions.

In Section 6.4 of the Overview report, the data were log-transformed prior to developing the models, the results of the models will need to be back-transformed per Equation 7 to represent emissions in units of grams or kilograms.

$$Y_{bp} = e^{(\overline{y_p})} * \overline{E}_i - C$$

Where:

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

To complete the back transformation, users need two parameters that are specific to each model: 1)  $\overline{E}_i$ , the residual between model-predicted and observed (or measured) emissions on the natural log scale; and 2)  $C$ , which is a constant added to the data prior to the log transformation. The values for  $\overline{E}_i$  and  $C$  for the dairy models are provided in Table 7-1.

For transparency and to help stakeholders better understand the process of calculating emissions, this section will walk through example calculations to estimate NH<sub>3</sub> emissions from a mechanically ventilated barn, milking center, naturally ventilated barn, and lagoon.

The examples in this section use a fictional farm located in Brown County, Wisconsin on January 1, 2021. Wisconsin was chosen as it is a top five milk producing state according to the USDA Economic Research Service data (<https://www.ers.usda.gov/webdocs/DataFiles/48685/milkcowsandprod.xlsx?v=9708>). The ambient weather data used in each equation can be obtained for free from several sources including the National Centers for Environmental Information (NCEI; <https://www.ncdc.noaa.gov/cdo-web/>). NCEI stores hourly and daily ambient data from various monitors located across the country that can be used for emissions estimation. The Green Bay International Airport, WI site (WBAN: 14898), a Local Climatological Data (LCD) Station located in Brown County was selected as to represent the meteorological information for a theoretical farm for testing. Its data file provides the daily average values of the key meteorological parameters needed for calculations.

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

$$\frac{V}{V_r} = \left(\frac{Z}{Z_r}\right)^m \quad \text{Equation 24}$$

Where  $V_r$  is the wind velocity at a height of 10 m ( $Z_r$ ) and  $V$  is the wind velocity height at 2.5 m ( $Z$ ), and  $m$  is the friction coefficient, which is a function of atmospheric stability and the underlying surface roughness. The value of  $m$  can vary, ranging from 0 to 1, with lower values over low roughness surfaces (water) and higher values for rougher terrain such as rolling terrain or urban settings (Arya, 1999). To adjust the 10 m NWS wind measurement to a height comparable to the study data used to develop the model, the equation can be rewritten, resulting in the following equation:

$$V_{2.5m} = \left(\frac{2.5}{10}\right)^m \times V_{10m} \quad \text{Equation 23}$$

In addition to weather information, the models also use the number of cows present in the barn. For this example farm, we assume the barn has a capacity of 500 cows. The equations use

thousands of cows, so this value will be divided by 1,000 for use in the emissions models. A summary of the input values for the example calculations is provided in Table 8-1.

**Table 8-1. Daily calculation parameter values.**

Parameter	Value
Daily Average Ambient Temperature (°C) <sup>a</sup>	-9.4
Daily Average Relative Humidity (%) <sup>a</sup>	86
Daily Average Wind Speed (ms <sup>-1</sup> ) <sup>a</sup>	2.55
Inventory (head)	500
Friction coefficient for naturally ventilated barn and corral <sup>b</sup>	0.25
Friction coefficient for lagoon <sup>c</sup>	0.125

<sup>a</sup> Daily average values from the NWS.

<sup>b</sup> Value for wooded countryside from Masters (2013).

<sup>c</sup> Average of the values for calm water and tall grass on level ground from Masters (2013).

### 8.1.1 Mechanically Ventilated Barn Example

For this example, we will assume the barn uses a scrape manure management system, which would use Equation 1 in Section 5.1 to calculate the log transformed values as follows:

$$\ln(NH_3) = 1.86494 + 1.773832 * Inventory + 0.029586 * Amb_T$$

$$\ln(NH_3) = 1.86494 + 0.1.773832 * \left(\frac{500}{1,000}\right) + 0.029586 * -9.4$$

$$\ln(NH_3) = 1.86494 + 0.8869 - 0.2781$$

$$\ln(NH_3) = 2.4737$$

To back transform the results to NH<sub>3</sub> in kg, use Equation 7 from the Overview report. For a flush managed mechanically ventilated barn,  $\bar{E}_l$  is 1.03966 and C is 3.

$$NH_3 = e^{2.4731} \times 1.03966 - 3$$

This comes to 9.34 kg NH<sub>3</sub> for the day. This process is repeated for each day, then the daily emissions are added together to get an annual estimate of emissions. After considering the values for each day in 2021, the total annual emissions for the barn was calculated at 7,108 kg. To calculate the uncertainty associated with this estimate, use Equation 22 with the Sr value from Table 7-2. This results in an annual uncertainty of ± 351.77 kg. Thus, the final annual estimate for this barn is 7,108 kg ± 351.77 kg. This calculation would be repeated for any other mechanically ventilated barn on the site.

### 8.1.2 Milking Center Example

For this example, we will use Equation 5 in Section 5.2 to calculate the log transformed values as follows:

$$\ln(NH_3) = 2.505637 + 0.046434 * Amb_T$$

$$\ln(NH_3) = 2.505637 + 0.04643 * -9.4$$

$$\ln(NH_3) = 2.505637 - 0.4368$$

$$\ln(NH_3) = 2.0692$$

To back transform the results to NH<sub>3</sub> in kg, use Equation 7 from the Overview report. For a milking center,  $\bar{E}_l$  is 1.03966 and C is 3.

$$NH_3\left(\frac{g}{d \cdot head}\right) = e^{2.0692} \times 1.2169 - 3$$

$$NH_3\left(\frac{g}{d \cdot head}\right) = 6.64$$

This comes to 6.64 g NH<sub>3</sub>/d-head, which we can multiply by the 500 head to get 3.32 kg NH<sub>3</sub> for the day. This process is repeated for each day, then the daily emissions are added together to get an annual estimate of emissions. After considering the values for each day in 2021, the total annual emissions for the milking center were calculated at 8,323 g/head (4,161.53 kg). To calculate the uncertainty associated with this estimate, use Equation 22 with the Sr value from Table 7-2 and the annual emissions in the units provided by the model. This results in an annual uncertainty of ± 555.12 g/hd. Thus, the final annual estimate for this milking center is 4,161.53 kg ± 555.12 kg.

### 8.1.3 Naturally Ventilated Barn Example

For this example, we will use Equation 10 in Section 5.3 and the wind speed correction equation presented in Section 8.1 to calculate the log transformed values as follows:

$$\ln(NH_3) = 0.188357 + 3.451939 * Inventory + 0.048153 * 0.707107 * WindSpeed$$

$$\ln(NH_3) = 0.188357 + 3.451939 * \left(\frac{500}{1,000}\right) + 0.034049 * 2.55$$

$$\ln(NH_3) = 0.188357 + 1.7260 + 0.08683 \ln(NH_3) = 2.001$$

To back transform the results to NH<sub>3</sub> in kg, use Equation 7 from the Overview report. For a naturally ventilated barn,  $\bar{E}_l$  is 1.46499 and C is 3.

$$NH_3 = e^{2.001} \times 1.46499 - 3$$

This comes to 7.84 kg NH<sub>3</sub> for the day. This process is repeated for each day, then the daily emissions are added together to get an annual estimate of emissions. After considering the values for each day in 2021, the total annual emissions for the barn were calculated at 2,859 kg. To calculate the uncertainty associated with this estimate, use Equation 22 with the Sr value from Table 7-2. This results in an annual uncertainty of ± 739.97 kg. Thus, the final annual estimate for this barn is 2,859 kg ± 739.97 kg. This calculation would be repeated for any other naturally ventilated barn on the site.

#### 8.1.4 Lagoon Example

For this example, we will use Equation 15 in Section 5.4 to calculate the log transformed values as follows:

$$\ln(NH_3) = 1.396734 + 0.027201 * Amb_T$$

$$\ln(NH_3) = 1.396734 + 0.027201 * -9.4$$

$$\ln(NH_3) = 1.396734 - 0.2557$$

$$\ln(NH_3) = 1.1410$$

To back transform the results to NH<sub>3</sub> in kg, use Equation 7 from the Overview report. For a lagoon,  $\bar{E}_l$  is 1.0079 and C is 3.

$$NH_3 = e^{1.1410} \times 1.0079 - 3$$

This comes to 0.1548 g NH<sub>3</sub>/d-m<sup>2</sup>. This is multiplied by the surface area of the lagoon to estimate emissions for the whole lagoon. For this example, we will assume the lagoon is 10,000 m<sup>2</sup>, which would result in emissions of 1,548 g NH<sub>3</sub> for the day.

This process is repeated for each day, then the daily emissions are added together to get an annual estimate of emissions. After considering the values for each day in 2021, the total annual emissions for the lagoon were calculated at 1,310.47 g NH<sub>3</sub>/m<sup>2</sup> (13,104.75 kg). To calculate the uncertainty associated with this estimate, use Equation 22 with the Sr value from Table 7-2. This results in an annual uncertainty of ± 0.04 g/m<sup>2</sup>. Thus, the final annual estimate for this lagoon is 1,310.47 g NH<sub>3</sub>/m<sup>2</sup> ± 0.04 g/m<sup>2</sup>. This calculation would be repeated for any other lagoon on the site.

#### 8.1.5 Corral Example

For this example, we will use Equation 17 in Section 5.5 to calculate the log transformed values as follows:

$$\ln(NH_3) = 1.053805 + 0.004993 * Amb_T + 0.0031 * Amb_{RH} + 0.017832 * 0.707107 * WindSpeed$$

$$n(NH_3) = 1.053805 + 0.004993 * -9.4 + 0.0031 * 86 + 0.012609 * 2.55$$

$$\ln(NH_3) = 1.053805 - 0.0469 + 0.266 + 0.03215$$

$$\ln(NH_3) = 1.3056$$

To back transform the results to NH<sub>3</sub> in mg, use Equation 7 from the Overview report. For a corral,  $\bar{E}_t$  is 1.0066 and C is 3.

$$NH_3 = e^{1.3056} \times 1.0066 - 3$$

This comes to 0.7143 mg NH<sub>3</sub>/d-m<sup>2</sup>-head. This is multiplied by the surface area of the corral and inventory to estimate emissions for the whole corral. For this example, we will assume the surface area of the corral is 100,000 m<sup>2</sup> and the farm population is 3,400 head, which would result in emissions of 243 kg NH<sub>3</sub> for the day.

This process is repeated for each day, then the daily emissions are added together to get an annual estimate of emissions. After considering the values for each day in 2021, the total annual emissions for the corral were calculated to be 383.46 mg NH<sub>3</sub>/m<sup>2</sup>-head (130,376 kg). To calculate the uncertainty associated with this estimate, use Equation 22 with the Sr value from Table 7-2 and the annual emissions in the units provided by the model. This results in an annual uncertainty of ± 47.79 mg. Thus, the final annual estimate for this corral is 130,376 kg ± 47.79 kg.

### 8.1.6 Combining Structures

To calculate total farm emissions, the emissions from each unit are added. As an example, consider a farm with a 500 head mechanically ventilated barn, 500 head naturally ventilated barn, milking center with a 500 head capacity at any given time, and 10,000 m<sup>2</sup> lagoon. That is, the same emissions as the examples in sections 8.1.1 through 8.1.4. The annual farm emissions estimate from four sources is:

$$\text{Farm Total Emissions} = 7,108 + 2,859 + 4,161.53 + 13,104.75 + 130,376$$

$$\text{Farm Total Emissions} = 157,609.7 \text{ kg } NH_3$$

To estimate the total farm uncertainty, use Equation 23:

$$\text{Total Farm Uncertainty} = \sqrt{U_{barn1}^2 + U_{barn2}^2 + U_{milking\ center}^2 + U_{lagoon}^2 + U_{corral}^2}$$

$$\text{Total Farm Uncertainty} = \sqrt{(351.77)^2 + (739.97)^2 + (555.12)^2 + (0.04)^2 + (47.79)^2}$$

$$\text{Total Farm Uncertainty} = 990.83 \text{ kg}$$

The final annual NH<sub>3</sub> estimate for the farm is 157,609.7 ± 990.83 kg.

## 8.2 Model Sensitivity Testing

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

### 8.2.1 Sensitivity to Inventory

To test the sensitivity of the confinement sources to inventory, the initial placement was doubled to 1,000 cows. Using the same meteorology from Section 8.1, the emissions for the dairy barns on January 1, 2020, is summarized in Table 8-2. For mechanically ventilated barns and milking centers, doubling the inventory at least doubled the NH<sub>3</sub> emissions for the same meteorological conditions. For naturally ventilated barns, doubling the inventory resulted in a sevenfold increase in NH<sub>3</sub> emissions. The large increase in the naturally ventilated barn emissions is further discussed in Section 8.2.3.3. These same ratios are seen when considering a year's worth of meteorology (Table 8-3).

**Table 8-2. Comparison of confinement source NH<sub>3</sub> emissions (kg) on January 1, 2021, for different inventory levels at a theoretical Brown County farm.**

Source Type	500 head	1,000 head
Mechanically Ventilated	9.34	26.91
Milking center	3.32	6.62
Naturally ventilated	8.23	62.49

**Table 8-3. Comparison of confinement source total 2021 NH<sub>3</sub> emissions (kg) for different inventory levels at a theoretical Brown County farm.**

Source Type	500 head	1,000 head
Mechanically Ventilated	7,108	18,820
Milking center	4,162	8,323
Naturally ventilated	3,463	24,511

For lagoons, doubling the surface area of the lagoon doubles both the daily and annual NH<sub>3</sub> emissions (Table 8-4). For corrals, doubling the inventory present doubles both the daily and annual NH<sub>3</sub> emissions (Table 8-5). The observed relationships suggest the models are sensitive to the size parameters, while scaling appropriately.

**Table 8-4. Comparison of lagoon NH<sub>3</sub> emissions for different surface areas for theoretical Brown County farm.**

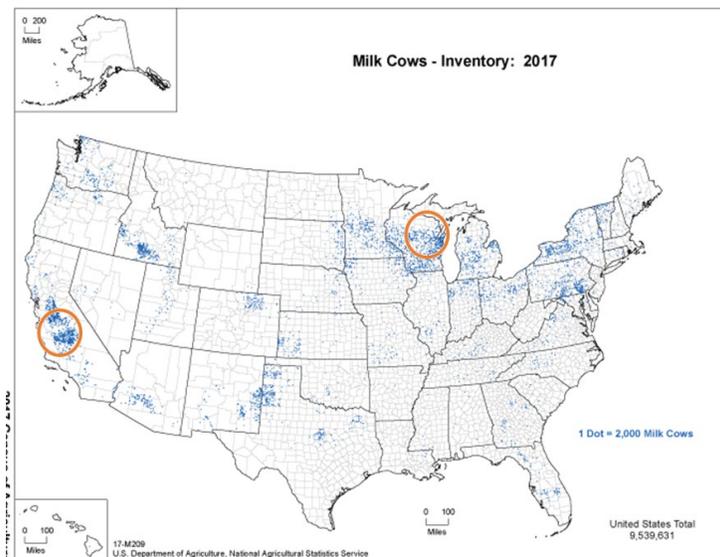
NH <sub>3</sub> Emissions (kg)	10,000 m <sup>2</sup> Surface Area	20,000 m <sup>2</sup> Surface Area
Daily (1/1/2021)	1.51	3.02
Annual (2021)	8,961	17,922

**Table 8-5. Comparison of estimated corral NH<sub>3</sub> emissions for different inventory levels for theoretical Brown County farm.**

NH <sub>3</sub> Emissions (kg)	3,400 Head	6,800 Head
Daily (1/1/2021)	259.48	518.96
Annual (2021)	124,562	249,125

### 8.2.2 Sensitivity to Climate

To further test model sensitivity, specifically that climate differences were producing different emissions results, EPA calculated the emissions for the same farm in two distinctly different climate regions. The first was the theoretical farm in Brown County, Wisconsin from the previous examples (Section 8.1). The NH<sub>3</sub> emissions for these same theoretical barns were calculated using meteorological data from Livermore Municipal Airport in Alameda County, California. These locations were chosen based on 2017 Census of agriculture data indicating areas of high dairy inventory (Figure 8-1). USDA Economic Research Service data (available at: <https://www.ers.usda.gov/webdocs/DataFiles/48685/milkcow sandprod.xlsx?v=9708>) also notes California and Wisconsin are the top two dairy producing states in the country, further affirming the reasonableness of the testing locations.



**Figure 8-1. 2017 Census of Agriculture plot indicating dairy inventory.**

Orange circles indicate approximate locations of test meteorology from Wisconsin (WI) and California (CA). Source: [https://www.nass.usda.gov/Publications/AgCensus/2017/Online\\_Resources/Ag\\_Atlas\\_Maps/17-M209g.php](https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/Ag_Atlas_Maps/17-M209g.php)

For the test sites, the temperatures from the Wisconsin (WI) site were generally less than the California (CA) site (Figure 8-2). On average, the temperatures in Wisconsin were 7 °C less than those in California (Table 8-6), with difference between individual monthly averages varying from 1.6 to 20.8°C lower, except for July when Wisconsin edged 0.6 °C higher. With respect to relative humidity, the California and Wisconsin sites experienced a similar range of daily average relative humidities throughout the year (Figure 8-3 and Table 8-7). Wisconsin edged a little higher July through October, leading to an overall average of 1.6% higher. Average daily wind speeds (Figure 8-4 and Table 8-7) were generally lower in California, with monthly average barely higher June through August. The following sections provide a summary of the calculations using the California meteorological data compared to the previous examples.

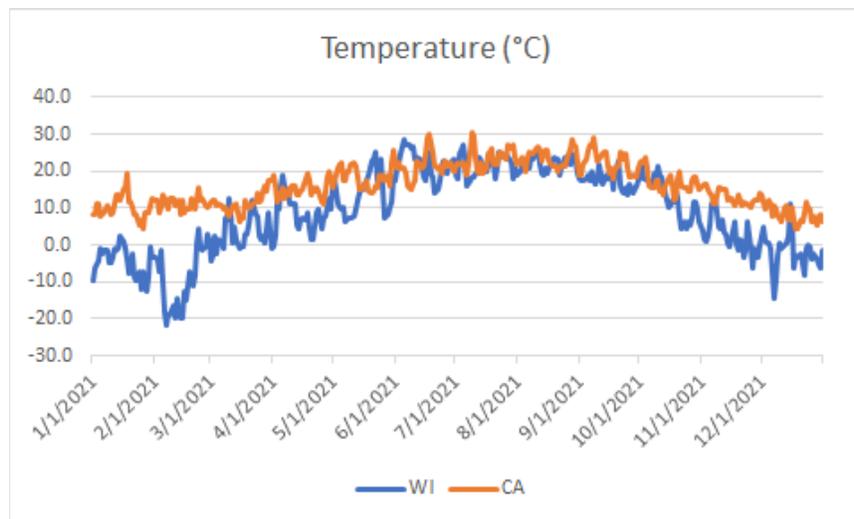


Figure 8-2. Comparison on average daily temperatures at test locations in Wisconsin (WI) and California (CA).

Table 8-6. Summary of average daily temperature at the two meteorological sites.

Site	Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Overall
WI	Min	-12.8	-21.7	-2.8	1.7	6.1	13.9	16.1	17.8	13.3	3.9	-6.1	-14.4	-21.7
WI	Max	2.2	4.4	12.8	18.9	25.0	28.3	27.2	25.0	22.8	21.7	12.8	11.1	28.3
WI	Average	-4.8	-9.5	3.4	9.1	14.0	21.9	21.5	21.9	17.3	12.6	2.2	-2.0	9.0
CA	Min	4.4	8.3	6.1	11.1	13.9	15.0	18.9	18.9	17.8	12.2	10.0	0.0	0.0
CA	Max	19.4	15.6	18.9	20.0	25.6	30.0	30.6	28.3	28.9	23.9	16.7	12.2	30.6
CA	Average	10.3	11.3	11.5	15.1	18.4	21.3	23.5	23.4	22.4	16.9	13.0	8.0	16.3

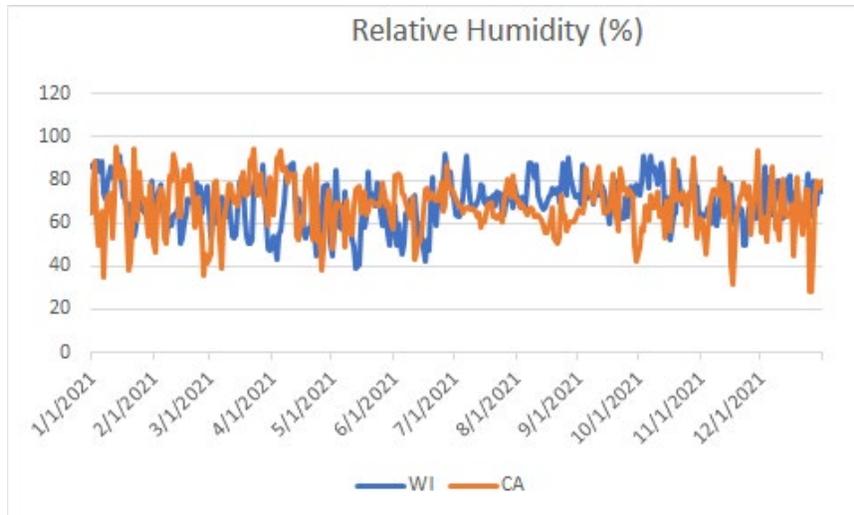


Figure 8-3. Comparison of average daily relative humidities at test locations in Wisconsin (WI) and California (CA).

Table 8-7. Summary of average daily relative humidity at the two meteorological sites.

Site	Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Overall
WI	Min	54.0	51.0	47.0	43.0	39.0	42.0	63.0	66.0	60.0	52.0	50.0	0.0	0.0
WI	Max	91.0	79.0	87.0	88.0	85.0	92.0	91.0	90.0	87.0	91.0	81.0	86.0	92.0
WI	Average	75.9	66.4	64.2	63.7	63.1	64.9	72.1	76.1	72.3	75.8	66.5	69.4	69.2
CA	Min	35.0	35.9	39.4	38.6	49.2	42.7	58.1	51.0	42.3	53.0	31.8	28.0	28.0
CA	Max	95.3	92.0	94.4	93.5	82.0	86.7	82.1	73.0	86.4	90.7	93.9	86.3	95.3
CA	Average	68.3	66.2	73.0	70.3	67.5	69.9	67.3	62.3	70.3	67.6	67.5	64.6	67.8

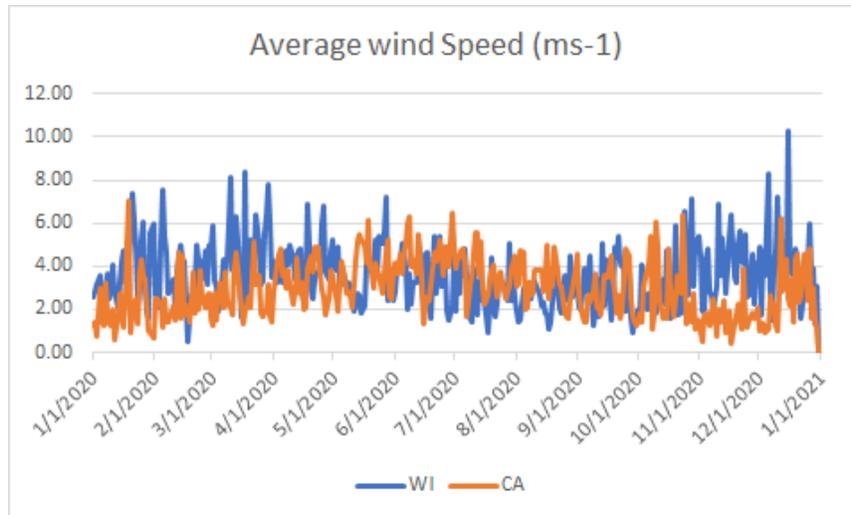


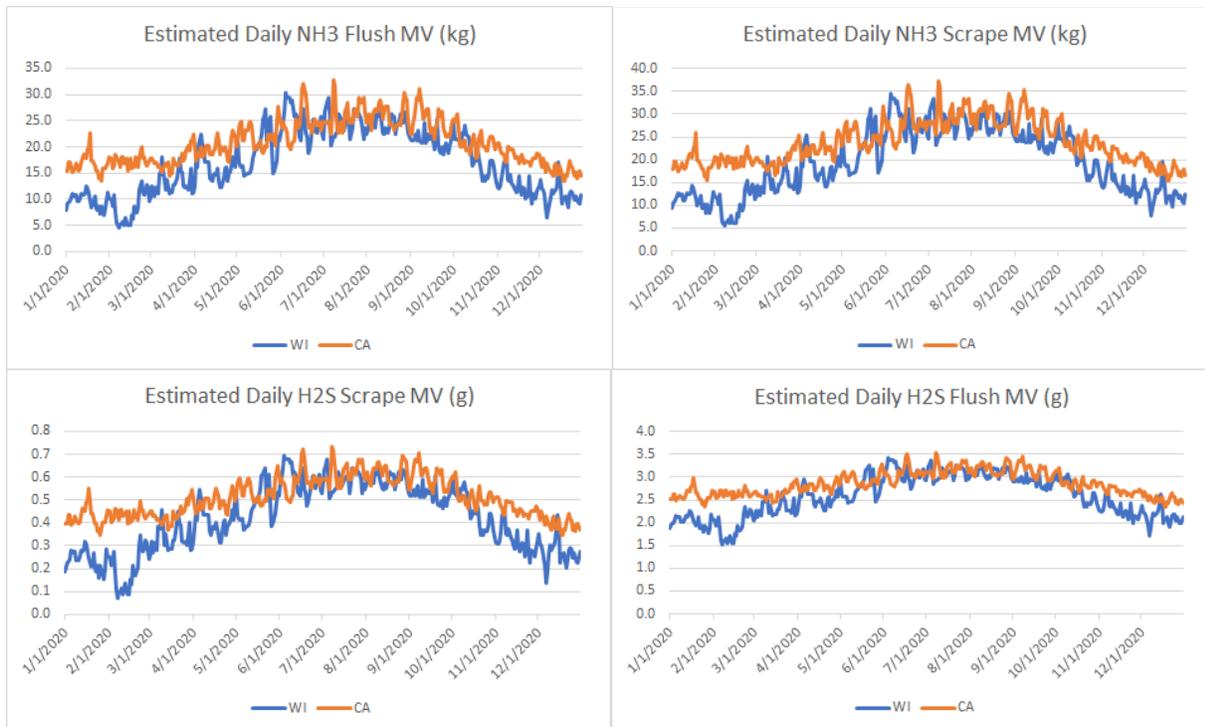
Figure 8-4. Comparison of average daily wind speeds at test locations in Wisconsin (WI) and California (CA).

Table 8-8. Summary of average daily wind speeds at the two meteorological sites.

Site	Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Overall
WI	Min	1.4	0.5	1.5	2.2	1.8	1.5	0.9	1.1	0.9	1.6	1.9	0.0	0.0
WI	Max	7.4	7.6	8.4	6.9	7.2	5.4	5.1	4.5	5.4	7.2	6.9	10.3	10.3
WI	Average	3.6	3.8	4.5	4.1	3.6	3.5	2.9	2.5	3.0	3.4	3.9	4.0	3.6
CA	Min	0.6	1.2	1.2	1.7	1.9	1.3	1.7	1.6	1.2	1.1	0.4	0.0	0.0
CA	Max	7.0	4.6	5.1	4.9	6.2	6.4	5.6	5.0	4.8	6.4	3.9	6.2	7.0
CA	Average	2.2	2.4	2.6	3.4	3.7	4.2	3.7	3.2	2.6	2.7	1.6	2.5	2.9

### 8.2.2.1 Mechanically Ventilated Barn

When the daily calculations are performed for the entire year for a mechanically ventilated dairy barn with 500 cows, the California site typically has higher daily emissions for both NH<sub>3</sub> and H<sub>2</sub>S and for either manure management system than the Wisconsin site (Figure 8-5). Table 8-9 contains the estimated annual emissions for the different combinations of pollutant and manure management system. For the mechanically ventilated scrape barn from the example in Section 8.1.1, the total annual NH<sub>3</sub> emissions estimate for the farm using meteorological data from California was 8,689 kg— a 1,581 kg increase from the same mechanically ventilated barn with meteorological data from Wisconsin. A similar trend is seen across the other pollutant and manure management system combinations. This is consistent with the trend of lower temperatures yielding lower emissions seen during the data exploration in Section 4. Overall, this suggests that the emissions models can account for regional temperature differences in the results for mechanically ventilated barns.



**Figure 8-5. Comparison of daily mechanically ventilated barn emissions at test dairy in locations WI and CA.**

**Table 8-9. Total annual emissions from a theoretical mechanically ventilated barn in WI and CA.**

<b>Pollutant</b>	<b>WI Emissions (kg per year)</b>	<b>CA Emissions (kg per year)</b>
H2S - Flush	152	186
H <sub>2</sub> S - Scrape	940	1,044
NH <sub>3</sub> - Flush	6,193	7,597
NH <sub>3</sub> - Scrape	7,108	8,689

### 8.2.2.2 Milking Center

Repeating the daily calculations for a 500 head capacity milking center using the California meteorological data show the warmer site typically has greater daily emissions for all pollutants (Figure 8-6). Table 8-10 has the estimated annual emissions of each pollutant studied. For the milking center from the example in Section 8.1.2, the total estimated annual NH<sub>3</sub> emissions increase by 1,317 kg by using California meteorological data. A similar trend is seen across the other pollutants, with increases ranging from 38% to 152%. This is consistent with the trend of lower temperatures yielding lower emissions seen during the data exploration in Section 4. Overall, this suggests that the emissions models can account for regional temperature differences in the results for milking centers.

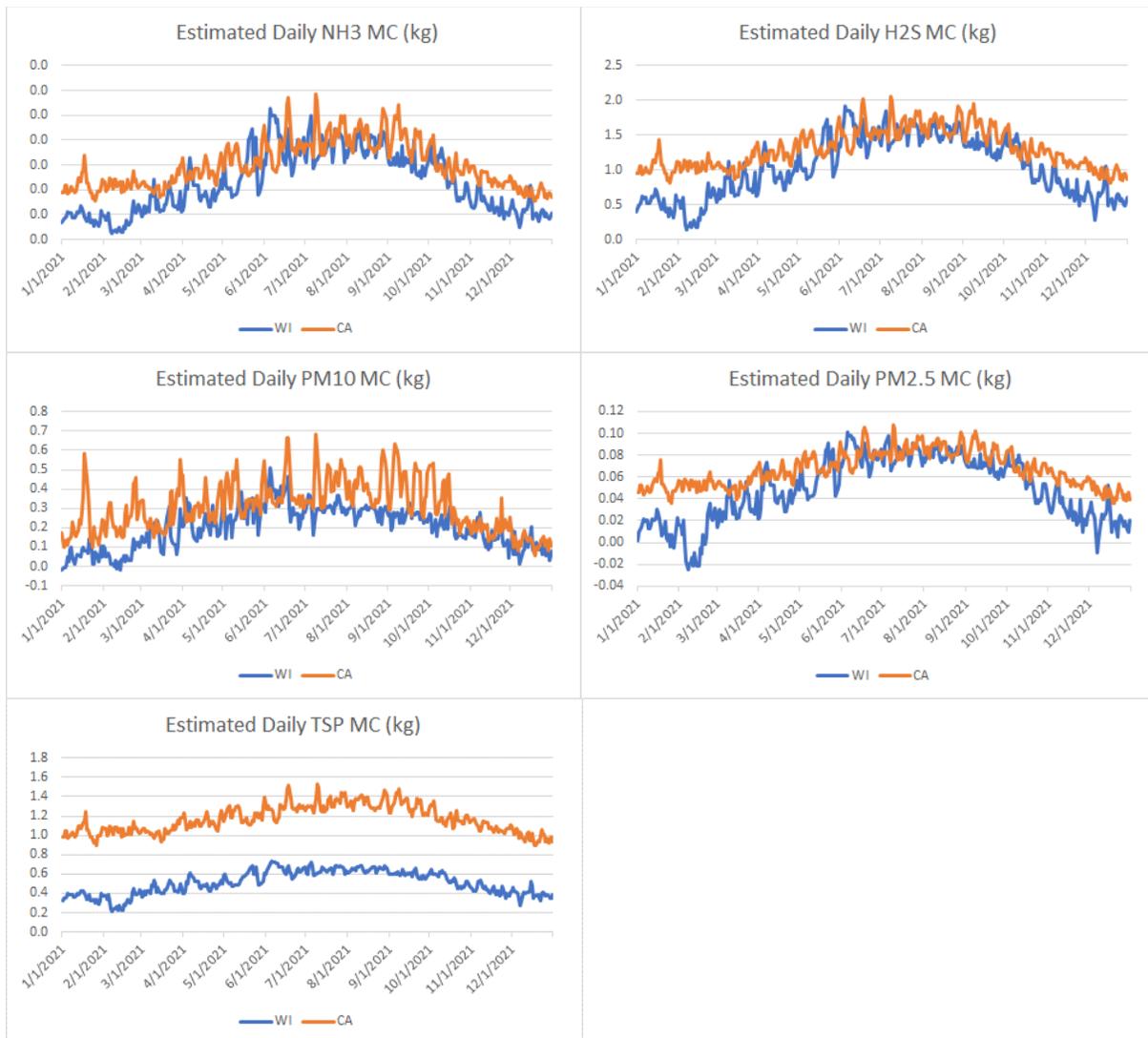


Figure 8-6. Comparison of daily milking center emissions at test dairy locations in WI and CA.

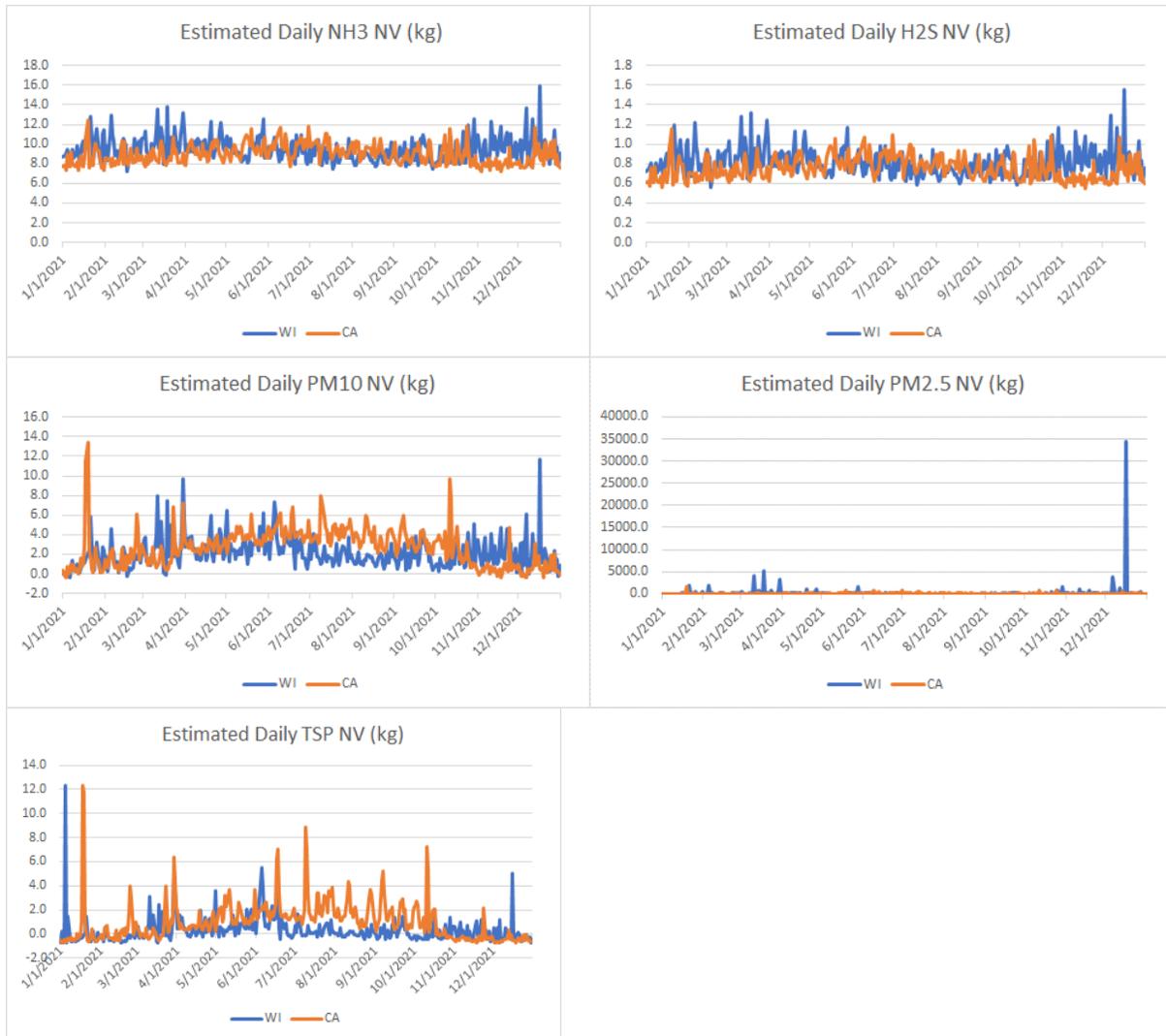
Table 8-10. Total annual emissions from a theoretical milking center in WI and CA.

Pollutant	WI Emissions (kg per year)	CA Emissions (kg per year)
NH <sub>3</sub>	4,162	5,479
H <sub>2</sub> S	189	474
PM <sub>10</sub>	74	112
PM <sub>2.5</sub>	18	24
TSP	185	427

### 8.2.2.3 Naturally Ventilated Barn

A naturally ventilated dairy barn with 500 cows in California typically has lower daily emissions than the same barn in Wisconsin (Figure 8-7) for gaseous pollutants and PM<sub>2.5</sub>. Table 8-11 has the estimated annual emissions of the pollutants studied. The differences in the annual gaseous pollutants are minor, as the models are based on average daily wind speed which is only

slightly different between the sites. Table 8-11 shows a larger difference with the PM<sub>2.5</sub> annual emissions, and the plot shows several large spikes when using the Wisconsin meteorological data. Looking into the data, these data points are associated with days with high average daily wind speeds and suggests some limitation in the model performance for these instances. This is discussed further in Section 8.2.3.3. For PM<sub>10</sub> and TSP, the spikes in emissions are generally due to higher wind speeds combined with lower relative humidities to mitigate the emissions. These relationships are explored more in section 8.2.3.3.



**Figure 8-7. Comparison of daily naturally ventilated barn emissions at test dairy locations in WI and CA.**

**Table 8-11. Total annual emissions from a theoretical milking center in WI and CA.**

Pollutant	WI Emissions (kg per year)	CA Emissions (kg per year)
NH <sub>3</sub>	3,463	3,274
H <sub>2</sub> S	297	275

Pollutant	WI Emissions (kg per year)	CA Emissions (kg per year)
PM <sub>10</sub>	777	962
PM <sub>2.5</sub>	89,168	23,113
TSP	112	369

### 8.2.2.4 Lagoon

Repeating the daily calculations for the dairy lagoon using the California meteorological data typically has higher daily emissions values than when using the Wisconsin meteorological data (Table 8-8). Table 8-12 has the estimated annual emissions of each pollutant studied and shows a roughly 40% increase for both pollutants using the warmer temperatures from California. This is consistent with the trend of warmer temperatures yielding greater emissions seen during the data exploration in Section 4 and noted in the literature review in Section 3. Overall, this suggests that the emissions models are capable of accounting for the different growing regions in the lagoon results.

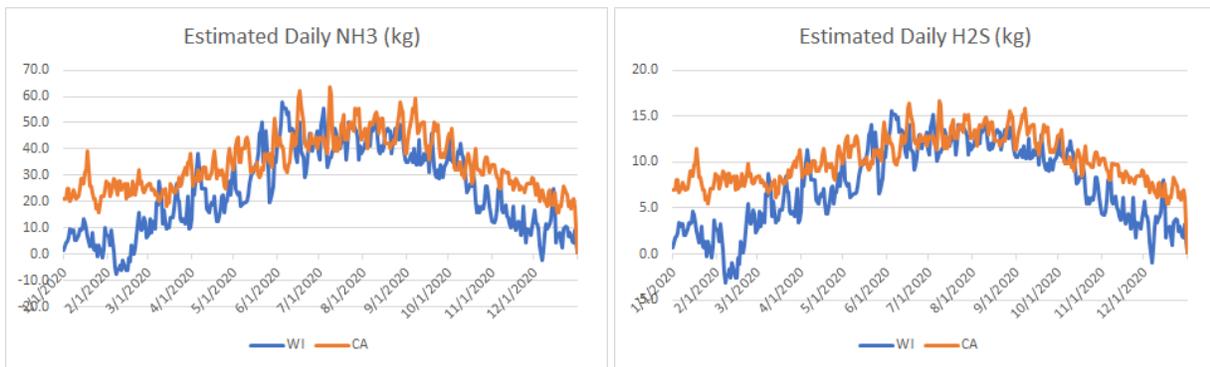


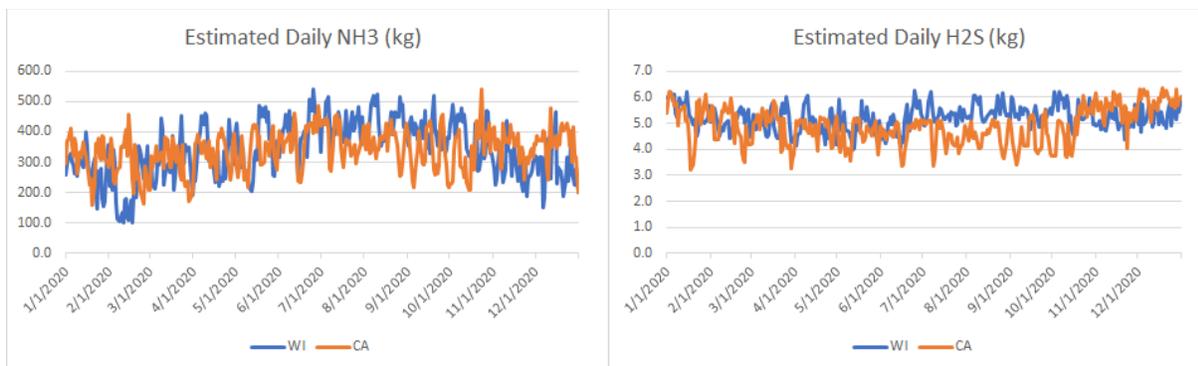
Figure 8-8. Comparison of daily lagoon emissions at test dairy locations in WI and CA.

Table 8-12. Total annual emissions from a theoretical lagoon in WI and CA.

Pollutant	WI Emissions (kg per year)	CA Emissions (kg per year)
NH <sub>3</sub>	8,961	12,525
H <sub>2</sub> S	2,734.2	3,748.8

### 8.2.2.5 Corral

The emissions estimates for a corral using the meteorological data from California, are slightly lower than calculations with the Wisconsin meteorological data (Figure 8-9). Table 8-13 has the estimated annual emissions of each pollutant and shows the total annual NH<sub>3</sub> emissions estimate for the theoretical California corral was 124,261 kg, which is a 302 kg decrease from the same theoretical corral in Wisconsin. The H<sub>2</sub>S model only shows a minor difference between the emissions for the two climates. This generally limited sensitivity is discussed more in Section 8.2.3.5.



**Figure 8-9. Comparison of daily milking center emissions at test dairy locations in WI and CA.**

**Table 8-13. Total annual emissions from a theoretical milking center in WI and CA.**

Pollutant	WI Emissions (kg per year)	CA Emissions (kg per year)
NH <sub>3</sub>	124,562	124,261
H <sub>2</sub> S	1,902.7	1,789.7

### 8.2.3 Model Limitations

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

The dairy equations included some combination of inventory, ambient temperature, ambient relative humidity, and wind speed. The ranges of ambient parameters are based on the NAEMS dataset. The number of cows in a single barn or milking center are based on barn capacity numbers provided by consent agreement participants. The range values evaluated for each parameter are in Table 8-14.

This analysis does not account for interaction between multiple terms within an equation, which could further affect the results. For example, a dairy barn with higher ambient temperatures would be able to cover a larger range of inventory per barn before producing negative NH<sub>3</sub> emissions. Conversely, a barn with lower ambient temperatures would cover a

smaller range of inventory before producing negative NH<sub>3</sub> emissions values. However, the analysis does provide a general range where the model produces reasonable results.

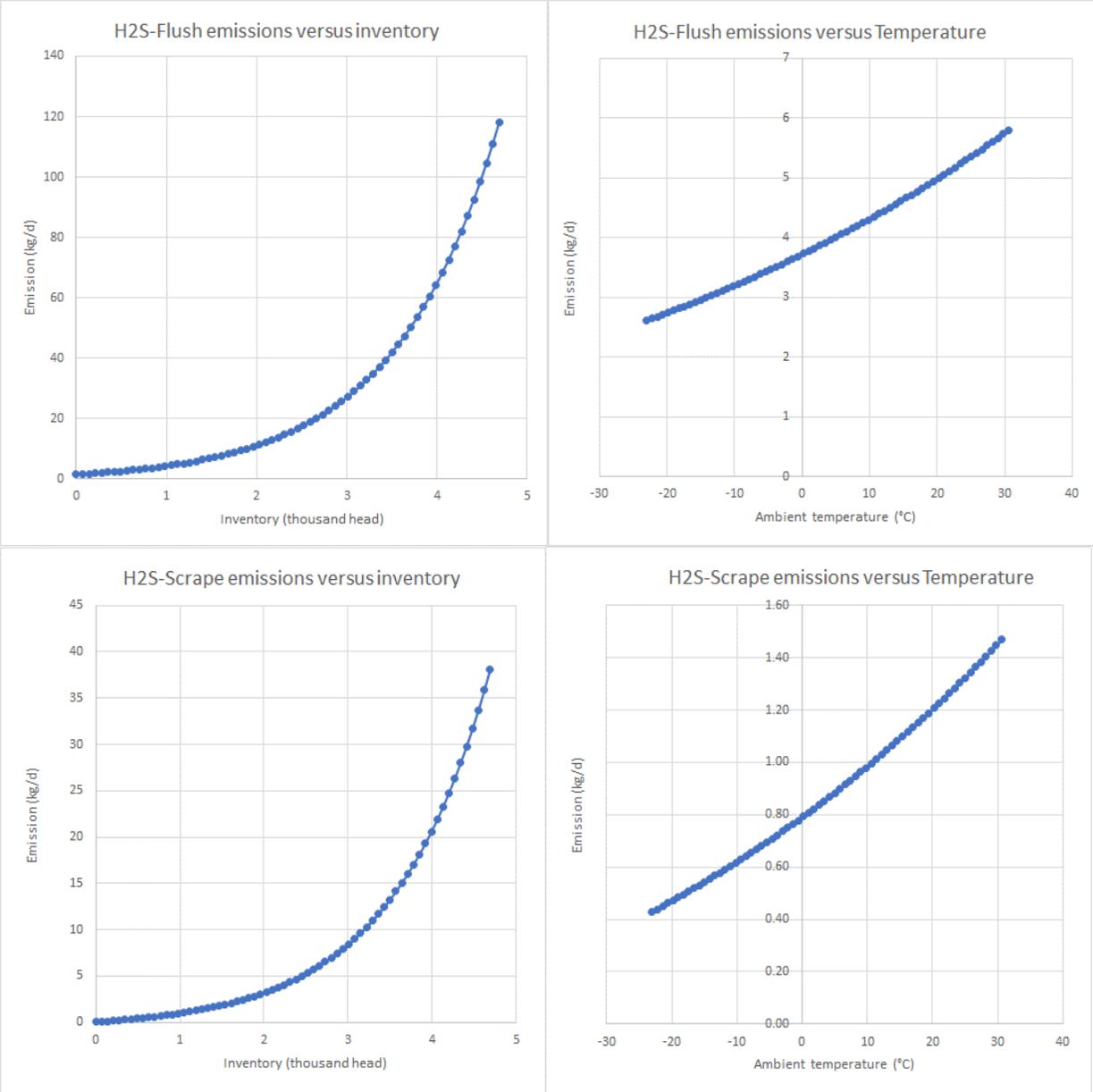
To further explore any limitations in the models, emissions were calculated for all combinations across the range of values specified in Table 8-14. A list of all the combinations of the three inputs was created using the R statistical software. R was then used to calculate the emissions using the method shown in section 8.1. The results were then filtered down to only the results that produced negative values to generate the plots for each pollutant. The following sections outline the analysis for each of the selected models.

**Table 8-14. Parameter ranges evaluated for the dairy models.**

Parameter	Upper Limit	Lower Limit	Average Value	Increment
Ambient temperature (°C)	32.0	-23	10.0	0.8
Ambient relative humidity (%)	93	24	68.1	1
Wind speed (ms <sup>-1</sup> )	11.2	0.00	2.3	0.15
Inventory (head)	5,000	0	1,000	70

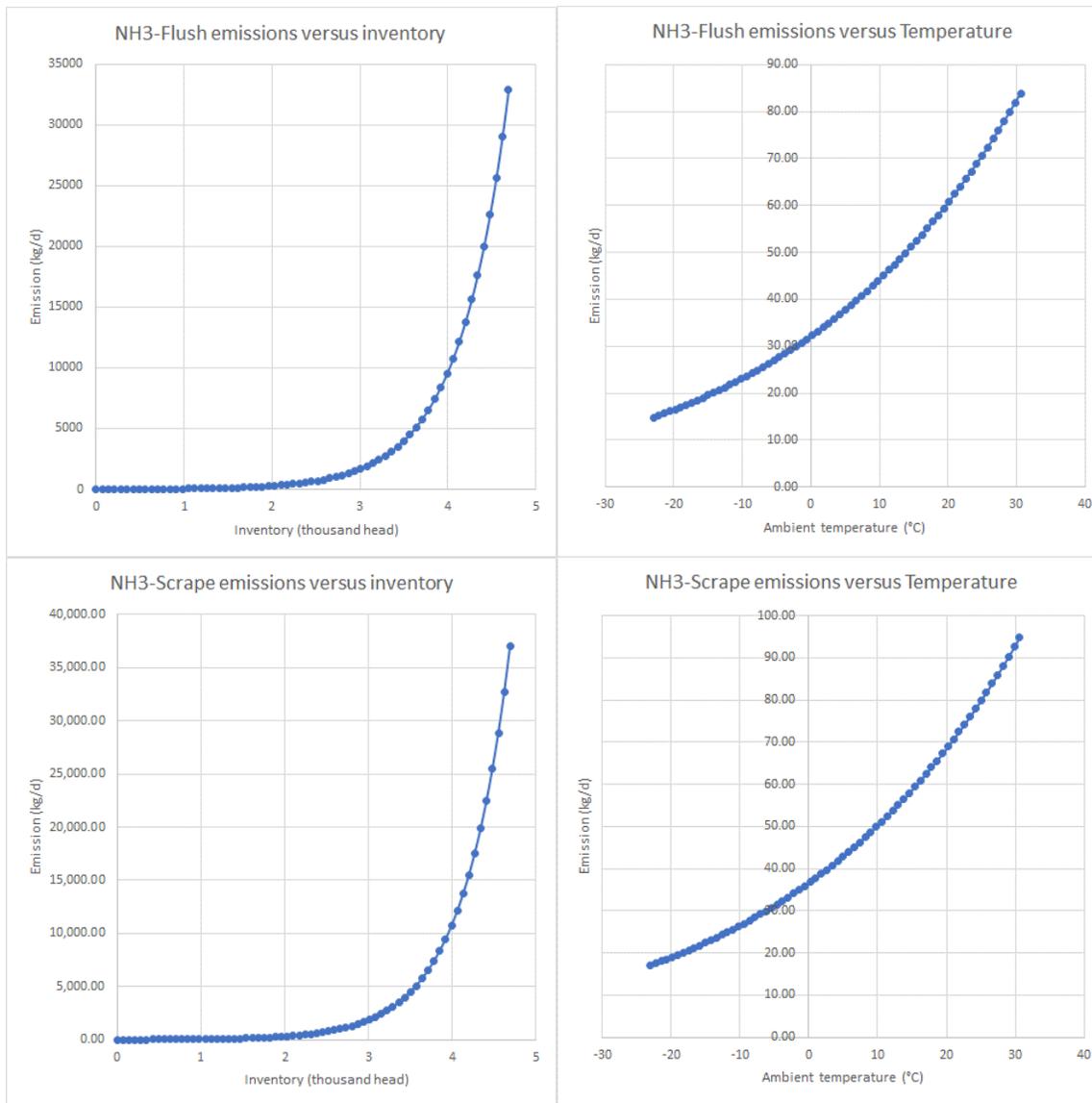
### **8.2.3.1 Mechanically Ventilated Barn**

The initial analysis for mechanically ventilated barns is presented in Figure 8-10 and Figure 8-11. Neither the H<sub>2</sub>S (Figure 8-10) nor NH<sub>3</sub> (Figure 8-11) models produce negative emissions under average conditions. Additional analysis of the 5,110 combinations of conditions evaluated produced negative values. The models also produce a rapid increase in emissions when estimating barns with inventories greater than 2,000 head. The largest barn in the NAEMS had an average daily population of 833, which would account for the unrealistic behavior with extreme inventory numbers. Based on the consent agreement participant data, more than 90% of the participating barns fall below a capacity of 2,000 head. This suggests the model would still be appropriate for the bulk of the participants. EPA will explore models that predict emissions normalized by inventory, as these models will produce a linear relationship between inventory and emissions (with other factors constant), regardless of the size of the operation.



**Figure 8-10. Mechanically ventilated barn limitation tests for H<sub>2</sub>S.**

Visualization of the results for H<sub>2</sub>S – Flush (top row) and H<sub>2</sub>S – Scrape (bottom row) tests of inventory (left) and ambient temperature (right).

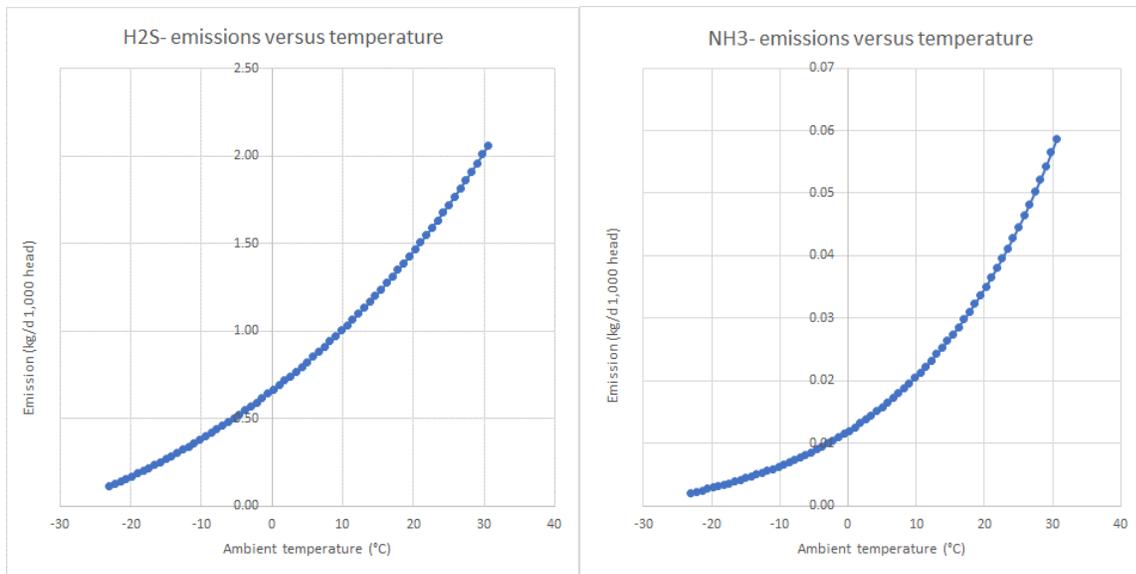


**Figure 8-11. Mechanically ventilated barn limitation tests for NH<sub>3</sub>.**

Visualization of the results for NH<sub>3</sub> – Flush (top row) and NH<sub>3</sub> – Scrape (bottom row) tests of inventory (left) and ambient temperature (right).

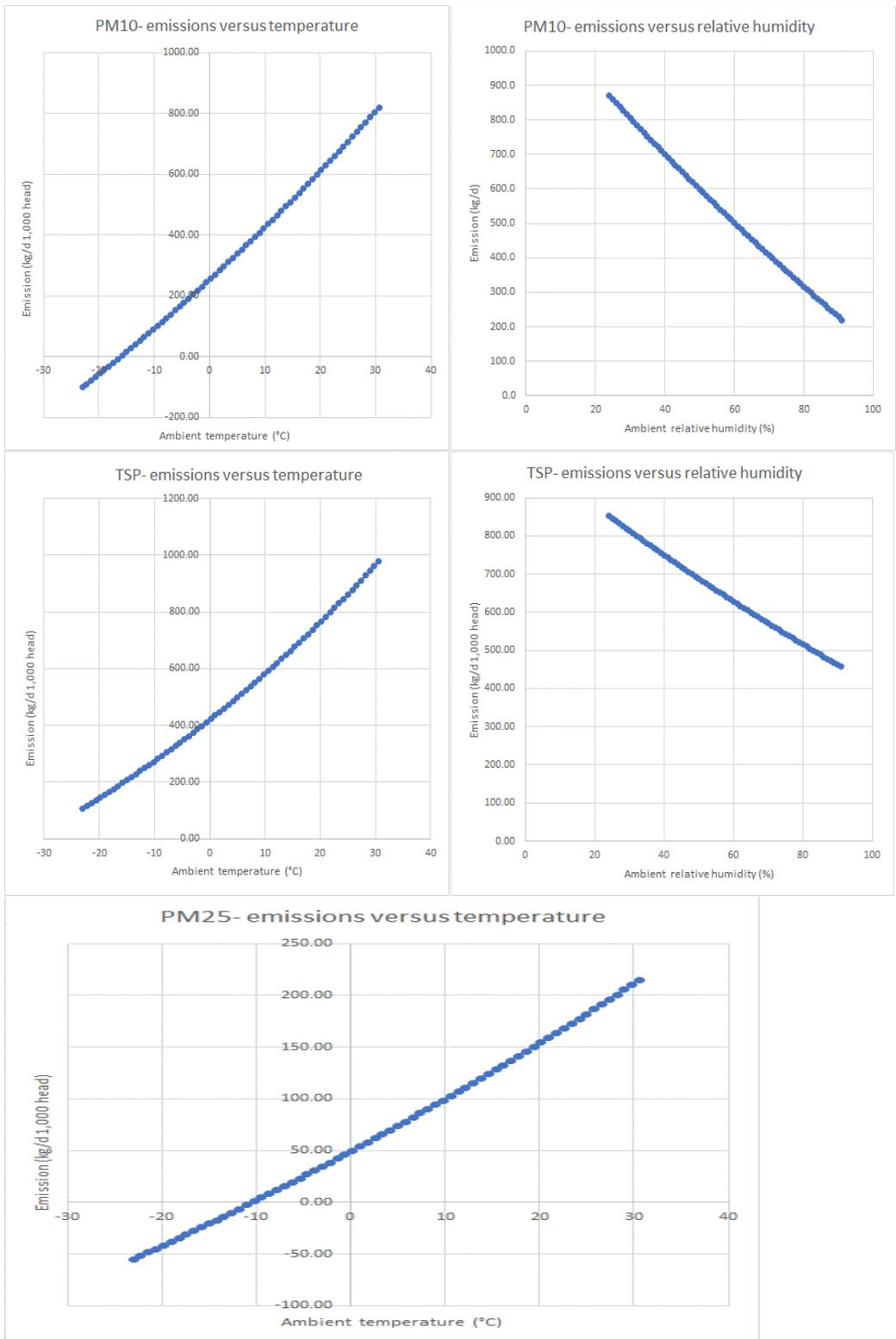
### 8.2.3.2 Milking Center

The milking centers analysis for gaseous pollutants is presented in Figure 8-12 and PM is presented in Figure 8-13. Neither the H<sub>2</sub>S nor NH<sub>3</sub> (Figure 8-12) models produce negative emissions under average conditions. The relationship of emissions to increasing temperature is fairly linear through the expected conditions and does not display any extreme behavior that would suggest extrapolation issues.

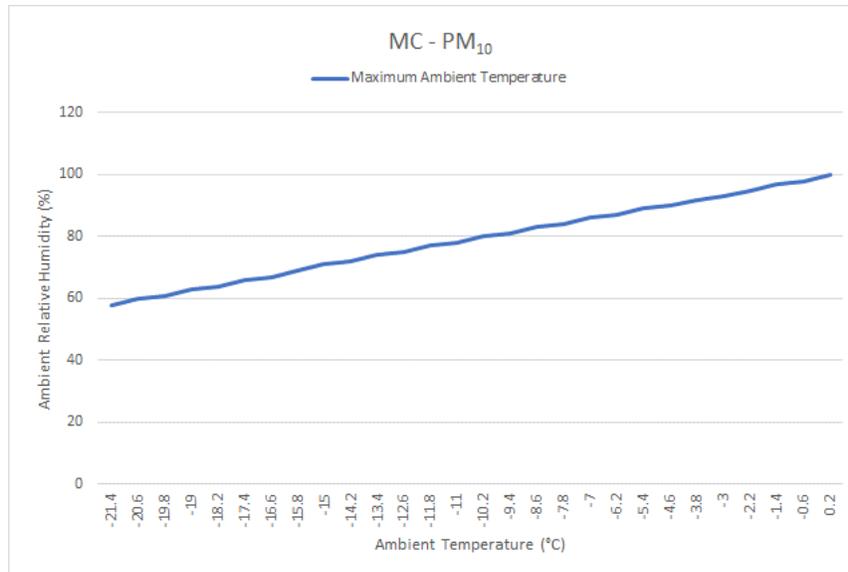


**Figure 8-12. Milking center limitation tests for gaseous pollutants.**  
 Visualization of the results for H<sub>2</sub>S (left) and NH<sub>3</sub> (right) tests of ambient temperature.

The PM<sub>10</sub> and PM<sub>2.5</sub> models (Figure 8-13) do produce negative emissions values less than -11 °C and -18.2 °C for PM<sub>10</sub> and PM<sub>2.5</sub> models, respectively, at average relative humidity levels. Additional analysis of 5,390 combinations of temperature and relative humidity values shows the PM<sub>10</sub> model (Figure 8-14) will produce negative emissions estimates when temperatures fall below zero in an increasingly drier environment. That is, the lower the temperature, the lower the relative humidity needed to produce a negative emissions value. For example, the equation for PM<sub>10</sub> will produce negative emissions at any level of relative humidity when ambient temperature falls just below zero. Similarly, at -21.4 °C, the equation can produce negative number when relative humidity is less than or equal to ~60%.



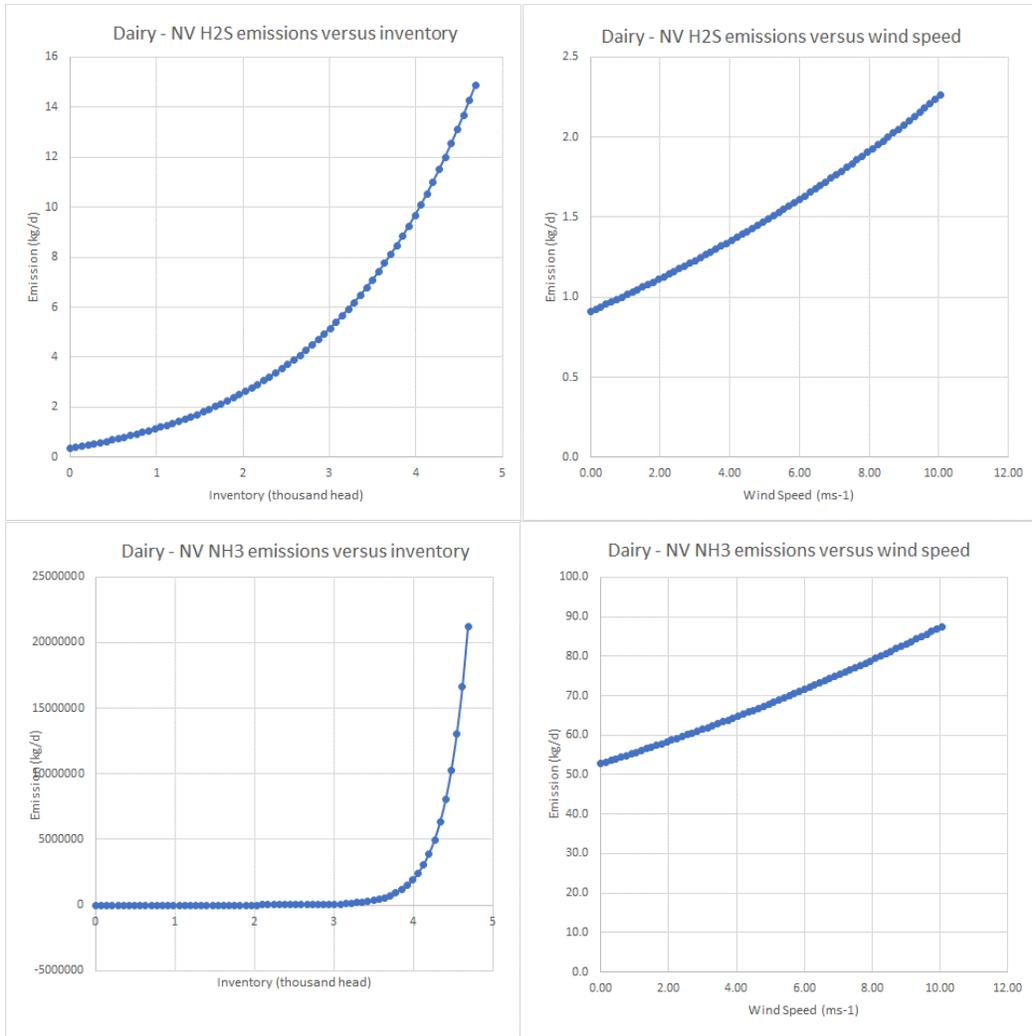
**Figure 8-13. Milking center limitation tests for PM.**  
 Visualization of the results for PM10 (top row), TSP (center row), and PM<sub>2.5</sub> (bottom row) tests of ambient temperature (left) and ambient relative humidity(right).



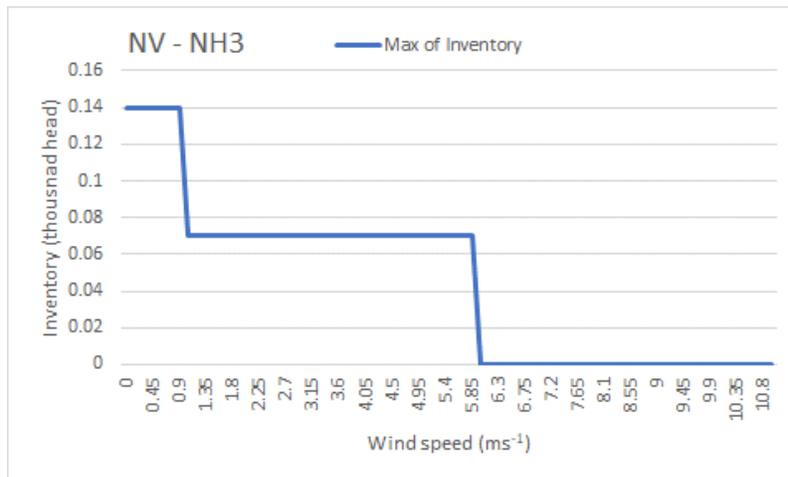
**Figure 8-14. Maximum values of relative humidity for each temperature at which the PM10 equation yields negative emissions.**

### 8.2.3.3 Naturally Ventilated Barn

The naturally ventilated barn analysis for gaseous pollutants is presented in Figure 8-15. Analysis for PM<sub>10</sub>, PM<sub>2.5</sub>, and TSP are presented in Figure 8-17, Figure 8-19, and Figure 8-18, respectively, and PM is presented in Figure 8-13. The H<sub>2</sub>S (Figure 8-12) model does not produce negative emissions under average conditions with varying inventory. The NH<sub>3</sub> model will produce negative emissions for very small inventories (i.e., less than 70 head) under average conditions. Further testing of 5,548 combinations of wind speed and inventory show at very low wind speeds (< 1 ms<sup>-1</sup>), an inventory as large as 140 cows will produce negative emissions. As wind speed increases, the corresponding inventory needed to produce a negative number also decreases. These thresholds are demonstrated in Figure 8-16. The sensitivity analysis testing shows rapid increases in NH<sub>3</sub> and H<sub>2</sub>S emissions at high inventories. EPA will explore models that predict emissions normalized by inventory, as these models will produce a linear relationship between inventory and emissions (with other factors constant), regardless of the size of the operation.



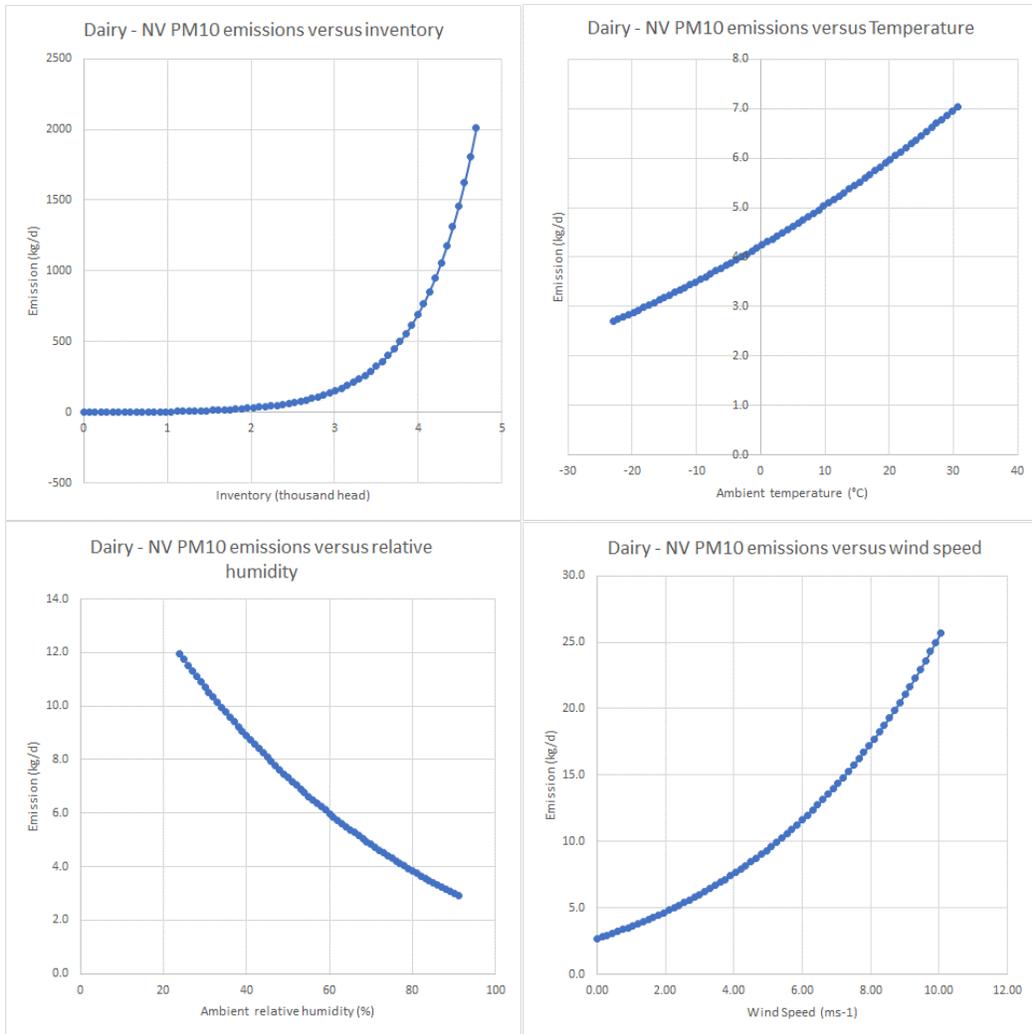
**Figure 8-15. Naturally ventilated barn limitation tests for gaseous pollutants.** Visualization of the results for H<sub>2</sub>S (top row) and NH<sub>3</sub> (bottom row) tests of inventory (left) and wind speed (right).



**Figure 8-16. Maximum values of inventory for each wind speed at which the NH<sub>3</sub> equation yields negative emissions.**

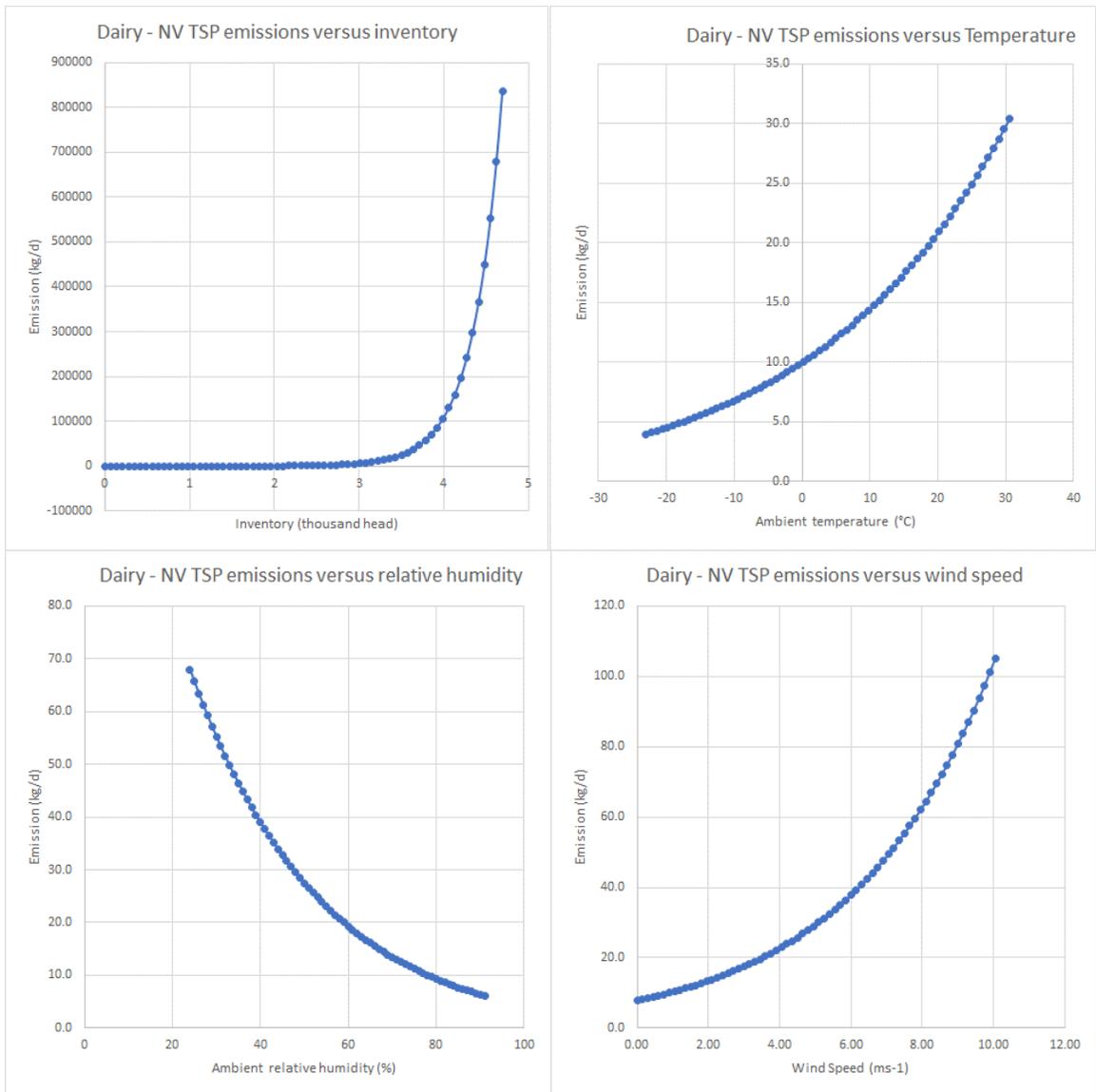
Though it is hard to see on the figures, the PM<sub>10</sub> and TSP models (Figure 8-17 and Figure 8-18) produce negative values under average conditions for very small inventory levels. Further analysis of 29,903,720 combinations of inventory, ambient temperature, ambient relative humidity, and wind speed show that the models will produce negative values for progressively lower temperatures and winds speeds for increasing temperatures (Figure 8-20). For example, with the PM<sub>10</sub> model (top graph, Figure 8-20) for an empty barn, the model will produce a negative emissions value for temperatures less than 32 °C and wind speed less than 9 ms<sup>-1</sup>. As inventory increases to 1,050 head, negative emissions only occur at temperatures below -30 °C and wind speeds less than 1 ms<sup>-1</sup>. The sensitivity analysis testing shows rapid increases in PM<sub>10</sub> and TSP emissions at high inventories. EPA will explore models that predict emissions normalized by inventory, as these models will produce a linear relationship between inventory and emissions (with other factors constant), regardless of the size of the operation.

The PM<sub>2.5</sub> model (Figure 8-19) did not produce negative values under average conditions. However, looking across the combinations of inventory, ambient temperature, ambient relative humidity, and wind speed, the PM<sub>2.5</sub> model produces negative emissions estimates at low wind speeds and temperatures combined with low inventory levels (Figure 8-20). As inventory levels increase, negative emissions estimates can occur at higher values of temperature and wind speed. This is due to the negative relationship between PM<sub>2.5</sub> and inventory in the model, which will need to be further explored. One option is to explore models that predict emissions normalized by inventory, as these models will produce a positive linear relationship between inventory and emissions (with other factors constant), regardless of the size of the operation.



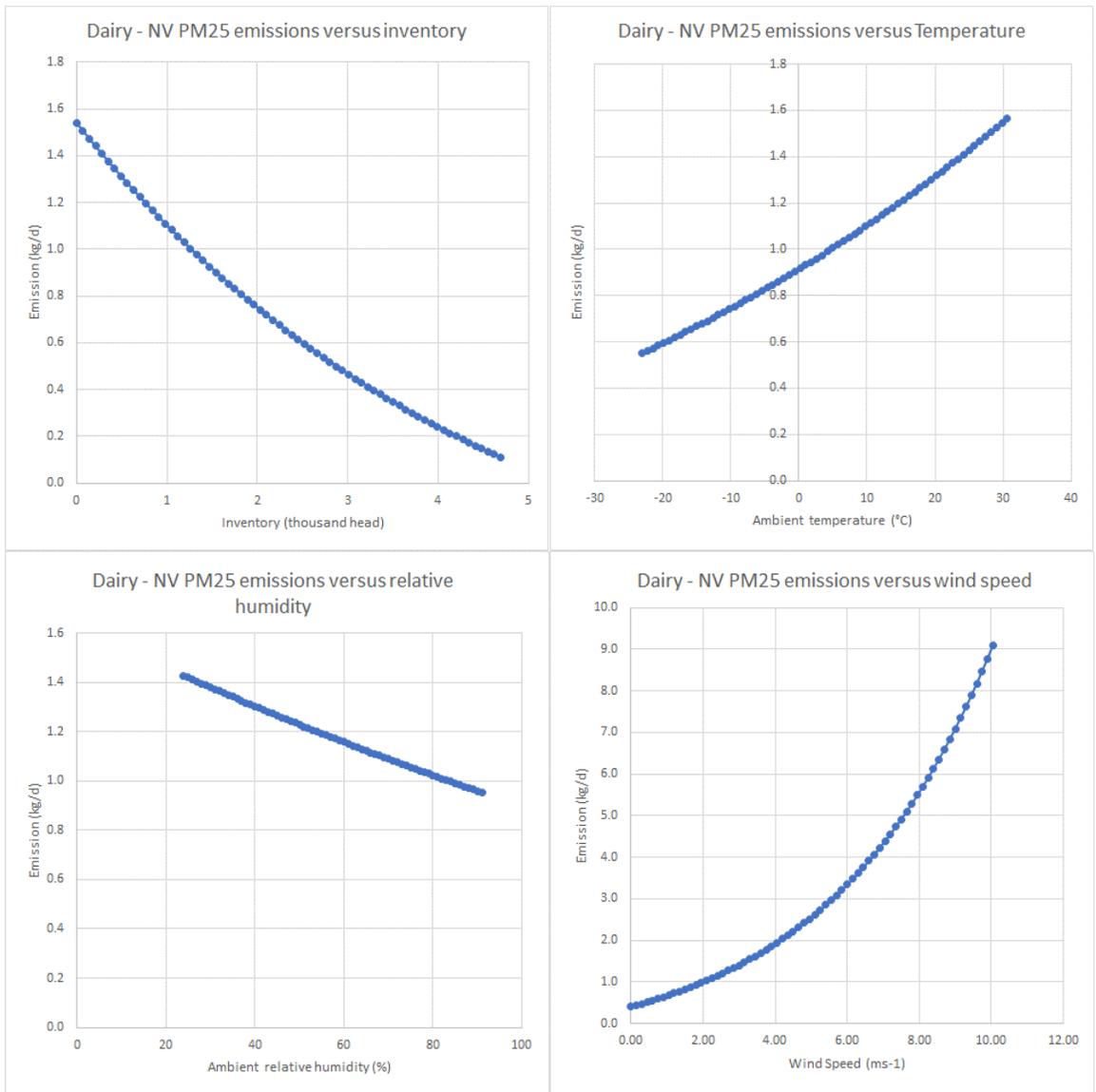
**Figure 8-17. Naturally ventilated barn limitation tests for PM<sub>10</sub>.**

Visualization of the results for PM<sub>10</sub> tests of inventory (top left), ambient temperature (top right), relative humidity (bottom left), and wind speed (bottom right).



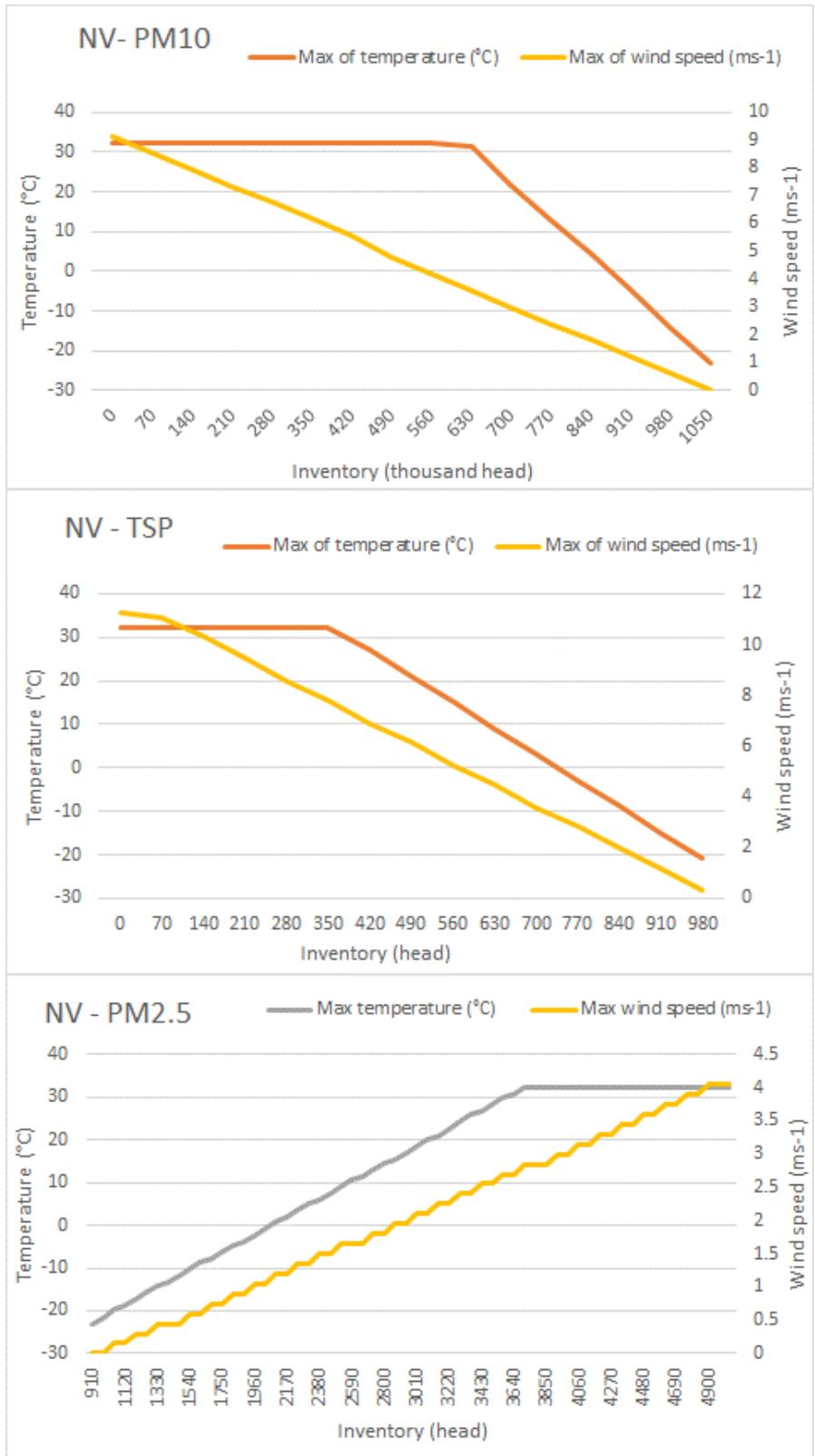
**Figure 8-18. Naturally ventilated barn limitation tests for TSP.**

Visualization of the results for TSP tests of inventory (top left), ambient temperature (top right), relative humidity (bottom left), and wind speed (bottom right).



**Figure 8-19. Naturally ventilated barn limitation tests for PM<sub>2.5</sub>.**

Visualization of the results for PM<sub>2.5</sub> tests of inventory (top left), ambient temperature (top right), relative humidity (bottom left), and wind speed (bottom right).

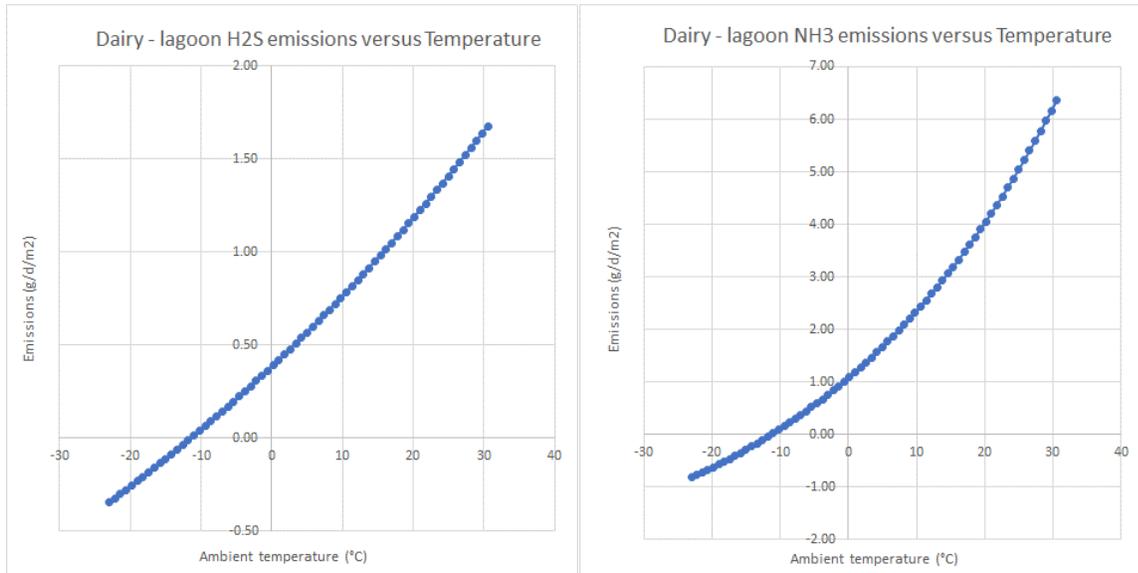


**Figure 8-20. Maximum values of wind speed and temperature for each inventory level at which the PM equations yields negative emissions.**

Visualizations of the results for PM<sub>10</sub> (top), TSP (middle) and PM<sub>2.5</sub> (bottom).

### 8.2.3.4 Lagoon

The lagoon analysis for gaseous pollutants is presented in Figure 8-21. Both  $\text{NH}_3$  and  $\text{H}_2\text{S}$  will produce negative emissions values when temperatures dip below  $-11.8^\circ\text{C}$ . EPA will evaluate whether the model should include a “floor”, that is past a certain temperature it is assumed the lagoon is frozen and is producing minimal emissions. The relationship between temperature and emissions is positive with no large changes in emissions sensitivity.

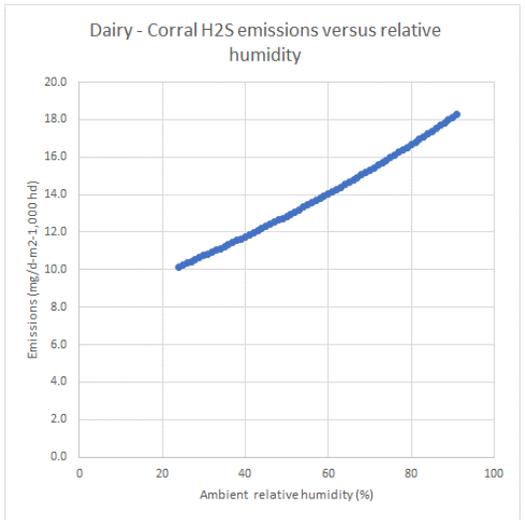


**Figure 8-21. Lagoon limitation tests for gaseous pollutants.**

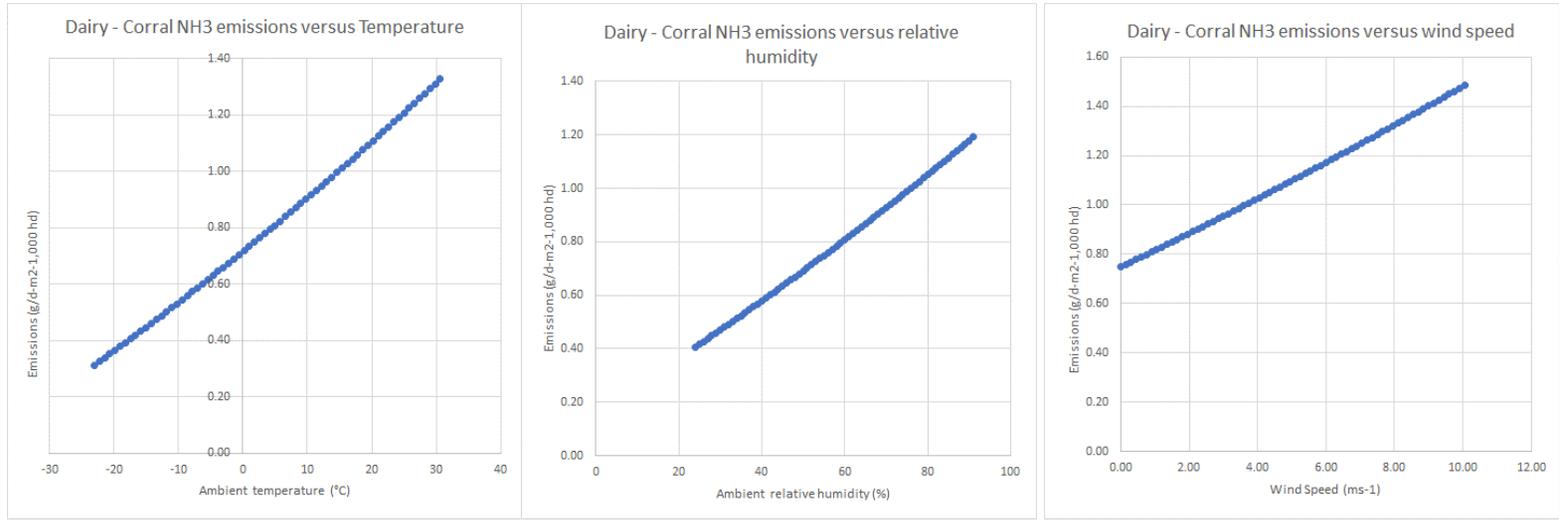
Visualization of the results for tests of ambient temperature for  $\text{H}_2\text{S}$  (left) and  $\text{NH}_3$  (right).

### 8.2.3.5 Corral

The corral analyses for  $\text{H}_2\text{S}$  and  $\text{NH}_3$  are presented in Figure 8-22 and Figure 8-23, respectively. Neither the  $\text{H}_2\text{S}$  nor the  $\text{NH}_3$  model produce negative emissions under average conditions. However, analyzing 397, 936 combinations of temperature, relative humidity, and wind speed, found that the  $\text{NH}_3$  model will produce negative emissions estimates at low temperatures ( $< 7.8^\circ\text{C}$ ) combined with low relative humidities ( $< 46\%$ ) and low wind speeds ( $< 3.9\text{ ms}^{-1}$ ). Figure 8-24 show that as temperature increases, there is a smaller range of relative humidity and wind speeds that produce negative emissions. Otherwise, the relationships between emissions and predictors do not show any rapid changes in emissions sensitivity that are causes of concern.



**Figure 8-22. Corral limitation tests for H<sub>2</sub>S.**  
 Visualization of the results for tests of relative humidity for H<sub>2</sub>S.



**Figure 8-23. Corral limitation tests for NH<sub>3</sub>.**  
 Visualization of the results for NH<sub>3</sub> tests of ambient temperature (left), relative humidity (center), and wind speed (right).

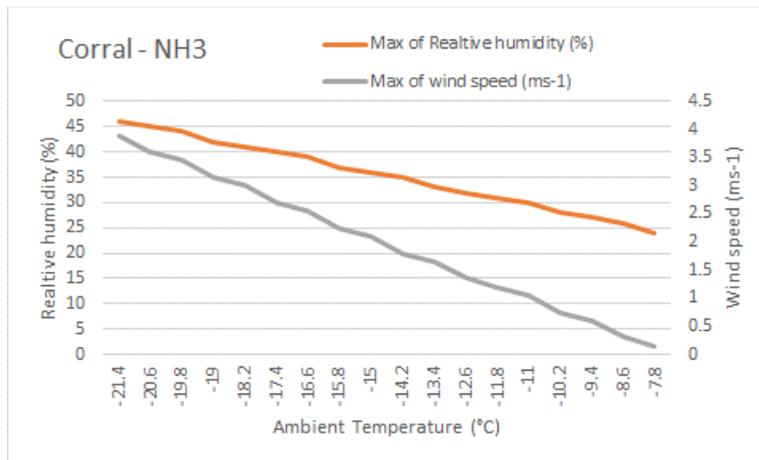


Figure 8-24. Maximum values of wind speed and relative humidity for each temperature at which the PM equations yields negative emissions.

### 8.3 Comparison to Literature

To further validate the EEMs developed under this effort, EPA compared the results for the emissions models to the emissions calculated using emissions factors found in literature. EPA scanned the literature for a variety of emissions factors for this comparison. EPA selected a variety of recent factors not derived from the NAEMS for comparison, which are summarized separately for barns, lagoons, and corrals in Table 8-15, Table 8-16, and Table 8-17, respectively. There were no emissions factors identified for milking centers during the literature review. For the mechanically ventilated barns, the original units provided in Teye, F.K and Hautala, M. (2010) were  $\text{g m}^{-2} \text{hr}^{-1}$ , which were converted to  $\text{kg hd}^{-1} \text{yr}^{-1}$  based on the reported floor area of  $774 \text{ m}^2$  and inventory of 65 head. For naturally ventilated barns, values were converted based on  $500 \text{ kg AU}^{-1}$ , and an average weight of 635 kg per head, based on the NAEMS farms. For the lagoon and corral sources, surface areas in hectare were converted using the standard factor of  $10,000 \text{ m}^2/\text{ha}$ . These converted emissions factors were then applied to the theoretical farm sources from the previous example calculations. The following sections summarize the results for each source type.

Table 8-15. Emissions factors for dairy barns from literature.

Source	Farm Source	Pollutant	$\text{mg sec}^{-1} \text{hd}^{-1}$	$\mu\text{g sec}^{-1} \text{hd}^{-1}$	$\text{kg hd}^{-1} \text{d}^{-1}$	$\text{g m}^2 \text{hr}$	$\text{kg hd}^{-1} \text{yr}^{-1}$
Teye, F.K and Hautala, M. (2010)	Mechanically ventilated barn	$\text{NH}_3$	-	-	-	0.12 <sup>a</sup>	12.52
Huang (2017)	Naturally ventilated barn	$\text{NH}_3$	0.98 <sup>a</sup>	-	-	-	30.91
Leytem, et al. (2012)	Naturally ventilated barn	$\text{NH}_3$	-	-	0.08 <sup>a</sup>	-	29.20
Huang (2017)	Naturally ventilated barn	$\text{H}_2\text{S}$	-	18.5 <sup>a</sup>	-	-	0.58

<sup>a</sup> As reported in source.

**Table 8-16. Emissions factors for dairy lagoons from literature.**

Source	Farm Source	Pollutant	kg/ha-d	g/m <sup>2</sup> -d	kg/m <sup>2</sup> -yr
Leytem, A.B., et al. (2011)	Lagoon <sup>a</sup>	NH <sub>3</sub>	-	2.0 <sup>b</sup>	0.73
Leytem, A.B., et al. (2018)	Lagoon	NH <sub>3</sub>	43 <sup>a, c</sup>	-	1.57

<sup>a</sup> Identified in the study as a wastewater pond.

<sup>b</sup> As reported in source.

<sup>c</sup> Rate reported for lagoon associated with a freestall barn (location ID D4).

**Table 8-17. Emissions factors for dairy corrals from literature.**

Source	Farm Source	Pollutant	g/hd-d	kg/hd-d
Leytem, A.B., et al. (2011)	Corral	NH <sub>3</sub>	-	0.13 <sup>a</sup>
Moore, K.D., (2014)	Corral	NH <sub>3</sub>	134.2 <sup>a</sup>	0.134
Bonifacio, H.F., et al. (2015)	Corral	NH <sub>3</sub>	155 <sup>a</sup>	0.155

<sup>a</sup> As reported in source.

### 8.3.1 Mechanically Ventilated Barn

Comparisons were made for an inventory of 500 cows and 1,000 cows for both a cold weather location (Wisconsin) and a warm weather location (California). The results for comparing the calculations for NH<sub>3</sub> emissions for mechanically ventilated scrape barns are presented in Table 8-18, and flush barn in Table 8-19. For both inventory levels, the emissions factor from Teye and Hautala (2010) produces an estimate that falls just below the estimate produced by the emissions models developed in this report. For the flush barns, the estimates based on Teye and Hautala (2010) fall between the estimate for the smaller barn (500 head) and just below the model estimates for the larger barn (1,000). For both manure management types, the models developed in the text represent an increase from previously published literature.

**Table 8-18. Comparison of resulting mechanically ventilated scrape barn NH<sub>3</sub> emissions (kg yr<sup>-1</sup>) from various estimation methods.**

Meteorology Site	Inventory (hd)	EPA 2022 Models	Teye and Hautala (2010)
WI	500	7,098	6,259
CA	500	8,689	6,259
WI	1,000	18,794	12,517
CA	1,000	22,657	12,517

**Table 8-19. Comparison of resulting mechanically ventilated flush barn NH<sub>3</sub> emissions (kg yr<sup>-1</sup>) from various estimation methods.**

Meteorology Site	Inventory (hd)	EPA 2022 Models	Teye and Hautala (2010)
WI	500	6,183	6,259
CA	500	7,597	6,259
WI	1,000	16,574	12,517
CA	1,000	20,006	12,517

### 8.3.2 Naturally Ventilated Barn

Like the mechanically ventilated examples, comparisons were made for an inventory of 500 cows and 1,000 cows for both a cold weather location (WI) and a warm weather location (CA). The results for NH<sub>3</sub> are presented in Table 8-20. For the smaller barn (500 head), the estimates for both the cold and warm meteorological conditions fall well below the estimates generated by the factors from literature. The estimates for the larger barn (1,000) the models presented in this work are closer to the estimates provided by emissions factors from literature. This reiterates the results from the sensitivity analysis, where the emissions estimates from the models increase rapidly with size.

For H<sub>2</sub>S (Table 8-21), the estimates based on the models developed in this report are slightly greater for the smaller barn in a cold climate compared to literature. The large inventory examples and the 500 head barn in a warm climate are slightly lower than estimates based on literature.

**Table 8-20. Comparison of resulting naturally ventilated barn NH<sub>3</sub> emissions (kg/yr) from various estimation methods.**

Meteorology Site	Inventory (hd)	EPA 2022 Models	Huang (2017)	Leytem, et al. (2012)
WI	500	4,194	15,453	14,600
CA	500	3,816	15,453	14,600
WI	1,000	28,137	30,905	29,200
CA	1,000	26,050	30,905	29,200

**Table 8-21. Comparison of resulting naturally ventilated barn H<sub>2</sub>S emissions (kg/yr) from various estimation methods.**

Meteorology Site	Inventory (hd)	EPA 2022 Models	Huang (2017)
WI	500	310	292
CA	500	289	292
WI	1,000	477	583
CA	1,000	447	583

### 8.3.3 Lagoon

For lagoons, comparisons were made for both a cold weather location (WI) and a warm weather location (CA) assuming a surface area of 10,000 m<sup>2</sup>. The NH<sub>3</sub> results in Table 8-22 show the models developed in this report generate an estimate that falls between the factors from literature.

**Table 8-22. Comparison of resulting dairy lagoon NH<sub>3</sub> emissions (kg yr<sup>-1</sup>) from various estimation methods.**

Meteorology Site	Surface Area (m <sup>2</sup> )	EPA 2022 Models	Leytem, A.B., et al. (2011)	Leytem, A.B., et al. (2018)
WI	10,000	8,961	7,300	15,695
CA	10,000	12,525	7,300	15,695

#### 8.3.4 Corral

For corrals, the comparison was made for both cold (WI) and warm (CA) meteorological scenarios. Calculations were also made for a small farm (500 head) and a larger farm (1,000 head), assuming a surface area of 10,000 m<sup>2</sup> for each farm for the method developed in this report. The summary for NH<sub>3</sub> in Table 8-23 shows the estimates based on the EPA 2022 draft methods are comparable to the estimates based on emissions factors from literature.

**Table 8-23. Comparison of resulting dairy corral NH<sub>3</sub> emissions (kg yr<sup>-1</sup>) from various estimation methods.**

Meteorology Site	Inventory (hd)	Surface Area (m <sup>2</sup> )	EPA 2022 Models	Leytem, A.B., et al. (2011)	Moore, K.D., et al. (2014)	Bonifacio, H.F., et al. (2015)
WI	500	10,000	23,975	23,725	28,288	24,492
CA	500	10,000	22,551	23,725	28,288	24,492
WI	1,000	10,000	47,949	47,450	56,575	48,983
CA	1,000	10,000	45,101	47,450	56,575	48,983

## 8.4 Replication of Independent Measurements

A final test of the developed models is to compare the predicted emissions to observed values from an independent study. For this test, EPA was able to obtain some of the data from the Harper, et al. (2009) study of lagoons in Wisconsin. The data available are for NH<sub>3</sub> emissions for two of the three sites, for fall and summer monitoring periods. EPA was also able to obtain data from the Leytem et al. (2013) study, where an open-freestall production facility was monitored in southern Idaho. Measurements were collected for both the open-freestall area and the wastewater ponds. The data from the Idaho open-freestall area was used to test the corral model and data from the Wisconsin lagoons and the Idaho wastewater pond data was used to test the lagoon model.

The data provided included the necessary information to estimate emissions using the developed emissions models. These estimates were then compared to the observed values, when available, using the same model performance statistics noted in Section 6 of the Overview report. Scatter plots were also developed to present the ordered pairs with observations on the x-axis and the model predicted values on y-axis. These plots are useful for indicating trends of either over- or under-prediction across the range of values. The plots include the 1:1 line (solid line) and the

1:0.5 and 1:2 lines (dashed lines). Points that fall on the 1:1 line were predicted correctly, and points that fall between the 1:0.5 and 1:2 are within a factor of two observations. Good model performance would be indicated by scatter contained within a factor of two of the 1:1 line, that is between the 1:0.5 and 1:2 lines. Looking for scatter confined to within a factor of two of the observation has been used as a model performance metric in air quality modeling by EPA for some time (Chang and Hanna, 2004) and continues to be included in EPA’s Atmospheric Model Evaluation Tool (Appel, et al. 2011), which is the current model evaluation platform. The following sections summarize the result for each source type.

### 8.4.1 Lagoon

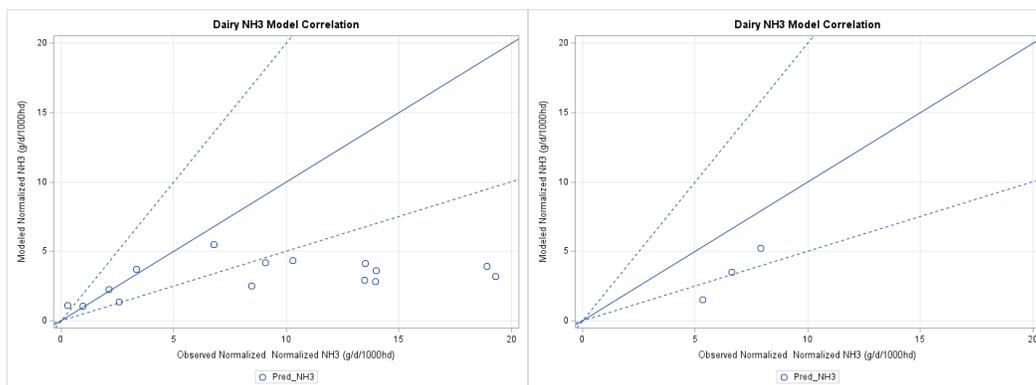
The model performance statistics (Table 8-24) indicate an under-prediction of emissions at both sites. Figure 8-25 shows that the largest under-predictions occur for observations greater than 10 g d<sup>-1</sup> 1,000 hd<sup>-1</sup>, as indicated by the drop below the 1:1.05 line on the plot for the Idaho site. This suggests the current formulation of the model underestimates the highest emissions.

**Table 8-24. Model performance evaluation statistics for lagoon NH<sub>3</sub> estimates.**

Site	n	LNME <sup>a</sup> (%)	NME <sup>b</sup> (%)	ME <sup>b</sup> (g d <sup>-1</sup> 1,000 hd <sup>-1</sup> )	MB <sup>b</sup> (g d <sup>-1</sup> 1,000 hd <sup>-1</sup> )	NMB <sup>b</sup> (%)	Corr.
ID	23	26.177	69.196	4.800	-4.681	-67.47	0.497
WI	3	20.271	48.388	3.209	-3.209	-48.39	0.999

<sup>a</sup> Based on transformed data (i.e., ln(NH<sub>3</sub>)).

<sup>b</sup> Based on back-transformed data.



**Figure 8-25. Scatter plot of the observed lagoon NH<sub>3</sub> emissions versus the emissions model estimates.**

Results from the Idaho site (left) and Wisconsin site (right).

### 8.4.2 Corral

The model performance statistics (Table 8-25) show an under-prediction of emissions from the corral. The plot of observed versus estimated emissions (Figure 8-26) show there are slight overpredictions at low emissions levels, as the points fall above the 1:1 line, and an

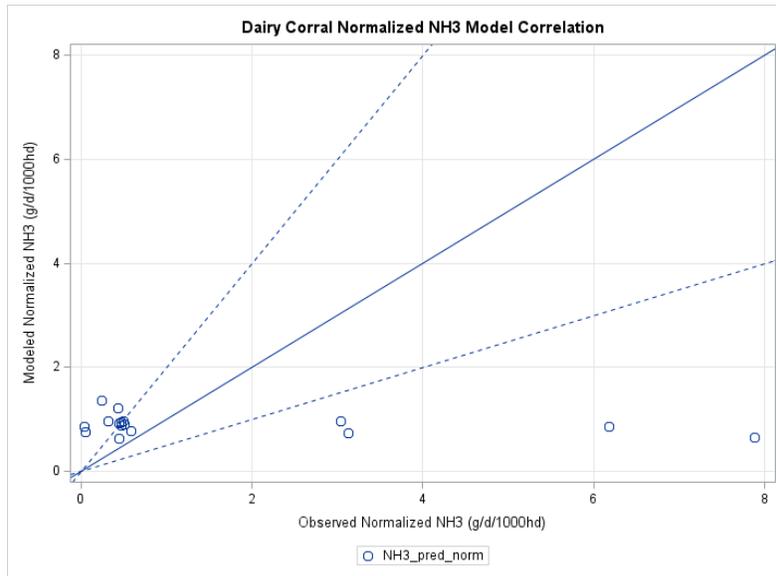
underprediction at higher observed emissions levels. As with the lagoon model, this suggests an underprediction of the highest emissions values in the model.

**Table 8-25. Model performance evaluation statistics for corral NH<sub>3</sub> estimates.**

Site	n	LNME <sup>a</sup> (%)	NME <sup>b</sup> (%)	ME <sup>b</sup> (g d <sup>-1</sup> 1,000 hd <sup>-1</sup> )	MB <sup>b</sup> (g d <sup>-1</sup> 1,000 hd <sup>-1</sup> )	NMB <sup>b</sup> (%)	Corr.
WI	18	17.371	70.689	1.316	-0.574	-30.84	-0.351

<sup>a</sup> Based on transformed data (i.e., ln(NH<sub>3</sub>)).

<sup>b</sup> Based on back-transformed data.



**Figure 8-26. Scatter plot of the observed corral NH<sub>3</sub> emissions versus the emissions model estimates.**

## 9 CONCLUSIONS

Consistent with the Air Compliance Agreement with the AFO industry, EPA has developed emissions estimation methods for NH<sub>3</sub>, H<sub>2</sub>S, PM<sub>10</sub>, PM<sub>2.5</sub>, and TSP for confinement and open sources associated with dairy operations. These draft statistical models focus on parameters that have been identified in published peer-reviewed journals as having empirical relationships with emissions. These relationships were evaluated within the NAEMS dataset before selecting parameters for emissions model development. EPA also considered which variables could be measured or obtained with minimal effort.

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

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

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

## 10 REFERENCES

- Aarnink, A.J.A., Ellen, H.H., 2007. Processes and factors affecting dust emissions from livestock production. In: Proceedings of DustConf 2007. How to Improve Air Quality. International Conference, Maastricht, The Netherlands.
- Appel, K.W., Gilliam, R.C., Davis, N., Zubrow, A., and Howard, S.C. (2011). Overview of the Atmospheric Model Evaluation Tool (AMET) v1.1 for evaluating meteorological and air quality models, *Environ. Modell. Softw.*, 26(4), 434-443.
- Arogo, J., Zhang, R., Riskowski, G. L., Christianson, L. L., and Day, D. L. (1999). Mass transfer coefficient of ammonia in liquid swine manure and aqueous solution. *Journal of Agricultural Engineering Research*, 73(1), 77e86.
- Arogo, Jactone, Philip W. Westerman, Albert J. Heber, Wayne P. Robarge, and John J. Classen. Ammonia Emissions from Animal Feeding Operations. *Animal Agriculture and the Environment*, National Center for Manure and Animal Waste Management White Papers. St. Joseph, MI: ASABE, 2006. doi:<https://doi.org/10.13031/2013.20247>.
- Arya, S.P. (1999). *Air pollution meteorology and dispersion*. Oxford University Press. Blunden, J., and Aneja, V.P. (2008). Characterizing ammonia and hydrogen sulfide emissions from a swine waste treatment lagoon in North Carolina. *Atmospheric Environment* 42, 3277-3290.
- B. Bjerg, T. Norton, T. Banhazi, G. Zhang, T. Bartzanas, P. Liberati, G. Cascone, I.-B. Lee, and A. Marucci. "Modelling of ammonia emissions from naturally ventilated livestock buildings. Part 1: Ammonia release modelling" *Biosystems engineering* 116, no. 3 (2013): 232-245. doi: 10.1016/j.biosystemseng.2013.08.001.
- Bogan, B.W., A. Chandrasekar, S. McGlynn, C.A. Gooch, and A.J. Heber. 2010. National Air Emissions Monitoring Study: Data from Dairy Freestall Barn and Milking Center in New York- Site NY5B. Final Report. Purdue University, West Lafayette, IN, July 2.
- Bonifacio, Henry and Rotz, C.A. and Leytem, A.B. and Waldrip, Heidi and R.W.Todd. (2015). Process-based modeling of ammonia and nitrous oxide emissions from open-lot beef and dairy facilities. *Transactions of the ASABE (American Society of Agricultural and Biological Engineers)*. 58. 827-846.
- Bougouin, A., Leytem, A., Dijkstra, J., Dungan, R. S., and Kebreab, E. (2016). Nutritional and Environmental Effects on Ammonia Emissions from Dairy Cattle Housing: A Meta-Analysis. *Journal of environmental quality*, 45(4), 1123-1132.
- Cambra-López, M., Aarnink, A.J.A., Zhao, Y., Calvet, S., and Torres, A.G. (2010). Airborne particulate matter from livestock production systems: A review of an air pollution problem. *Environmental Pollution* 158, 1-17.
- Cambra-López, M., Torres, A. G., Aarnink, A. J. A., and Ogink, N. W. M. (2011). Source analysis of fine and coarse particulate matter from livestock houses. *Atmospheric Environment*, 45(3), 694-707. doi:10.1016/j.atmosenv.2010.10.018.
- Chang, J., Hanna, S. Air quality model performance evaluation. *Meteorol Atmos Phys* 87, 167–196 (2004). <https://doi.org/10.1007/s00703-003-0070-7>.

- Christensen J.R., Nash, M.S., Chaloud D., and Pitchford A. 2016. Spatial Distribution of Small Water Body Types Across Indiana Ecoregions. *Ecohydrology*. 9,122-137. Available at: [https://cfpub.epa.gov/si/si\\_public\\_record\\_report.cfm?dirEntryId=308263](https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=308263) and Lab=NERL.
- Cortus, E.L., L. D. Jacobson, B.P. Hetchler, and A.J. Heber. 2010. National Air Emissions Monitoring Study: Emissions Data from Two Freestall Dairy Barns in Wisconsin - Site WI5B. Final Report. Purdue University, West Lafayette, IN, July 2.
- Dandan Huang and Huiqing Guo (2017) Diurnal and seasonal variations of odor and gas emissions from a naturally ventilated free-stall dairy barn on the Canadian prairies, *Journal of the Air and Waste Management Association*, 67:10, 1092-1105, DOI:10.1080/10962247.2017.1329172.
- Feidler, A.M., Müller, H.J., 2011. Emissions of ammonia and methane from a livestock building natural cross ventilation. *Meteorologische Zeitschrift* 20 (1), 059e065.
- Garcia, J., Bennett, D. H., Tancredi, D., Schenker, M. B., Mitchell, D., and Mitloehner, F. M. (2013). A survey of particulate matter on California dairy farms. *Journal of environmental quality*, 42(1), 40-47.
- Grant, R.H. 2008, Quality Assurance Project Plan for the National Air Emissions Monitoring Study (Open Source Emissions Component), Ver. 4, Purdue Applied Meteorology Laboratory, Department of Agronomy, Purdue University.
- Grant, R.H. and M.T. Boehm. (2010a). National Air Emissions Monitoring Study: Data from the eastern US milk production facility IN5A. Final Report to the Agricultural Air Research Council. Purdue University, West Lafayette, IN, June 4.
- Grant, R.H. and M.T. Boehm. (2010b). National Air Emissions Monitoring Study: Data from the southwest milk producer facility TX5A. Final Report to the Agricultural Air Research Council. Purdue University, West Lafayette, IN, July 2.
- Grant, R.H. and M.T. Boehm. (2010c.) National Air Emissions Monitoring Study: Data from the northwestern US milk production facility WA5A. Final Report to the Agricultural Air Research Council. Purdue University, West Lafayette, IN, July 2.
- Grant, R.H. and M.T. Boehm. (2010d). National Air Emissions Monitoring Study: Data from the midwestern US milk production facility WI5A. Final Report to the Agricultural Air Research Council. Purdue University, West Lafayette, IN, July 2.
- Grant, R. H., Boehm, M. T., and Lawrence, A. F. (2013). Comparison of a backward-Lagrangian stochastic and vertical radial plume mapping methods for estimating animal waste lagoon emissions. *Agricultural and Forest Meteorology*, 180, 236-248. doi:10.1016/j.agrformet.2013.06.013.
- Grant, R.H., Boehm, M.T., Lawrence, A.F., and Heber, A.J. (2013b). Ammonia emissions from anaerobic treatment lagoons at sow and finishing farms in Oklahoma. *Agricultural and Forest Meteorology* 180, 203-210.
- Grant, R.H. and Boehm, M.T (2015). Manure ammonia and hydrogen sulfide emissions from a western storage basin. *Journal of environmental quality*, 45, 127-136.

- Grant, R. H., and Boehm, M. T. (2020). Ammonia Emissions from Differing Manure Storage Facilities at Two Midwestern Free-Stall Dairies. *Atmosphere*, 11(10), 1108.
- Grant, R. H., Boehm, M. T., and Hagevoort, G. R. (2020). Ammonia Emissions from a Western Open-Lot Dairy. *Atmosphere*, 11(9), 913.
- Harper, L.A., T.K. Flesch, J.M. Powell, W.K. Coblenz, W.E. Jokela, N.P. Martin, Ammonia emissions from dairy production in Wisconsin, *Journal of Dairy Science*, Volume 92, Issue 5, 2009, Pages 2326-2337, ISSN 0022-0302, <https://doi.org/10.3168/jds.2008-1753>.
- Heber A.J., Ni, J-Q., Ramirez, J.C., Schrock, W., and Elkins, J. (2008). Quality assurance project plan for the National Air Emissions Monitoring Study (barn component). Purdue University.
- Herbut, P., and Angrecka, S. (2014). Ammonia Concentrations in a Free-Stall Dairy Barn. *Annals of Animal Science*, 14(1), 153-166. doi:10.2478/aoas-2013-0065.
- Joo, H., Ndegwa, P.M., Wang, X., Heber, A.J., Ni, J.Q., Cortus, E.L., Ramirez-Dorronsoro, J.C., Bogan, B.W. and Chai, L., 2015. Ammonia and hydrogen sulfide concentrations and emissions for naturally ventilated freestall dairy barns. *Transactions of the ASABE*, 58(5), pp.1321-1331.
- Kavolelis, B. (2003). Influence ventilation rate on ammonia concentration and emission in animal house. *Polish Journal of Environmental Studies*, 12(6), 709-712.
- Leeden, Rien and Meijer, Erik and Busing, Frank. (2008). Resampling Multilevel Models. 10.1007/978-0-387-73186-5\_11.
- Leytem, A. B., Dungan, R. S., Bjorneberg, D. L., and Koehn, A. C. (2011). Emissions of ammonia, methane, carbon dioxide, and nitrous oxide from dairy cattle housing and manure management systems. *Journal of environmental quality*, 40(5), 1383–1394. <https://doi.org/10.2134/jeq2009.0515>.
- Leytem, A. B., Dungan, R. S., Bjorneberg, D. L., and Koehn, A. C. (2013). Greenhouse gas and ammonia emissions from an open-freestall dairy in southern Idaho. *Journal of Environmental Quality*, 42, 10-20.
- Leytem, A. B., Bjorneberg, D. L., Al Rotz, C., Moraes, L. E., Kebreab, E., and Dungan, R. S. (2018). Ammonia emissions from dairy lagoons in the western US. *Transactions of the ASABE*, 61(3), 1001-1015.
- Lim, T.T., Y. Jin, J.H. Ha, and A.J. Heber. 2010. National Air Emissions Monitoring Study: Emissions Data from Two Freestall Barns and a Milking Center at a Dairy Farm in Indiana - Site IN5B. Final Report. Purdue University, West Lafayette, IN, July 30.
- Maasikmets, Marek, Erik Teinemaa, Allan Kaasik, Veljo Kimmel, Measurement and analysis of ammonia, hydrogen sulphide and odour emissions from the cattle farming in Estonia, *Biosystems Engineering*, Volume 139, 2015, Pages 48-59, ISSN 1537-5110, <https://doi.org/10.1016/j.biosystemseng.2015.08.002>.
- Masters, G.M. (2013). Renewable and efficient electric power systems. John Wiley & Sons. [http://www.a-ghadimi.com/files/Courses/Renewable%20Energy/REN\\_Book.pdf](http://www.a-ghadimi.com/files/Courses/Renewable%20Energy/REN_Book.pdf).

- Meisinger, J. J., and Jokela, W. E. (2000). Ammonia volatilization from dairy and poultry manure. Proc Managing nutrients and pathogens from animal agriculture. Camp Hill, PA, 28-30.
- Montes, F., C.A. Rotz, and H. Chaoui. 2009. Process modeling of ammonia volatilization from ammonium solution and manure surfaces. Trans. ASABE 52(5):1707-1719.
- Moore, K. D.; Young, E.; Gurell, C.; Wojcik, M. D.; Martin, R. S.; Bingham, G. E.; Pfeiffer, R. L.; Prueger, J. H.; and Hatfield, J. L., "Ammonia Measurements and Emissions from a California Dairy Using Point and Remote Sensors" (2014). Space Dynamics Lab Publications. Paper 95.
- Mostafa, E., Nannen, C., Henseler, J., Diekmann, B., Gates, R., and Buescher, W. (2016). Physical properties of particulate matter from animal houses-empirical studies to improve emission modelling. Environ Sci Pollut Res Int, 23(12), 12253-12263. doi:10.1007/s11356-016-6424-8.
- Ngwabie, N. M., K. H. Jeppsson, G. Gustafsson, and S. Nimmermark. "Effects of Animal Activity and Air Temperature on Methane and Ammonia Emissions from a Naturally Ventilated Building for Dairy Cows." *Atmospheric Environment* 45, no. 37 (Dec 2011): 6760-68. <https://doi.org/10.1016/j.atmosenv.2011.08.027>.
- Philippe, F. X., Cabaraux, J. F., and Nicks, B. (2011). Ammonia emissions from pig houses: Influencing factors and mitigation techniques. Agriculture, Ecosystems and Environment, 141(3e4),245e260. <http://doi.org/10.1016/j.agee.2011.03.012>.
- Samer, M., C. Ammon, C. Loebstin, M. Fiedler, W. Berg, P. Sanftleben, and R. Brunsch. "Moisture balance and tracer gas technique for ventilation rates measurement and greenhouse gases and ammonia emissions quantification in naturally ventilated buildings." *Building and Environment* 50 (2012): 10-20.
- Ramirez-Dorransoro, J.C., H.S. Joo, P. Ndegwa, and A.J. Heber. 2010. National Air Emissions Monitoring Study: Data from Two Dairy Freestall Barns in Washington WA5B, Final Report. Purdue University, West Lafayette, IN, July 30.
- Rotz, C Alan, Dawn S Chianese, Felipe Montes, Sasha Hafner, and Henry F Bonifacio. "Dairy Gas Emissions Model." (2014).
- Saha, C. K., C. Ammon, W. Berg, M. Fiedler, C. Loebstin, P. Sanftleben, R. Brunsch, and T. Amon. "Seasonal and diel variations of ammonia and methane emissions from a naturally ventilated dairy building and the associated factors influencing emissions." *Science of the total environment* 468 (2014): 53-62.
- Sanchis, E., Calvet, S., del Prado, A., and Estelles, F. (2019). A meta-analysis of environmental factor effects on ammonia emissions from dairy cattle houses. *Biosystems Engineering*, 178, 176-183. doi:10.1016/j.biosystemseng.2018.11.017.
- Schmithausen, A. J., Schiefler, I., Trimborn, M., Gerlach, K., Sudekum, K. H., Pries, M., and Buscher, W. (2018). Quantification of Methane and Ammonia Emissions in a Naturally Ventilated Barn by Using Defined Criteria to Calculate Emission Rates. *Animals*, 8(5), 75. doi:ARTN 7510.3390/ani8050075.

- Schrade, S., Zeyer, K., Gygax, L., Emmenegger, L., Hartung, E., and Keck, M. (2012). Ammonia emissions and emission factors of naturally ventilated dairy housing with solid floors and an outdoor exercise area in Switzerland. *Atmospheric Environment*, 47, 183-194. doi:10.1016/j.atmosenv.2011.11.015.
- Shi, Zhifang, Xiaoqin Sun, Yao Lu, Lei Xi, and Xin Zhao. "Emissions of ammonia and hydrogen sulfide from typical dairy barns in central China and major factors influencing the emissions." *Scientific Reports* 9, no. 1 (2019): 1-12. <https://doi.org/10.1038/s41598-019-50269-y>.
- Sommer, S.G., Christensen, M.L., Schmidt, T., Jensen, L.S., 2013. *Animal Manure Recycling: Treatment and Management*. John Wiley Sons Ltd, West Sussex, UK.
- Takai H., Pedersen S., Johnsen J.O., Metz J.H.M., Koerkamp P.W.G.G., Uenk G.H., Phillips V.R., Holden M.R., Sneath R.W., Short J.L., White R.P., Hartung J., Seedorf J., Schroder M., Linkert K.H., Wathes C.M. 1998. Concentrations and emissions of airborne dust in livestock buildings in Northern Europe. *J. Agr. Eng. Res.*, 70: 59-77. doi: 10.1006/jaer.1997.0280.
- Teye, F. K., and Hautala, M. (2010). A comparative assessment of four methods for estimating ammonia emissions at microclimatic locations in a dairy building. *International journal of biometeorology*, 54(1), 63–74. <https://doi.org/10.1007/s00484-009-0255-y>.
- U.S. EPA Science Advisory Board (SAB), 2013. *SAB Review of Emissions-Estimating Methodologies for Broiler Animal Feeding Operations and for Lagoons and Basins at Swine and Dairy Animal Feeding Operations*, EPA-SAB-13-003.
- Wu, W., Zhang, G., and Kai, P. (2012). Ammonia and methane emissions from two naturally ventilated dairy cattle buildings and the influence of climatic factors on ammonia emissions. *Atmospheric Environment*, 61, 232-243. doi:10.1016/j.atmosenv.2012.07.050.
- Zhao, Y., F.M. Mitloehner, L. Chai, J.C. Ramirez, K. Wang, J. Ni, C. Diehl, E.L. Cortus, T.T. Lim, B.W. Bogan, I. Kilic, and A.J. Heber. 2010. *National Air Emissions Monitoring Study: Data from Two Dairy Freestall Barns in California - Site CA5B. Final Report*. Purdue University, West Lafayette, IN, July 30.