

2014

Environmental assessment and control towards improved swine breeding-gestation-farrowing operation in the Midwestern United States

John Stinn
Iowa State University

Follow this and additional works at: <http://lib.dr.iastate.edu/etd>

 Part of the [Agriculture Commons](#), and the [Bioresource and Agricultural Engineering Commons](#)

Recommended Citation

Stinn, John, "Environmental assessment and control towards improved swine breeding-gestation-farrowing operation in the Midwestern United States" (2014). *Graduate Theses and Dissertations*. 14062.
<http://lib.dr.iastate.edu/etd/14062>

This Dissertation is brought to you for free and open access by the Graduate College at Iowa State University Digital Repository. It has been accepted for inclusion in Graduate Theses and Dissertations by an authorized administrator of Iowa State University Digital Repository. For more information, please contact digirep@iastate.edu.

Environmental assessment and control towards improved swine breeding-gestation-farrowing operation in the Midwestern United States

by

John Paul Stinn

A dissertation submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Agricultural Engineering

Program of Study Committee:
Hongwei Xin, Major Professor
Robert Burns
Daniel Andersen
Kenneth Stalder
Steven Trabue

Iowa State University

Ames, Iowa

2014

Copyright © John Paul Stinn, 2014. All rights reserved.

DEDICATION

This work is dedicated to my wife and my family, for all of their love and support over the years.

TABLE OF CONTENTS

LIST OF FIGURES	vi
LIST OF TABLES	ix
ACKNOWLEDGEMENTS	xi
CHAPTER 1. GENERAL INTRODUCTION.....	1
Air quality	1
The farrowing environment	3
Organization of Dissertation.....	5
References.....	6
CHAPTER 2. AMMONIA AND GREENHOUSE GAS CONCENTRATIONS AND EMISSIONS OF A MODERN U.S. SWINE BREEDING-GESTATION-FARROWING SYSTEM.....	8
Abstract.....	8
Introduction.....	9
Materials and Methods.....	13
Results and Discussion.....	24
Summary and Conclusions.....	48
Acknowledgements.....	49
References.....	50

CHAPTER 3. HEAT AND MOISTURE PRODUCTION RATES OF A U.S. SWINE BREEDING-GESTATION-FARROWING SYSTEM	54
Abstract	54
Introduction	56
Materials and Methods	58
Results and Discussion	70
Summary and Conclusions	85
Acknowledgements	88
References	88
CHAPTER 4. HEAT LAMP VS. HEAT MAT AS LOCALIZED HEAT SOURCE IN SWINE FARROWING CRATE	91
Abstract	91
Introduction	92
Materials and Methods	95
Results and Discussion	100
Summary and Conclusions	110
Acknowledgements	111
References	111

CHAPTER 5. COMPARISON OF FOURIER TRANSFORM INFRARED SPECTROSCOPY AND PHOTOACOUSTIC INFRARED SPECTROSCOPY FOR MEASUREMENT OF AMMONIA AND GREENHOUSE GASES	113
Abstract	113
Introduction.....	114
Materials and Methods.....	117
Results and Discussion.....	122
Summary and Conclusions.....	135
Acknowledgments.....	137
References.....	138
CHAPTER 6. FINAL SUMMARY AND RECOMMENDATIONS.....	140
Future Research Recommendations	144

LIST OF FIGURES

Figure 2.1. An aerial view of the breeding-gestation-farrowing farm.....	14
Figure 2.2. Schematic representation of farrowing rooms F1 and F2.....	15
Figure 2.3. Schematic representation of breeding/early gestation and late gestation barns ...	16
Figure 2.4. Gas, dew point, and building measurement and monitoring system	19
Figure 2.5. <i>In-situ</i> ventilation fan calibration device and example performance curves	20
Figure 2.6. Dynamic flux chamber floating on manure in outside storage.....	22
Figure 2.7. Lactating sow and litter body mass curve	25
Figure 2.8. Daily temperature, relative humidity, and ventilation rate of the breeding/early gestation and late gestation barns.	27
Figure 2.9. Average daily gaseous concentrations vs. ambient temperature for the breeding/early gestation and late gestation barns.	28
Figure 2.10. Daily temperature, humidity, and ventilation rate of the farrowing rooms	31
Figure 2.11. Daily gas concentrations vs. ambient temperature for the farrowing rooms.	32
Figure 2.12. Daily emission rates for the breeding/early gestation and late gestation barns..	35
Figure 2.13. Daily emission rates vs. daily ambient temperature for gestation barns.	36
Figure 2.14. Daily emission rates for the farrowing rooms.	39
Figure 2.15. Daily ammonia and carbon dioxide emission rates over two farrowing turns. ..	40
Figure 2.16. Daily emission rates vs. daily ambient temperature for the farrowing rooms	41
Figure 2.17. Average fluxes from external manure storage.....	43
Figure 3.1. Aerial view of the breeding-gestation-farrowing farm	59
Figure 3.2. Schematic representation of farrowing rooms F1 and F2.....	60
Figure 3.3. Schematic representation of breeding/early gestation and late gestation barns. ..	62
Figure 3.4. Innova 1412 and Rosemount 755A paramagnetic analyzers.....	65
Figure 3.5. Gas, dew point, and building measurement and monitoring system.	65
Figure 3.6. In-situ ventilation fan calibration device and example performance curves	66
Figure 3.7. Lactating sow and litter body mass curve.	71

Figure 3.8. Diurnal patterns of heat and moisture production for the late gestation barn	72
Figure 3.9. Daily respiratory quotient of gestating sows	73
Figure 3.10. Daily total heat production rate of gestating sows.	74
Figure 3.11. Daily barn-level latent heat production rate of gestating sows	74
Figure 3.12. Daily barn-level sensible heat production rate of gestating sows	75
Figure 3.13. Daily heat and moisture production of gestating sows vs. daily mean barn temperature.....	76
Figure 3.14. Diurnal patterns of total, latent, and sensible heat production rates.	77
Figure 3.15. Daily respiratory quotient of sows and litters.	79
Figure 3.16. Daily total heat production rate of sows and litters.....	79
Figure 3.17. Daily latent heat production rate of sows and litters.	80
Figure 3.18. Daily sensible heat production rate of sows and litters	80
Figure 3.19. Daily total, latent, and sensible heat production rate of sows and litters.	83
Figure 4.1. Schematic of farrowing rooms for mat vs. lamp comparison.	96
Figure 4.2. Installed localized heating sources in this study.....	98
Figure 4.3. Thermographical images of heat lamps and heat mat	99
Figure 4.4. Average weight gain of piglets	101
Figure 4.5. Mortality rate of piglets	102
Figure 4.6. Diurnal heat mat and heat lamp instantaneous and cumulative power use	103
Figure 4.7. Heat mat and heat lamp daily and cumulative turn power consumption.....	103
Figure 4.8. Power consumption for each turn.	104
Figure 4.9. Heat mat and lamp utilization by piglets from birth to 3d of age.....	106
Figure 4.10. Heat mat and lamp utilization by piglets from 4 to 8 days of age.	106
Figure 4.11. Heat mat and lamp utilization by piglets from 9 to 13 days of age.	107
Figure 4.12. Heat mat and lamp utilization by piglets from 14 to 18 days of age	107
Figure 4.13. Average daily heat source use by piglets by piglet age.	108

Figure 5.1. Absorbance spectra of select compounds.	116
Figure 5.2. Schematic diagram of photoacoustic infrared spectrometer.	118
Figure 5.3. Schematic diagram of Fourier Transform Infrared Spectrometer.	119
Figure 5.4. Fourier transform infrared spectrometer as installed in field.	120
Figure 5.5. Concentrations measured by the FTIR vs. the PAS. Gas sampling time per location: 240s. The FTIR had a sample integration time of 60s and a flow rate of 5 LPM.	124
Figure 5.6. Concentrations measured by the FTIR vs. the PAS. Gas sampling time per location: 240s. The FTIR had a sample integration time of 30s and a flow rate of 5 LPM.	125
Figure 5.7. Concentrations measured by the FTIR vs. the PAS. Gas sampling time per location: 120s. The FTIR had a sample integration time of 30s and a flow rate of 5 LPM.	126
Figure 5.8. Concentrations measured by the FTIR vs. the PAS. Gas sampling time per location: 360s. The FTIR had a sample integration time of 30s and a flow rate of 3 LPM.	127
Figure 5.9. Percent differences between PAS and FTIR for indoor locations	131
Figure 5.10. Absolute differences between FTIR and PAS for ambient air samples	133
Figure 5.11. PAS and FTIR analyzer responses to exposure to NH ₃ . SIT of 30s.	134
Figure 5.12. PAS and FTIR analyzer responses to exposure to NH ₃ . SIT of 30s and 60s ...	135

LIST OF TABLES

Table 2.1. Overview of gaseous emission rates from swine facilities.	12
Table 2.2. Overview of gaseous emission rates from outdoor swine manure storages.	13
Table 2.3. Characteristics of barns and rooms monitored in this study.	14
Table 2.4. Sow body mass by parity for gestating sows.	25
Table 2.5. Daily gas concentrations by gestation barn.	26
Table 2.6. Daily gas concentration by farrowing room.	30
Table 2.7. Mean daily barn emission rates by gestation barn.	34
Table 2.8. Mean daily emission rate for lactating sows and litters.	38
Table 2.9. Average daily gaseous flux and emission rates from external manure storage.	43
Table 2.10. Barn and swine operation-level mean emission rate.	45
Table 2.11. Swine operation emission partitioning.	45
Table 3.1. Selected pig heat and moisture production rate literature values.	58
Table 3.2. Characteristics of barns and rooms monitored in this study.	60
Table 3.3. Sow body mass by parity for gestating sows.	71
Table 3.4. Summary of diurnal heat and moisture production rates for gestating sows.	75
Table 3.5. Summary of diurnal heat and moisture production rates for lactating sows.	81
Table 3.6. Gestating sow heat and moisture production rate comparison to Standards.	84
Table 3.7. Lactating sow heat and moisture production rate comparison to Standards.	85
Table 4.1. Average temperature and RH near the mats and lamps.	100
Table 4.2. Room and surface temperature of heat mats or heat lamps.	105
Table 4.3. Summary of heat source usage for each production stage.	109

Table 5.1. PAS optical filter output wavelengths and detection limits.	116
Table 5.2. Detection limits of FTIR.....	121
Table 5.3. Testing periods for FTIR SIT and duration per sample location.	122
Table 5.4. Summary of linear fit parameters (SE) for FTIR vs. PAS concentrations.....	128
Table 5.5. Response times to 98% of expected concentration (T_{98}) for the PAS and FTIR.	135

ACKNOWLEDGEMENTS

I would like to thank all those who have contributed to my graduate experience and education at Iowa State. First, I would like to thank Dr. Xin for taking on a new graduate student whom he had never met or worked with and finding funding to more than cover my research needs. Your guidance had been invaluable in my growth and the unique experiences you provided (especially the international travel) added so much to my time at Iowa State. I would also like to thank Dr. Burns for starting me in research as an undergrad and for recommending me for graduate work under Dr. Xin. To Dr. Andersen, your patience and enthusiasm for research and learning, dating back to when we sat back-to-back in the grad student office, have been a tremendous example for me to follow. Thank you also to my committee members Drs. Stalder and Trabue. Your input and unique perspectives have helped me to see my work from new angles.

I would like to thank the staff and graduate students that I've had the privilege of working with over the years. Tim, Morgan, Laura, and Hong, your experiences and knowledge made my work a little easier and much more enjoyable. Thank you to all the others who helped with my work through farm visits, fabrication, and data analysis: Matt, Sarah, Jace, Mike, Kyle, Koryne, and Kurt.

Finally, thank you to my family and friends for your love and support. Special thanks to my wife, Niki, who encouraged and pushed me along the way while also adding much needed balance to my life.

CHAPTER 1

GENERAL INTRODUCTION

The U.S. swine industry has undergone significant changes over the past 50 years. The industry has moved from many, smaller scale producers with multiple production stages on one farm to fewer, larger scale producers with production stages separated out to multiple farms. These changes occurred due to many factors, including reduced profit margins, producer specialization and consolidation. In recent years, the high feed costs, high startup costs, and market risk have made finishing contracts a popular business model in the industry, which means more hogs are owned by fewer producers. As pig production has consolidated, large sow facilities have become more common to allow resource concentration (e.g. labor and expertise) and fewer physical locations. These large sow farms have environmental concerns at the animal, barn, and ecosystem level. Maintaining ideal environment for the animals is critical to maximize animal comfort and production. One component of animal environment is air quality. Air quality is a concern for the environment, and both human and animal health, and is dependent on the ventilation system design and performance, manure handling, and building management.

Air quality

An increasingly important air quality concern is aerial emissions from the facility. Ammonia (NH_3) is usually of concern for its potential negative impacts on ecological systems due to wet and/or dry depositions. When ammonia is deposited onto the soil

nitrification occurs and leads to soil acidification and potential nutrient imbalances of Ca, K, and Mg. (Harper et al., 2000). The three major greenhouse gasses (GHGs) of concern in terms of having potential to affect climate variability are carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄). The US EPA estimates that agriculture is responsible for 8.1% of the total GHG emissions in the US (2014 US Greenhouse Gas Inventory Report). However, limited emissions data are available for the breeding/gestation and farrowing stages of production, especially for Iowa weather and production methods. With the US breeding pig inventory at 5.85 million head as of March 28, 2014 and Iowa leading the US with over 17% of the breeding inventory (USDA NASS, 2014), there is a need for accurate emission factors under Iowa conditions to improve the national inventory estimates of air emissions from animal production systems. As mitigation technologies are developed to reduce emissions, having accurate baseline emission rates is essential to evaluate the effectiveness of potential mitigation technologies, and to direct technology development toward the areas of animal production that have the largest emissions footprint.

A new factor that has been affecting change in the industry in recent years is the push for improved animal welfare. This push is from many different groups, including animal rights organizations, retailers, and consumers. One major push the industry is facing is the movement away from gestation stalls toward pen or group housing of sows. The pressure to change is being applied by retailers like McDonald's (Storm, 2013) that are receiving pressure from their consumers and organizations such as the Humane Society of the United States (HSUS) (Walzer, 2011). Additionally, these organizations have been successful

legislatively and obtained bans on gestation crates in the European Union, Florida, Arizona, California, and Rhode Island. Smithfield Farms and Cargill have both stated that their entire sow population will be group housed by 2017. A major issue with this change over is that it is being done for one reason, the perceived improvement in sow welfare. However, the potential impacts in other areas, such as air quality, must also be addressed. Changing the stocking density and activity level of the sows by moving to group housing will require a change in the ventilation system to maintain indoor air quality. Ventilation system design is based on animal heat production (HP) and moisture production (MP) rates. For sows, the current ventilation design standards are based on data from the 1950s and 1970s (Bond et al., 1959; Ota et al., 1975). As sow size, performance, and production practices have changed since those reports were published, it is likely the HP and MP from current sows is different and thus ventilation system design would be improved with updated heat and moisture production rates. Additionally, the sow activity level will impact its HP and MP and thus different production systems (crate vs. pen gestation) will likely have different HP rates and different stocking densities that will affect the overall ventilation design. Furthermore, the increased sow productivity (piglets/litter) since the previous studies likely means the HP and MP for lactating sows and litters have changed. Thus, updated rates are needed to allow for correct ventilation system design.

The farrowing environment

Conventional farrowing stalls are the most prevalent indoor systems in the U.S. today, representing approximately 85% of the swine industry (Marchant-Forde, 2011). In

addition to reducing piglet mortality, conventional farrowing stalls have made sow management easier and more effective and allows for a higher sow stocking density per land unit (Fraser & Broom, 1997). However, the basic farrowing crate design has changed little since the Midwest Plan Service Swine Housing and Equipment Handbook (MWPS, 1983) published recommendations for farrowing crate design. This is a concern as from 2007 to 2012, the U.S. swine industry averages for the total born and number born alive increased by 1.1 and 1.2 piglets per sow per farrowing event, respectively. However, in that same time span the average number of piglets weaned per litter has only increased by 0.8 piglets while the pre-weaning mortality has increased from 14.2% to 15.5% (Stalder, 2013). This may indicate that the current farrowing crate is inadequate either in creep area or heated creep area to accommodate the larger litter sizes. Producers have started moving towards larger farrowing stalls to accommodate the larger sows and litters. However, increasing the space quantity is not necessarily the same as improving the space quality. To understand space quality and quantity needs, quantification of sow production performance and behavior is needed. Products are available to producers that provide a larger heated area for the piglets. However, the impact on piglet performance and behavior of an expanded heat source needs to be quantified to allow for informed producer decision making.

To address the questions on current breeding/gestation and farrowing environments the studies detailed in this dissertation were developed. The objectives of the studies in this dissertation were to:

- Quantify NH_3 and GHG concentrations and emissions of a swine breeding-gestation-farrowing system in the Midwest U.S. over an extended (2-year) period.
- Quantify total heat production rate (THP) of breeding/gestating sows and lactating sows with litters that is partitioned into barn-level sensible heat production rate (SHP) and latent heat production or moisture production rate (LHP, MP).
- Compare heat mat vs. heat lamp as localized heating source for swine farrowing with regards to piglet performance (mortality, body weight gain), electric power usage, and heat source utilization by the piglets.
- Compare a Fourier Transform infrared spectrometer (FTIR) and a photoacoustic infrared spectrometer (PAS) for field measurements of gaseous concentrations at the swine production facility.

Organization of Dissertation

This dissertation is comprised of four papers that correspond to the respective research objectives. The papers are the result of 33 months of continual monitoring at a commercial swine breeding-gestation-farrowing facility. The first paper characterizes the gaseous concentrations and emissions of two breeding/gestation barns, two farrowing rooms, and external manure storage for a 29-month period. These data fill a gap in the U.S. NH_3 and GHG emissions inventory. The second paper quantifies the heat and moisture production

rates of breeding/gestating sows and lactating sows with litters for a 16-month period. These data will help updating the standards for engineering design and operation of modern swine housing. The third paper compares heat mat vs. heat lamp as localized heating source for prewean piglets for three farrowing rooms over a 12-month period (16 farrowing cycles). The fourth paper compares two gas analyzers, a Fourier transform infrared spectrometer (FTIR) and a photoacoustic infrared spectrometer (PAS), for the field measurement of NH₃ and GHG concentrations over a 5-month period in a swine facility.

References

EPA. 2014. Inventory of Greenhouse Gas Emissions and Sinks: 1990-2005. Washington, DC. United States Environmental Protection Agency.

Fraser, A.F. and Broom, D.M. 1997. Pig welfare problems. In: Farm Animal Behaviour and Welfare pp 358-369. CAB INT, Norton, U.K..

Harper, L.A., R.R. Sharpe, and T.B. Parkin. 2000. Gaseous nitrogen emissions from anaerobic swine lagoons: ammonia, nitrous oxide, and dinitrogen gas. Journal of Environmental Quality 29: 1356-1365.

Marchant-Forde J. 2011. Swine Welfare Factsheet. USDA-ARS-MWA Livestock Behavior Research Unit. Summer 2011.

Midwest Plan Service Swine Housing and Equipment Handbook. 1983. Midwest Plan Service, Iowa State University, Ames, Iowa.

Stalder, K. J. 2013. Pork Industry Productivity Analysis. National Pork Board. Des Moines, IA.

Storm, Stephanie. 2012. McDonald's set to phase out suppliers' use of sow crates. *The New York Times*. February 13, 2012.

USDA, 2014. Quarterly Hogs and Pigs. USDA Reference No. 1949-1921. United States Department of Agriculture and National Agriculture Statistics Service.

Walzer, Philip. 2011. Smithfield to end use of gestation crates by 2017. *The Virginian-Pilot*. December 9, 2011.

CHAPTER 2

**AMMONIA AND GREENHOUSE GAS CONCENTRATIONS AND EMISSIONS OF
A MODERN U.S. SWINE BREEDING-GESTATION-FARROWING SYSTEM**

J.P. Stinn, H. Xin, T.A. Shepherd, H. Li, and R.T. Burns

A manuscript being reviewed for publication in *Atmospheric Environment*

Abstract

Aerial emissions from livestock production continue to be an area of attention and concern for both the potential health and environmental impacts. However, information of gaseous, especially greenhouse gas (GHG), emissions for swine breeding/gestation and farrowing production systems is meager. The purpose of this study was to quantify ammonia (NH₃), carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄) concentrations and emissions from a modern breeding-gestation-farrowing system located in central Iowa, USA. A 4,300-sow farm was selected for the extensive field monitoring which employed a Mobile Air Emission Monitoring Unit equipped with state-of-the-art gas analyzers and a data acquisition system. The monitored portion of the facility consisted of a deep-pit breeding/early gestation (B/EG) barn (1800 head), the deep-pit late gestation (LG) barn (1800 head), and two shallow-pit (pull-plug) farrowing rooms (40 head per room). A dynamic flux chamber was used to monitor gaseous emissions from the external manure storage for the farrowing rooms. Data were collected for 29 consecutive months (January 2011 through June 2013). Daily indoor NH₃, CO₂, N₂O, and CH₄ concentrations (ppm, mean

±SD) were 12.0 (±7.6), 1594 (±797), 0.31 (±0.11), and 28.5 (±9.8), respectively, in the breeding/gestation barns; and 9.7 (±4.1), 1536 (±701), 0.30 (±0.10), and 78.3 (±37), respectively, in the farrowing rooms. Daily emissions per animal unit (AU, 500 kg live weight) were 35.1 g NH₃, 7.46 kg CO₂, 0.17 g N₂O, and 263.4 g CH₄ for sows in the B/EG barn; and 28.2 g NH₃, 6.50 kg CO₂, 0.12 g N₂O, and 201.3 g CH₄ for sows in the LG barn. The average daily emissions per AU (sow and piglets) of the farrowing rooms during the lactation period (birth to weaning) were: 59.7 g NH₃, 16.4 kg CO₂, 0.73 g N₂O, and 107 g CH₄. For the monitored period, the external manure storage had the following average daily emission per m² surface area: 1.26 g NH₃, 137 g CO₂, and 94.8g CH₄, which was equivalent to daily emissions per AU in the farrowing rooms of 12.2 g NH₃, 1055 g CO₂, and 867 g CH₄. The swine operation (including manure storage) average daily emissions per AU were 38.5 g NH₃, 8.73 kg CO₂ (including 7.3 kg from animal respiration), 0.25 g N₂O, and 301 g CH₄.

Keywords. Ammonia, Greenhouse Gas, Aerial Emissions, Concentrations, Swine Gestation, Swine Farrowing

Introduction

Gaseous emissions from livestock production have received increasing attention as concern has grown over their environmental and health impacts. It is important to study these emissions to understand the quantity and composition of gasses being emitted to the atmosphere. Local concerns over gaseous emissions are usually focused on the odor and environmental impacts. For example, ammonia (NH₃) is usually of concern for its potential

negative impacts on ecological systems due to wet and/or dry depositions. The three major greenhouse gasses (GHGs) of concern in terms of having potential to affect climate variability are carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄). In order to understand the magnitude of GHG emissions from livestock production, reliable emission factors for different livestock production systems in different geographic/climatic areas must be determined. The US EPA estimates that agriculture is responsible for 8.1% of the total GHG emissions in the US (2014 US Greenhouse Gas Inventory Report). The US breeding pig inventory was 5.85 million head as of March 28, 2014 and Iowa leads the US with over 17% of the breeding inventory (USDA NASS, 2014). Currently, limited emissions data are available for the breeding/gestation and farrowing stages of production. As mitigation technologies are developed to reduce emissions, having accurate baseline emission rates is essential to evaluate the effectiveness of potential mitigation technologies, and to direct technology development toward the areas of animal production that have the largest emissions footprint. An overview of emission rates reported in literature is provided in Table 2.1. The studies are difficult to compare as they represent different climatic/geographic areas, manure management, and production strategies. Additionally, the frequency and intensity of the measurements in each study vary considerably.

The flux of gases from the manure is impacted by factors including temperature (Khan et al., 1997), wind speed (Sebacher et al., 1983), exposed surface area, manure pH, and manure volume (Park et al., 2006). Quantifying the impact of these factors on emissions reported in literature (table 2.2) is challenging as manure storage emissions have been

monitored with several methods, including flux chambers, micrometeorological mass balance (MMB), and open-path (path integrated) systems.

The objective of this study was to quantify concentrations and emissions of GHG and NH_3 from a modern U.S. breeding-gestation-farrowing system over an extended period. In doing so, house temperatures, relative humidity (RH) and ventilation rates (VR) were also determined on continuous basis. Results of this study will contribute to establishing or improving the baseline GHG and NH_3 emissions data for swine production cycle under the U.S. production conditions. Twenty-nine consecutive months were monitored continuously, from January 2011 to June 2013.

Table 2.1. Overview of ammonia (NH₃), carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) emission rates from swine gestation and farrowing facilities.

Production Stage	Manure Collection System	Location	Emission Rate, g d ⁻¹ AU ⁻¹				Source
			NH ₃	CO ₂	CH ₄	N ₂ O	
Gestation	Deep-pit	Iowa	34.7 and 59.0	--	--	--	Cortus et al., 2010a
Gestation	Recharge, 1 wk	Oklahoma	23.1 and 24.0	--	--	--	Cortus et al., 2010b
Gestation	Slatted Floor	Europe	22.3 to 40.8	--	--	--	Groot Koerkamp et al., 1998
Gestation	Deep-pit	North Dakota	32.4	--	--	--	Rahman et al., 2012
Gestation	Pull-plug, 3 wk	North Dakota	11.5	--	--	--	Rahman et al., 2012
Gestation	Deep-pit	Minnesota	2.2	--	--	--	Zhu et al., 2000
Gestation	Immediate Removal	China	--	5,920	9.6	0.75	Dong et al., 2007
Gestation	Slatted Floor	Canada	--	10,500 and 13,450	35 and 135	0	Lague et al., 2004
Gestation	Flushed, 1 wk	Canada	--	4808 and 11,514	73 and 118	--	Zhang et al., 2007
Farrowing	Pull-plug, 3 wk	Iowa	17.9	--	--	--	Cortus et al., 2010a
Farrowing	Recharge, 2.5 wk	Oklahoma	37.9	--	--	--	Cortus et al., 2010b
Farrowing	Slatted Floor	Europe	63.2	--	--	--	Groot Koerkamp et al., 1998
Farrowing	Pull-plug, 3 wk	North Dakota	3.3 and 5.4	--	--	--	Rahman et al., 2012
Farrowing	Deep-pit	Minnesota	42.8	--	--	--	Zhu et al., 2000
Farrowing	Immediate Removal	China	--	7,490	9.6	0.54	Dong et al., 2007
Farrowing	Slatted Floor	Canada	--	18,400 and 24,600	50 and 315	0 and 0	Lague et al., 2004
Farrowing	Pull-plug, 1 wk	North Carolina	--	--	728	--	Sharpe et al., 2001
Farrowing	Flushed, 3 wk	Canada	--	11,576 and 16,588	184 and 351	0 and 0	Zhang et al., 2007

Table 2.2. Overview of emission rates of ammonia (NH₃), carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) from outdoor swine manure storages.

Manure Storage Type	Measurement Method	Location	Flux, g d ⁻¹ AU ⁻¹				Source
			NH ₃	CO ₂	CH ₄	N ₂ O	
Anaerobic Lagoons	Chamber	North Carolina	--	--	1.93	--	Aneja et al., 2000
Tank	Chamber	Denmark	0.02 to 0.29	--	--	--	Husted et al., 1994
Tank	Chamber	Canada	--	5.89	1.9	0	Lague et al., 2005
Anaerobic Lagoons	MMB ^a	Georgia	0.0065 to 0.204	0.0004 to 0.03	0.005 to 0.52	0 to 0.013	Harper et al., 2000
Anaerobic Lagoons	MMB ^a	Canada	--	--	0 to 1.62	0 to 1.22	Park et al., 2006
Tank	MMB ^a	Georgia	--	--	0.19 to 0.25	--	Sharpe et al., 1999
Tank	MMB ^a	Canada	--	--	0.08 to 3.8	0 to 0	Wagner-Riddle et al., 2006

^aMMB=Micrometeorological Mass Balance

Materials and Methods

Site Description

A 4,300-sow (PIC genetics) capacity breeding-gestation-farrowing facility located in central Iowa was used in this field monitoring study (fig. 2.1, table 2.3). The facility consisted of two farrowing barns with nine farrowing rooms each, a breeding/early gestation (B/EG) barn, a late gestation (LG) barn and an external above-ground manure storage tank for the farrowing operation. The farrowing rooms (fig. 2.2) each measured 15.5 m L × 13.9 m W (50 ft L × 45 ft W) and utilized a shallow pull-plug manure pit (0.61 m or 2 ft deep) that was drained after every turn (approx. 21 days) into an external storage tank (48.8 m diameter and 4.6 m deep). Each room had 40 farrowing crates arranged in four rows. Sows were moved into the rooms at 2 to 4 days preparturition. Piglets were weaned at 18 to 20 days of age typically, at which time the rooms were depopulated and cleaned by power washing.

One, 66,000 W (225,000 Btu hr⁻¹) unvented LP heater provided supplemental heat in each room. Water was supplied through nipple drinkers. The nine rooms in each farrowing building shared a common hallway that tempers the incoming air by heating in winter and evaporative cooling in summer. Ventilation for each room was provided by two 0.3m (12 inch) single-speed, two 0.6m (24 inch) variable-speed, one 0.91m (36 inch) single-speed, and one 1.2m (48 inch) single-speed exhaust fans that were controlled to operate in stages.



Figure 2.1. The breeding-gestation-farrowing facility aerial view for the farm monitored in a study evaluating gaseous emissions from a swine operation.

Table 2.3. Characteristics of barns and rooms monitored in this study.

Designation	B/EG	LG	F1	F2
Barn/Room Name	Breeding/Early Gestation	Late Gestation	Farrowing Room 1	Farrowing Room 2
Production Stage	Weaned - Day 40	Day 41-Day 111	Day 112 - Wean	Day 112 - Wean
Barn Dimensions, L×W×H	121.9m × 30.5m × 2.7m	121.9m × 30.5m × 2.7m	15.5m × 13.9m × 2.7m	15.5m × 13.9m × 2.7m
Capacity	1800 sows	1800 sows	40 sows and litters	40 sows and litters
Manure Pit Depth	3.05m	3.05m	0.61m	0.61m
Manure Removal Frequency	Semi-annual	Semi-annual	Between Cycles (20-22d)	Between Cycles (20-22d)
Pit Fan Number and Diameter	12×0.61m	12×0.61m	2×0.3m	2×0.3m
Wall Fan Number and Diameter	15×1.37m	15×1.37m	2×0.6m; 1×0.91m; 1×1.2m	2×0.6m; 1×0.91m; 1×1.2m

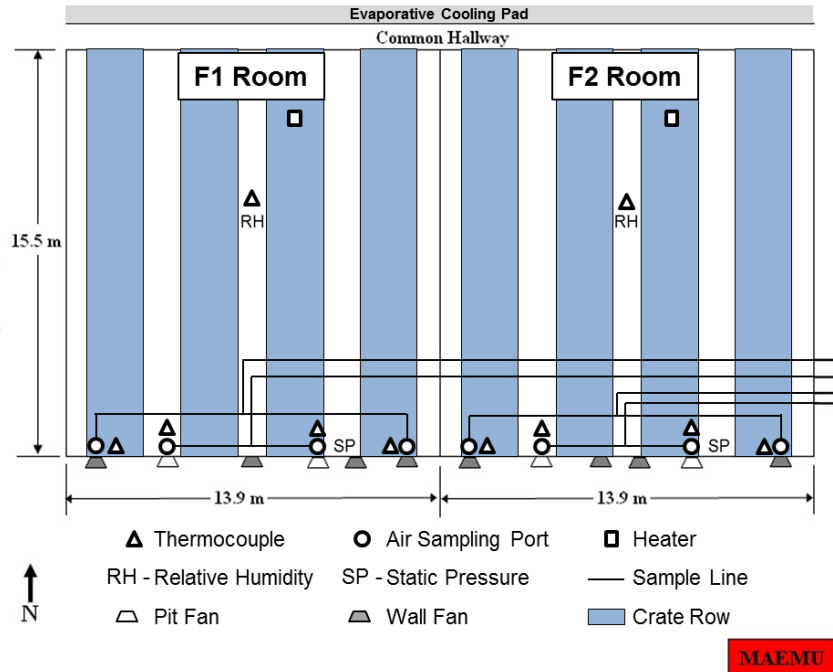


Figure 2.2. Farrowing room (F1 and F2) schematic drawing showing air sampling, temperature, static pressure, and relative humidity measurement locations from a study evaluating gaseous emissions from a swine operation.

The B/EG barn and the LG barn had the same dimensions, ventilation design, and 1800-head capacity each (fig. 2.3). Sows were housed in the B/EG barn post weaning until approximately day 40 of gestation. They were then housed in the LG barn until 2 to 4 days preparturition. In both barns the sows were housed in individual stalls 2.1 m L × 0.61 m W (7 ft L × 2 ft W). Each barn utilized a below slat deep manure pit 3.05 m (10 ft) in depth for manure storage. The deep-pit storages were emptied semi-annually, in the fall and spring. The barns had dimensions of 121.9m L × 30.5m W (400 ft L × 100 ft W) and used mechanical ventilation year round. Each barn had twelve, 0.61m (24 inch) pit fans spaced along the length of the barns and fifteen, 1.37m (52 inch) fans on the west walls. The pit fans provided low stage ventilation while the wall fans provided tunnel ventilation during warm weather. Bi-flow actuated ceiling inlets were used for lower ventilation stages. Evaporative

cooling pads on the east walls cooled incoming air during hot weather. Ten, 66,000 W (225,000 Btu hr⁻¹) unvented LP heaters provided supplemental heat in each barn. Water was supplied through common water troughs that ran the length of the buildings.

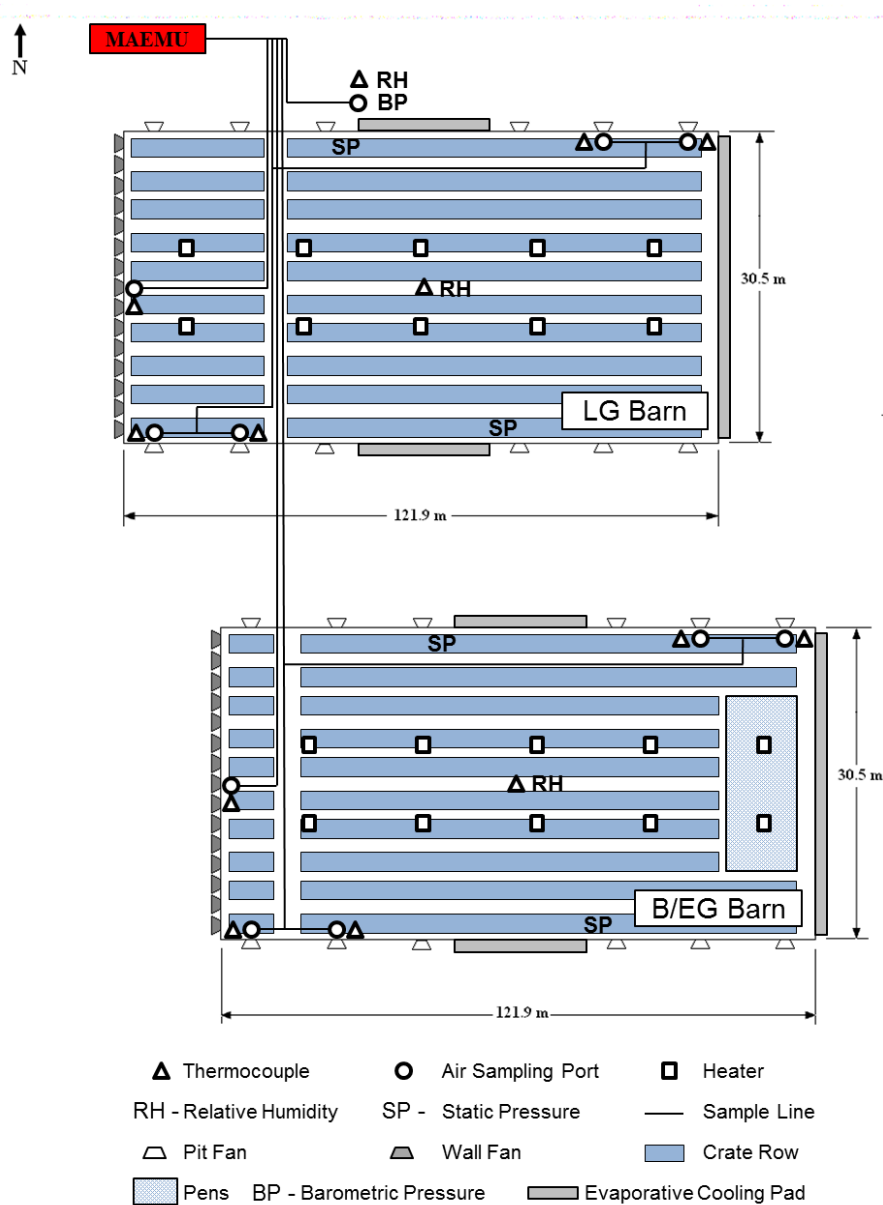


Figure 2.3. Breeding/early gestation (B/EG) and late gestation (LG) barn schematic drawing showing air sampling, temperature, static pressure, relative humidity, and barometric pressure measurement locations from a study evaluating gaseous emissions from a swine operation.

The sows were fed a corn/soy diet that was adjusted based on production stage and body condition. For gestating sows, the ration had a metabolic energy (ME) content of 3095 kcal/kg and a crude protein (CP) content of 21.04%. Gestating sows were fed once a day (07:00h). Gestating sows with body condition score 1 (skinniest sows) were fed 4.5 kg per day and condition score 3 sows (heaviest) were fed 1.8 kg per day. Condition 2 sows were fed 2.3 to 3.2 kg of feed per day depending on gestation status. Once the gestating sows were moved to the farrowing rooms approximately 2 to 4 days before farrowing, they were fed 1.8 kg per day until farrowing. For lactating sows (post farrowing) ME content was 3278 kcal/kg and CP content was 21.14%. Lactating sows were fed four times per day (00:00, 09:00, 12:00, and 18:00h) with each feeding at up to 3.6 kg for a maximum daily feed intake of 14.5 kg.

Instrumentation and Measurement System

A Mobile Air Emissions Monitoring Unit (MAEMU) was used to continuously collect data on gaseous concentrations, thermal conditions, and operational status of the ventilation fans from the previously described barns and farrowing rooms. A detailed description of the MAEMU and its standard operation protocols can be found in Moody et al. (2008). The MAEMU housed, among other measurement and data acquisition equipment, a photoacoustic multi-gas analyzer (INNOVA Model 1412, INNOVA AirTech Instruments

A/S, Ballerup Denmark¹) to measure NH₃, CO₂, N₂O, and CH₄ concentrations and dew point. The multi-gas (INNOVA) analyzer was challenged weekly and calibrated as needed. A positive pressure gas sampling system was housed in the MAEMU and was controlled by the data acquisition system (fig. 2.4). There were a total of 18 in-barn sample locations which, when composited based on barn and fan stage, resulted in eight in-barn samples plus one ambient sample location. Pit fan sampling ports were located below the slats/floor in the deep-pit head space directly under each pit fan in the pump out accesses. Wall fan sampling ports were located approximately 1.0 m in front of each wall fan. The sample port locations were chosen to best represent the exhaust air leaving each barn/room. The sample lines were fluorinated ethylene propylene (FEP) Teflon tubing and were equipped with a dust filter (3011 NAPA, Atlanta, Georgia, USA) and a 47mm filter membrane (5 to 6 µm, Savillex, Eden Prairie, Minnesota, USA) to prevent particles from clogging the tubing or damaging a gas analyzer. All filters, sample lines, and sample pumps were checked weekly for leaks or blockages and addressed as needed. To ensure accurate gas concentration measurement given the response time of the analyzers, each location was sampled for 8 min, with the first 7.5 min for instrument stabilization and the last 0.5 min readings for measurement. Each in-barn location was sampled sequentially so that sampling a complete round of the barn locations took 64 min. An ambient sample was taken at a less frequent rate (every 128 min) due to the relative stability of its composition.

¹ Mention of company or product names is for presentation completeness, and does not represent endorsement by the authors or their affiliated institutions, nor does it imply exclusion of other suitable products.

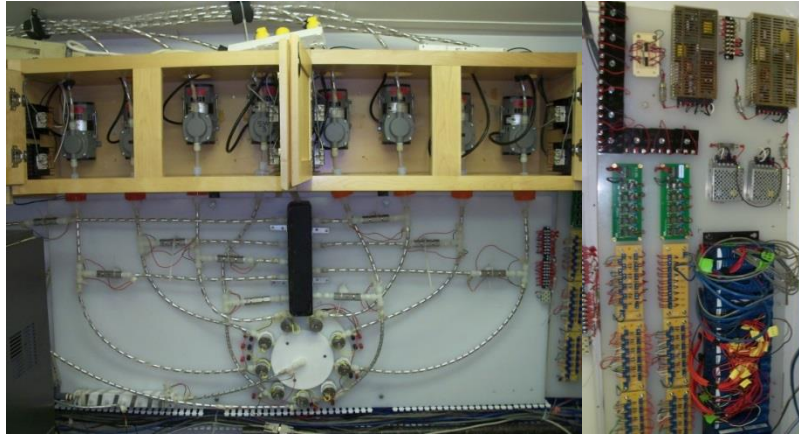


Figure 2.4. Gas, dew point, and building measurement and monitoring system: positive pressure gas sampling system (left) and data acquisition system (right).

Selected fans representing each ventilation stage (at least 50% of each stage fans) were calibrated *in situ* at multiple operating points using a Fan Assessment Numeration System (FANS) (Gates et al., 2004) to develop performance curves (fig 2.5). *In situ* calibrations occurred semi-annually to quantify any changes in fan performance due to degradation or maintenance. Measured changes in fan performance were then incorporated into the data processing program by interpolating between fan performance curves on a monthly basis. The on/off status of each fan was monitored continuously by an inductive current switch on the fan motor's power cord (Muhlbauer et al., 2011) with its analog output connected to the data acquisition system. The speed of each variable-speed fan was measured by Hall Effect speed sensors (GS100701, Cherry Corp, Pleasant Prairie, Wisconsin, USA). Static pressure sensors (Model 264, Setra, Boxborough, Massachusetts, USA) were located near the south wall of each farrowing room and near the middle of the north and south walls in the B/EG and LG barns (fig. 2.2 and 2.3).

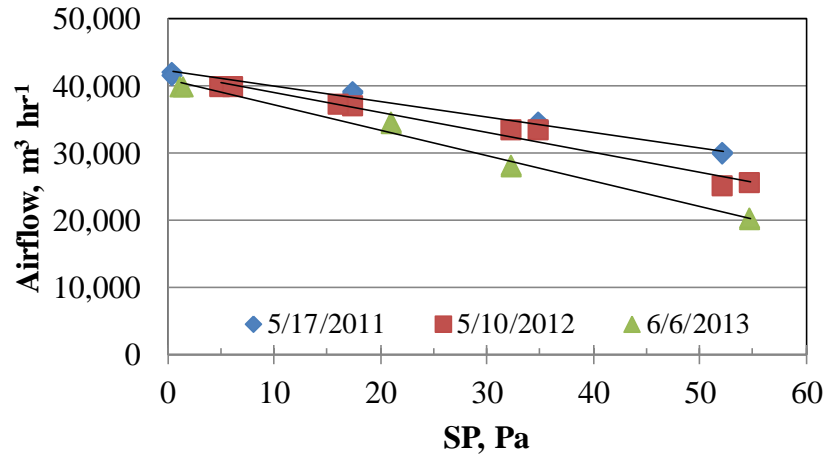


Figure 2.5. The *in-situ* ventilation fan calibration device used to determine air flow rate of the exhaust fans (left) and example performance curves for the same fan measured at intervals during the project.

Two farrowing rooms (F1 and F2) were selected for monitoring (fig. 2.2). A composite air sample was taken from each pit fan, and a second composite sample was taken from the two lowest stage wall fans. The B/EG and LG barns were sampled and monitored identically (fig. 2.3). Namely, exhaust air samples from each barn were drawn as a composite from four of the lowest ventilation stage pit fans with a second sample being drawn from the lowest stage endwall fan. Air temperature, relative humidity (RH), static pressure (SP), fan operation status, heater operation status, and barometric pressure were measured and recorded at 1s intervals. The data were then averaged over 30 s to match the sampling frequency of the INNOVA. Gaseous emission rates were calculated every 30 s and used to determine the daily emissions of each gas.

The emission rates are calculated for the entire barn or room. The population of animals in the monitored barns or rooms was recorded by farm staff and conveyed to the research team. Additionally, sow and piglet weights were collected to allow for calculation of the specific emission rates (per AU, AU = animal unit = 500 kg live body mass). As part of a

separate project, piglet weights were taken on day 1 or 2 and at weaning, with selected litters weighed at 6 day intervals from birth to weaning. This allowed for the development of a piglet growth curve. Sow weights were collected from a group of 75 sows entering farrowing and post wean. Selected sows from each parity were also weighed at day 7 and day 14 post parturition. From these sow weights and piglet weights, curves were developed to span the farrowing/lactation cycle.

The external manure storage had a diameter of 48.8m and a depth of 4.57m, but management controlled the manure depth below 3.05m until the last three months of the study. Manure originated in the farrowing rooms and was added every day from the farrowing room that was being weaned. The storage was pumped twice a year, in the fall and spring. A dynamic flux chamber system (DFC) was developed similar to that described by Acevedo et al. (2009). In short, the DFC was made of a 0.32 m diameter semi-spherical stainless steel vessel with a volume of a 12.3 L (fig. 2.6). The DFC had an internal sample port and an adjustable exhaust valve located at the top of the vessel. It also had four air inlet ports that split from one line, equally distributed along the perimeter of the vessel positioned to form a race-track airflow pattern for good air mixing inside the DFC. Air flow to and from the chamber was carried through 45 m of Nalgene tubing with sample pumps and flow meters maintaining airflow of 6 L min⁻¹ (30 air changes per hour). The flux chamber was floated on the manure surface for a range of ambient conditions. Gas concentrations entering and exiting the chamber were measured with an INNOVA 1412 photoacoustic analyzer.

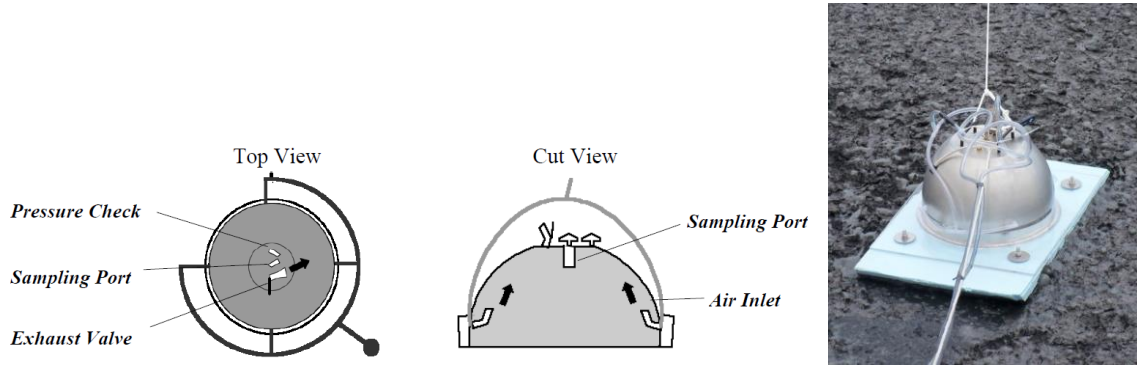


Figure 2.6. Dynamic flux chamber system schematic (left) and floating on manure in outside storage (right).

Gaseous Emission Rate Determination

Emission rates from the barns for each monitored constituent were calculated as mass of the gas emitted per unit time using the following equation:

$$ER_G = \sum Q \left([G]_e - \frac{\rho_e}{\rho_i} [G]_i \right) * 10^{-6} * \frac{T_{std}}{T_a} * \frac{P_a}{P_{std}} * \frac{w}{V} \quad (1)$$

Where ER_G = Gas emission rate for the house, $g \text{ hr}^{-1} \text{ house}^{-1}$

Q = Exhaust ventilation rate of the house at field temperature and barometric pressure, $m^3 \text{ hr}^{-1} \text{ house}^{-1}$

$[G]_i, [G]_e$ = Gas concentration of incoming and exhaust ventilation air, respectively, ppm_v

W = Molar weight of the gas, $g \text{ mole}^{-1}$ (e.g., 17.031 for NH_3)

V = Molar volume of gas at standard temperature (0°C) and pressure (101.325 kPa), $0.022414 \text{ m}^3 \text{ mole}^{-1}$

T_{std} = Standard temperature, 273.15 K

T_a = Ambient air temperature, K

ρ_i, ρ_e = Density of incoming and exhaust air, respectively, $g \text{ cm}^{-3}$

P_{std} = Standard barometric pressure, 101.325 kPa

P_a = Atmospheric barometric pressure at the monitoring site, kPa

Emission flux rates (F) from the manure storage vat were calculated as mass of gas emitted per unit time by unit surface area using the following equation (Acevedo et al., 2009):

$$F = Q_c([C]_e - [C]_i) * 10^{-6} * \frac{T_{std}}{T_a} * \frac{P_a}{P_{std}} * \frac{w}{V} * \frac{1}{A_c} \quad (2)$$

Where F = Flux, g hr⁻¹ m⁻²

Q_c = Incoming flow rate of the chamber, L min⁻¹

$[G]_i$, $[G]_e$ = Gas concentration of incoming and exhaust ventilation air, respectively, ppmv

W = Molar weight of the gas, g mole⁻¹ (e.g., 17.031 for NH₃)

V = Molar volume of gas at standard temperature (0°C) and pressure (101.325 kPa), 0.022414 m³ mole⁻¹

T_{std} = Standard temperature, 273.15 K

T_a = Sample air temperature, K

P_{std} = Standard barometric pressure, 101.325 kPa

P_a = Atmospheric barometric pressure at monitoring site, kPa

A_c = Area covered by the flux chamber, 0.0804 m²

The site was visited each week for quality assurance. Temperature, RH, and pressure sensors were checked for reasonable values and replaced as needed. Sampling pumps and valves were checked for flow, leaks, and correct switching. Fans were checked for operational status and sampling ports were checked for flow rate, with filters changed as

needed. The INNOVA analyzer was challenged against span gases and a zero gas. If the INNOVA was not within 5% of expected values it was recalibrated. More detailed descriptions of site visit procedures were described in the quality assurance project plan (QAPP) (Moody, et al., 2008) that this project also followed.

For each day of the 29-month monitoring (January 2011 to June 2013), data completeness was defined as at least 75% of the possible data points in one day meeting the quality control criteria. Data for a portion of a day might be missing due to instrument maintenance, malfunction, or site activity (e.g., washing down farrowing rooms). Data associated with the days that did not meet these completeness criteria were excluded from the analysis.

Results and Discussion

Daily gaseous emission rates were deemed valid 751 out of 873 monitored days, yielding an overall data completeness of 86%. Except where noted, CO₂ emissions reported in this paper include CO₂ from animal respiration. The CO₂ produced by manure was estimated as 2% of the barn or room level CO₂ production based on flux chamber measurements on the deep-pit manure surface and measurements of an empty farrowing room with full shallow-pit. Figure 2.7 shows the average body mass (BM) of a sow and litter vs. day of the farrowing cycle, with day 0 being the day of parturition. Table 2.4 shows the sow BM in the B/EG and LG barns for each parity. The average BM for each barn was calculated based on the parity distribution provided by the producer. The average BM (lower

and upper limits of 95% CI) of sows was 204 kg (197 and 210) in the B/EG barn and 219 kg (213 and 225) in the LG barn.

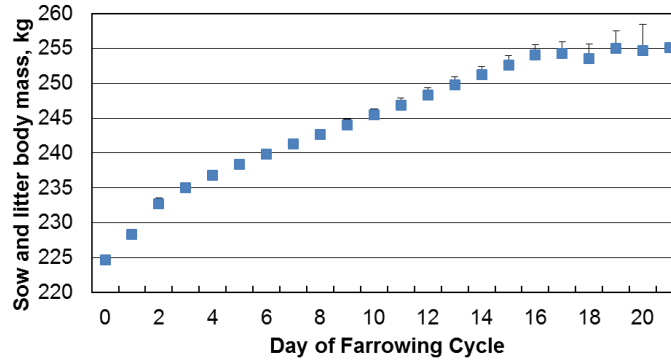


Figure 2.7. Lactating sow and litter body mass (BM) curve [$\text{kg (sow+litter)}^{-1}$] during the monitoring period (mean \pm SE) in a study measuring gaseous emissions in a swine facility.

Table 2.4. Sow body mass (BM, kg sow^{-1}) by parity and average BM based on the parity distribution for breeding/early gestation (B/EG) and late gestation (LG) barns in a study measuring gaseous emissions in a swine facility.

Production Stage	Variable	Parity							Avg. BM
		0	1	2	3	4	5	≥ 6	
	Population Distribution	8%	22%	20%	18%	13%	10%	9%	
B/EG	BM (kg sow^{-1})	140	179	202	210	231	231	242	204
	SE	6.5	5.8	5.4	12.8	7.3	8.3	10.2	3.2
LG	BM (kg sow^{-1})	173	201	211	230	237	242	247	219
	SE	6.5	7.1	6.8	8.5	7.6	7.7	10.2	3.0

Indoor Air Quality

B/EG and LG Barns

Figure 2.8 depicts the profiles of air temperature, RH, and ventilation rate (VR) of the B/EG and LG barns. The barns held a fairly constant temperature except during the summer months when, despite using evaporative cooling pads, the barns experienced a slight rise in temperature. The indoor RH was typically between 40% and 60%, except during the summer

months when evaporative cooling pad use increased the barn humidity. The VR was typically between 25 and 300 m³ hr⁻¹ head⁻¹, which is slightly higher than the recommended 20 and 255 m³ hr⁻¹ head⁻¹ (MWPS-1, 1983). Ambient temperature influences VR and thus indoor gaseous concentrations. The NH₃, CO₂, and CH₄ concentrations decreased with increasing ambient temperature. The daily N₂O concentrations showed a quadratic relationship to ambient temperature, with minimum concentrations near 10°C. This is likely due to the higher H₂O levels during warmer periods cross-interfering with N₂O measurements. Figure 2.9 shows these trends.

The daily concentration values for the B/EG barn, LG barn, and gestation barn average are summarized in Table 2.5. Neither the B/EG barn nor the LG barn exceeded OSHA 8-hour time weighted average concentrations of 50 ppm for NH₃ and 10,000 ppm for CO₂. The average daily NH₃ concentrations did exceed 25 ppm on 1 day in the B/EG barn. Overall daily gas concentrations for the breeding/gestation barns were 9.7, 1536, 0.30, and 78.3 ppm for NH₃, CO₂, N₂O, and CH₄, respectively.

Table 2.5. Daily concentrations [mean (SD)] for the breeding/early gestation (B/EG) and late gestation (LG) barns and overall.

Source	Gas Concentration, ppm			
	NH ₃	CO ₂	N ₂ O	CH ₄
B/EG	9.7 (4.3)	1530 (704)	0.30 (0.10)	78.9 (38.6)
LG	9.7 (3.9)	1542 (698)	0.30 (0.09)	77.7 (35.5)
Overall	9.7 (4.1)	1536 (701)	0.30 (0.10)	78.3 (37.0)

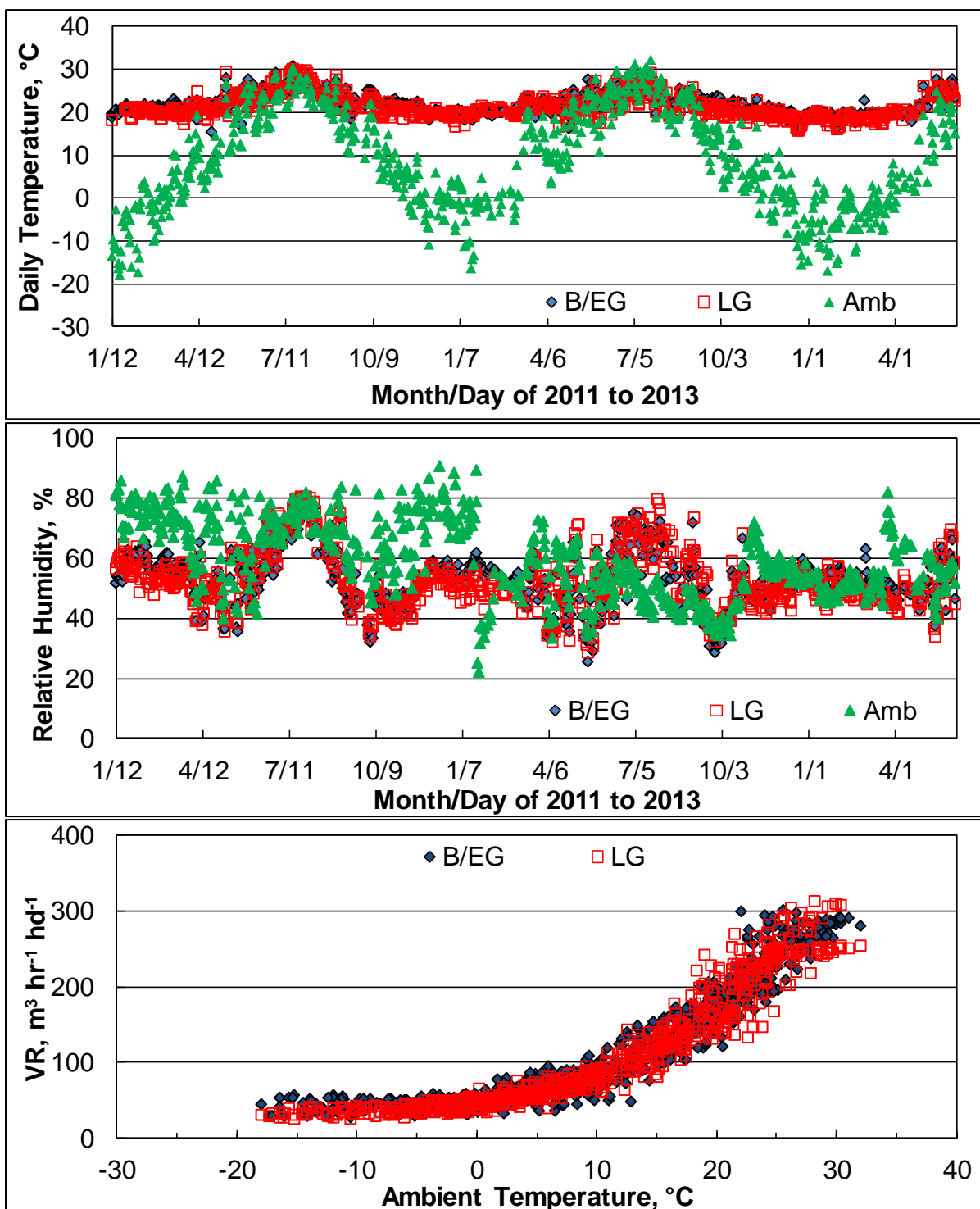


Figure 2.8. Daily temperature, relative humidity, and ventilation rate (VR) of the breeding/early gestation (B/EG) and late gestation (LG) barns.

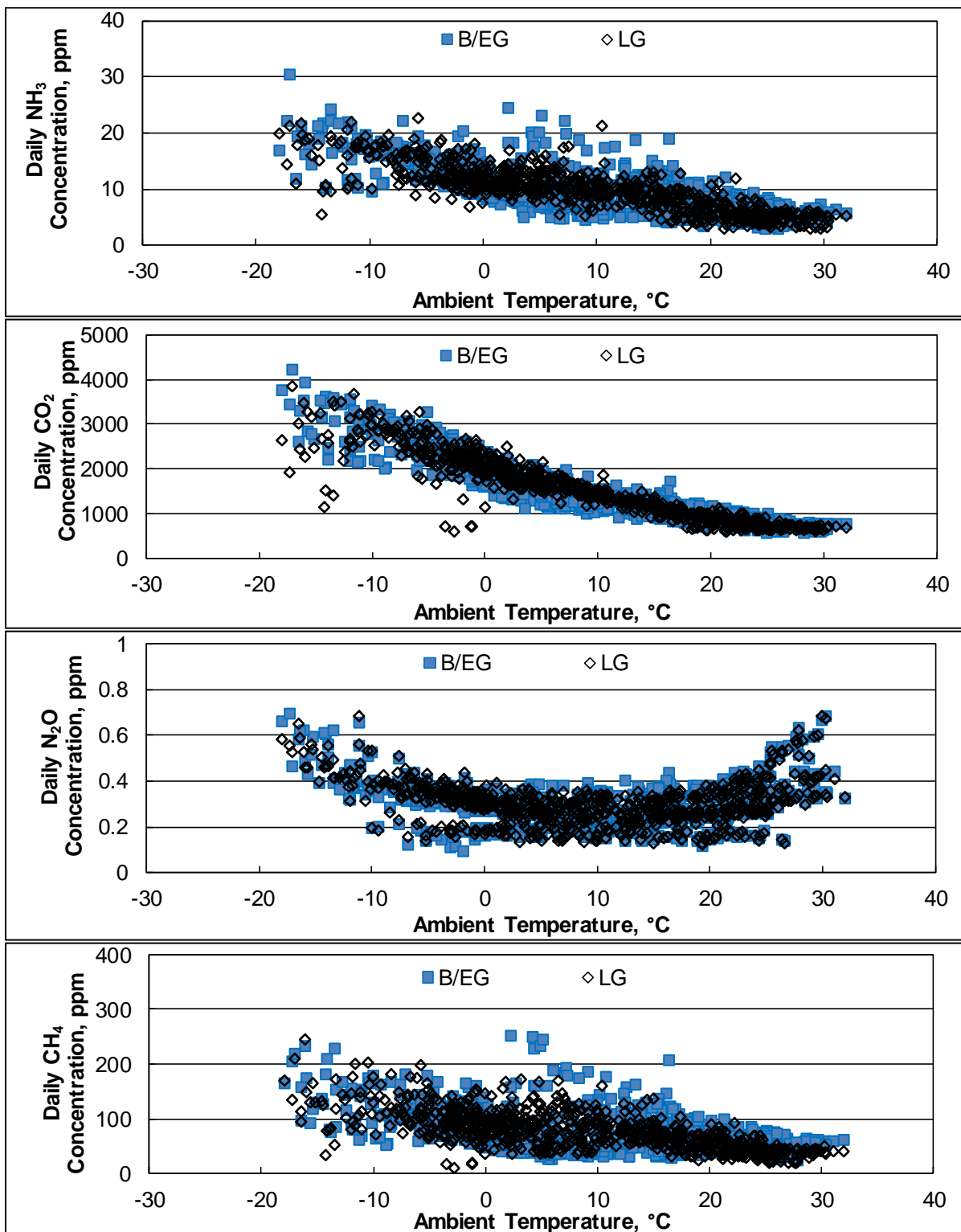


Figure 2.9. Average daily gaseous concentrations (ppm) vs. ambient temperature for the breeding/early gestation (B/EG) and late gestation (LG) barns.

Farrowing Rooms (F1 and F2)

Figure 2.10 depicts the profiles of temperatures, RH, and VR of the F1 and F2 rooms. The rooms held a fairly consistent temperature curve except during the summer months when, despite using evaporative cooling pads, the rooms had a slight rise in temperature. The indoor RH was typically between 30% and 60%, except during the summer months when evaporative cooling pad use increased the room humidity. The VR was typically between 70 and 1000 $\text{m}^3 \text{hr}^{-1} (\text{sow+litter})^{-1}$, which is slightly higher than the recommended 34 and 850 $\text{m}^3 \text{hr}^{-1} \text{head}^{-1}$ (MWPS-1, 1983). Once again NH_3 , CO_2 , and CH_4 concentrations decreased with increasing ambient temperature. The daily N_2O concentrations showed a quadratic relationship to ambient temperature, with minimum concentrations near 10°C. Figure 2.11 shows these trends.

The daily concentration values for the F1 room, F2 room, and farrowing room average are summarized in Table 2.6. Indoor gaseous concentrations are of concern for both human and pig exposure. Neither the F1 nor F2 room exceeded OSHA 8-hour time weighted average concentrations of 50 ppm for NH_3 and 10,000 ppm for CO_2 . The average daily NH_3 concentrations did exceed 25 ppm on 12 days in F1 room and 71 days in F2 room. Overall daily gas concentrations for the farrowing rooms were 12.0, 1594, 0.31, and 28.5 ppm for NH_3 , CO_2 , N_2O , and CH_4 , respectively.

Table 2.6. Daily gas concentration means (SD) by farrowing room (F1 and F2) and overall.

Source	Gas Concentration, ppm			
	NH ₃	CO ₂	N ₂ O	CH ₄
F1	11.0	1556	0.31	27.4
	(6.8)	(783)	(0.11)	(10.1)
F2	13.0	1631	0.31	29.6
	(8.5)	(811)	(0.11)	(9.5)
Overall	12.0	1594	0.31	28.5
	(7.6)	(797)	(0.11)	(9.8)

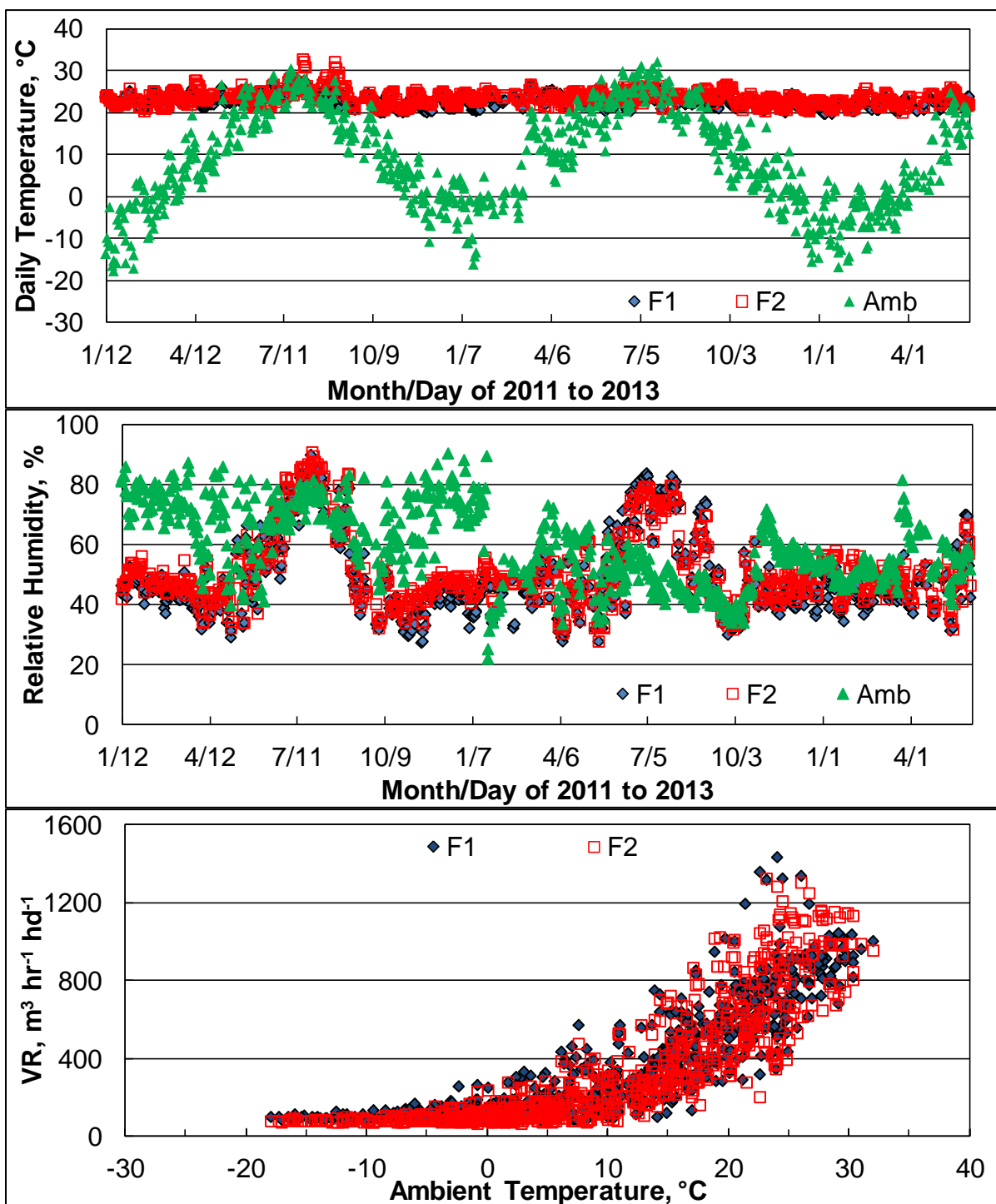


Figure 2.10. Daily mean temperature, relative humidity, and ventilation rate (VR) of the farrowing rooms (F1 and F2) and daily mean ambient (Amb) temperature and relative humidity

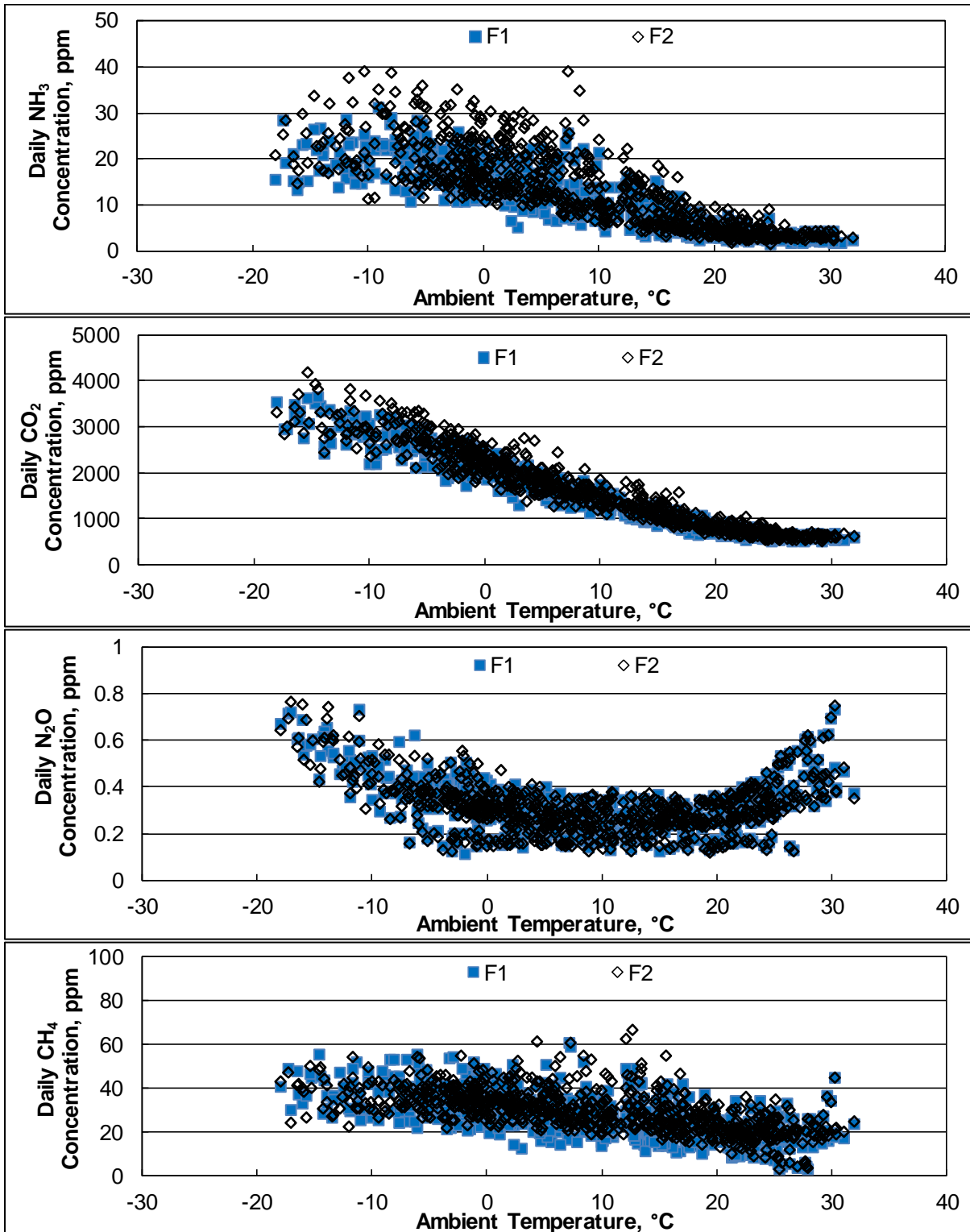


Figure 2.11. Daily mean gas concentrations (ppm) vs. ambient temperature for the farrowing rooms (F1 and F2).

Gaseous Emissions

B/EG and LG Barns

The gaseous emission rates from the B/EG and LG barns over the monitoring period are shown in Figure 2.12. The emission rates are reported as an emissions per animal unit (AU, AU=500 kg live body mass). The sow body mass (BM) averaged 204 and 219 kg in the B/EG and LG barns, respectively. The CH₄ emission was affected by the manure accumulation time in that it tends to build with increase manure accumulation and then drops abruptly upon manure removal (pump-out) from the storage pits. The impact of ambient temperature on emissions is shown in Figure 2.13. CO₂ emissions had a negative relationship with ambient temperature at lower temperature range (<0°C), presumably arising from increased metabolic rate at correspondingly lower indoor temperatures. N₂O emissions showed similar behavior as N₂O concentrations vs. ambient temperature, with a minimum occurring in the temperature range of -5 to 5°C. There were no clear trends in NH₃ and CH₄ emissions relative to ambient temperature.

The average daily emission rates for the B/EG barn, LG barn, and gestation average are summarized in Table 2.7. The B/EG barn had higher per AU emission rates of all gases compared to the LG barn. This outcome might be due to the larger population and BM of sows in the LG barn while both barns had identical deep-pit volumes and floor areas (emission is driven by the surface area of the manure storage).

Table 2.7. Mean (SE) daily barn emission rate, ventilation rate (VR), and sow body mass during the monitoring period for breeding/early gestation (B/EG), late gestation (LG), and overall gestation stages.

Stage	Ave. Body Mass, kg sow ⁻¹		VR, m ³ hr ⁻¹ sow ⁻¹	Emission Rate, g AU ⁻¹ d ⁻¹			
				NH ₃	CO ₂ *	N ₂ O	CH ₄
B/EG	204	Mean	109	35.1	7460	0.17	263
		SE	2.8	0.4	58	0.01	3.3
LG	219	Mean	107	28.2	6496	0.12	201
		SE	2.8	0.3	50	0.01	2.7
Gestation Average	212	Mean	108	31.7	6978	0.14	232
		SE	2.8	0.3	54	0.01	3.0

AU = animal unit = 500 kg live body mass

*Including CO₂ from animal respiration (~96%)

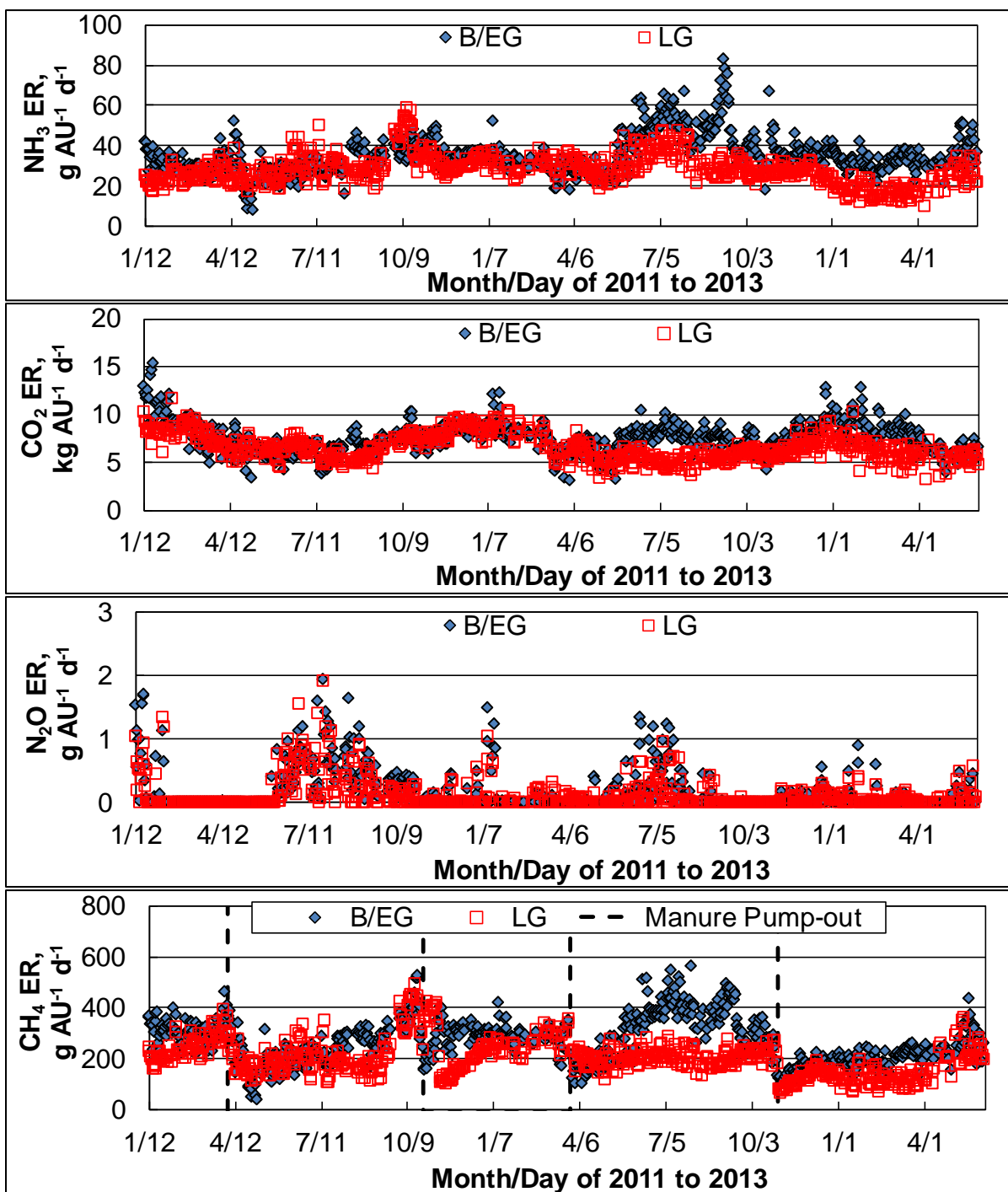


Figure 2.12. Daily ammonia (NH_3), carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) emission rates (ER) for the breeding/early gestation (B/EG) and late gestation (LG) barns.

*Manure removal events from the deep-pit storages are noted by vertical lines

*AU = animal unit = 500 kg live body mass

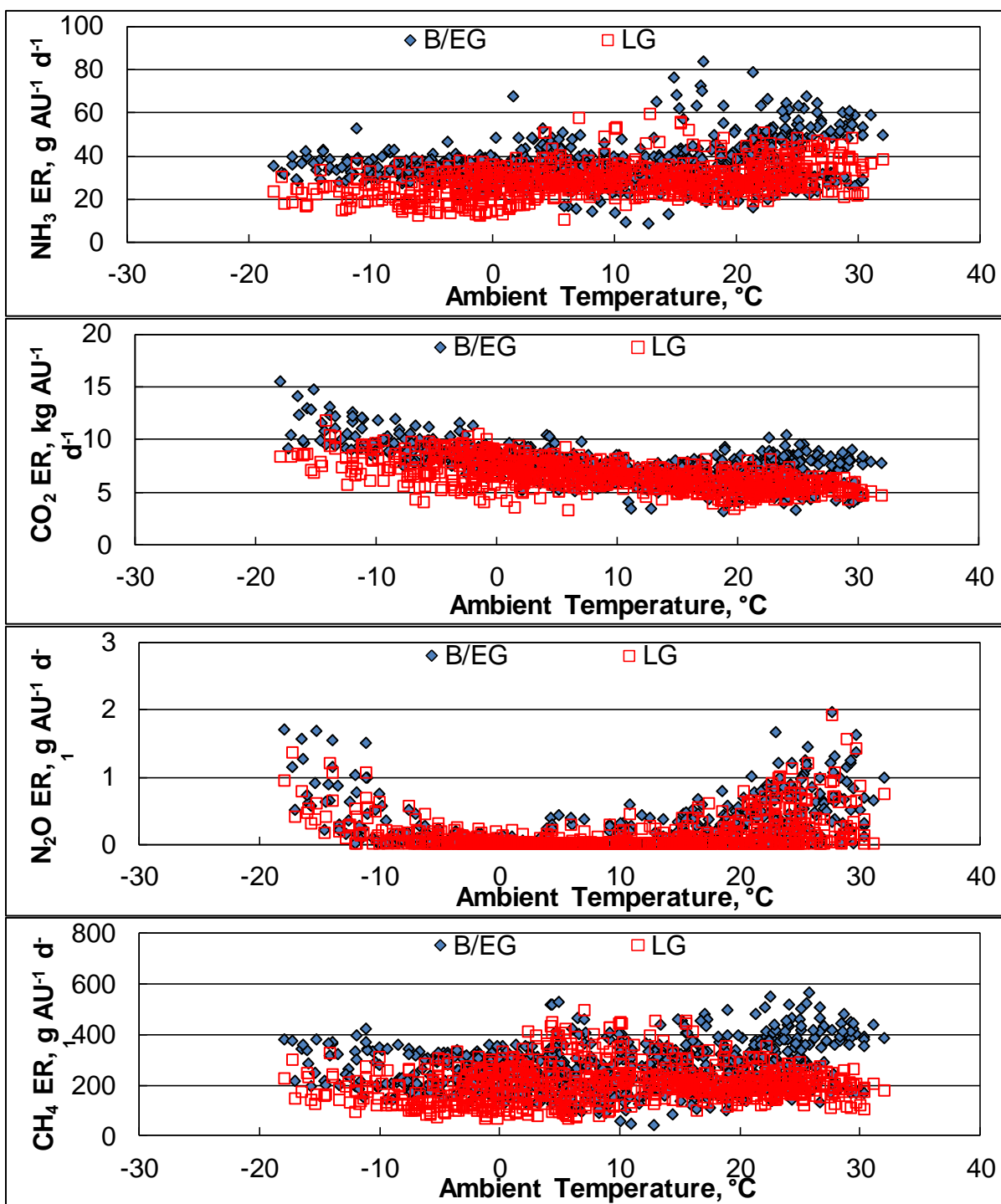


Figure 2.13. Daily ammonia (NH_3), carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) emission rates (ER) vs. daily ambient temperature for breeding/early gestation (B/EG) and late gestation (LG) barns.

*AU = animal unit = 500 kg live body mass

Farrowing Rooms (F1 and F2)

The gaseous emission rates for the F1 and F2 rooms over the monitoring period are shown in Figure 2.14. As with the B/E and LG barns, emission rates are reported on the per AU basis. The emissions are largely impacted by the farrowing cycle, as the shallow pits were emptied and the rooms cleaned after each turn. This cyclical emission pattern is shown in Figure 2.15 for NH_3 and CO_2 emissions for two turns. The impact of ambient temperature on emissions is shown in Figure 2.16. The relationships between the gaseous emissions and ambient temperature followed the same trends as observed with the gestation barns.

The average daily emission rates of the farrowing rooms during the lactation period were further divided into different periods, as reported in Table 2.8. The NH_3 and CO_2 emission rates increased with day of turn (i.e., piglet age) while N_2O and CH_4 emissions remained by and large unchanged. On a per sow+litter basis, CH_4 emissions increased with piglet age.

Table 2.8. Mean (SE) daily emission rate, ventilation rate (VR), and sow and litter body mass during the monitoring period by production stage (piglet age) and whole cycle mean for lactating sows and litters.

Production Stage	Ave. Body Mass, kg (sow+litter) ⁻¹		VR, m ³ hr ⁻¹ (sow+litter) ⁻¹	Emission Rate, g AU ⁻¹ d ⁻¹			
				NH ₃	CO ₂ *	N ₂ O	CH ₄
Preparturition	222	Mean	251	54.5	10,493	1.00	100
		SE	21	2.0	426	0.09	4.8
Birth-Day 6 (Week 0)	236	Mean	317	52.3	13,513	0.77	99
		SE	12	1.0	241	0.04	2.2
Day 7-12 (Week 1)	247	Mean	356	62.5	17,653	0.67	113
		SE	13	1.2	330	0.04	2.3
Day 13-18 (Week 2)	256	Mean	380	65.4	18,506	0.73	111
		SE	13	1.3	360	0.04	2.3
Day 0-18 (Whole Turn)	246	Mean	349	59.7	16,397	0.73	107
		SE	13	1.2	306	0.04	2.3

AU = animal unit = 500 kg live body mass

Production Stage based on piglet age

*Including CO₂ from animal respiration (~96%)

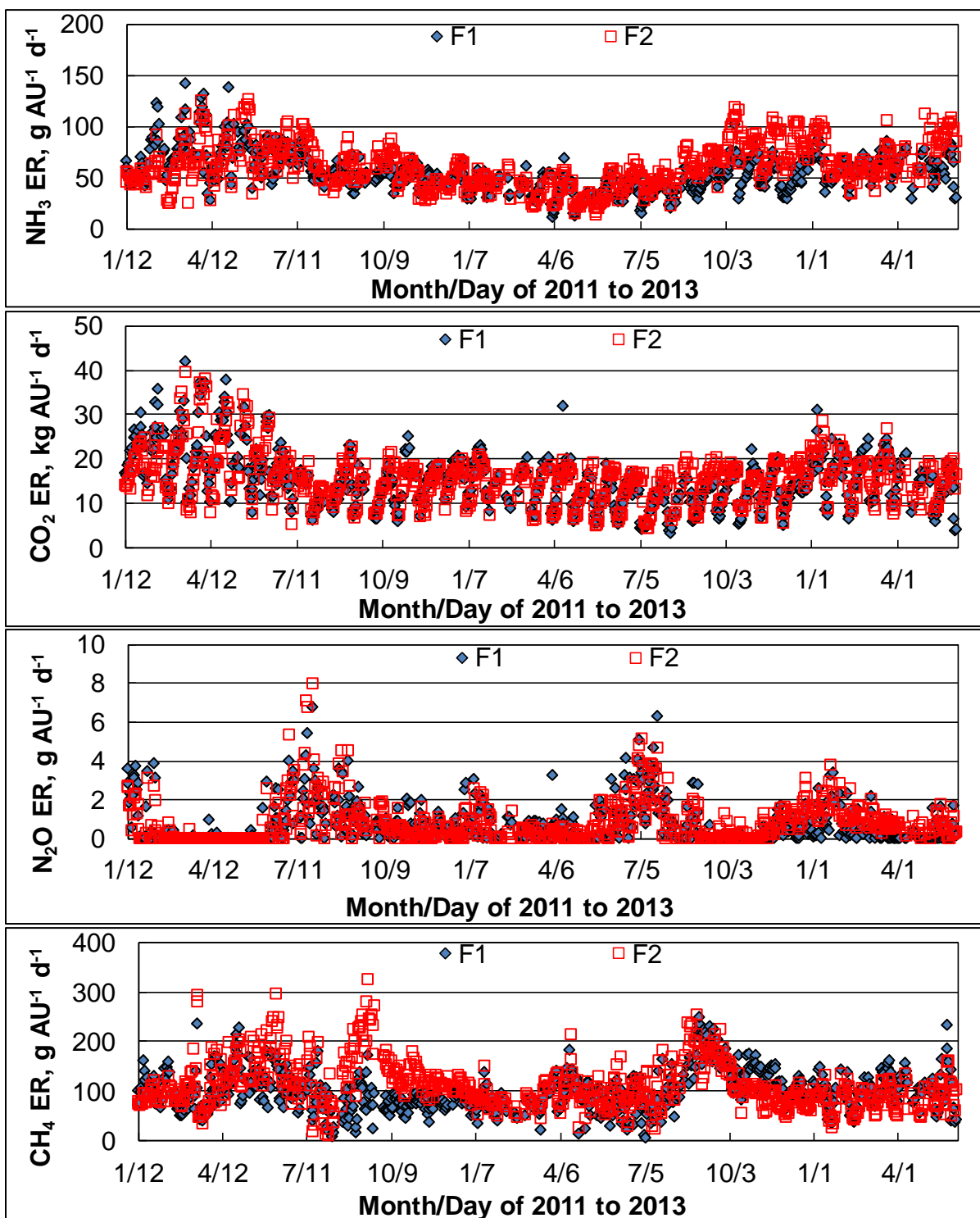


Figure 2.14. Daily ammonia (NH₃), carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄) emission rates (ER) for the farrowing rooms (F1 and F2).

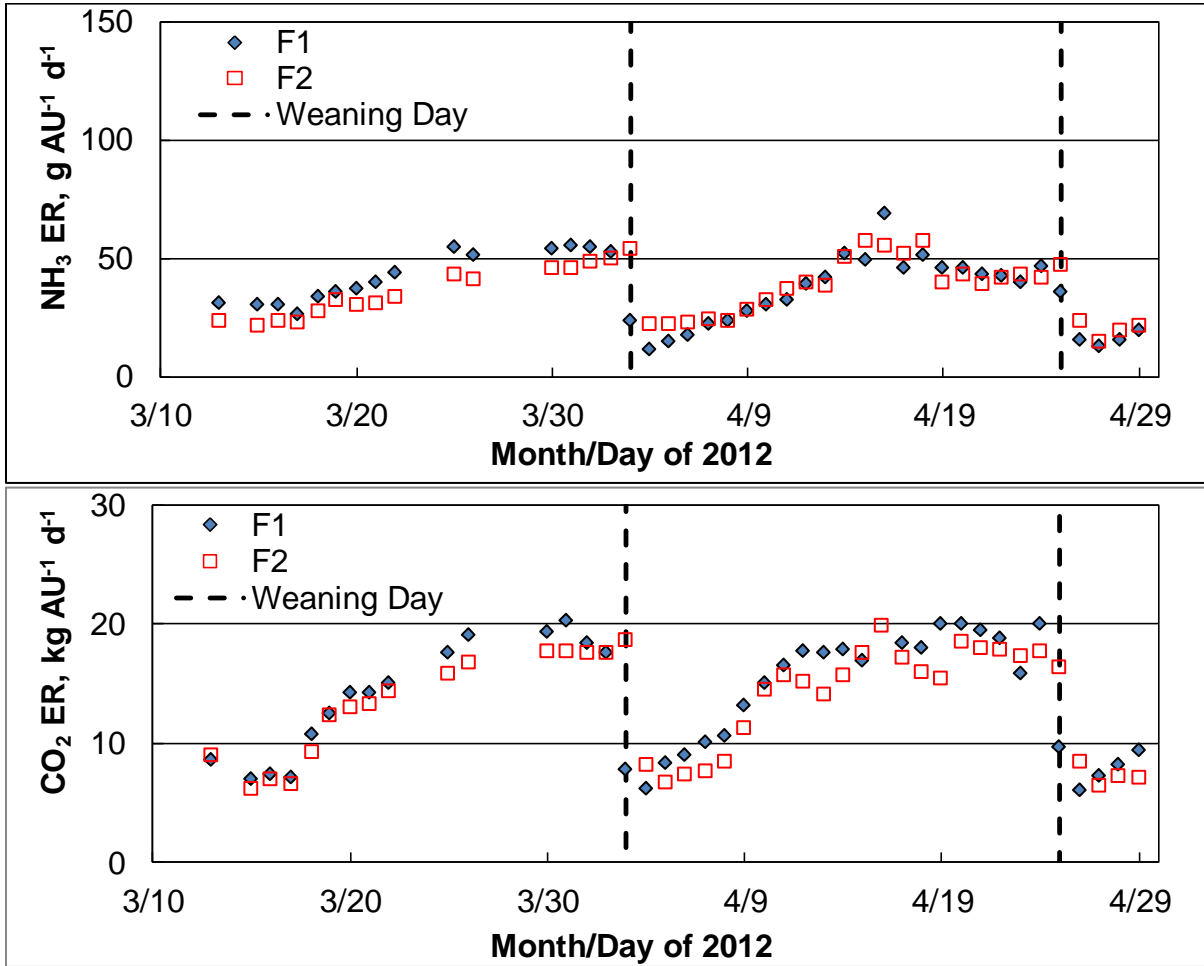


Figure 2.15. Daily ammonia (NH₃) and carbon dioxide (CO₂) emission rates (ER) for farrowing rooms F1 and F2 over two lactations.

*Lactation cycle typically 18-22 days in length

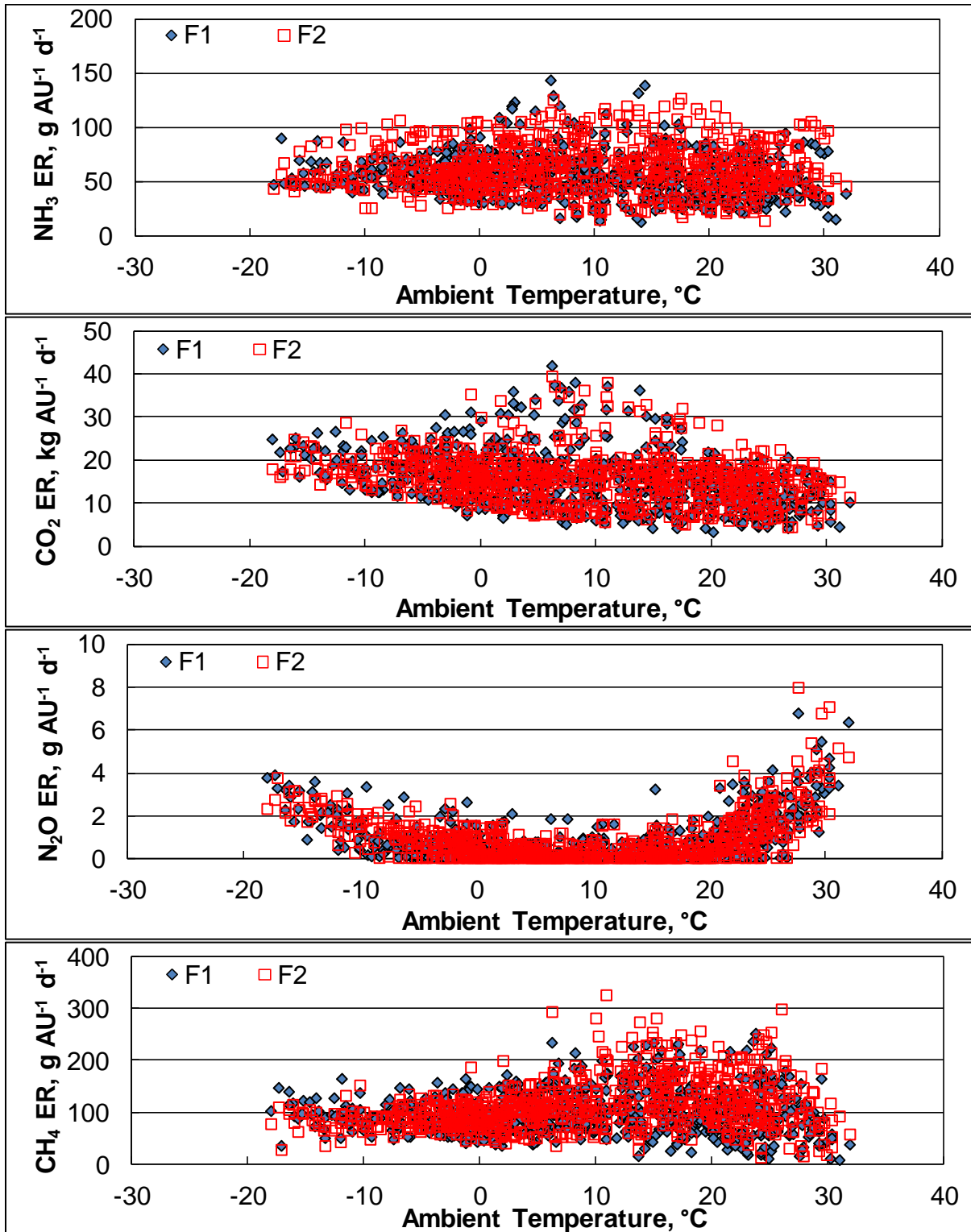


Figure 2.16. Daily ammonia (NH₃), carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄) emission rates (ER) vs. daily ambient temperature by farrowing room (F1 and F2).

External Manure Storage

Figure 2.17 shows emission fluxes from the external manure storage as measured by the dynamic flux chamber at an air exchange rate of 30 air changes per hour (ACH). The emissions fluxes were correlated to the average daily ambient temperature measured by the MAEMU. Thus allowing the flux values to be estimated for the entire monitoring period. Table 2.9 shows the average fluxes from the manure surface, in $\text{g m}^{-2} \text{hr}^{-1}$, and the average emission rates, in $\text{g AU}^{-1} \text{d}^{-1}$ and kg d^{-1} , using the best fit models from Figure 2.17 and the average daily ambient temperatures. No N_2O flux values are shown as the differences between the measured concentrations of ambient and exhaust air from the dynamic flux chamber were below the resolution (0.066 ppm) of the INNOVA 1412 gas analyzer. Spatial gaseous flux variability from the manure storage was also measured. Nine sample locations with a 12.2 m grid spacing (centered at middle of storage) were monitored with a 3-chamber system over a one-month period. The 3 chambers were moved between locations every 2 to 4 days. No significant difference was observed for NH_3 ($p>0.9$), CO_2 ($p>0.1$), and CH_4 ($p>0.12$) fluxes between the 9 locations. No significant N_2O fluxes were observed at any location.

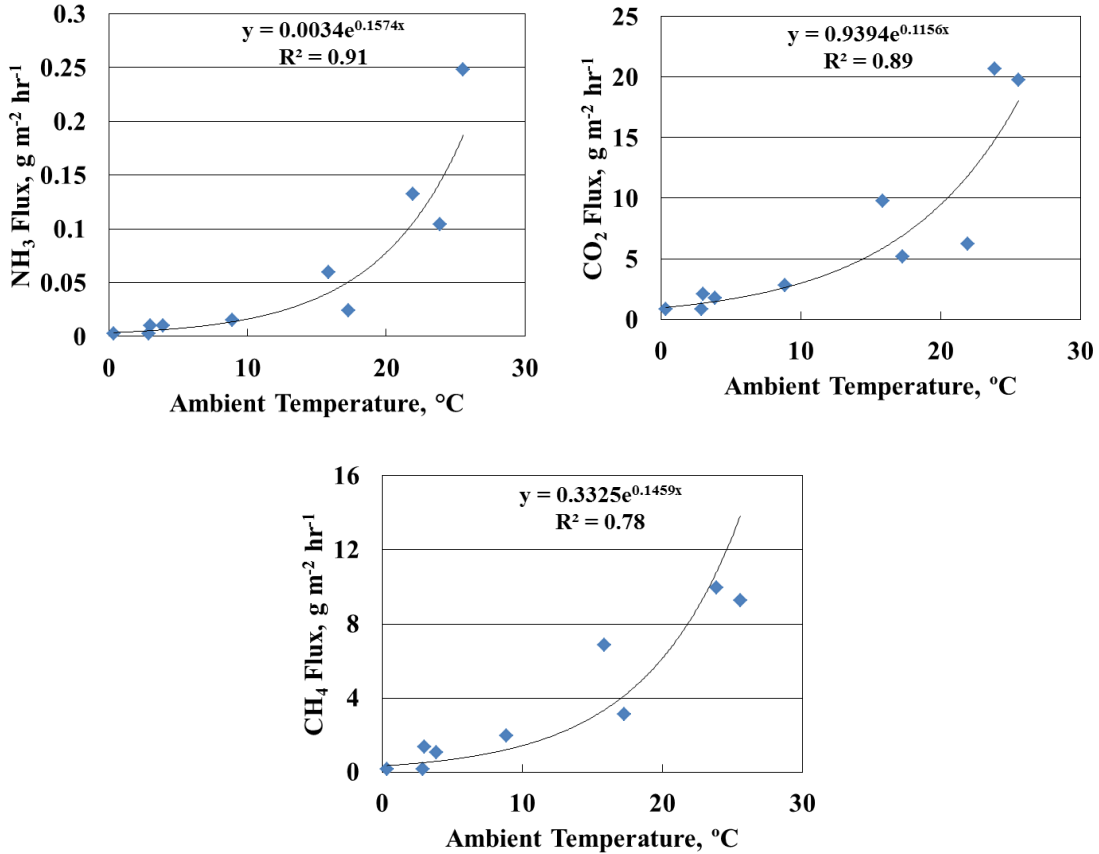


Figure 2.17. Average ammonia (NH₃), carbon dioxide (CO₂), and methane (CH₄) flux from external manure storage measured with dynamic flux chamber at 30 air changes per hour (ACH).

Table 2.9. Average daily flux and emission rates for ammonia (NH₃), carbon dioxide (CO₂), and methane (CH₄) from external manure storage (720 sows+litters contributing).

Variable		NH ₃	CO ₂	CH ₄
Flux, g m ⁻² hr ⁻¹	Mean	0.05	5.7	4.0
	SD	(0.1)	(7.1)	(5.8)
Emission Rate, g AU ⁻¹ d ⁻¹	Mean	7.0	757	526
	SD	(11.0)	(943)	(776)
Emission Rate, kg d ⁻¹	Mean	2.5	268	186
	SD	(3.9)	(334)	(275)

AU = animal unit = 500 kg live body mass

Swine Operation Emissions

As listed in Table 2.10, the swine operation (including manure storage) emission rates on per AU basis (mean \pm SD, g AU⁻¹ day⁻¹) were 38.5 (\pm 9.3) of NH₃, 8731 (\pm 1666) of CO₂ (8415 from animal respiration), 0.24 (\pm 0.25) of N₂O, and 301 (\pm 187) of CH₄. Based on the daily NH₃ emissions, the animal number needed to trigger the Emergency Planning and Community Right-to-Know Act (EPCRA) reporting threshold of 45.5 kg NH₃ per day is 2702 sows. The swine operation emission rates for GHG gases, converted to CO₂ equivalents based on their respective global warming potential, on per AU basis (mean \pm SD, g CO₂-eq AU⁻¹ day⁻¹) were 8731 (\pm 1666) for CO₂ (8415 from animal respiration), 75.7 (\pm 76.9) for N₂O, and 6330 (\pm 4485) for CH₄.

Swine operation emission rate partitioning, including CO₂ from animal respiration, is listed in Table 2.11. Combined emissions from the breeding/gestation barns accounted for 66% of NH₃, 63% of CO₂, 45% of N₂O, and 60% of CH₄ emissions. The farrowing barns accounted for 30% of NH₃, 35% of CO₂, 55% of N₂O, and 7% of CH₄ emissions. The external manure storage accounted for 4% of NH₃, 2% of CO₂, 0% of N₂O, and 33% of CH₄ emissions. The rapid chemo-biological production and rapid volatilization of NH₃ after waste excretion from the animals leads to the large partitioning of NH₃ from the barn sources compared to the external manure storage. The biological production of CH₄ requires either an established anaerobic bacterial population or sufficient storage time for the conditions to form, thus the large proportion of CH₄ emissions from the deep-pit barns and external manure storage compared to the shallow-pit farrowing rooms.

Table 2.10. Barn and swine operation (including manure storage) mean (SD) ammonia (NH₃), carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄) (g d⁻¹ AU⁻¹) and total GHG (CO_{2eq} d⁻¹ AU⁻¹) emission rate.

	NH ₃	CO ₂ *	N ₂ O	CH ₄	Total GHG**, CO ₂ -eq. day ⁻¹ AU ⁻¹
Breeding/Gestation Barns, g day ⁻¹ AU ⁻¹	31.7 (6.2)	6,978 (1,072)	0.14 (0.20)	232 (59)	11,903
Farrowing Barns, g day ⁻¹ AU ⁻¹	59.7 (13.5)	16,397 (3572)	0.73 (0.47)	107 (27)	18,870
External Manure Storage, g day ⁻¹ AU ⁻¹	7.0 (11.0)	758 (944)	--	526 (777)	11,808
Swine Operation Emission Rate, g day ⁻¹ AU ⁻¹	38.5 (9.3)	8,731 (1,666)	0.24 (0.25)	301 (187)	15,137
Swine Operation Emission Rate, g CO ₂ Equivalents day ⁻¹ AU ⁻¹	--	8,731 (1,666)	75.7 (76.9)	6,330 (4,485)	

AU = animal unit = 500 kg live body mass

Swine operation includes all animal buildings and manure storage

*Including CO₂ from animal respiration (~96%)

**Excluding respiration CO₂

Table 2.11. Swine operation emission percentage for each major source: Breeding/Gestation Barns, Farrowing Barns, and External Manure Storage for ammonia (NH₃), carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄)

Source	Percent of Swine Operation Emissions			
	NH ₃	CO ₂	N ₂ O	CH ₄
Breeding/Gestation Barns	66%	63%*	45%	60%
Farrowing Barns	30%	35%*	55%	7%
Manure Storage	4%	2%	--	33%

*Including CO₂ from animal respiration (~96%)

Swine operation includes all animal buildings and manure storage

Comparison to Literature Values

For the breeding/gestation barns, NH₃ emission rate of 31.7 g AU⁻¹ d⁻¹ obtained from the current study was in the literature value range of 1.3 to 59.0 g AU⁻¹ d⁻¹ (Cortus et al., 2010a; Cortus et al., 2010b; Groot Koerkamp et al., 1998; Rahman et al., 2012; Zhu et al.,

2000); CO₂ emission rate of 6,978 g AU⁻¹ d⁻¹ in the literature value range of 4808 to 13,450 g AU⁻¹ d⁻¹; and N₂O emission rate of 0.14 g AU⁻¹ d⁻¹ in the literature value range of 0 to 0.75 g AU⁻¹ d⁻¹. However, CH₄ emission rate observed for the gestation barns in this study of 232 g AU⁻¹ d⁻¹ was above the literature range of 9.6 to 135 g AU⁻¹ d⁻¹ (Dong et al., 2007; Lague et al., 2004; Zhang et al., 2007). The CH₄ emission rates in literature are from either shallow pit or immediate manure removal barns compared to the deep-pit below-slat manure storage in this study. The larger stored manure volume and longer accumulation time should lead to higher CH₄ emissions due to the development of stable anaerobic conditions for methanogen bacteria.

For the farrowing rooms, NH₃ emission rate from this study (59.7 g AU⁻¹ d⁻¹) falls within the literature range of 3.3 to 63.2 g AU⁻¹ d⁻¹ (Cortus et al., 2010a; Cortus et al., 2010b; Groot Koerkamp et al., 1998; Rahman et al., 2012; Zhu et al., 2000). The same is true with the CO₂ emission rate – 16,397 g AU⁻¹ d⁻¹ vs. the literature range of 7,490 to 24,600 g AU⁻¹ d⁻¹; and CH₄ emission rate –107 g AU⁻¹ d⁻¹ vs. the literature range of 9.6 to 728 g AU⁻¹ d⁻¹ (Dong et al., 2007; Lague et al. 2004; Zhang et al., 2007). However, N₂O emission rate observed for the farrowing barns in this study (0.73 g AU⁻¹ d⁻¹) was above the literature range of 0 to 0.54 g AU⁻¹ d⁻¹. N₂O concentrations of the exhaust air from swine housing are typically low (0.31 ppm in this study) and difficult to discern from ambient concentrations without a properly calibrated analyzer. Additionally, this study found N₂O emissions to vary considerably from day to day with many days having non-detectable emission. Thus less

frequent and shorter duration sampling periods employed in such studies could lead to inaccuracies from missed day-to-day emission variations.

Error Analysis

Quality control procedures outlined in Moody et al. (2008) were followed to maintain emission rate determination accuracy. However, it is still prudent to perform and report the study result uncertainty. Using the method described in Gates et al. (2009), an emission uncertainty was determined for multiple scenarios involving different component uncertainties. The INNOVA concentration measurement uncertainty was varied from 0.5% to 5% to represent the best expected instrument accuracy and the worst uncertainty before the instrument would be recalibrated. Temperature ranges were chosen to represent cold ($<7.2^{\circ}\text{C}$), mild ($7.2\text{-}26.7^{\circ}\text{C}$), and hot ($>26.7^{\circ}\text{C}$) ambient conditions. The average daily static pressure and VR for each of these categories was found and used to determine the running fan number and size. The average change in fan performance between calibration events was found for each fan size present at the farm. This value was used as the uncertainty in VR for each fan. This VR uncertainty represents the worst case scenario, as fan performance is most likely to change gradually over time due to degradation (e.g. belt loosening, dust accumulation) and our calculation compensated for this by linearly interpolating, on a monthly basis, the fan performance curves between calibration events. Thus, the fan VR uncertainty was reduced by a conservative 50% to provide an estimate of VR uncertainty with month-by-month interpolation.

The emission rate uncertainty ranged from 3.7% to 6.3% and 3.9% to 7.1% for the B/EG and LG barns across the scenarios for ambient conditions (hot, mild, cold), instrument uncertainty (0.5% to 5%), and VR uncertainty (100% or 50% of average change in fan performance). The emission rate uncertainty ranged from 11.1% to 15.3% and 19.1% to 28.9% for the F1 and F2 rooms across the scenarios for ambient conditions (hot, mild, cold), instrument uncertainty (0.5% to 5%), and ventilation uncertainty (100% or 50% of average change in fan performance). Again, the lower uncertainty ranges are more representative of actual conditions as the frequent fan calibrations and linear interpolations of performance curves between calibration events reduce the uncertainty of VR. The overall emission uncertainty across all ambient conditions for typical uncertainties (instrument at 2.5%, 50% of average change in fan performance) was 4.5% and 13.1% for the breeding/gestation barns and farrowing rooms, respectively. The greater uncertainty of the farrowing emissions compared to the gestation emissions is primarily due to the low VR of the farrowing rooms and the greater VR uncertainty for the variable speed fans due to lower performance and degradation.

Summary and Conclusions

Gaseous concentrations and emissions of NH₃, CO₂, CH₄, and N₂O for a swine breeding-gestation-farrowing facility in Iowa were continuously monitored for 29 months. The following observations and conclusions were made.

- Daily indoor NH₃, CO₂, CH₄, and N₂O concentrations of the breeding/gestation barns (mean ±SD) were 9.7 (±4.1) ppm, 1536 (±701) ppm, 78.3 (±37) ppm, and 0.30 (±0.10)

ppm, respectively. Daily indoor NH₃, CO₂, CH₄, and N₂O concentrations of the farrowing rooms (mean ±SD) were 12.0 (±7.6) ppm, 1594 (±797) ppm, 28.5 (±9.8) ppm, and 0.31 (±0.11) ppm, respectively.

- Swine operation (including manure storage) emission rates of NH₃, CO₂, CH₄, and N₂O gases (mean ±SE) were 38.5 (±9.3), 8,731 (±1,666), 301 (±187), and 0.24 (±0.25) g AU⁻¹ d⁻¹, respectively. Daily total GHG emissions were 15.1 kg CO₂-eq. AU⁻¹ d⁻¹ after removing CO₂ production due to animal respiration.
- The breeding/gestation barns accounted for 66% of NH₃, 63% of CO₂, 60% of CH₄, and 45% of N₂O emissions; the farrowing barns accounted for 30% of NH₃, 35% of CO₂, 7% of CH₄, and 55% of N₂O emissions; and the external manure storage accounted for 4% of NH₃, 2% of CO₂, 33% of CH₄, and 0% of N₂O emissions.

Acknowledgements

Funding for the study was provided in part by the Iowa Pork Producers Association (NPB Project #10-006 and #12-118) and in-kind contribution of the Mobile Air Emissions Monitoring Unit by Iowa State University. Additionally, we thank the local swine producer for providing access to the facility and cooperation during the project.

References

Acevedo, R.R., H. Li, H. Xin, and S. Roberts. 2009. Evaluation of a Flux Chamber for Assessing Gaseous Emissions and Treatment Effects of Poultry Manure. ASABE Paper #096392. St. Joseph, MI: ASABE.

Aneja, V.P., J.P. Chauhan, and J.T. Walker. 2000. Characterization of atmospheric ammonia emissions from swine waste storage and treatment lagoons. *Journal of Geophysical Research* 105(D9): 11,535-11,545.

CIGR report. 2002. Climatization of animal houses. Fourth report of working group. Heat and moisture production at animal and house levels. Horsens, Denmark.

Cortus, E.L., J. Koziel, L. Cai, S.J. Hoff, J. Harmon, J. Mickelson, and A.J. Heber. 2010a. National Air Emissions Monitoring Study: Emissions Data from Two Sow Barns and One Swine Farrowing Room in Iowa- Site IA4B. Final Report. Purdue University, West Lafayette, IN, July 26.

Cortus, E.L., K. D. Casey, A. P. Caramanica, K. J. Mickey and A.J. Heber. 2010b. National Air Emissions Monitoring Study: Emissions Data from Two Sow Barns and One Swine Farrowing Room in Oklahoma- Site OK4B. Final Report. Purdue University, West Lafayette, IN, July 2.

Dong, H., Z. Zhu, B. Shang, G. Kang, H. Zhu, and H. Xin. 2007. Greenhouse gas emissions from swine barns of various production stages in suburban Beijing, China. *Atmospheric Environment* 41:2391-2399.

EPA. 2011. Inventory of Greenhouse Gas Emissions and Sinks: 1990-2005. Washington, DC. United States Environmental Protection Agency.

Gates, R. S., K. D. Casey, H. Xin, E. F. Wheeler, and J.D. Simmons. 2004. Fan Assessment Numeration System (FANS) design and calibration specifications. *Transactions of the ASAE* 47(6):1765-1778.

Gates, R. S., K. D. Casey, H. Xin, and R. T. Burns. 2009. Building emissions uncertainty estimates. *Transactions of the ASABE* 52(4): 1345-1351.

Groot Koerkamp, P.W.G., J.H.M. Metz, G.H. Uenk, V.R. Phillips, M.R. Holden, R.W. Sneath, J.L. Short, R.P. White, J. Hartung, J. Seedorf, M. Schroder, K.H. Linkert, S. Pederson, H. Takai, J.O. Johnsen, and C.M. Wathes. 1998. Concentrations and emissions of ammonia in livestock buildings in Northern Europe. *Journal of Agricultural Engineering Research* 70(1): 79-95.

Harper, L.A., R.R. Sharpe, and T.B. Parkin. 2000. Gaseous nitrogen emissions from anaerobic swine lagoons: ammonia, nitrous oxide, and dinitrogen gas. *Journal of Environmental Quality* 29:1356-1365.

Husted, S.. 1994. Seasonal variation in methane emission from stored slurry and solid manures. *Journal of Environmental Quality* 23: 585-592.

Khan, R.Z., C. Muller, and S.G. Sommer. 1997. Micrometeorological mass balance technique for measuring CH₄ emission from stored cattle slurry. *Biology and Fertility of Soils* 24: 442-444.

Lague, C., E. Gaudet, J. Agnew, and T.A. Fonstad. 2005. Greenhouse gas emissions from liquid swine manure storage facilities in Saskatchewan. *Transactions of the ASAE* 48(6): 2289-2296.

Lague, C., A. Marquis, S. Godbout, R. Lagace, T.A. Fonstad, S. Lemay, R. Joncas, and L. Jaulin. 2003. Greenhouse gas emissions from swine operations in Quebec and Saskatchewan: benchmark assessments. Prairie Swine Centre Annual Research Report 14-16.

Midwest Plan Service Structures and Environment Handbook, MWPS-1. 1983. Midwest Plan Service, Iowa State University, Ames, Iowa.

Moody, L., H. Li, R. Burns, H. Xin, and R. Gates. 2008. A Quality Assurance Project Plan for Monitoring Gaseous and Particulate Matter Emissions from Broiler Housing. ASABE #913C08e. St. Joseph, Michigan.

Muhlbauer R.V., T.A. Shepherd, H. Li, R.T. Burns, and H. Xin. 2011. Technical Note: Development and application of an induction-operated current switch for monitoring fan operation. *Applied Engineering in Agriculture* 27(2): 287-292.

Park, K.H., A.G. Thompson, M. Marinier, K. Clark, and C. Wagner-Riddle. 2005. Greenhouse gas emissions from stored liquid swine manure in a cold climate. *Atmospheric Environment* 40: 618-627.

Rahman, S., and D. Newman. 2012. Odor, ammonia, and hydrogen sulfide concentration and emissions from two farrowing-gestation swine operations in North Dakota. *Applied Engineering in Agriculture* 28(1): 107-115.

Sebacher, D.I., R.C. Harriss, and K.B. Bartlett. 1983. Methane flux across the air-water interface: air velocity effects. *Tellus* 35B: 103-109.

Sharpe, R.R., and L.A. Harper. 1999. Methane emissions from an anaerobic swine lagoon. *Atmospheric Environment* 33: 3627-3633.

USDA, 2014. Quarterly Hogs and Pigs. USDA Reference No. 1949-1921. United States Department of Agriculture and National Agriculture Statistics Service.

Wagner-Riddle, C., K.H. Park, and G.W. Thurtell. 2006. A micrometeorological mass balance approach for greenhouse gas flux measurements from stored animal manure. *Agricultural and Forest Meteorology* 136: 175-187.

Zhang, Q., X. Zhou, N. Cicek, and M. Tenuta. 2007. Measurement of odor and greenhouse gas emissions in two swine farrowing operations. *Canadian Biosystems Engineering* 49: 6.13-6.20.

Zhu, T., L. Jacobson, D. Schmidt, and R. Nicolai. 2000. Daily variations in odor and gas emissions from animal facilities. *Applied Engineering in Agriculture* 16(2): 153-158.

CHAPTER 3**HEAT AND MOISTURE PRODUCTION RATES OF A U.S. SWINE BREEDING-
GESTATION-FARROWING SYSTEM**

J.P. Stinn and H. Xin

A manuscript prepared for submission to Transactions of the ASABE

Abstract

Current recommendations for swine building ventilation system design to maintain an environment conducive to animal productivity and well-being are based on heat and moisture production rates measured in the 1950s and 1970s. Advancements in animal genetics, nutrition and management practices to increase productivity and pork quality since then have led to considerable changes in heat and moisture production rates of modern swine and their housing systems. This study quantifies total heat production rate (THP) of the animals which is partitioned into house-level latent heat or moisture production rate (LHP, MP) and house-level sensible heat production rate (SHP) of a 4,300-sow breeding, gestation, and farrowing facility in Iowa for 16 consecutive months. The THP was determined using indirect animal calorimetry, LHP or MP was determined from mass balance, and SHP was calculated as the difference between THP and LHP. A Mobile Air

Emission Monitoring Unit (MAEMU) equipped with state-of-the-art gas analyzers and a data acquisition system was used to monitor the deep-pit breeding/early gestation barn (1800 head, $204 \pm 3.2 \text{ kg hd}^{-1}$ (mean \pm SE)), the deep-pit late gestation barn (1800 head, $219 \pm 3.0 \text{ kg hd}^{-1}$), and two shallow-pit (pull-plug) farrowing rooms (40 sow/litter per room, $223 \pm 0.4 \text{ kg hd}^{-1}$). Results from the study show that THP at 20°C averages 1.8 W/kg for sows in the breeding/early gestation stage, 1.5 W/kg for sows in the late gestation stage, and 3.9 W/kg for sows and litters in week 0 of the lactation stage. The corresponding house-level LHP for the three stages averages 0.7 W/kg (early gestation), 0.6 W/kg (late gestation), and 2.1 W/kg (lactation, week 0). Finally the corresponding house-level SHP for the three stages averages 1.1 W/kg (early gestation), 0.9 W/kg (late gestation), and 1.8 W/kg (lactation, week 0). Compared with the ASABE standards, values from the current study for gestation sows in their early and late pregnancy stages showed increases of 28% and 8% in THP, 53% and 22% in LHP, and 16% and 2% in SHP, respectively. Values for lactating sows and litters during the first week after parturition showed increases of 23% in THP, 48% in LHP, and 11% in SHP relative to the ASABE standards. The reductions of THP from day to night for the three stages were 32% (early gestation), 27% (late gestation), and 7% (lactation). These data will help updating the standards for engineering design and operation of modern swine housing.

Keywords. ASABE standards, Bioenergetics, House-level heat and moisture production, sows, Ventilation design

Introduction

Maintaining an optimal indoor environment for all stages of swine production is critical to enhance animal well-being and maximize production. With mechanically-ventilated barns typically used in swine breeding, gestation, and farrowing facilities, the ventilation system is the primary control of the environmental conditions, including temperature, humidity, and gas concentrations. The need for environmental control places a high level of importance on having a properly designed ventilation system, especially as the industry moves towards increasing sow space allotments in order to address consumer preferences and animal welfare concerns. While ventilation systems in livestock barns provide control of indoor air quality for gas concentrations, design of the ventilation systems is fundamentally based on the heat production rates of the animals housed in the structure. Generally the proper indoor air quality will be achieved when the indoor air moisture and temperature are adequately controlled. Therefore, it is critical to have accurate values for both the total heat production rate (THP) of the animals and, more importantly, its partitioning into house-level moisture production rate (MP) or latent heat production rate (LHP) and house-level sensible heat production rate (SHP). When the current ASABE standards are examined, however, the THP, MP and SHP values used are from studies conducted in the 1950s and 1970s (Bond et al., 1959 and Ota et al., 1975) and modern studies are lacking. Since the Bond et al. (1959) study, only Brown-Brandl et al. (2014) has measured HP and MP of gestating gilts and lactating sows and litters. With remarkable changes in genetics, nutrition/feeding, and production methods (Brown-Brandl et al., 2004),

it is prudent to update the THP, MP, and SHP values for swine and their housing systems under modern production practices.

Table 3.1 shows previous studies quantifying the heat production for sows and piglets. Harmon et al. (1997) measured THP, MP and SHP of early weaned pigs and found increases of 135% in MP and 55% in THP for 4 to 6 kg piglets relative to the current ASABE standard. Brown-Brandl et al. (2014) measured THP, MP, and SHP of gestating gilts and lactating sows and litters. The gestating gilts had a 122% higher measured HP than by extrapolating HP curves for growing pigs. The lactating sows and litters had HP values comparable to the ASABE Standards on a unit mass basis, but with 30 kg heavier sows and litters at parturition. Additionally, these studies do not provide the diurnal pattern of HP. This could be critical as HP is closely tied to animal activity and can differ significantly depending on the time of day. This change in HP will have an impact on the ventilation and supplemental heating needs of the animals. The new THP, MP and SHP data can also be used to update common design resources such as the Midwest Plan Service Structures and Environment Handbook (MWPS-1, 1983) and the CIGR Handbook on Climatization of Animal Houses (CIGR, 2002).

Therefore, the objective of this study was to quantify THP and its partitioning into house-level LHP and house-level SHP for a Midwestern USA swine breeding/gestation/farrowing facility. The diurnal patterns of HP, specifically the day/night splits will also be delineated. Sixteen months were monitored continuously, from February 2012 to June 2013.

Table 3.1. Selected literature values on specific total heat production rate (THP), latent heat production rate (LHP) and sensible heat production rate (SHP) of pigs.

Source	Production Stage	Temperature (°C)	Body Mass (kg)	THP (W/kg)	LHP (W/kg)	SHP (W/kg)
Cairnie and Pullar (1957)	Early weaned pigs	15	4.0	6.4	--	--
		20	4.0	5.2	--	--
		25	4.0	4.5	--	--
Bond et al. (1959)	Lactating sow and litter	15	180	1.6	0.4	1.2
		20	180	1.4	0.4	1.0
		25	180	1.3	0.5	0.8
Ota et al. (1975)	Weaned pigs	29	3.2	3.8	--	--
		29	4.5	3.1	--	--
McCraken and Caldwell (1980)	Early weaned pigs	20	3.3	6.0	--	--
		29	3.3	4.1-5.2	--	--
McCraken and Gray (1984)	Early weaned pigs	25	3.2	5.2	--	--
		25	4.2	4.7	--	--
		25	4.9	4.3	--	--
		23	5.0	4.3	--	--
		23	5.9	4.7	--	--
		23	6.0	4.6	--	--
		23.3	4.4	5.6	2.6	3.0
Harmon et al. (1997)	Early weaned pigs	25.6	4.4	5.1	2.6	2.5
		23.3	6.1	5.8	2.8	3.0
		25.6	6.0	6.0	3.0	3.0
Brown-Brandl (2014)	Gestating Gilts	23.5	148	2.95	1.35	1.60
	Gestating Gilts	20.7	137.8	3.04	1.85	1.19
	Preparturition	23.7	183.2	1.89	1.27	0.62
	Birth-Day 7	24.7	208.9	2.55	2.09	0.46
	Day 8-14	24.1	221.5	3.80	1.81	2.09
	Day 15-21	24.7	248.8	3.70	2.03	1.67
	Day 22-Weaning	24.9	282.6	3.28	1.62	1.66

Materials and Methods

Site Description

A 4,300-sow (PIC genetics) capacity breeding-gestation-farrowing facility located in central Iowa was used in this field monitoring study (fig. 3.1; table 3.2). The facility consisted of two farrowing barns with nine farrowing rooms each, a breeding/early gestation

(B/EG) barn, a late gestation (LG) barn and an external above-ground manure storage tank for the farrowing operation. The farrowing rooms (fig. 3.2) each measured 15.5 m L \times 13.9 m W (50 ft L \times 45 ft W) and utilized a shallow pull-plug manure pit (0.61 m or 2 ft deep) that was drained after every turn (approx. 21 days) into an external storage tank. Each room had 40 farrowing crates arranged in four rows. Sows were moved into the rooms at 2 to 4 days preparturition. Piglets were weaned at 18 to 20 days of age typically, at which time the rooms were depopulated and cleaned by power washing. One, 66,000 W (225,000 Btu hr⁻¹) unvented LP heater provided supplemental heat in each room. Water was supplied through nipple drinkers. The nine rooms in each farrowing building shared a common hallway that tempers the incoming air by heating in winter and evaporative cooling in summer. Ventilation for each room was provided by two 0.3m (12 inch) single-speed, two 0.6m (24 inch) variable-speed, one 0.91m (36 inch) single-speed, and one 1.2m (48 inch) single-speed exhaust fans that were controlled to operate in stages.



Figure 3.1. The breeding-gestation-farrowing facility aerial view for the farm monitored in a study evaluating heat and moisture production from a swine operation.

Table 3.2. Characteristics of barns and rooms monitored in this study.

Designation	B/EG	LG	F1	F2
Barn/Room Name	Breeding/Early Gestation	Late Gestation	Farrowing Room 1	Farrowing Room 2
Production Stage	Weaned - Day 40	Day 41-Day 111	Day 112 - Wean	Day 112 - Wean
Barn Dimensions, L×W×H	121.9m × 30.5m × 2.7m	121.9m × 30.5m × 2.7m	15.5m × 13.9m × 2.7m	15.5m × 13.9m × 2.7m
Capacity	1800 sows	1800 sows	40 sows and litters	40 sows and litters
Manure Pit Depth	3.05m	3.05m	0.61m	0.61m
Manure Removal Frequency	Semi-annual	Semi-annual	Between Cycles (20-22d)	Between Cycles (20-22d)
Pit Fan Number and Diameter	12×0.61m	12×0.61m	2×0.3m	2×0.3m
Wall Fan Number and Diameter	15×1.37m	15×1.37m	2×0.6m; 1×0.91m; 1×1.2m	2×0.6m; 1×0.91m; 1×1.2m

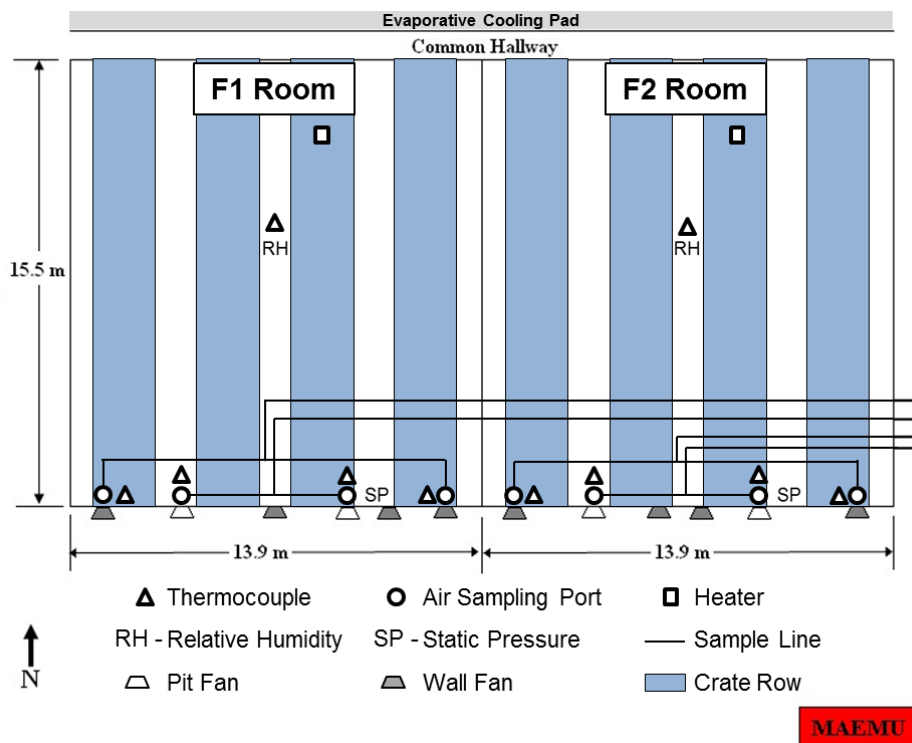


Figure 3.2. Farrowing room (F1 and F2) schematic drawing showing air sampling, temperature, static pressure, and relative humidity measurement locations from a study evaluating heat and moisture production from a swine operation.

The B/EG barn and the LG barn had the same dimensions, ventilation design, and 1800-head capacity each (fig. 3.3). Sows were housed in the B/EG barn post weaning until approximately day 40 of gestation. They were then housed in the LG barn until 2 to 4 days preparturition. In both barns the sows were housed in individual stalls 2.1 m L \times 0.61 m W (7 ft L \times 2 ft W). Each barn utilized a below slat deep manure pit 3.05 m (10 ft) in depth for manure storage. The deep-pit storages were emptied semi-annually, in the fall and spring. The barns had dimensions of 121.9m L \times 30.5m W (400 ft L \times 100 ft W) and used mechanical ventilation year round. Each barn had twelve, 0.61m (24 inch) pit fans spaced along the length of the barns and fifteen, 1.37m (52 inch) fans on the west walls. The pit fans provided low stage ventilation while the wall fans provided tunnel ventilation during warm weather. Bi-flow actuated ceiling inlets were used for lower ventilation stages. Evaporative cooling pads on the east walls cooled incoming air during hot weather. Ten, 66,000 W (225,000 Btu hr⁻¹) unvented LP heaters provided supplemental heat in each barn. Water was supplied through common water troughs that ran the length of the buildings.

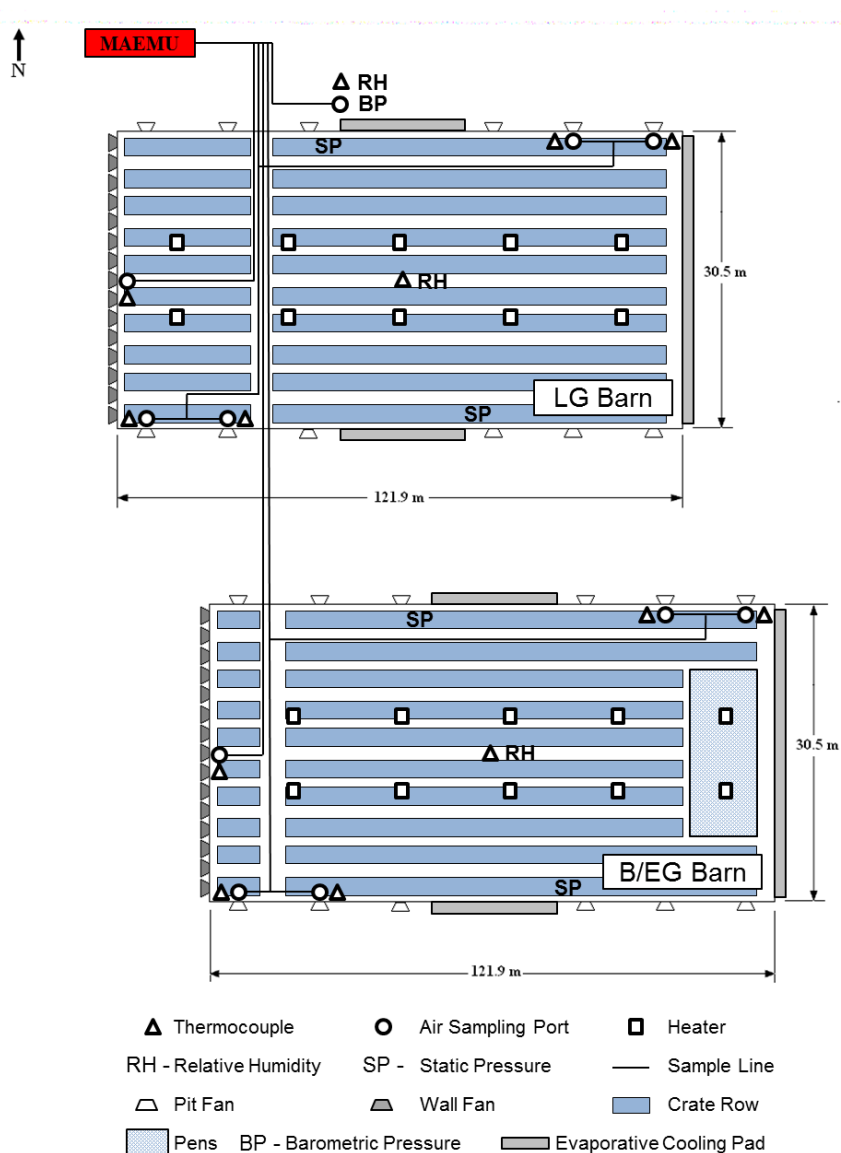


Figure 3.3. Breeding/early gestation (B/EG) and late gestation (LG) barn schematic drawing showing air sampling, temperature, static pressure, relative humidity, and barometric pressure measurement locations from a study evaluating heat and moisture production from a swine operation.

The sows were fed a corn/soy diet that was adjusted based on production stage and body condition. For gestating sows, the ration had a metabolic energy (ME) content of 3095 kcal/kg and a crude protein (CP) content of 21.04%. Gestating sows were fed once a day (07:00h). Gestating sows with body condition score 1 (skinniest sows) were fed 4.5 kg per

day and condition score 3 sows (heaviest) were fed 1.8 kg per day. Condition 2 sows were fed 2.3 to 3.2 kg of feed per day depending on gestation status. Once the gestating sows were moved to the farrowing rooms approximately 2 to 4 days before farrowing, they were fed 1.8 kg per day until farrowing. For lactating sows (post farrowing) ME content was 3278 kcal/kg and CP content was 21.14%. Lactating sows were fed four times per day (00:00, 09:00, 12:00, and 18:00h) with each feeding at up to 3.6 kg for a maximum daily feed intake of 14.5 kg.

Instrumentation and Measurement System

A Mobile Air Emissions Monitoring Unit (MAEMU) was used to continuously collect data on gaseous concentrations, thermal conditions, and operational status of the ventilation fans from the previously described barns and farrowing rooms. A detailed description of the MAEMU and its standard operation protocols can be found in Moody et al. (2008). The MAEMU housed, among other measurement and data acquisition equipment, a photoacoustic multi-gas analyzer (INNOVA Model 1412, INNOVA AirTech Instruments A/S, Ballerup Denmark¹) to measure CO₂ concentrations and dew point and a paramagnetic oxygen gas analyzer (model 755A, Rosemount Analytical, Irvine, California, USA) to measure O₂ concentrations (fig. 3.4). The multi-gas (INNOVA) analyzer was challenged weekly and calibrated as needed. The O₂ (Rosemount) analyzer, due to a slight drifting

¹ Mention of company or product names is for presentation completeness, and does not represent endorsement by the authors or their affiliated institutions, nor does it imply exclusion of other suitable products.

tendency, was challenged and calibrated weekly. A positive pressure gas sampling system was housed in the MAEMU and was controlled by the data acquisition system (fig. 3.5). There were eighteen total in-barn sample locations which, when composited based on barn and fan stage, resulted in eight in-barn samples plus one ambient sample location. Pit fan sampling ports were located below the slats/floor in the deep-pit head space directly under each pit fan in the pump out accesses. Wall fan sampling ports were located approximately 1.0 m in front of each wall fan. The sample port locations were chosen to represent the exhaust air leaving each barn/room. The sample lines were fluorinated ethylene propylene (FEP) Teflon tubing and were equipped with a dust filter (3011 NAPA, Atlanta, Georgia, USA) and a 47mm filter membrane (5 to 6 μm , Savillex, Eden Prairie, Minnesota, USA) to prevent particles from clogging the tubing or damaging a gas analyzer. All filters, sample lines, and sample pumps were checked weekly for leaks or blockages and addressed as needed. To ensure accurate gas concentration measurement given the analyzer response time, each location was sampled for 8 minutes, with the first 7.5 minutes for instrument stabilization and the last 0.5 minute readings for measurement. Each in-barn location was sampled sequentially so that a complete round of the barn locations occurred in 64 minutes. An ambient sample was taken at a less frequent rate (every 128 minutes) due to the relative stability of its composition.



Figure 3.4. INNOVA 1412 photoacoustic multi-gas analyzer for CO₂ concentration and dew point measurements (left) and Rosemount 755A paramagnetic analyzer for O₂ concentration measurement (right).

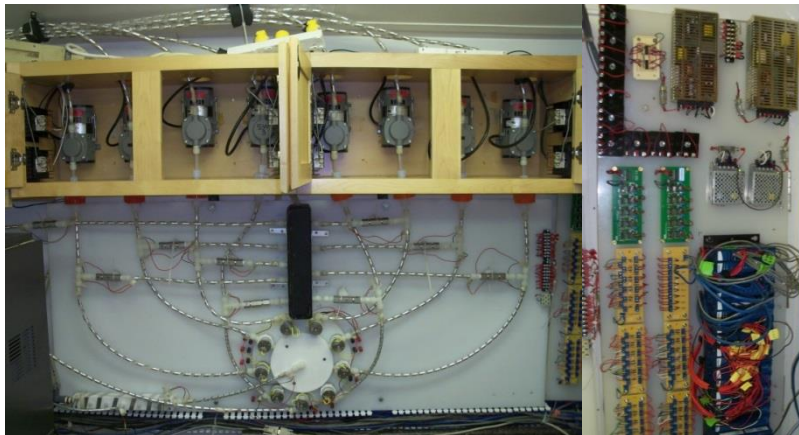


Figure 3.5. Gas, dew point, and building measurement and monitoring system: positive pressure gas sampling system (left) and data acquisition system (right).

Selected fans representing each ventilation stage (at least 50% of each stage fans) were calibrated *in situ* at multiple operating points using a Fan Assessment Numeration System (FANS) (Gates et al., 2004) to develop performance curves (fig 3.6). *In situ* calibrations occurred semi-annually to quantify any changes in fan performance due to degradation or maintenance. Measured changes in fan performance were then incorporated into the data processing program by interpolating between fan performance curves on a monthly basis. The on/off status of each fan was monitored continuously by an inductive current switch on the fan motor's power cord (Muhlbauer et al., 2011) with its analog output connected to the data acquisition system. Each variable-speed fan speed was measured by

Hall Effect speed sensors (GS100701, Cherry Corp, Pleasant Prairie, Wisconsin, USA). Static pressure sensors (Model 264, Setra, Boxborough, Massachusetts, USA) were located near the south wall in each farrowing room and near the middle of the north and south walls in the B/EG and LG barns (fig. 3.2 and 3.3).

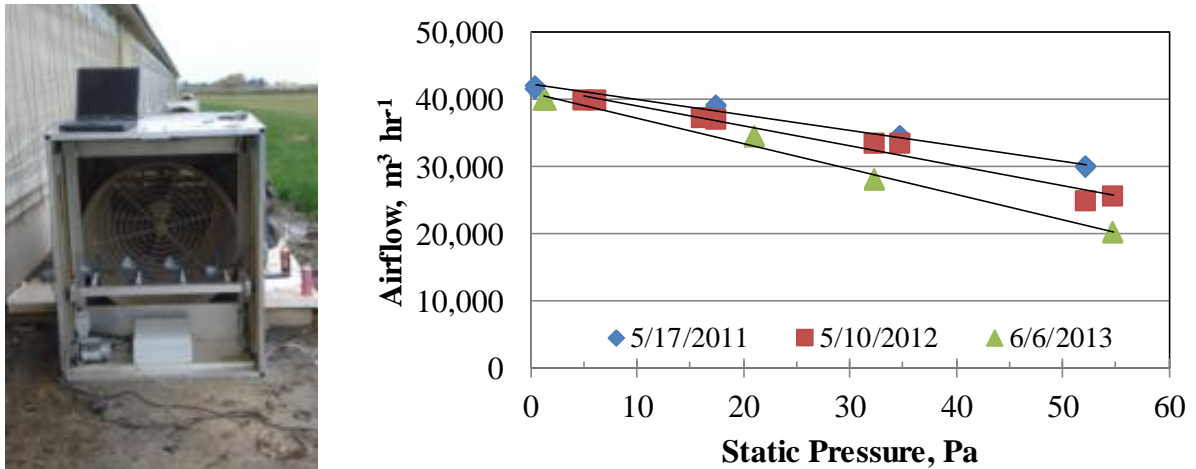


Figure 3.6. The in-situ ventilation fan calibration device used to determine exhaust fan (left) air flow rate) and example performance curves for the same fan measured at intervals during the project.

Two farrowing rooms (F1 and F2) were selected for monitoring (fig. 3.2). A composite air sample was taken from each pit fan, and a second composite sample was taken from the two lowest stage wall fans. The B/EG and LG barns were sampled and monitored identically (fig. 3.3). Namely, exhaust air samples from each barn were drawn as a composite from four of the lowest ventilation stage pit fans with a second sample being drawn from the lowest stage endwall fan. Air temperature, relative humidity (RH), static pressure (SP), fan operation status, heater operation status, O₂ concentration, and barometric pressure were measured and recorded at 1s intervals. The data were then averaged over 30 s to match the sampling frequency of the INNOVA. Heat and moisture production rates were calculated

every 30 s and averaged to determine daily time-weighted average (TWA), as well as daytime and nighttime values.

Determination of THP, House-Level MP or LHP and House-Level SHP

THP of the pigs was determined using the indirect calorimetry technique. THP is related to O₂ consumption and CO₂ production (for monogastric animals) using the following relationship (Brouwer, 1965):

$$THP = 16.18(O_2 - O_{2heater}) + 5.02(CO_2 - CO_{2manure} - CO_{2heater}) \quad (1)$$

$$RQ = (CO_2 - CO_{2manure} - CO_{2heater}) / (O_2 - O_{2heater}) \quad (2)$$

Where THP = total heat production rate of the pigs in the building, W

RQ = respiratory quotient, unitless

O₂ = total oxygen consumption rate of the barn or room, mL s⁻¹

CO₂ = total carbon dioxide production rate of the barn or room, mL s⁻¹

CO_{2manure} = carbon dioxide produced from manure, mL s⁻¹

CO_{2heater}, O_{2heater} = carbon dioxide produced and oxygen consumed by heaters, mL s⁻¹

The CO₂ produced by manure was estimated as 2% of the barn or room level CO₂ production based on deep-pit flux chamber measurements and an empty farrowing room with full shallow-pit measurement. The CO₂ production from the heater was determined to be 1268 mL s⁻¹ based on an empty, clean farrowing room measurement with a running heater. The O₂ consumption and moisture production were calculated through stoichiometry to be 2323 ml O₂ s⁻¹ and 1.37 g H₂O s⁻¹, respectively. The total O₂ consumption rate and CO₂

production rate were determined from incoming and exhaust O₂ and CO₂ concentrations and the building ventilation rate, with adjustments made for changes in temperature, pressure, moisture content, and air composition (McLean, 1972).

$$O_2 = \left(\frac{V_o}{\alpha} \right) ([O_{2a}] - \alpha [O_{2o}]) \times 10^{-6} \quad (3)$$

$$CO_2 = \left(\frac{V_o}{\alpha} \right) (\alpha [CO_{2o}] - [CO_{2a}]) \times 10^{-6} \quad (4)$$

$$\alpha = \left(\frac{V_o}{V_a} \right) = \frac{1 - ([O_{2a}] + [CO_{2a}]) \times 10^{-6}}{1 - ([O_{2o}] + [CO_{2o}]) \times 10^{-6}} \quad (5)$$

Where O₂ = total oxygen consumption rate of the barn or room, mL s⁻¹

CO₂ = total carbon dioxide production rate of the barn or room, mL s⁻¹

[O_{2o}], [O_{2a}] = oxygen concentration at outlet and ambient, respectively, ppm

[CO_{2o}], [CO_{2a}] = carbon dioxide concentration at outlet and ambient, respectively, ppm

α =

V_o, V_a = ventilation rate at STPD (O°C, 101.325 kPa, dry basis) at outlet and ambient, respectively, mL s⁻¹

The house-level MP (or LHP), which includes latent heat of the pigs and moisture evaporation from manure, evaporative cooling pads, or water troughs, was calculated from a mass-balance equation:

$$MP = \rho V_o (W_o - W_a) - MP_{heater} / 1000 \quad (6)$$

$$LHP = MP \times h_{fg} \times 1000 \quad (7)$$

Where MP = barn or room-level moisture production rate, kg H₂O s⁻¹

W_o, W_a = humidity ration of outlet and ambient air, respectively, kg H₂O (kg dry air)⁻¹

1

ρ = air density of exhaust air, kg m⁻³

MP_{heater} = moisture production rate of heater, g H₂O s⁻¹

LHP = latent heat production rate at barn or room level, W

h_{fg} = latent heat of vaporization for water, 2427 J g⁻¹

1000 = conversion of MP from kg s⁻¹ to g s⁻¹

The house-level SHP was calculated as the difference between THP and the house-level LHP:

$$SHP = THP - LHP \quad (8)$$

Heat and moisture production rates calculated in the equations above are for the entire barn or room. The animal population in the monitored barns or rooms was recorded by farm staff and conveyed to the research team. Additionally, sow and piglet weights were collected to allow for specific heat and moisture production rate calculation (per kg of body mass). As part of a separate project, piglet weights were taken on day 1 or 2 and at weaning, with selected litters weighed at 6 day intervals from birth to weaning. This allowed for the development of a piglet growth curve. Sow weights were collected from a group of 75 sows

entering farrowing and post wean. Selected sows from each parity were weighed at day 7 and day 14 post parturition. From the sow weights and piglet weights, curves were developed to span the farrowing/lactation cycle.

For each day of the 16-month monitoring period (February 2012 to June 2013), data completeness was defined as at least 75% of the possible data points in one day meeting the quality control criteria. Data for a portion of a day might be missing due to instrument maintenance, malfunction, or site activity (e.g., washing down farrowing rooms). Data associated with the days that did not meet these completeness criteria were excluded from the analysis.

Results and Discussion

For the monitoring duration (Feb 2012-June 2013), average daily heat production rates were obtained for 169 days (35% of monitored days) for the B/EG barn, 186 days (39%) for the LG barn, 180 days (37%) for the F1 room, and 227 days (47%) for the F2 room.

Figure 3.7 shows the average body mass (BM) for a sow and litter by lactation cycle day, with Day 0 being the day of parturition in the room. Table 3.3 shows the sow BM in the B/EG and LG barns for each parity. The average BM for each barn was calculated based on the parity distribution provided by the producer. The average BM (lower and upper limit of 95% CI) of sows was 204 kg (197 and 210) in the B/EG barn and 219 kg (213 and 225) in the LG barn.

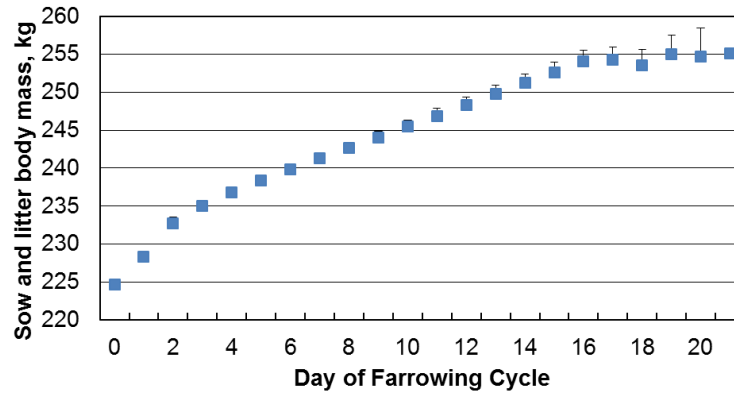


Figure 3.7. Lactating sow and litter body mass (BM) curve [kg (sow+litter)⁻¹] during the monitoring period (mean±SE) in a study evaluating heat and moisture production in a swine facility.

Table 3.3. Sow body mass (BM, kg sow⁻¹) by parity and average BM based on the parity distribution for breeding/early gestation (B/EG) and late gestation (LG) barns in a study evaluating heat and moisture production in a swine facility.

Production Stage	Variables	Parity							Avg. BM
		0	1	2	3	4	5	>=6	
	Population Distribution	8%	22%	20%	18%	13%	10%	9%	
B/EG	BM (kg sow ⁻¹)	140	179	202	210	231	231	242	204
	SE	6.5	5.8	5.4	12.8	7.3	8.3	10.2	3.2
LG	BM (kg sow ⁻¹)	173	201	211	230	237	242	247	219
	SE	6.5	7.1	6.8	8.5	7.6	7.7	10.2	3.0

HP of B/EG and LG Barns

The diurnal HP patterns for the B/EG and LG barns show a sharp increase in THP, LHP, and SHP with the daily 07:00h feeding and then a gradual decrease until the workers leave the barns at 16:00h. Figure 3.8 shows an example of this pattern from the LG barn. This behavior shows the relationship between animal activity and heat production rate, and how heat production can be affected by management practices such as single event feeding.

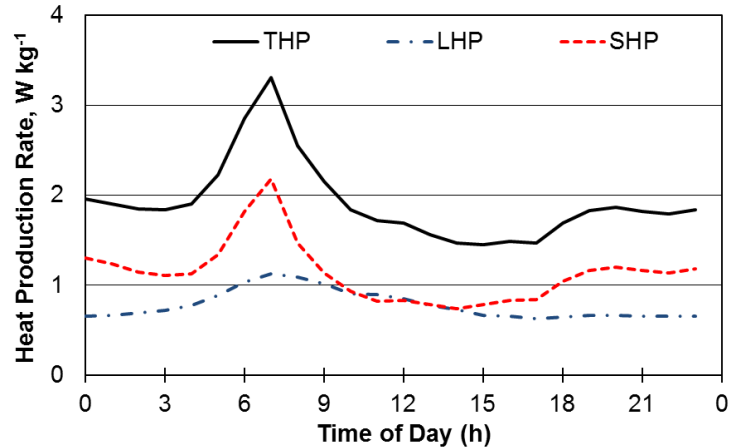


Figure 3.8. Typical whole-barn diurnal patterns of total, latent, and sensible heat production rates (THP, LHP, and SHP) for the late gestation (LG) barn in winter. Workers were present in the barn from 06:00h to 16:00h. The sows were fed at 07:00h.

Respiratory quotient (RQ) ranged from 0.76 to 1.3 (fig. 3.9), with daily mean (\pm SE) of 1.05 (\pm 0.01) for the B/EG barn and 1.05 (\pm 0.01) for the LG barn. Daily mean values for THP, barn-level LHP, and barn-level SHP are shown in Figures 3.10, 3.11, and 3.12 for the B/EG and LG barns. The results from the B/EG and LG barns are summarized in Table 3.4, which includes the diurnal split (day vs. night) and the time-weighted average (TWA) values of THP, LHP, and SHP. The results were further divided into temperature categories comparable with those in the ASABE Standards (ASABE, 2013). The comparison of the results and the ASABE Standards is discussed later in this paper.

The TWA values for the 20°C temperature category for B/EG and LG barns (mean \pm SE, W kg⁻¹) were 1.80 (\pm 0.03) and 1.52 (\pm 0.02) in THP, 0.72 (\pm 0.01) and 0.57 (\pm 0.01) in LHP, and 1.07 (\pm 0.03) and 0.94 (\pm 0.02) in SHP. The TWA values for the 25°C temperature category for the B/EG and LG barns (mean \pm SE, W kg⁻¹) were 1.82 (\pm 0.03) and 1.23 (\pm 0.02) in THP, 1.03 (\pm 0.03) and 0.83 (\pm 0.02) in LHP, and 0.79 (\pm 0.03) and 0.40 (\pm 0.02) in SHP. Overall, for the B/EG barn the ranges of THP, LHP, and SHP were, respectively, 1.12 to 3.20

$W\text{ kg}^{-1}$, 0.27 to 1.77 $W\text{ kg}^{-1}$, and 0.48 to 2.35 $W\text{ kg}^{-1}$. For the LG barn the ranges of THP, LHP, and SHP were, respectively, 0.81 to 2.86 $W\text{ kg}^{-1}$, 0.31 to 1.24 $W\text{ kg}^{-1}$, and 0.35 to 2.19 $W\text{ kg}^{-1}$.

The reduction in THP from day to night for the 20°C and 25°C temperature categories was, respectively, 32% and 27% for the B/EG barn and 27% and 19% for the LG barn. For the B/EG barn the barn-level LHP accounted for, on average, 40% of the THP for the 20°C temperature category and 57% of the THP for the 25°C temperature category. For the LG barn the barn-level LHP accounted for 38% of the THP at 20°C temperature and 67% of the THP at 25°C temperature. The standards (ASABE, 2013) report a 34% and 41% partitioning of THP to LHP at 20°C and 25°C, respectively. This shift of partitioning of THP to a higher level of LHP is to be expected as barn temperature rises, a result of increased animal latent heat dissipation and evaporation of moisture sources in the barn.

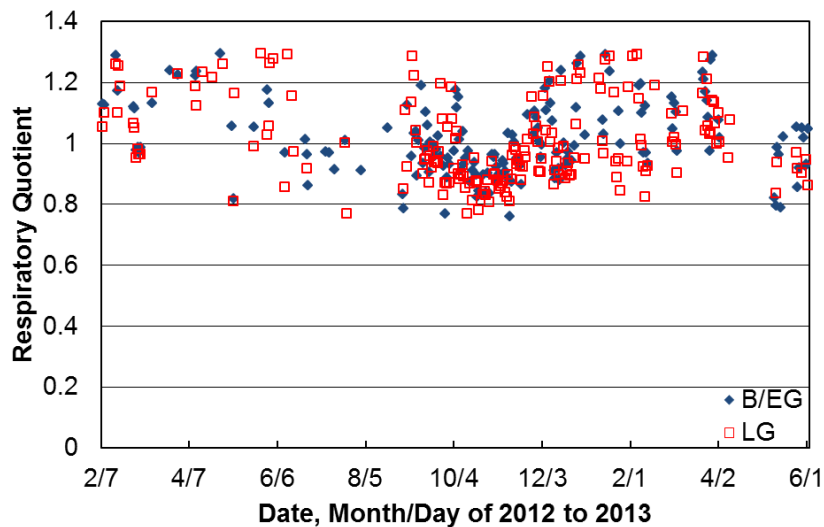


Figure 3.9. Daily mean respiratory quotient (RQ) of sows in the breeding/early gestation (B/EG) and late gestation (LG) barns. Sows were in the B/EG barn from day of weaning to day 40 of gestation and in the LG from day 40 to day 112 of gestation. Workers were present in the barn from 06:00h to 16:00h. The sows were fed at 07:00h.

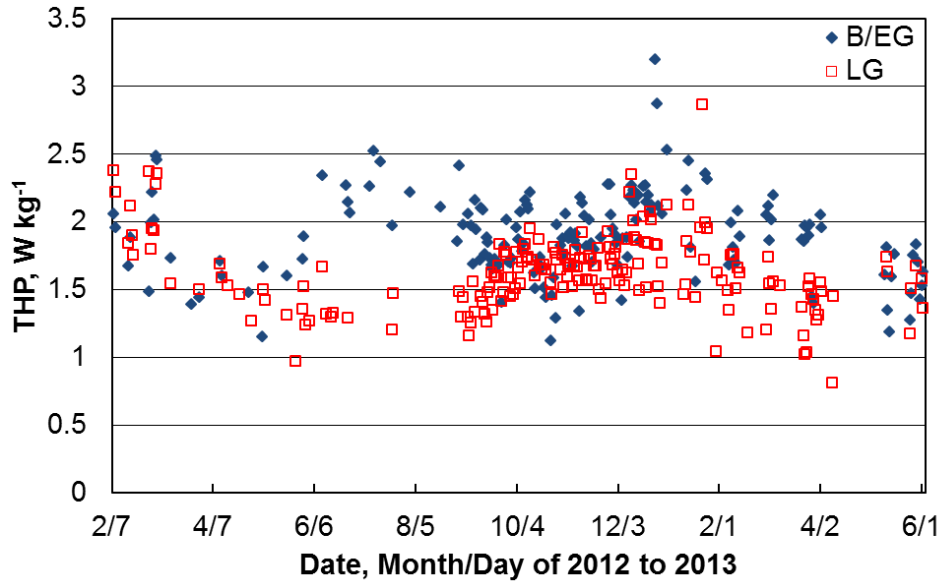


Figure 3.10. Daily mean total heat production rate (THP) of sows in the breeding/early gestation (B/EG) and late gestation (LG) barns. Sows were in the B/EG barn from day of weaning to day 40 of gestation and in the LG barn from day 40 to day 112 of gestation. Workers were present in the barn from 06:00h to 16:00h. The sows were fed at 07:00h.

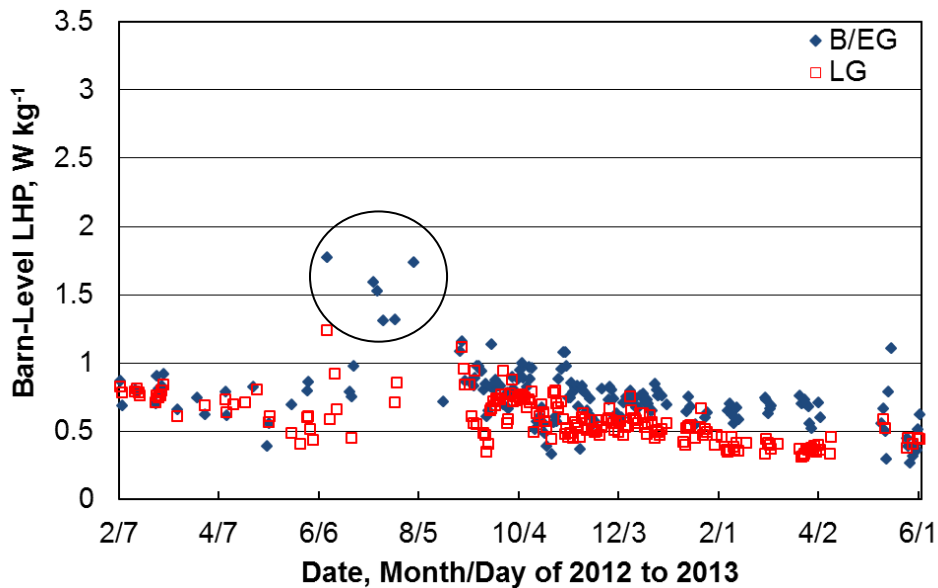


Figure 3.11. Daily mean barn-level latent heat production rate (LHP) of sows in the breeding/early gestation (B/EG) and late gestation (LG) barns. The higher LHP data points highlighted in the circle resulted from use of evaporative cooling pads. Sows were in the B/EG barn from day of weaning to day 40 of gestation and in the LG barn from day 40 to day 112 of gestation. Workers were present in the barn from 06:00h to 16:00h. The sows were fed at 07:00h.

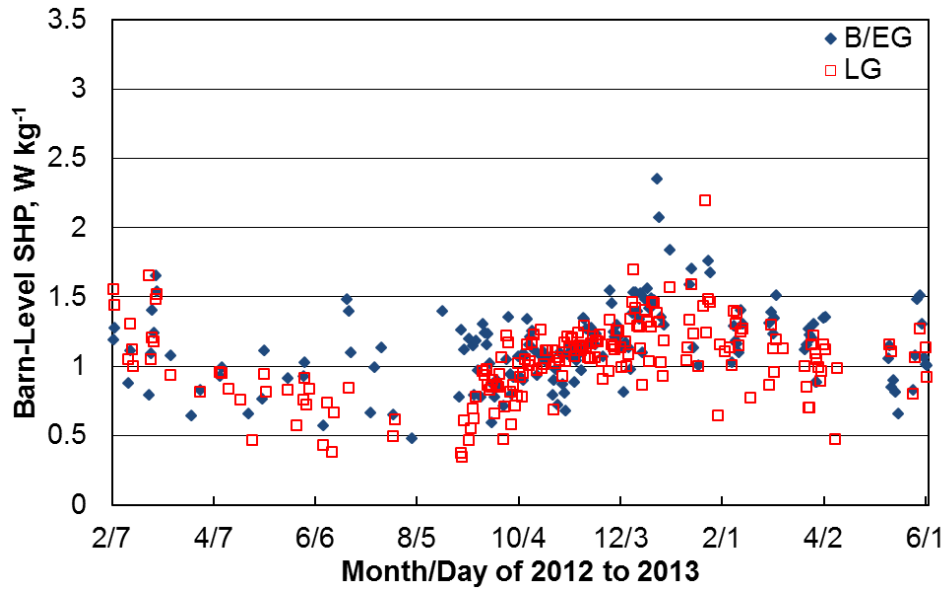


Figure 3.12. Daily mean barn-level sensible heat production rate (SHP) of sows in the breeding/early gestation (B/EG) and late gestation (LG) barns. Sows were in the B/EG barn from day of weaning to day 40 of gestation and in the LG barn from day 40 to day 112 of gestation. Workers were present in the barn from 06:00h to 16:00h. The sows were fed at 07:00h.

Table 3.4. Summary of diurnal values for total heat production rate (THP), barn-level latent heat production rate (LHP), and barn-level sensible heat production rate (SHP) (W kg⁻¹) and time-weighted average (TWA) values of THP, LHP, SHP, and respiratory quotient (RQ) for the breeding/early gestation (B/EG) and late gestation (LG) barns at barn temperature of 20°C and 25°C.

Barn	Temperature	RQ		THP (W kg ⁻¹)			LHP (W kg ⁻¹)			SHP (W kg ⁻¹)		
		TWA		Day	Night	TWA	Day	Night	TWA	Day	Night	TWA
B/EG	20°C	Mean	1.05	2.17	1.48	1.80	0.88	0.59	0.72	1.29	0.89	1.07
		SE	0.01	0.04	0.03	0.03	0.01	0.01	0.01	0.04	0.02	0.03
	25°C	Mean	1.15	2.13	1.56	1.82	1.16	0.92	1.03	0.98	0.64	0.79
		SE	0.01	0.04	0.03	0.03	0.02	0.03	0.03	0.04	0.03	0.03
LG	20°C	Mean	1.05	1.78	1.30	1.52	0.71	0.46	0.57	1.07	0.83	0.94
		SE	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.03	0.02	0.02
	25°C	Mean	1.16	1.37	1.11	1.23	0.86	0.80	0.83	0.51	0.31	0.40
		SE	0.01	0.03	0.02	0.02	0.02	0.03	0.02	0.03	0.02	0.02

The impact of barn temperature on heat production rate is shown in Figure 3.13. The trends of increasing SHP with decreasing temperature and increasing LHP with increasing temperatures are noticeable. The highlighted points in Figures 3.11 and 3.13 arose from the use of evaporative cooling pads to cool the air entering the barn, thus demonstrating the impact facility design and operation can have on the thermal loads and the environmental conditions.

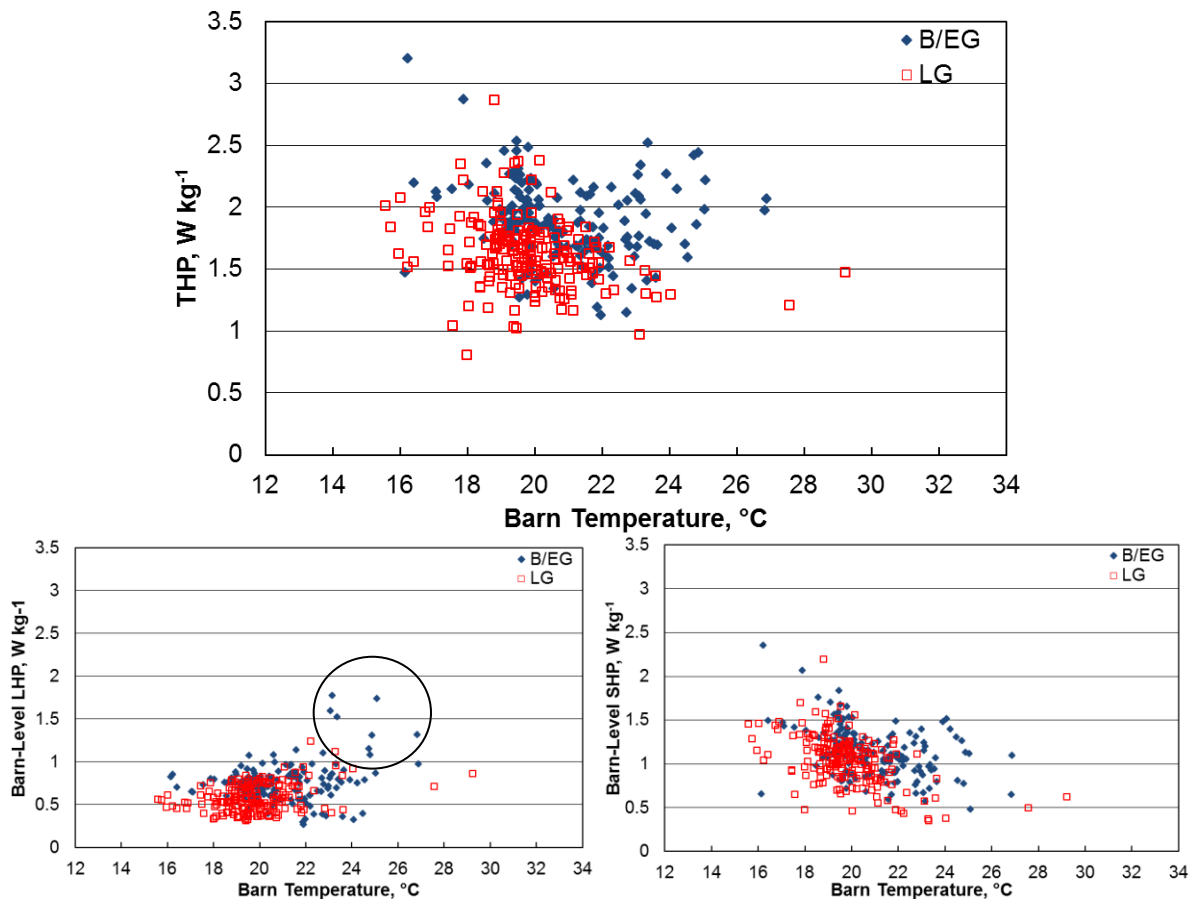


Figure 3.13. Daily mean total heat production rate (THP), barn-level latent heat production rate (LHP), and barn-level sensible heat production rate (SHP) of sows in the breeding/early gestation (B/EG) and late gestation (LG) barns versus daily mean barn temperature. Highlighted data points resulted from use of evaporative cooling pads on incoming ventilation air. Sows were in B/EG barn from day of weaning to day 40 of gestation and in the LG barn from day 40 to day 112 of gestation.

HP of Farrowing Rooms (F1 and F2)

Sample diurnal THP, LHP, and SHP patterns in wintertime are shown in Figure 3.14. A significant diurnal pattern is not as evident as with sows in the gestation stage. This is likely due to the multiple feedings of the lactating sow at 00:00h, 09:00h, 12:00h, and 18:00h and to the frequent feeding activities of the piglets.

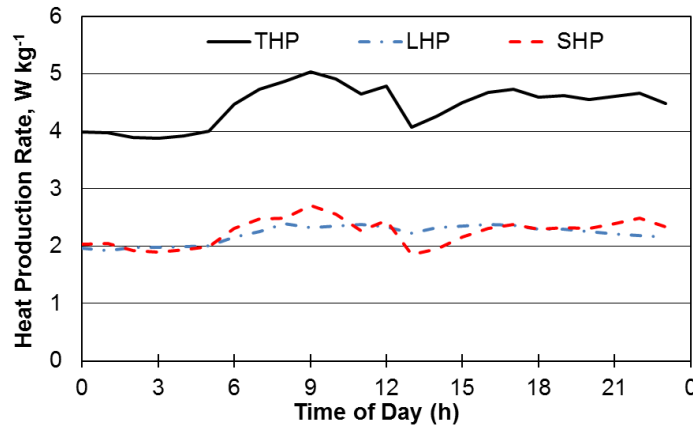


Figure 3.14. Typical whole-room winter diurnal patterns of total, room-level latent, and room-level sensible heat production rates (THP, LHP, SHP) for lactating sows and litters.

RQ ranged from 0.7 to 1.30 (fig. 3.15) with daily average values (\pm SE) of 1.04 (\pm 0.06) at 20°C and 1.04 (\pm 0.04) at 25°C. Average daily THP, LHP, and SHP rates over the monitoring period are shown in Figures 3.16, 3.17, and 3.18, respectively. In all the figures, the increasing heat production rates during each 18-22 day farrowing turn are evident. This is due to the rapid growing of piglets and the sows gaining access to almost *ad libitum* feeding after parturition. The results for the F1 and F2 rooms are summarized in Table 3.5, which includes the diurnal split (day vs. night) and the TWA values of THP, LHP, and SHP. The results were further divided into temperature and production stage categories that can be compared with the ASABE Standards (ASABE, 2013).

The TWA values for the 20°C temperature category and week 0 stage for lactating sows and litters (mean \pm SE, W kg⁻¹) were 3.87 (\pm 0.28) in THP, 2.05 (\pm 0.15) in LHP, and 1.80 (\pm 0.28) in SHP. The TWA values for the 25°C temperature category and week 0 stage for lactating sows and litters (mean \pm SE, W kg⁻¹) were 3.20 (\pm 0.21) in THP, 1.92 (\pm 0.11) in LHP, and 1.44 (\pm 0.15) in SHP. Overall, the ranges of THP, LHP, and SHP were 1.35 to 7.40 W kg⁻¹, 0.71 to 3.27 W kg⁻¹, and 0.36 to 4.56 W kg⁻¹, respectively.

The reduction in THP from day to night for the 20°C and 25°C temperature categories during week 0 was 6% and 9%, respectively. Here we observe a less drop in heat production at night compared to the B/EG and LG barns. Again, the multiple sow feeding events and the regular piglet feedings likely contribute to this smaller heat production decrease. The room-level LHP accounted for, on average, 53% of the THP at 20°C temperature and 60% of the THP at 25°C temperature during week 0. This shift of partitioning of THP to a higher level of LHP is to be expected as barn temperature rises.

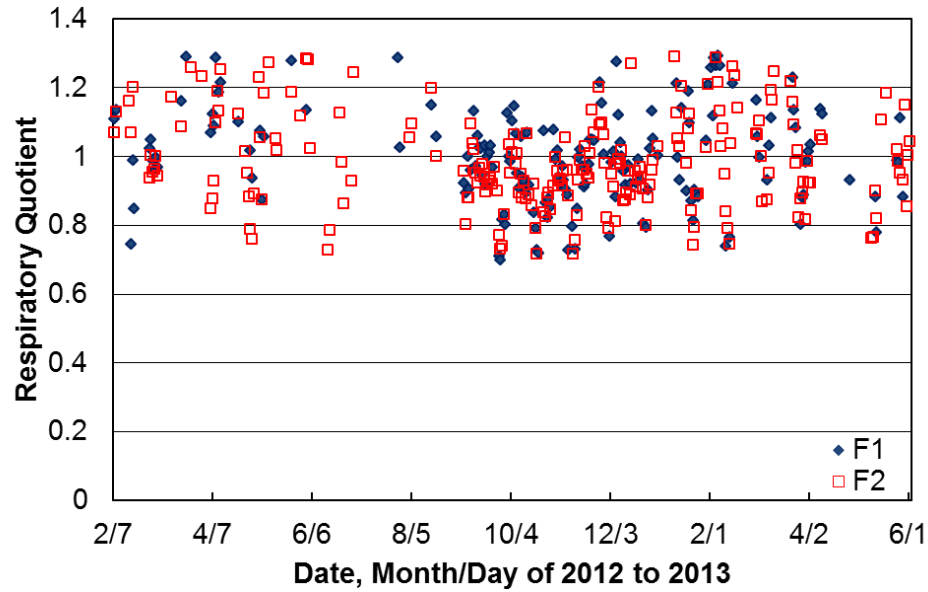


Figure 3.15. Daily mean respiratory quotient (RQ) of sows and litters in the farrowing rooms F1 and F2. The piglets were weaned at 18 to 22 days of age. Rooms were occupied by workers from 06:00h to 16:00h. The sows were fed at 00:00h, 09:00h, 12:00h, and 18:00h.

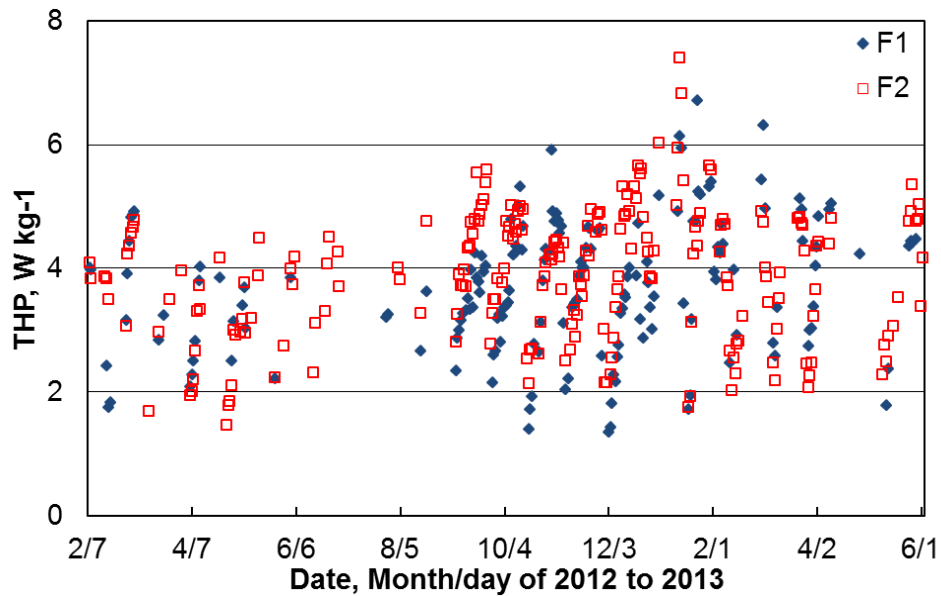


Figure 3.16. Daily mean total heat production rate (THP) of sows and litters in the farrowing rooms F1 and F2. The piglets were weaned at 18 to 22 days of age. Rooms were occupied by workers from 06:00h to 16:00h. The sows were fed at 00:00h, 09:00h, 12:00h, and 18:00h.

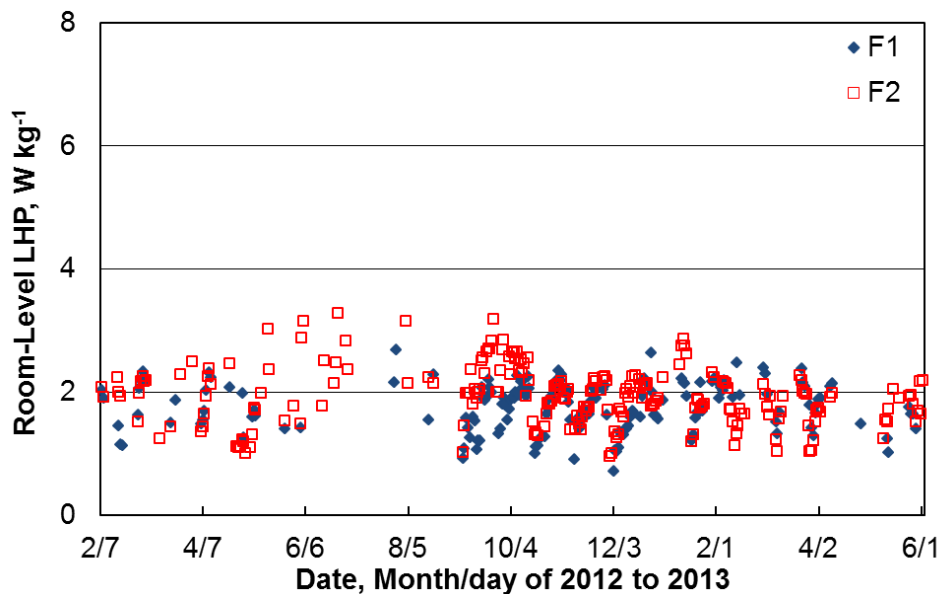


Figure 3.17. Daily mean room-level latent heat production rate (LHP) of sows and litters in the farrowing rooms F1 and F2. The piglets were weaned at 18 to 22 days of age. Rooms were occupied by workers from 06:00h to 16:00h. The sows were fed at 00:00h, 09:00h, 12:00h, and 18:00h.

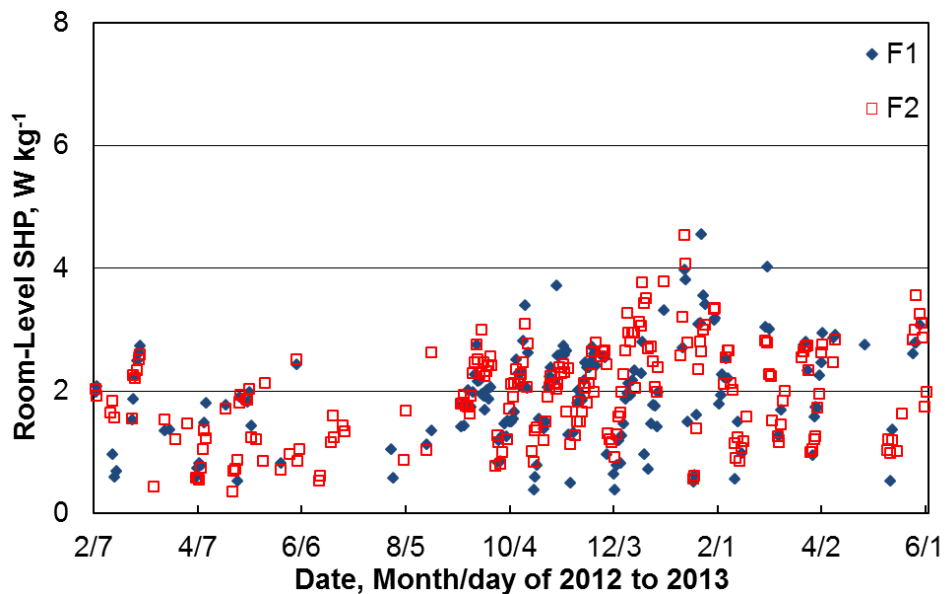


Figure 3.18. Daily mean room-level sensible heat production rate (SHP) of sows and litters in the farrowing rooms F1 and F2. The piglets were weaned at 18 to 22 days of age. Rooms were occupied by workers from 06:00h to 16:00h. The sows were fed at 00:00h, 09:00h, 12:00h, and 18:00h.

Table 3.5. Summary of diurnal values for total heat production rate (THP), room-level latent heat production rate (LHP), and room-level sensible heat production rate (SHP) ($W\text{ kg}^{-1}$) and time-weighted average (TWA) values of THP, LHP, SHP, and respiratory quotient (RQ) of lactating sows and litters at room temperature of 20°C and 25°C for the periods of preparturition, day of birth (day 0) to day 6, day 7 to day 12, and day 13 to day 18 (weaning). THP and SHP show a trend of increasing with decreasing temperature and increasing piglet age, while LHP remains relatively unchanged.

Stage	Avg. Body Mass (kg of sow+litter)		RQ		THP ($W\text{ kg}^{-1}$)			LHP ($W\text{ kg}^{-1}$)			SHP ($W\text{ kg}^{-1}$)		
			Mean	TWA	Day	Night	TWA	Day	Night	TWA	Day	Night	TWA
Preparturition	221.5	20°C	Mean	1.03	4.28	3.97	4.11	2.24	1.98	2.10	2.04	2.00	2.01
			SE	0.03	0.24	0.26	0.25	0.05	0.07	0.06	0.22	0.26	0.24
		25°C	Mean	0.94	3.87	3.36	3.59	2.20	1.96	2.07	1.66	1.40	1.52
			SE	0.04	0.35	0.32	0.33	0.17	0.17	0.17	0.21	0.22	0.21
Birth-Day 6 (Week 0)	235.2	20°C	Mean	1.05	3.99	3.77	3.87	2.17	1.96	2.05	1.83	1.77	1.80
			SE	0.07	0.30	0.27	0.28	0.14	0.16	0.15	0.30	0.27	0.28
		25°C	Mean	1.01	3.36	3.06	3.20	2.08	1.79	1.92	1.45	1.43	1.44
			SE	0.04	0.19	0.23	0.21	0.12	0.11	0.11	0.13	0.16	0.15
Day 7-12 (Week 1)	246.9	20°C	Mean	1.03	4.36	4.16	4.25	2.16	1.98	2.07	2.17	2.21	2.19
			SE	0.05	0.24	0.18	0.21	0.16	0.16	0.16	0.31	0.23	0.26
		25°C	Mean	1.03	3.60	3.48	3.53	2.08	1.94	2.00	1.70	1.78	1.75
			SE	0.03	0.15	0.16	0.15	0.11	0.09	0.10	0.12	0.12	0.12
Day 13-18 (Week 2)	255.2	20°C	Mean	1.03	4.71	4.28	4.48	2.14	2.03	2.08	2.53	2.38	2.45
			SE	0.04	0.27	0.25	0.26	0.08	0.08	0.08	0.27	0.23	0.25
		25°C	Mean	1.07	3.79	3.51	3.64	1.93	1.68	1.79	1.77	1.63	1.69
			SE	0.04	0.23	0.22	0.23	0.11	0.10	0.10	0.20	0.22	0.21

The impact of room temperature on heat production is shown in Figure 3.19. The LHP remains relatively unchanged with changing room temperature while both THP and SHP are decreasing with increasing room temperature. These patterns are likely due to the sows and piglets having different thermoneutral ranges. Farrowing room temperatures are maintained in the sow's comfort range of 15.5°C to 18°C, and localized heating is provided for the piglets to maintain a higher temperature microenvironment of 32°C to 35°C (MWPS-8, 1983). This is done both for sow comfort and to reduce room heating costs. Despite this, if the piglets are not using the localized heat or if the localized heat is inadequate, the piglets will have to expend more energy to maintain homeostasis (constant core body temperature) and thus their SHP will increase. As the room temperature increases, the environment approaches more toward the piglet thermoneutral zone, hence resulting in a decrease in piglet SHP.

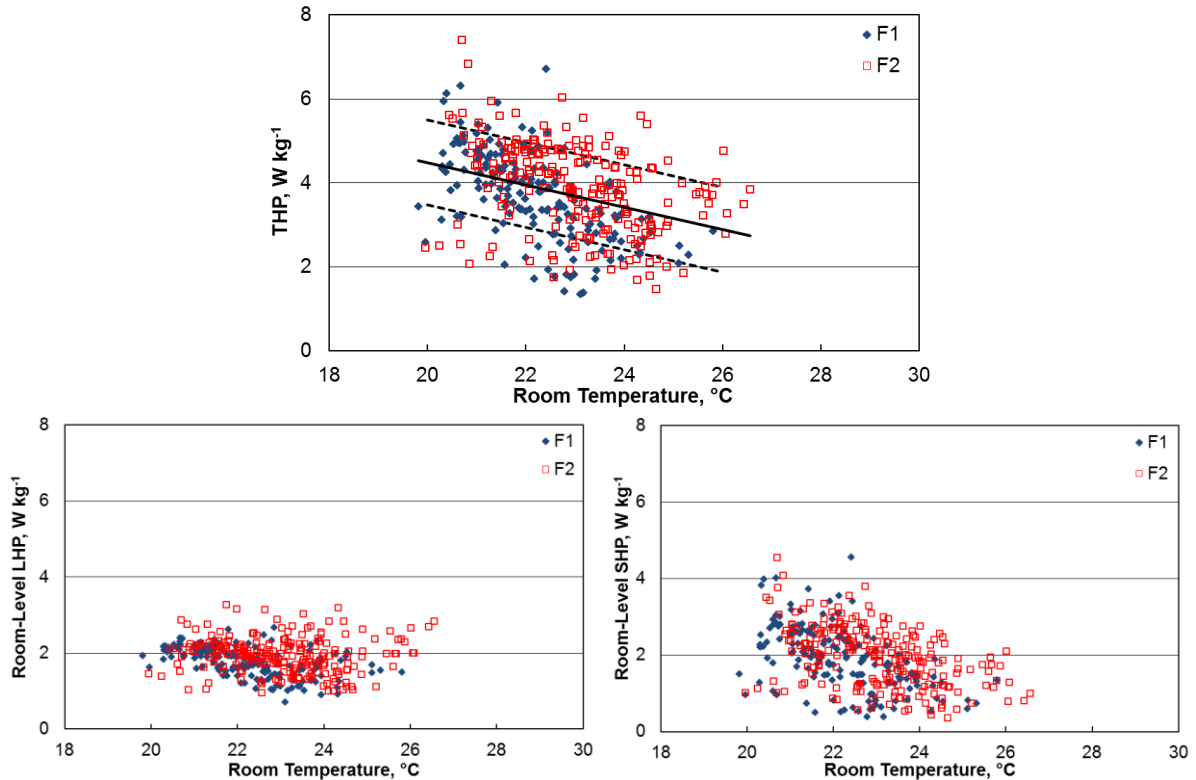


Figure 3.19. Daily mean total heat production rate (THP), room-level latent heat production rate (LHP), and room-level sensible heat production rate (SHP) of sows and litters in the farrowing rooms F1 and F2. A trend line with 95% confidence bounds is shown for the THP. The piglets were weaned at 18 to 22 days of age.

Comparison to ASABE Standards

Table 3.6 compares the measured heat production rates for the B/EG and LG barns to the ASABE standards (ASABE, 2013). Overall, the differences in heat production rates at 20°C between the current study and the standards for the B/EG and LG barns, were respectively, 28% and 8% higher for THP, 68% and 34% higher for barn-level LHP, 11% and -3% for barn-level SHP. The differences in heat production rates at 25°C between the current study and the standards for the B/EG and LG barns, were respectively, 40% and -5% for THP, 106% and 66% higher for barn-level LHP, -1% and -50% for barn-level SHP. These changes are on a unit BM basis, and the BM measured in this study (204 kg for B/EG

sows and 222 kg for LG sows) was higher than the BM of 180 kg used in the ASABE standards. Thus on a per sow basis the changes in HP are greater than these BM basis values.

Table 3.6. Heat and moisture production rate comparison between ASABE Standards and values measured in this study for breeding/early gestation (B/EG) and late gestation (LG) barns.

Temperature	Source		THP (W kg ⁻¹)	LHP (W kg ⁻¹)	SHP (W kg ⁻¹)
20°C	ASABE Standards		1.40	0.43	0.97
	This Study – B/EG	TWA	1.80	0.72	1.07
		% Difference	28%	68%	11%
	This Study – LG	TWA	1.52	0.57	0.94
		% Difference	8%	34%	-3%
	25°C	ASABE Standards		1.30	0.5
This Study – B/EG		TWA	1.82	1.03	0.79
		% Difference	40%	106%	-1%
This Study – LG		TWA	1.23	0.83	0.40
		% Difference	-5%	66%	-50%

*THP=Total heat production rate

*LHP=Barn-level latent heat production rate

*SHP=Barn-level sensible heat production rate

Table 3.7 compares the measured heat productions rates for the farrowing rooms to the standards (ASABE, 2013). The comparison is difficult due to differences in BM and farrowing duration. The standards list the sow and litter BM ranging from 177 kg at week 0 to 227 kg at week 8. The sow and litter BM in the current study ranged from 222 kg at birth to 257 kg at weaning (day 18). Thus, heat production rates measured during the first week of the farrowing cycle in the current study were compared to the standards values for similar production stage (week 0) and similar sow and litter weight (week 8). The differences at 25°C during the first week after birth, relative to the standards (ASABE, 2013) for week 0 and week 8 of farrowing, were, respectively, 23% and -18% for THP, 48% and -7% for barn-level LHP, 11% and -32% for barn-level SHP. Namely, the heat production rates of the

current study during the first week are lower than the standards values for week 8 (similar weight) but much higher than the standards values for week 0 (similar stage). This much higher THP, LHP, and SHP values for similar production stages illustrate the impact of the larger, higher producing modern sows and litters. It is critical to have accurate standards for housing design to minimize environmental stress so that the animal's productive potential can be better realized.

Table 3.7. Heat and moisture production rate comparison between ASABE Standards and values measured in this study for lactating sows and litters.

Source	Week of Farrowing Cycle	Sow+Litter Weight (kg)	Temperature (°C)	THP (W kg ⁻¹)	LHP (W kg ⁻¹)	SHP (W kg ⁻¹)
ASABE	0	177	16-27	2.6	1.3	1.3
	8	227	16-27	3.9	1.8	2.1
This Study	0	235.2	25	3.20	1.92	1.44
	Same stage	% Difference	(Week 0)	23%	48%	11%
	Similar BM	% Difference	(Week 8)	-18%	7%	-32%

*THP=Total heat production rate

*LHP=Room-level latent heat production rate

*SHP=Room-level sensible heat production rate

Summary and Conclusions

Swine ventilation design standards are based on heat production (HP) and moisture production (MP) values from studies in the 1950s and 1970s. Literature and standards since those studies have been lacking, especially for gestation and lactation swine production phases. In this extensive field study, total heat production rates (THP), barn-level latent heat production rates (LHP), and barn-level sensible heat production rates (SHP) were quantified over a 16-month period on a 4,300 sow modern breeding, gestation, and farrowing swine facility using indirect calorimetry technique. The quantification was made on a breeding/early gestation barn (B/EG, 1800 sows), a late gestation barn (LG, 1800 sows), and

two farrowing rooms (F1 and F2, 40 sows and litters each). The THP, barn-level LHP, and barn-level SHP values were determined for the day, night, and daily time-weighted average (TWA), as follows.

For the B/EG barn at 20°C,

- The THP rates for the three periods (day, night and TWA) were, respectively, 2.17, 1.48, and 1.80 W kg⁻¹.
- Barn-level LHP rates for the three periods were 0.88, 0.59, and 0.72 W kg⁻¹.
- Barn-level SHP rates for the three periods were 1.29, 0.89, and 1.07 W kg⁻¹.
- Day to night THP reduction for 20°C and 25°C were, respectively, were 32% and 27%.
- The partitioning of TWA THP into LHP at 20°C and 25°C were, respectively, were 40% and 57%

For the LG barn at 20°C,

- THP rates for the three periods (day, night and TWA) were, respectively, 1.78, 1.30, and 1.52 W kg⁻¹.
- Barn-level LHP rates for the three periods were 0.71, 0.46, and 0.57 W kg⁻¹.
- Barn-level SHP rates for the three periods were 1.07, 0.83, and 0.94 W kg⁻¹.
- Day to night THP reduction for 20°C and 25°C were, respectively, were 27% and 19%.
- The partitioning of TWA THP into LHP at 20°C and 25°C were, respectively, were 38% and 67%

For the farrowing rooms at 25°C during week 0,

- THP rates values for the three periods (day, night and TWA) were, respectively, 3.99, 3.77, and 3.87 W kg⁻¹.
- Room-level LHP rates for the three periods were 2.17, 1.96, and 2.05 W kg⁻¹.
- Room-level SHP rates for the three periods were 1.83, 1.77, and 1.80 W kg⁻¹.
- Day to night THP reduction for 20°C and 25°C were, respectively, were 6% and 9%.
- The partitioning of TWA THP into LHP at 20°C and 25°C were, respectively, were 53% and 60%

The B/EG barn at 20°C had changes (increases) of 28%, 68%, and 11% when compared to the ASABE Standards for THP, LHP, and SHP, respectively. The LG barn at 20°C had changes of 8%, 34%, and -3% when compared to the ASABE Standards for THP, LHP, and SHP, respectively. The farrowing rooms had changes (increases) of 23%, 48%, and 11% when compared to the ASABE Standards for THP, LHP, and SHP, respectively, at a similar production stage (week 0). The farrowing rooms had changes of -18%, 7%, and -32% when compared to ASABE Standards for THP, LHP, and SHP, respectively, at a similar sow and litter body mass. These data will contribute to the updating of the standards used in the design and operation of ventilation systems for modern swine breeding/gestation and farrowing facilities.

Acknowledgements

Funding for the study was provided in part by the Iowa Pork Producers Association (NPB Project #12-118) and in-kind contribution of the Mobile Air Emissions Monitoring Unit by Iowa State University. We also thank the swine producer for providing access to the facility and cooperation during the project.

References

ASABE Standards, 60th Ed. 2013. EP270.5. Design of ventilation systems for poultry and livestock shelters. St. Joseph, Mich: ASABE.

Bond, T.E., C.F. Kelly, H. Heitman, Jr. 1959. Hog house air conditioning and ventilation data. *Transactions of the ASAE* 2:1-4.

Brouwer, E. 1965. Report of the sub-committee on constant and factors. In: Energy Metabolism. Proc. Of the Third Symposium, 441-443, Scotland, European Association for Animal Production. Ed. K.L. Blaxter. London, England: Academic Press.

Brown-Brandl, T.M., M.D. Hayes, H. Xin, J.A. Nienaber, H. Li, R.A. Eigenberg, J.P. Stinn, T.A. Shepherd. 2014. Heat and moisture production of modern swine. *Transactions of the ASHRAE* 120(1): 469-489.

Brown-Brandl, T.M., J.A. Nienaber, H. Xin, R.S. Gates. 2004. A literature review of swine heat production. *Transactions of the ASAE* 47(1): 259-270.

Cairnie, A.B., J.D. Pullar. 1957. The metabolism of the young pig. *Journal of Physiology* 139(2):15P.

CIGR report. 2002. Climatization of animal houses. Fourth report of working group. Heat and moisture production at animal and house levels. Horsens, Denmark.

Gates, R. S., D. K. Casey, H. Xin, E. F. Wheeler, J.D. Simmons. 2004. Fan Assessment Numeration System (FANS) design and calibration specifications. *Transactions of the ASAE* 47(6):1765-1778.

Harmon, J.D., H. Xin, J. Shao. 1997. Energetics of segregated early-weaned pigs. *Transactions of the ASAE* 40(6): 1693-1698.

Le Dividich, J., M. Vermorel, J. Noblet, J.C. Bouvier, A. Aumaitre. 1980. Effects of environmental temperature on heat production, energy retention, protein, and fat gain in early weaned pigs. *British Journal of Nutrition* 44(3): 313:323.

McCracken, K.J., B.J. Caldwell, N. Walker. 1980. Studies on diurnal variations of heat production and the effective lower critical temperature of early-weaned pigs under commercial conditions of feeding and management. *British Journal of Nutrition* 43(2):321-328.

McCracken, K.J., R. Gray. 1984. Further studies on the heat production and effective lower critical temperature of early-weaned pigs under commercial conditions of feedings and management. *Animal Production* 39(2):283-290.

McLean, A.J. 1972. On the calculation of heat production from open-circuit calorimetric measurements. *British Journal of Nutrition* 27(3): 597-600.

Midwest Plan Service Structures and Environment Handbook, MWPS-1. 1983.
Midwest Plan Service, Iowa State University, Ames, Iowa.

Midwest Plan Service Swine Housing and Equipment Handbook. MWPS-8. 1983.
Midwest Plan Service, Iowa State University, Ames, Iowa.

Moody, L., H. Li, R. Burns, H. Xin, R. Gates. 2008. A Quality Assurance Project Plan for Monitoring Gaseous and Particulate Matter Emissions from Broiler Housing. ASABE #913C08e. St. Joseph, Michigan.

Muhlbauer R.V., T.A. Shepherd, H. Li, R.T. Burns, H. Xin. 2011. Technical Note: Development and application of an induction-operated current switch for monitoring fan operation. *Applied Engineering in Agriculture* 27(2): 287-292.

Ota, H., J.A. Whitehead, R.J. Davey. 1975. Heat production of male and female piglets. *Journal of Animal Science* 41:436-437.

CHAPTER 4**HEAT LAMP VS. HEAT MAT AS LOCALIZED HEAT SOURCE IN SWINE
FARROWING CRATE**

J.P. Stinn and H. Xin

A manuscript prepared for submission to *Transactions of the ASABE***Abstract**

Heat lamps and heat mats are the two main types of supplemental heat sources used to provide localized heating to pre-wean piglets in modern swine farrowing systems. Both localized heat sources aim to provide a warmer microenvironment for the piglets while allowing the room conditions to suite the sows' thermal environment needs. Previous work has shown that localized heating in farrowing operation is the most non-feed energy intensive phase in swine production, and new systems offer the possibility of reducing electricity consumption. However, the new heating system's effects on piglet performance (rate of gain, mortality) and heat source utilization must be quantified. For this study, three 40-crate farrowing rooms were equipped with 125W heat lamps in half of the crates and 290W 0.6m x 1.5m (2ft x 5ft) double heat mats shared between two crates in the other half of the crates. A temperature dependent, variable output controller regulates the power supply to the mats. The lamps were controlled on/off by the room ventilation system controller and turned off when the room temperature exceeded the set point by 5.5°C. Electricity usage of each half-room was measured separately with electric meters, and piglet performance was

recorded by farm personnel and our research group. Additionally, infrared thermographs were taken for a 24-hr period several times during the lactation period to capture the heat source utilization by the piglets. Average body weight gain (mean \pm SE) of piglets in the mat and lamp regimens was, respectively, 224 (\pm 5.7) g/d and 220 (\pm 5.9) g/d. Prewean mortality (mean \pm SE) for the mat and lamp regimens were, respectively, 7.8% (\pm 0.4%) and 7.4% (\pm 0.5%). Power use (mean \pm SE) for the mat and lamp regimens was respectively, 0.66 (\pm 0.06) kWh and 1.05 (\pm 0.04) kWh per kg weaned pig. Overall, the heat sources were occupied for 58% and 56% of the time for mats and lamps, respectively. When the heat source was utilized, at least two piglets were present 76% and 87% of the time for mats and lamps, respectively. Overall, the mats and lamps performed similarly except for power use.

Keywords. *Swine farrowing, Localized heating, Piglets thermal comfort, Energy efficiency, Thermography*

Introduction

From 2007 to 2012, the U.S. swine industry average number of piglets born and piglets born alive increased by 1.1 and 1.2 piglets per sow per farrowing event, respectively. However, in that same time span the average number of piglets weaned has only increased by 0.8 piglets per sow per farrowing event while the pre-weaning mortality has increased from 14.2% to 15.5% (Stalder, 2013). The preweaning mortality rate, coupled with the increased birth rate, means that 1.9 piglets per litter that are born alive are lost before weaning. Since the cost of maintaining a sow through breeding, gestation and farrowing is generally fixed and independent of litter size, a change in preweaning mortality rate resulting in an extra pig

per litter weaned approximately equates to an 11% reduction in fixed cost. Reducing prewean mortality by a small amount would have a significant impact on the swine industry.

The vast majority of preweaning mortality (60-70%) occurs within 3 days of birth, when infectious agents play a minor role (Herpin et al. 2002). One study found that 79% of preweaning mortalities were due to crushing of the piglets by the sow (Weary et al., 1998). While crushing by the sow may be the ultimate determination of death, multiple underlying causes increase the risk of crushing events (e.g. sow behavior, litter size, cold stress, starvation, disease). Following crushing, the primary cause of death after 3 days is related to weak piglets (e.g., enteric or respiratory diseases, or lack of nutrients) (McGlone and Johnson, 2002). These mortality figures are due to the challenge producers face of meeting the different thermal, space, and behavioral needs of the sow and piglets in a production system that also allows for specialized herd management.

Swine farrowing operations face the unique challenge of maintaining two distinct thermal environments in the same facility. Piglets require a dry, draft-free space at 32.2-35°C (90-95°F), while sows prefer a temperature of 15.5-18.3°C (60-65°F) (MWPS, 1983). To meet these two needs, the room temperature is often maintained at 18.3-23.9°C (65-75°F) range and localized heating is provided to the piglets. Within the last two decades, advancements in genetics and nutrition have provided significant increases in sow size, piglet numbers, and weaning weights. However, farrowing stalls in use today are typically based on design standards like the Midwest Plan Service Swine Housing and Equipment Handbook (MWPS, 1983) developed with data corresponding to significantly smaller sows and litters.

There are two main methods of localized heating in the U.S. swine industry, heat lamps and heat mats. The goal of the localized heating is to draw the piglets away from the sow when not nursing to avoid mortalities due to being laid or stepped on. There has been some work in the past examining the two heating systems. Zhou and Xin (1999) found that heat lamp usage by piglets was independent of light color (white or red) and that piglets used a varied output heat lamp more as they grew than a constant output lamp. This advantage of varied output carries over to heat mats. Some of the designs of heat mats in the past were inadequate in terms of even heat distribution. Depending on the design, some mats when on full power or if not controlled by a variable controller can be too hot for the piglets and reduce the usable heated area available (Zhang and Xin, 2000). When given a choice between both heat sources, heat lamps were chosen more than the heat mats during the first two days after parturition (Zhang and Xin, 2001). Previous study also suggested that the typical 0.3 by 1.2 m (1ft by 4ft) heat mat might not provide enough area, especially with the current size of litters at weaning (10.3 per litter; Stalder, 2013). Hence, larger heat mats (e.g. 0.3 by 1.5 m (1ft by 5ft)) were investigated in this study. However, all methods attempt to entice the piglet away from the sow with warmth only, when piglets are drawn to be near the sow by both the warmth and smell (Lay et al., 1999).

Data from the mid 90's indicate that the Iowa swine industry spends more than \$70 million on fuel and electric energy in producing market-size pigs (Xin et al., 1997). The annual energy costs could be partitioned into \$9.7 million in lighting, \$22.2 million in ventilation, and \$38.2 million in supplemental heating. It was further estimated that 70% of the supplemental heating cost (\$26.7 million) occurs in localized heating, mostly with heat

lamps, in the farrowing operations. Clearly, farrowing was/is the most (non-feed) energy intensive phase in swine production cycle. The combined potential energy savings and improved surface temperature control led to the use of a room temperature dependent variable power output controller for the heat mats.

The objective of this study was to quantify the effects of localized heating type – mat vs. lamp on piglet mortality, rate of gain, heat source utilization and electric power use in swine farrowing rooms.

Materials and Methods

A 4,300-sow capacity breeding/gestation/farrowing facility (PIC genetics) in central Iowa was used in this study. The farrowing portion of the facility consisted of two buildings with 9 farrowing rooms each. Three farrowing rooms, designated as Room F1, Room F2, and Room F3, were selected. The farrowing rooms were each 15.5m × 13.9m (51ft × 45.5ft) with a shallow-manure pit system (0.61m (2ft) deep) that was emptied after every turn (approx. 21 days). Each room had four rows of ten farrowing crates. The farrowing rooms shared a common hallway that was cooled by evaporative cooling pads during warm/hot weather. The rooms were filled and weaned within 3 to 4 days of each other. Room conditions at the piglet level were measured with temperature/relative humidity (RH) loggers (HOBO Pro V2, Onset Computer Corporation, Bourne, MA, USA).

The layout for heat mats and lamps in one of the farrowing rooms is shown in Figure 4.1. Twenty crates in each room used a 125 W heat lamp suspended over a 0.6 m × 1.2 m (2 ft × 4 ft) black rubber mat. The rubber mat was shared between two crates, giving each crate

0.37 m² (4 ft²) of mat area. The remaining twenty crates in each room used 0.6 m by 1.5 m (2 ft by 5 ft) Stanfield heat mats (290W, Osborne Industries, Osborne, KS, USA²). The heat mats were shared between two crates which provided each crate with 145W over a 0.46 m² (5 ft²) area. Figure 4.2 shows the installed heat lamps and heat mats in the farrowing rooms.

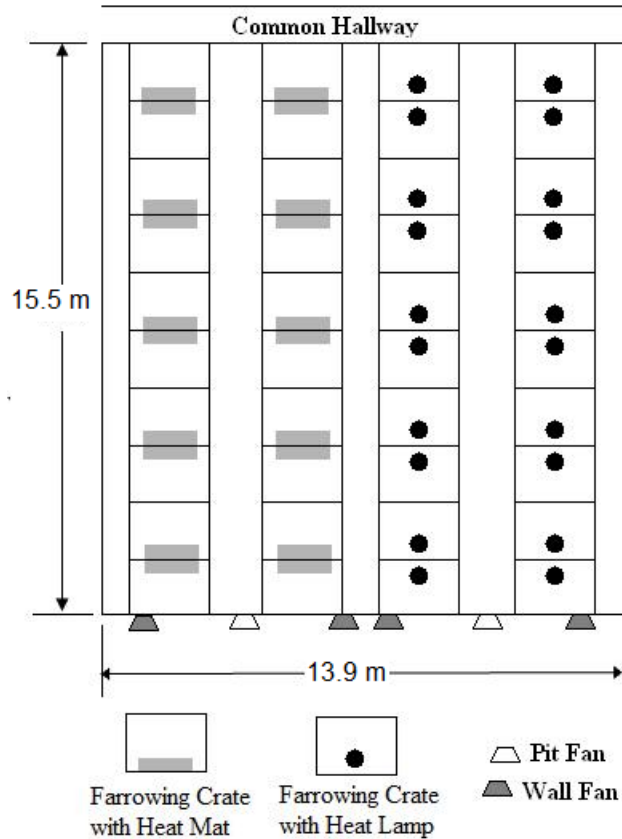


Figure 4.1. Farrowing room schematic for 20 crates utilizing heat mats and 20 crates utilizing heat lamps.

² Mention of company or product names is for presentation completeness, and does not represent endorsement by the authors or Iowa State University, nor does it imply exclusion of other suitable products.

The lamps were controlled with the room's environmental controller (Model TC5-2V8SA, Automated Production Systems, Assumption, IL, USA). The lamps were on except when the room temperature reached 5.5°C above the room set point. The mats were controlled with a separate control system (Osborne Heat Pad Controller, Osborne Industries, Osborne, KS, USA) that varied the power to the mats based on room temperature. Power usage of each heat source for each room was monitored with an electric meter (Model E10-320825-JKIT, E-Mon, Langhorne, PA, USA). Cumulative power use at the end of each farrowing cycle was recorded for each treatment. Instantaneous power use was collected by the data acquisition system of a Mobile Air Emission Monitoring Unit (MAEMU) installed at the facility for a separate project (Stinn et al., 2013)

Piglet weights were measured with a portable litter scale (WayPig Litter Scale, Raytec Manufacturing, Ephrata, PA, USA). All litters were weighed by farm workers after processing (tail clipping, castration) on day 1 or 2 post parturition. Randomly selected litters were weighed at intervals of four to six days for the development of growth curves. All litters for each heat source type were weighed together at weaning using a drive-on truck scale. Other production data, such as mortality numbers and causes, number of piglets born alive, and number of piglets weaned, were recorded by the farm personnel.



Figure 4.2. Installed localized heating sources in this study: Stanfield double heat mat (0.6 m × 1.5 m) 290W (145 W each side) heat mat (left) and 125 W heat lamps over a 0.6 m × 1.2 m rubber mat (right).

Piglet utilization of heat sources was monitored with infrared thermography cameras (Model T440, FLIR Systems Inc., Boston, MA, USA). The cameras were deployed for 24 hr periods over both heat sources at 4 to 5 d intervals during lactation and captured thermographs at 1-min intervals for each 24-hr period. The thermographs (fig. 4.3) were analyzed to determine heat source usage by the piglets through manual counting of the piglets utilizing the heat source in each image. These data were then analyzed to calculate the number of and duration of occupied and unoccupied events for each heat source. The time of occupation of different piglet numbers (1 to the litter size) were determined. The data were grouped by production stage (piglet age) into four groups: Birth to Day 3, Day 4 to 8, Day 9 to 13, and Day 14 to 18. The values were analyzed with Tukey's Studentized Range tests within each production stage for differences between the occupation times for different piglet numbers (1 to the litter size). The daily heat source use was determined for each observation period using the equation:

$$DSHU = \frac{\sum(PN \times Tn)}{LS \times PL} \times 100\% \quad (1)$$

Where DHSU = daily heat source use, %

PN = piglet number, 0 to litter size

Tn = time utilized by each piglet number, minutes

LS = litter size

PL = length of monitoring period, minutes

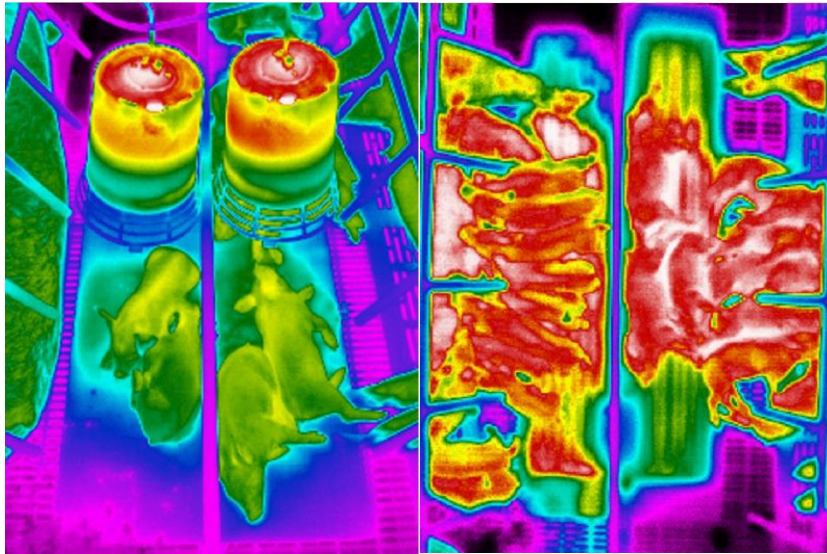


Figure 4.3. Thermographical images of heat lamps at pre-parturition height (left) and heat mat at full power (right).

Results and Discussion

For the duration of the project (September 2012 to September 2013) sixteen farrowing cycles were monitored. Temperature and RH for the monitored period are shown in Table 4.1.

Table 4.1. Average temperature and relative humidity (RH) near the mats and lamps and the overall averages.

		Temperature, °C	RH, %
Mat	Mean	23.5	60
	SD	1.5	12
Lamp	Mean	23.3	61
	SD	1.6	12
Overall	Mean	23.4	61
	SD	1.5	12

Average Weight Gain (AWG)

The average weight gain (AWG) of piglets in crates with heat mats vs. heat lamps is shown in Figure 4.4. AWG (mean \pm SE) was 224 g/d (\pm 5.7) and 220 g/d (\pm 5.9) for the mat and lamps, respectively and were not significantly different ($p = 0.64$). These values were comparable to those reported by Zhou and Xin (1999) and Beshada et al. (2006), ranging from 225 to 294 g/d and 221 to 268 g/d, respectively.

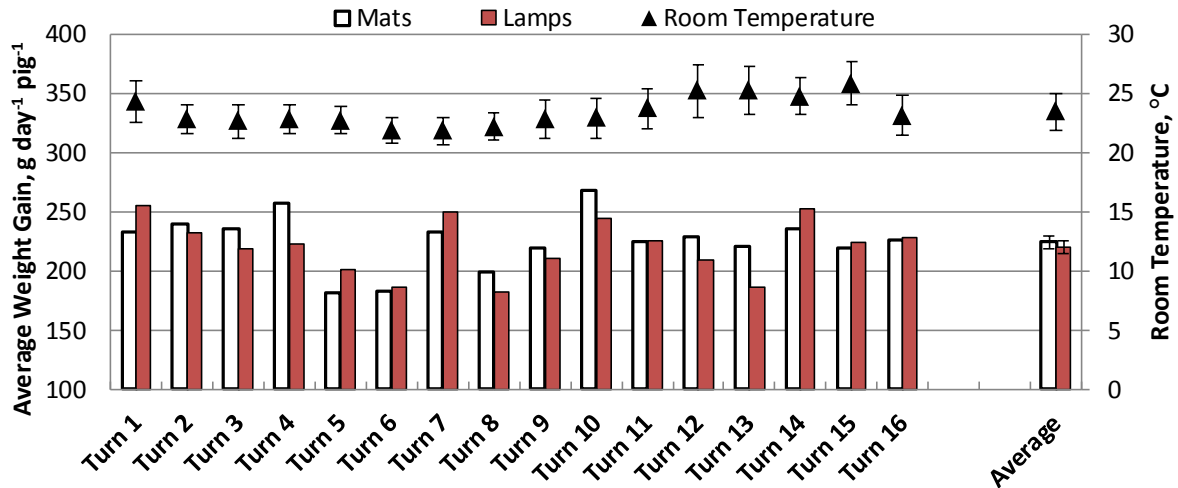


Figure 4.4. Piglet average weight gain (AWG) by farrowing crate localized heat source (heat mat or heat lamp) and by farrowing turn, the overall AWG (\pm SE), and the average room temperature (\pm SD) for each turn.

Mortality Rate

Figure 4.5 shows the comparison of mortality rates between the mats and lamps. Overall, the prewean mortality (mean \pm SE) for piglets was 7.8% (\pm 0.4%) with heat mats and 7.4% (\pm 0.5%) with heat lamps ($p=0.41$). Beshada et al. (2006) found mortality rates ranging from 7.3% to 14.5% over five farrowing turns for piglets raised with mats and lamps. Stalder (2013) reported an average prewean mortality rate of 15.5% for the swine industry in 2012, with the average prewean mortality rate of 8.4% for the top 25% sow farms.

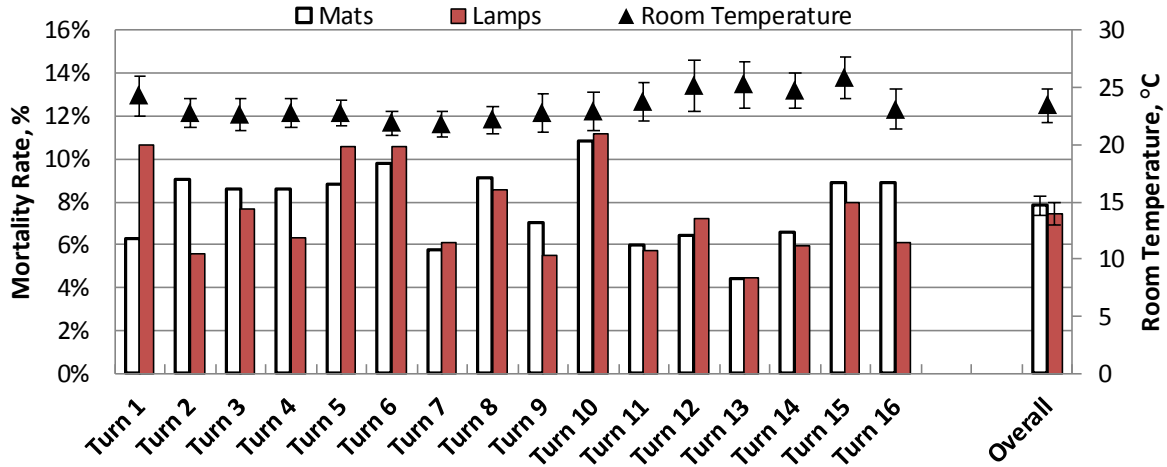


Figure 4.5. Piglet prewean mortality (by farrowing crate localized heat source (heat mat or heat lamp) and by farrowing turn, the overall mortality rate (\pm SE), and the average room temperature (\pm SD) for each turn.

Power Consumption

A sample of the instantaneous power use data is shown in Figure 4.6 from day 17 of a farrowing turn where the ambient temperature exceeded 25°C from 13:34 to 17:21. During this time the room temperature became elevated above 5.5°C above the room set point and the lamps were turned off by the controller. The mats were operating at less than 500W to maintain the desired surface temperature due to being near the end of the temperature curve on the mat controller. The mats also turned off in the afternoon due to the elevated temperature. Figure 4.7 shows the daily power consumption and cumulative power use over two farrowing cycles. Due to the higher full power output of the mats compared to the lamps (145W vs. 125W), the mats will consume more electricity until the temperature curve on the variable output controller begins to reduce the mat temperature and output with increased piglet age.

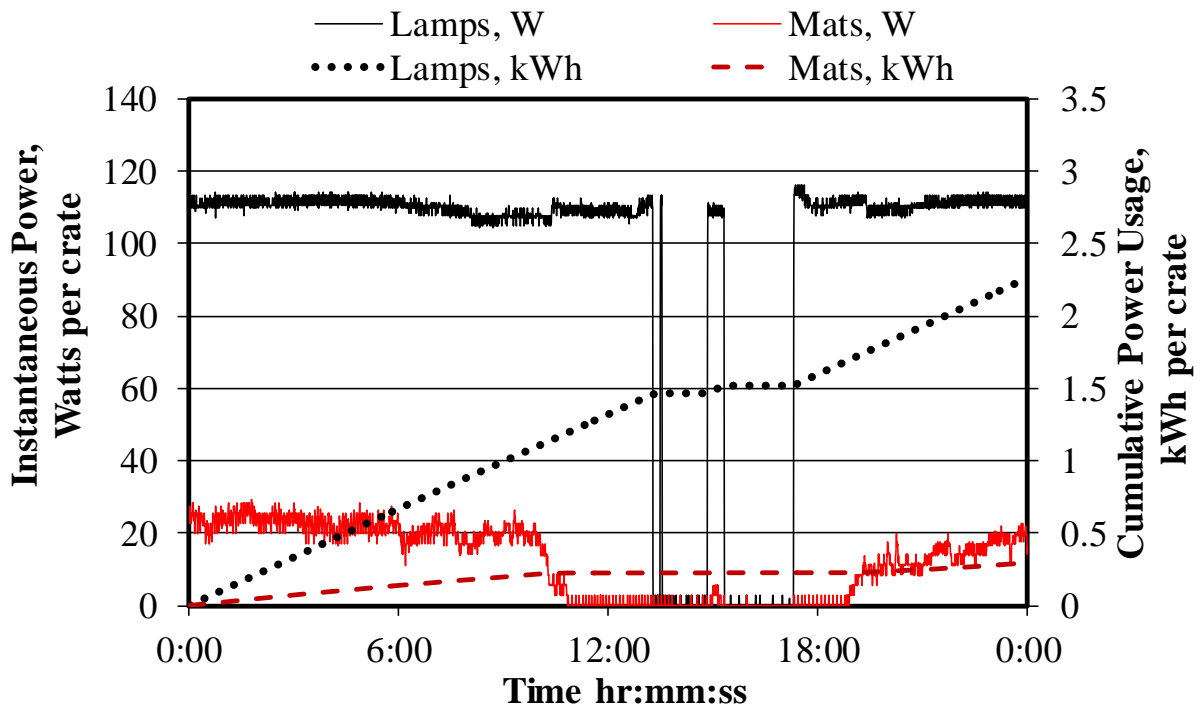


Figure 4.6. Diurnal heat mat and heat lamp instantaneous power and cumulative power use pattern on day 17 of farrowing cycle with ambient temperature exceeding 25°C from 13:34 to 17:21.

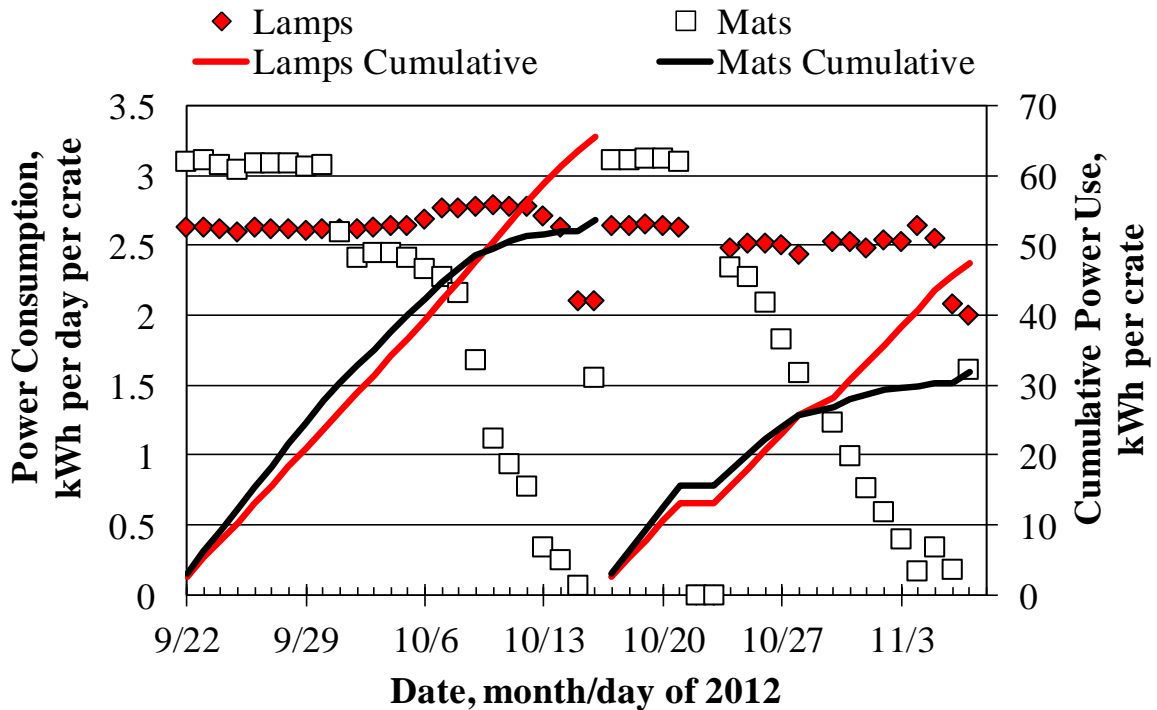


Figure 4.7. Heat mat and heat lamp daily and cumulative power consumption over two farrowing cycles.

The turn-by-turn power use values are shown in Figure 4.8. The cumulative power use per turn was normalized to the specific mass of weaned piglets. The mats consumed an average (\pm SE) of 0.66 (\pm 0.06) kWh per kg weaned piglet while the lamps consumed 1.05 (\pm 0.04) kWh per kg weaned piglet, 36% reduction by the mats ($p < 0.001$). At an assumed electricity rate of \$0.07 per kWh, this represents a \$0.026 per kg of weaned piglet or \$0.14 per weaned piglet energy savings by the mats. The pay-back period based on production values of this facility for mats due to the electricity savings is 3.4 years or 57 farrowing cycles.

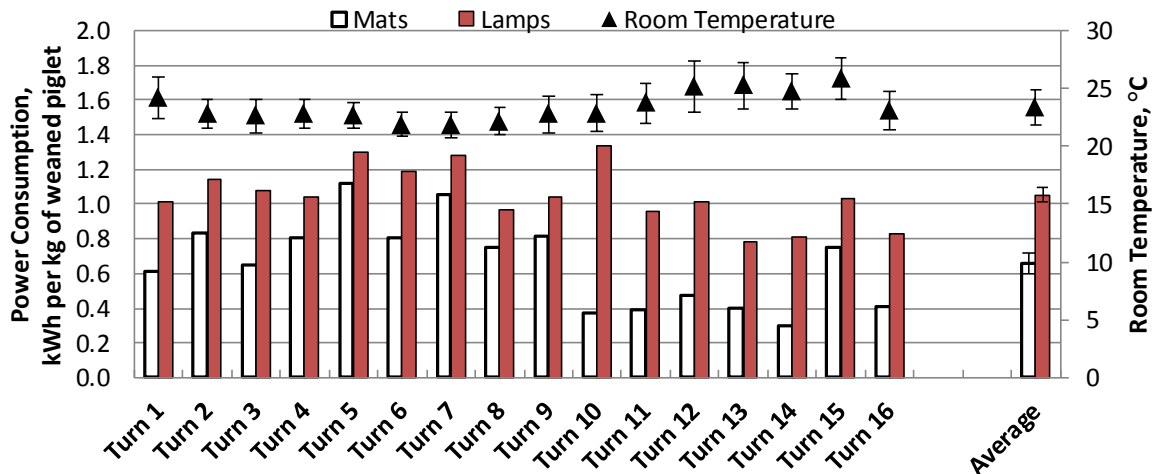


Figure 4.8. Power consumption per kg of weaned pig per farrowing turn by farrowing crate localized heat source (heat mat or heat lamp), the overall power consumption per kg of weaned pig (\pm SE), and the average room temperature (\pm SD) for each turn.

Heat Source Utilization

For each day of heat source utilization data, one thermograph per hour was selected that had no piglets utilizing the heat source. The average daily surface temperature of the heat mat or the black rubber mat for heat lamp was determined. The results are summarized in Table 4.2. The heat mat surface temperature drops from 40.5°C at the beginning of the cycle

to 27.0°C at the end. The heat lamp surface temperature remains constant except for the effect of decreasing room temperature.

Table 4.2. Room and surface temperature (SD) of heat mats or heat lamps for each production stage.

Production Stage	Mat			Lamp		
	Number of Days	Room Temperature, °C	Surface Temperature, °C	Number of Days	Room Temperature, °C	Surface Temperature, °C
Birth-Day 3	4	24.7 (0.06)	40.5 (7.5)	4	25 (0.81)	30.3 (2.1)
Day 4-8	4	24.9 (1.0)	34.7 (2.4)	4	25.9 (0.69)	32.5 (1.8)
Day 9-13	5	25.2 (2.6)	25.3 (1.1)	4	24.1 (1.7)	27.7 (4.4)
Day 14-18	3	24.6 (1.0)	27.0 (1.1)	3	23.7 (2.0)	27.1 (5.1)

The heat source utilization is shown in Figures 4.9, 4.10, 4.11, and 4.12 for production stages Birth to Day 3, Day 4 to 8, Day 9 to 13, and Day 14 to 18, respectively. The figures show the average percent of the day each heat source is un-occupied (0 piglets) or occupied by 1, 2, 3, 4, 5, 6, or > 6 piglets. The utilization for each heat source and piglet number were checked for significant differences within each production stage. Values with different letters are significantly different ($p < 0.05$). The time of non-occupancy is significantly higher than most of the rest of the utilization groupings. The time of non-occupancy is not significantly different across production stage or heat source. Vasdal et al. (2009) found that piglets used a heated creep area for 50% of the time from parturition to 4 days post parturition and that piglets rarely rested alone. For a similar production stage, this study found that piglets used a heat source 63% (mats) and 55% (lamps) of the time. When the piglets were utilizing the heat source, more than one piglet was present 76% and 87% of the time for mats and lamps, respectively.

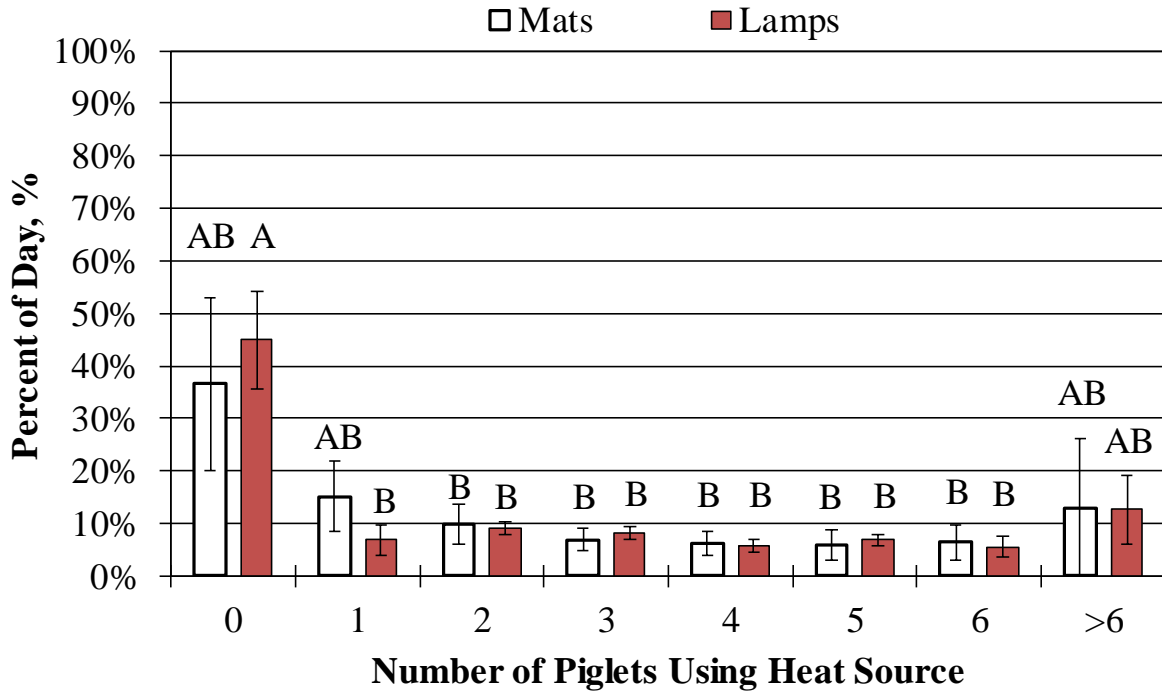


Figure 4.9. Heat mat and lamp utilization (percent of day (\pm SE)) by piglets from birth to 3d of age. Means with different letters are significantly different ($p < 0.05$).

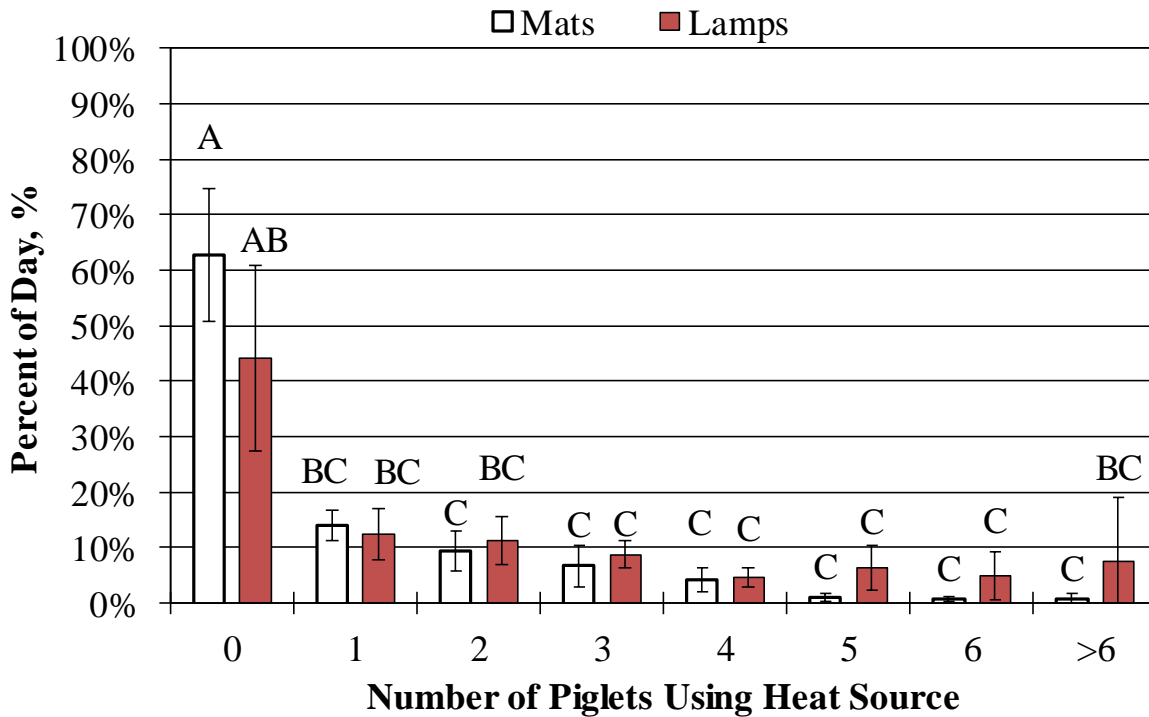


Figure 4.10. Heat mat and lamp utilization (percent of day (\pm SE)) by piglets from 4 to 8 days of age. Means with different letters are significantly different ($p < 0.05$).

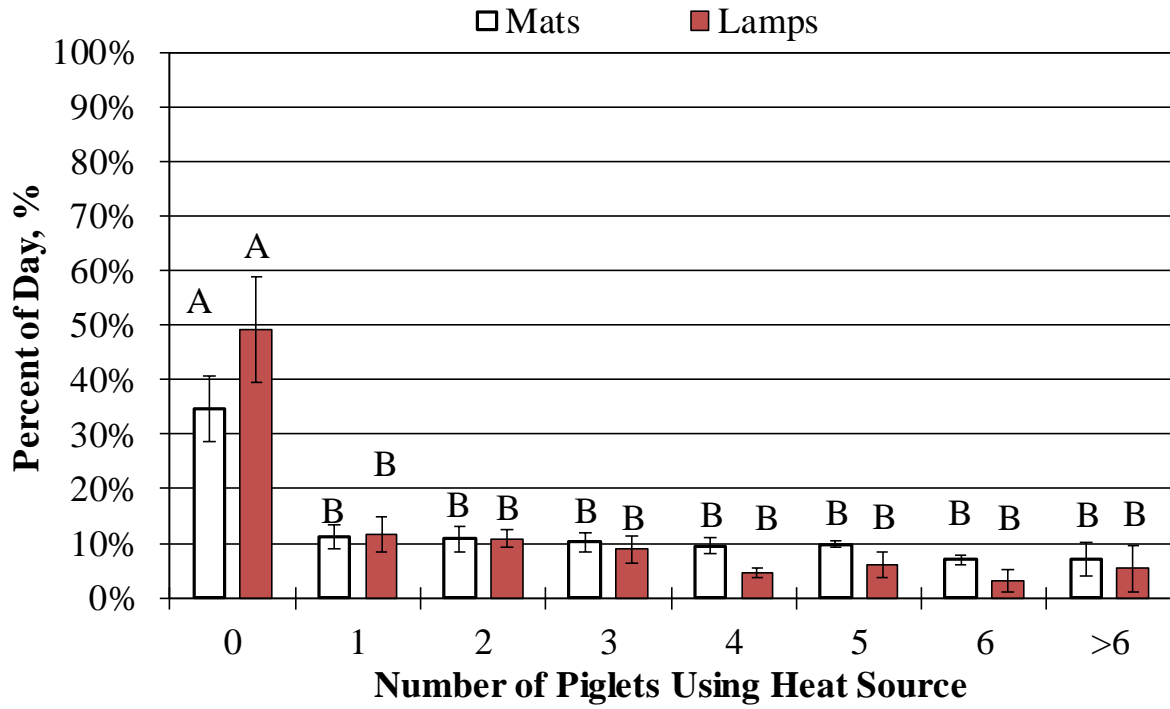


Figure 4.11. Heat mat and lamp utilization (percent of day (\pm SE)) by piglets from 9 to 13 days of age. Means with different letters are significantly different ($p < 0.05$).

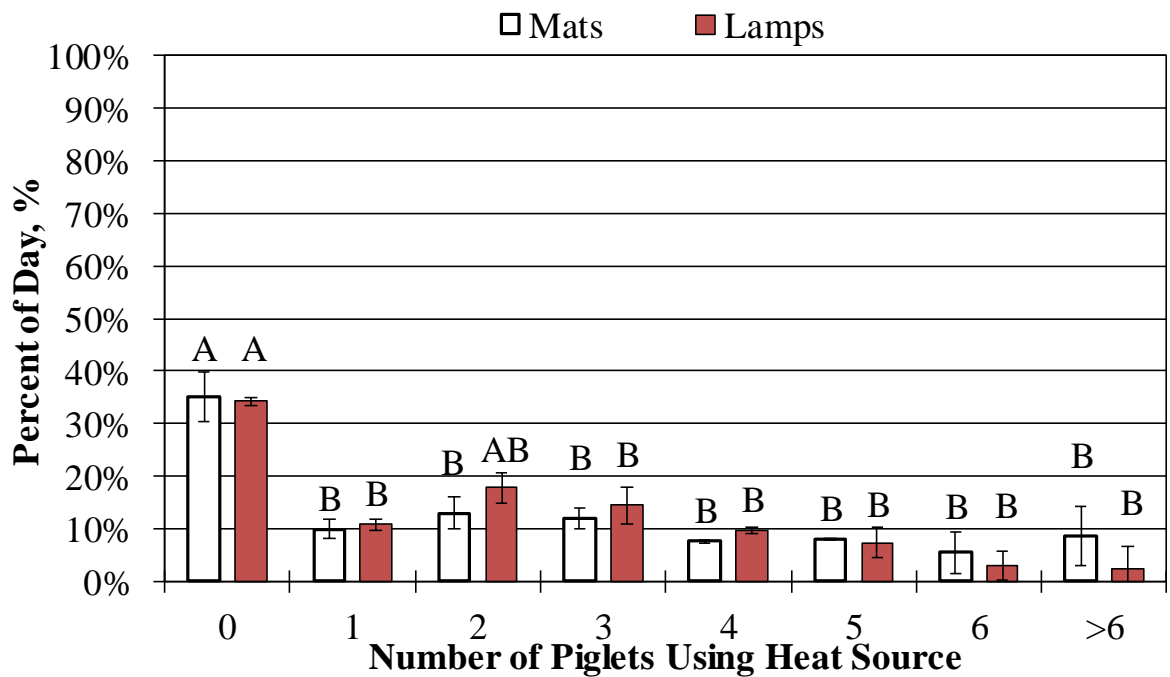


Figure 4.12. Heat mat and lamp utilization (percent of day (\pm SE)) by piglets from 14 to 18 days of age. Means with different letters are significantly different ($p < 0.05$).

The daily heat source use is shown in Figure 4.13. The mat and lamp behave similarly vs. piglet age. The heat source use is lowest for 6 to 9 days of age.

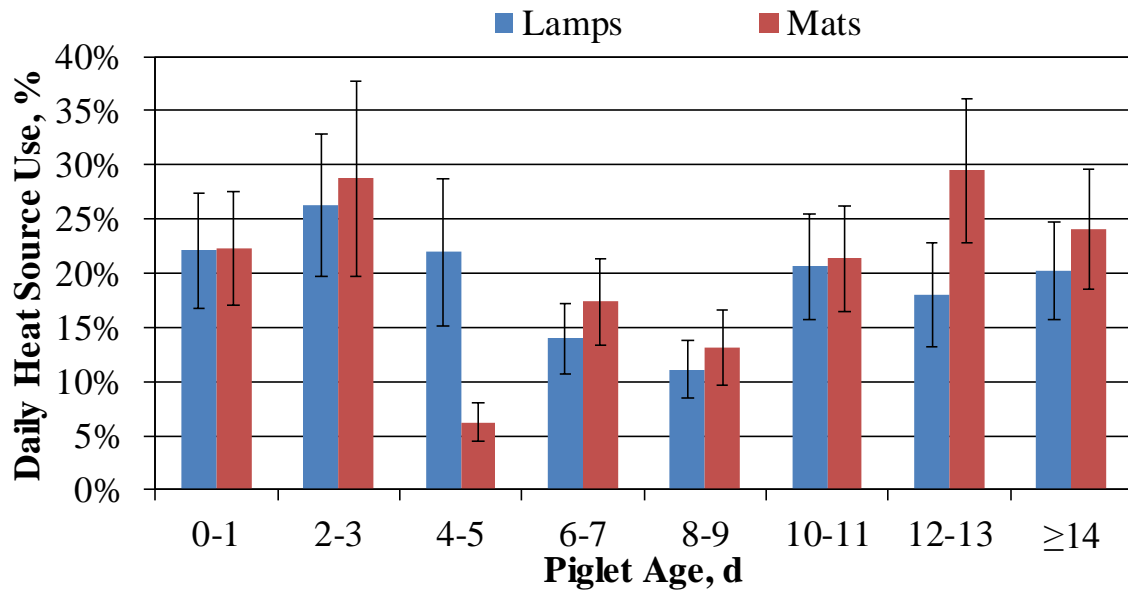


Figure 4.13. Average daily heat source use (\pm SE) by piglets by piglet age.

The number and duration of unoccupied and occupied events were determined (Table 4.3). No significant differences were found between values within each column ($p > 0.0521$). The event durations are also comparable across heat source type and production stage. The number of piglets utilizing the heat source while occupied by at least 1 piglet was calculated. Although not statistically significant, the Birth-Day 3 stage had a higher amount of occupancy than the other stages.

Table 4.3. Summary of heat source usage for each production stage, including number and duration of occupied and unoccupied events and average number of piglets utilizing heat source when the source is occupied. No significant differences were found for values within each column ($p>0.0521$)

			Unoccupied Events	Unoccupied Duration, min	Occupied Events	Occupied Duration, min	Number of Piglets per Occupied Event
Birth-Day 3	Mats	Mean	46.5	11.3	47.3	19.3	4.0
		<i>SE</i>	<i>11.8</i>	<i>1.7</i>	<i>11.6</i>	<i>7.7</i>	<i>1.1</i>
	Lamps	Mean	32.3	20.1	32.5	24.4	4.4
		<i>SE</i>	<i>4.8</i>	<i>6.3</i>	<i>5.1</i>	<i>6.6</i>	<i>0.5</i>
Day 4-8	Mats	Mean	68.5	13.2	68.5	7.8	2.3
		<i>SE</i>	<i>10.3</i>	<i>2.2</i>	<i>10.3</i>	<i>3.1</i>	<i>0.4</i>
	Lamps	Mean	42.3	15.0	42.5	19.0	3.6
		<i>SE</i>	<i>13.0</i>	<i>34.4</i>	<i>12.8</i>	<i>29.0</i>	<i>0.8</i>
Day 9-13	Mats	Mean	41.9	11.9	42.3	22.2	3.8
		<i>SE</i>	<i>3.6</i>	<i>2.7</i>	<i>3.5</i>	<i>2.5</i>	<i>0.2</i>
	Lamps	Mean	30.0	23.6	30.3	24.2	3.3
		<i>SE</i>	<i>4.1</i>	<i>7.0</i>	<i>4.2</i>	<i>8.5</i>	<i>0.5</i>
Day 14-18	Mats	Mean	39.7	12.8	40.7	22.9	3.7
		<i>SE</i>	<i>3.2</i>	<i>1.4</i>	<i>3.2</i>	<i>2.9</i>	<i>0.6</i>
	Lamps	Mean	42.7	11.6	43.0	22.0	3.1
		<i>SE</i>	<i>8.7</i>	<i>1.7</i>	<i>9.0</i>	<i>4.6</i>	<i>0.4</i>

The lack of differences between the two heat sources is possibly due to farrowing crate design and the sow. Piglet location in the crate is likely heavily influenced by sow posture. Piglets have a strong desire to feed and thus the direction of sow lie (i.e., teats toward or away from heat source) will have a large effect on piglet location. Further research in the piglet-sow interaction is needed to improve heat source design to provide a more desirable environment for the piglet.

Summary and Conclusions

Three, 40-crate farrowing rooms were selected for this comparison study. Half of each room used heat lamps for localized piglet heating while the other half of each room used heat mats. Sixteen farrowing cycles were monitored for power use, piglet performance, and piglet usage of localized heat source. The only significant impact of either localized heating system was on the power use, where the mats were 36% lower than the lamps. Specific observations are as follows.

- The average weight gain (\pm SE) for the mat and lamp raised pigs was 224 (\pm 5.7) g/d and 220 (\pm 5.9) g/d, respectively.
- The prewean mortality (\pm SE) for the mat and lamp raised piglets were 7.8% (\pm 0.4%) and 7.4% (\pm 0.5%), respectively.
- Power use (\pm SE) for the mats and lamps was 0.66 (\pm 0.06) kWh per kg weaned pig while the lamps consumed 1.05 (\pm 0.04) kWh per kg weaned pig, respectively. Resulting in a payback period for this production facility for mats over lamps of 3.4 years or 57 farrowing cycles.
- The average time of non-occupancy (\pm SE) was 44% (\pm 5.3%) and 42% (\pm 5.8%) for lamps and mats, respectively.
- The average daily heat source use (\pm SE) was 20% (\pm 3.1%) and 21% (\pm 3.4%) for lamps and mats, respectively.
- The occupied and unoccupied events and durations were not significantly different across production stage and heat source type ($p > 0.0521$).

Acknowledgements

The study was supported by a research grant from the Iowa Pork Producers Association and cooperation of the swine producer in allowing us the access to the production facility and animal production data. We also wish to sincerely thank all the individuals – undergraduate students, graduate students, professional staff, post-doc research associate and visiting professors who contributed to the implementation of this field study.

References

- Beshada, E., Q. Zhange, and R. Boris. 2006. A cost effective heating method for piglets in swine farrowing barns. CSBE Paper Number 06-224. McGillivray, Winnipeg.
- Herpin, P., M. Damon, and J. Le Dividich. 2002. Development of thermoregulation and neonatal survival in pigs. *Livestock Production Science* 78(2002): 25-45.
- Lay, D.C. Jr, Haussmann, M.F., Buchanan, H.S. and Daniels, M.J. 1999. Danger to pigs due to crushing can be reduced by the use of a simulated udder. *Journal of Animal Science* 77: 2060-2064.
- McGlone, J. J and A. K. Johnson. 2003. Welfare of the neonatal pig. In: Perspectives in Pig Science. Nottingham University Press. Nottingham, United Kingdom, pp 169-197.
- Midwest Plan Service Swine Housing and Equipment Handbook. 1983. Midwest Plan Service, Iowa State University, Ames, Iowa.
- Stalder, K. J.. Pork Industry Productivity Analysis. 2013. National Pork Board. Des Moines, IA.

- Stinn, J.P., H. Xin, T.A. Shepherd, H. Li, and R.T. Burns. 2013. Ammonia and Greenhouse Gas Emissions of a Midwestern Swine Breeding-Gestation-Farrowing Facility. *Proceedings of the 2013 ASABE International Meeting*. Kansas City, Missouri. July 21-24, 2013.
- Vasdal, G., I.L. Andersen, L.J. Pedersen. 2009. Piglet use of the creep area – Effects of breeding value and farrowing environment. *Applied Animal Behaviour Science* 120(2009): 62-67.
- Weary, D.M., P.A. Phillips, E.A. Pajor, D. Fraser, and B.K. Thompson. 1998. Crushing of piglets by sows: effects of litter features, pen features and sow behavior. *Applied Animal Behaviour Science* 61: 103-111.
- Xin, H., H. Zhou, and D.S. Bundy. 1997. Comparison of energy use and piglet performance between the conventional and an energy-efficient heat lamp. *Applied Engineering in Agriculture* 13(1): 95-99.
- Zhang, Q., and H. Xin. 2000. Static and dynamic temperature distribution of heat mats for swine farrowing creep heating. *Applied Engineering in Agriculture* 16(5): 563-569.
- Zhang, Q., and H. Xin. 2001. Responses of piglets to creep heat type and location in farrowing crate. *Applied Engineering in Agriculture* 17(4): 515-519.
- Zhou, H., and H. Xin. 1999. Effects of heat lamp output and color on piglets at cool and warm environments. *Applied Engineering in Agriculture* 15(4): 327-330.

CHAPTER 5

**COMPARISON OF FOURIER TRANSFORM INFRARED SPECTROSCOPY AND
PHOTOACOUSTIC INFRARED SPECTROSCOPY FOR MEASUREMENT OF
AMMONIA AND GREENHOUSE GASES****J.P. Stinn, H. Xin, and T.A. Shepherd**

A manuscript prepared for submission to Transactions of the ASABE

Abstract

Accurate measurement of gas concentrations is crucial to research in agricultural air quality, specifically when determining emission factors for agricultural operations. Four common gasses being assessed are ammonia (NH_3) and greenhouse gasses (GHG) of carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). In an attempt to explore alternative instruments for measuring gaseous concentrations, this study was conducted to compare a Fourier Transform Infrared Analyzer (FTIR) (CAI 600) with a commonly used photoacoustic IR multi-gas analyzer (INNOVA 1412) under field conditions of swine production emissions monitoring. The FTIR and PAS were installed side-by-side in a Mobile Air Emissions Monitoring Unit (MAEMU) at a commercial swine facility and operated for 5 months under a range of durations per sample location (120s, 240s, 360s) and FTIR sample integration times (30s, 60s). The response time of the analyzers to known gas concentrations was also tested in a laboratory setting. The FTIR and PAS had good agreement for NH_3 , CO_2 , and CH_4 field measurements. The linear regression slopes for FTIR vs. PAS ranged from 1.002 to

1.052 for NH₃, 0.980 to 1.002 for CO₂, and 0.996 to 1.017 for CH₄. The N₂O concentrations were < 0.8 ppm on the PAS and < 0.6ppm on the FTIR and the two analyzers had poor agreement at the individual sample levels. The relative difference between FTIR and PAS concentrations was generally larger at lower concentrations, decreased sample location times, and large indoor-ambient concentration differences. The PAS had the fastest response times to T₉₈ (time taken to display 98% of known concentration) for all gases, followed by the FTIR at 30s sample integration time. The FTIR at 60s sample integration time had the longest response times. This study revealed that the FTIR is comparable to the PAS for NH₃, CO₂, and CH₄ measurements, although care must be taken when there exist large changes from location to location to allow sufficient time for the FTIR to respond. Further investigation of the instruments at higher N₂O concentrations is needed to quantify their respective performance.

Keywords. *Gas analyzer, Air quality, Ammonia, Greenhouse gas (GHG)*

Introduction

The production and emissions of gases associated with animal agriculture can impact worker health, animal well-being, and the environment. Gas production rates depend on the animal species, manure management, diet, production system design (e.g., ventilation), and management (stocking density). Accurate measurement of gas concentrations at animal production facilities can be difficult, as changes in the ventilation rate or animal activity can have a large and rapid impact. This is especially important in circumstances where one instrument is used to measure gas concentrations at multiple sampling locations within the

same facility, as instruments are often deployed at a centralized location. Thus, the shorter the time increment between concentration measurement outputs and the more rapid the response of the instrument the more accurately the instrument can capture these rapid changes and the more sampling locations it can monitor in the same time frame.

A commonly used multi-gas analyzer in agricultural air quality research has been the INNOVA 1412³ (Lumasense Technologies, Denmark), a photoacoustic infrared spectrometer (PAS) capable of measuring up to 5 gases and water vapor simultaneously. PAS has been used to measure gas concentrations from many livestock production facilities including broiler barns (Moody et al., 2008), turkey barns (Li et al., 2011), swine barns (Pepple et al., 2011), and laying hens (Li et al, 2012; Hayes et al., 2013). One disadvantage to the PAS measurement method is the proximity of the absorbance wavelengths of gases and H₂O. Figure 5.1 shows the absorbance spectra of several compounds and the overlapping spectra that lead to cross-interferences. The PAS optical filters allow for measurements at narrow wavelengths bands. The wavelengths and wavenumbers used for measurement by the PAS of the gases of interest in this study, ammonia (NH₃), carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄), are shown in Table 5.1. Note the close proximity of CO₂ and N₂O ranges, along with the interferences of H₂O. Concerns over these cross-interferences have been raised and addressed (Iqbal et al., 2102; Nicoloso et al., 2013; Zhao et al., 2012). These

³ Mention of company or product names is for presentation completeness, and does not represent endorsement by the authors or their affiliated institutions.

cross-interferences can cause inaccuracies in measurements. However, careful calibration of the interferences can be done that will lead to accurate measurements.

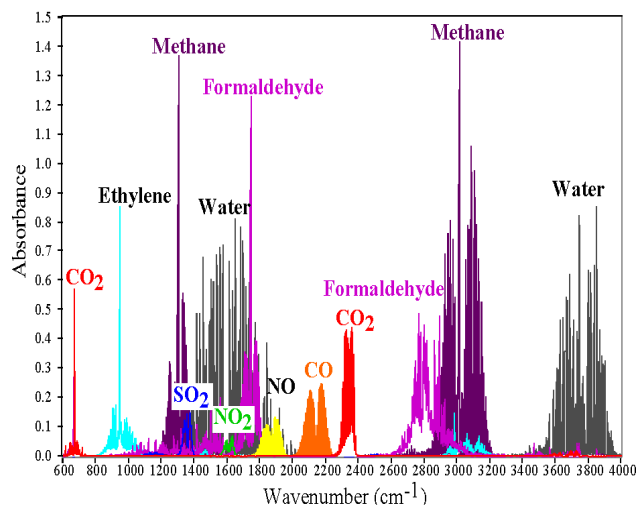


Figure 5.1. Absorbance spectra of select compounds showing overlapping spectra that can lead to cross-interferences.

Table 5.1. Photoacoustic infrared spectrometer (PAS) (INNOVA 1412) optical filter output wavelengths and detection limits for ammonia (NH₃), carbon dioxide (CO₂), nitrous oxide (N₂O), methane (CH₄), and water (H₂O).

Filter	Gas	Optical Filter Wavelength, μm	Wavenumber, cm^{-1}	Bandwidth, %	Detection Limit, ppm
UA0976	NH ₃	10.6	943	7%	0.44
UA0983	CO ₂	4.4	2273	1.30%	11
UA0985	N ₂ O	4.5	2222	2%	0.066
UA0969	CH ₄	8.0	1250	5.50%	0.4
SB0527	H ₂ O	5.1	1961	2%	50

An alternative to the PAS is the Fourier Transform Infrared Spectrometer (FTIR) (CAI 600 FTIR, California Analytical Instruments, Orange, California, USA). This specific FTIR model does not require a liquid nitrogen supply for optics purging which allows for more freedom in deployment and use of the instrument. It also allows for the simultaneous measurements of multiple (>30) gases. The FTIR has been primarily deployed in industrial

monitoring situations and thus its capability to accurately measure gas concentrations at animal production facilities is relatively unknown. Therefore, the objective of this project was to compare a PAS and a FTIR unit side-by-side at a swine breeding-gestation-farrowing facility. The two instruments were compared with respect to concentration measurement agreement and response time.

Materials and Methods

PAS Gas Concentration Measurement

A description of the PAS measurement can be found in Iqbal et al. (2012) and a schematic diagram in Figure 5.2. In short, the PAS unit uses modulated infrared (IR) light at a preselected wavelength for each gas. The desired wavelength is achieved by passing the IR light through an optical filter. The filtered and modulated IR light enters a sealed chamber (0.754 cm^3) and is absorbed by the gas where the modulation leads to rapid expansion and contraction of gases that absorb the specific IR wavelength. Microphones detect the pressure change caused by the expansion and contraction. The signal from the microphones for each optical filter, combined with calibration values for each gas and cross-interferences result in concentration values. The total sampling time for chamber purging, sample collection, and measurement of multiple gases is user adjustable. For this study, parameters were chosen that match those specified by Moody et al. (2008) and used by multiple studies since. The sample integration time (SIT) for each filter was 1s. The chamber flushing and tube flushing times were 2s and 3s, respectively. These parameters lead to an overall SIT of 30s. The PAS cycling was used as the counter for switching sampling locations. The PAS concentrations

were output through RS232 to the Mobile Air Emission Monitoring Unit (MAEMU) data acquisition system (DAQ) that recorded the PAS concentrations and other site data (e.g. temperature, relative humidity, running time of ventilation fans).

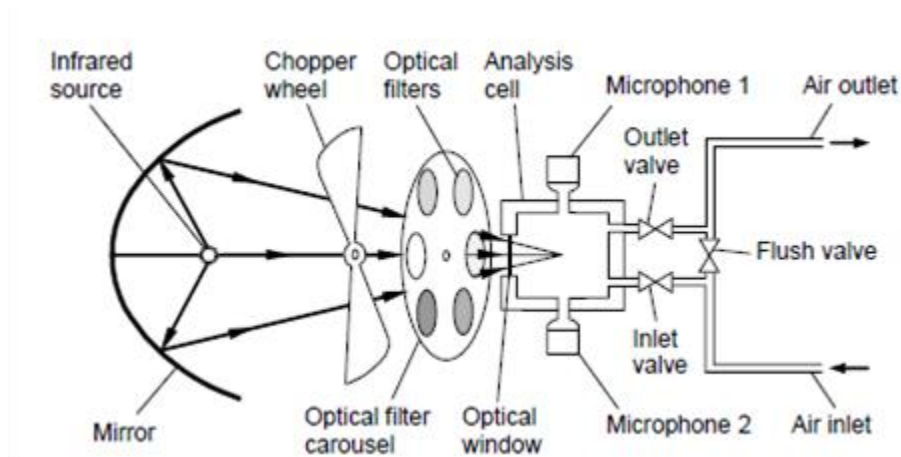


Figure 5.2. Schematic diagram of photoacoustic infrared spectrometer (PAS).

The PAS was calibrated by the project team with National Institute of Science and Technology (NIST) certified standard gases ($\pm 5\%$) according to expected concentrations in the animal facility. It was challenged weekly in the field with zero and span gases. The team has years of experience operating, maintaining, and calibrating PAS analyzers. The PAS in this study was equipped with optical filters for the measurement of NH_3 , CO_2 , CH_4 , N_2O , and H_2O .

FTIR Gas Concentration Measurement

The FTIR operates by measuring the absorbance spectrum of the gas sample for IR radiation in the 1 to 25 μm range. An IR source emits radiation that is reflected between multiple mirrors across a 0.8L gas cell (fig. 5.3). The reflections result in a 4.3m path length. The IR light that is not absorbed by the gasses in the cell is then measured with a room-

temperature deuterated triglycine sulfate (DTGS) detector. Through Fourier transformation the data are converted from the time domain to a frequency domain, which produces a single beam spectrum. The spectrum is taken a ratio with a background spectrum to produce an absorbance spectrum, which is quantified with chemometrics to produce concentration values. The number of sample spectra the FTIR captures can be user specified depending on operational conditions. For this study, 8 and 16 sample averages were used that correspond to sample integration times of 30s and 60s, respectively.

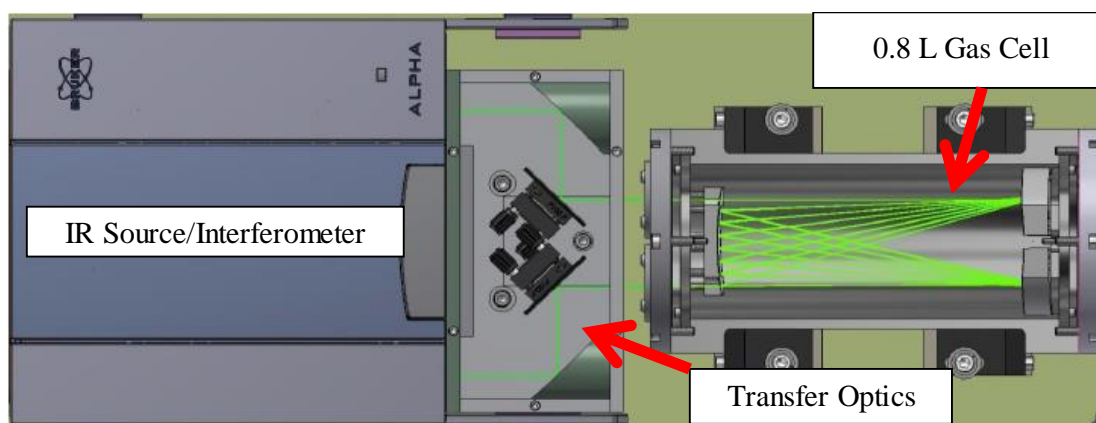


Figure 5.3. Schematic diagram of Fourier Transform Infrared Spectrometer (FTIR) with key components labeled.

The FTIR and associated components are shown in Figure 5.4. The purging air for the optics of the FTIR was provided by a zero-air generator. Sample air was pulled from a manifold and continuously pushed through the FTIR at a flow rate of 5 LPM by an external pump. A background scan for the FTIR was taken once a week using N_2 gas prior to challenging the PAS and FTIR with zero and span gases. The background scan compensated for any instrument drift. The FTIR's measurement cycle and data analysis was performed by OPUS software (Bruker Corp., Billerica, MA, USA) on a laptop connected by an Ethernet

cable. A Labview (National Instruments, Austin, Texas, USA) program output the concentration measurements through a shared router to the DAQ system where they were combined with the PAS concentrations and other site measurements and saved.

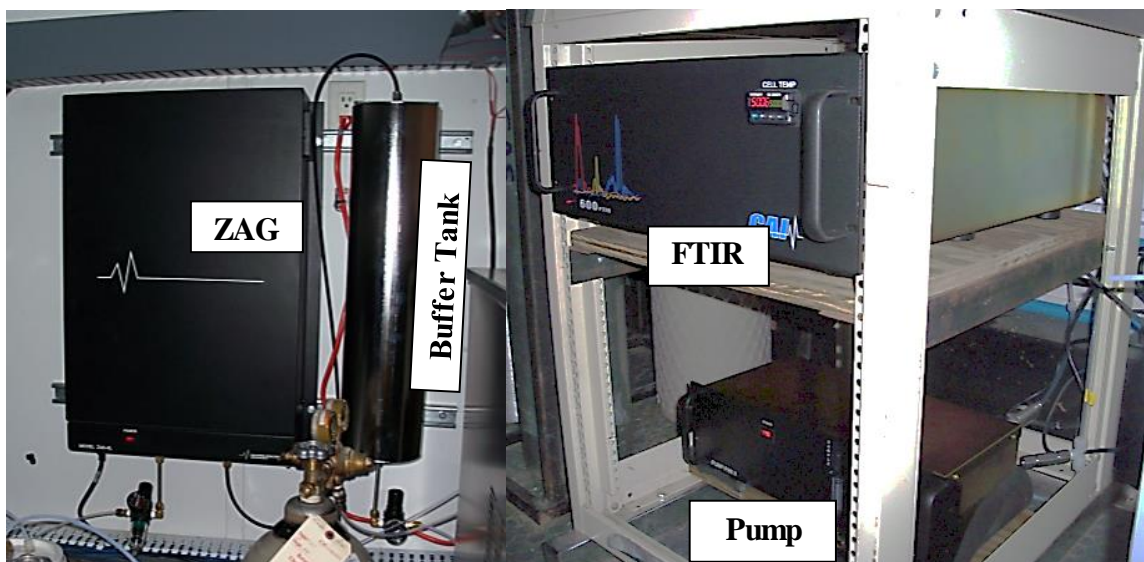


Figure 5.4. Fourier transform infrared spectrometer (FTIR) as installed in field with sample pump, zero air generator (ZAG) and buffer tank.

The FTIR was calibrated by the vendor (California Analytical Instruments, Orange, CA, USA) with NIST-certified standard gases ($\pm 5\%$) according to expected concentrations of the animal facility. The detection limits are shown in Table 5.2. It was challenged weekly in the field with zero and span calibration gases. New background scans (N_2 gas) were made weekly to account for any changes in instrument performance.

Table 5.2. Detection limits of FTIR (CAI 600) for ammonia (NH₃), carbon dioxide (CO₂), nitrous oxide (N₂O), methane (CH₄), and water (H₂O).

Gas	Detection Limit, ppm
NH ₃	0.0147
CO ₂	2.09
N ₂ O	0.008
CH ₄	0.0352
H ₂ O	54

Field Monitoring

The PAS and FTIR units were integrated side-by-side into a MAEMU that was used to monitor gaseous emissions from a swine breeding-gestation-farrowing system (Stinn et al., 2013). Description of the MAEMU operation and quality assurance/quality control protocols can be found in Moody et al. (2008). The analyzers drew the necessary air samples from the same manifold. The PAS operated with a 30s sampling interval, whereas the FTIR sampling interval was set to 30s or 60s. The duration of the sampling for each location in the barns was set to 120s, 240s, or 360s, which corresponded to 4, 8, or 12 samples by the PAS. The ambient air was sampled every 2h for 480s (16 PAS samples). The FTIR sample flow rate was reduced from 5 to 3 LPM for the final trial due to reduced air flow availability from the manifold to accommodate additional instruments. The last sample measurement by each analyzer before the MAEMU changed sample location was compared. This resulted in 240 to 720 (depending on sampling duration per location) measurement data points per day for comparison. The PAS and FTIR operated simultaneously from October 2011 to March 2012. A summary of the monitoring periods for each sampling setting is in Table 5.3.

Table 5.3. Testing periods for FTIR sample integration times and duration per sample location.

Trial Designation	Dates	Days Monitored	FTIR Sample Integration Time, s	FTIR Sample Flow Rate, LPM	Sample Duration per Indoor Location, s
60-240	10/18-11/17	26	60	5	240
30-240	11/18-11/22	5	30	5	240
30-120	11/23-2/7	54	30	5	120
30-360	2/8-3/5	13	30	3	360

Response Time

The PAS and FTIR units were operated side-by-side in a laboratory setting to compare the response times. The instruments were exposed to NIST standard gases ($\pm 5\%$) according to expected concentrations of the animal facility. The same sampling parameters used in the field monitoring portion were used, with the PAS sampling interval at 30s and the FTIR sampling integration time of 30s and 60s. The instrument measurements were recorded by a Labview program to a laptop computer. The response time is defined as the time for each instrument to reach 98% of the expected concentration (T_{98})

Results and Discussion

Field Comparison

The results of the in-field comparison show good agreement between the FTIR and PAS for NH_3 , CO_2 and CH_4 concentrations. The last sample of each analyzer for each sample location was plotted against each other and linear regression performed with the intercept held to 0. The results from the trials are show in Figure 5.5, 5.6, 5.7, and 5.8, respectively. The agreement holds for all trials, although some disagreement is apparent at low PAS concentration measurements for NH_3 and CH_4 , especially for trials 30-120 (30s FTIR SIT,

120s per location) and 30-360 (30s FTIR SIT, 360s per location). The measurements in question are ambient air measurements, for which the FTIR lacks sufficient time to adjust from high (barn) concentrations to low (ambient) concentrations due to too short of sample duration (120s) or reduced sample flow rate (5 vs. 3 LPM). N₂O does not show a relationship between FTIR and PAS as the concentration ranges of 0.2 to 0.8 ppm for the PAS and 0.2 to 0.5 ppm for the FTIR are rather narrow compared to the detection limits of each instrument (0.066 ppm for PAS, 0.08ppm for FTIR). Model fit parameters m (slope) and root mean squared error (RMSE) are shown in Table 5.4 for each gas in each trial. The slope values were all found to be significantly different from 1 ($p < 0.01$), although all regressions (exempting N₂O) found the instruments were within 5.2% of each other.

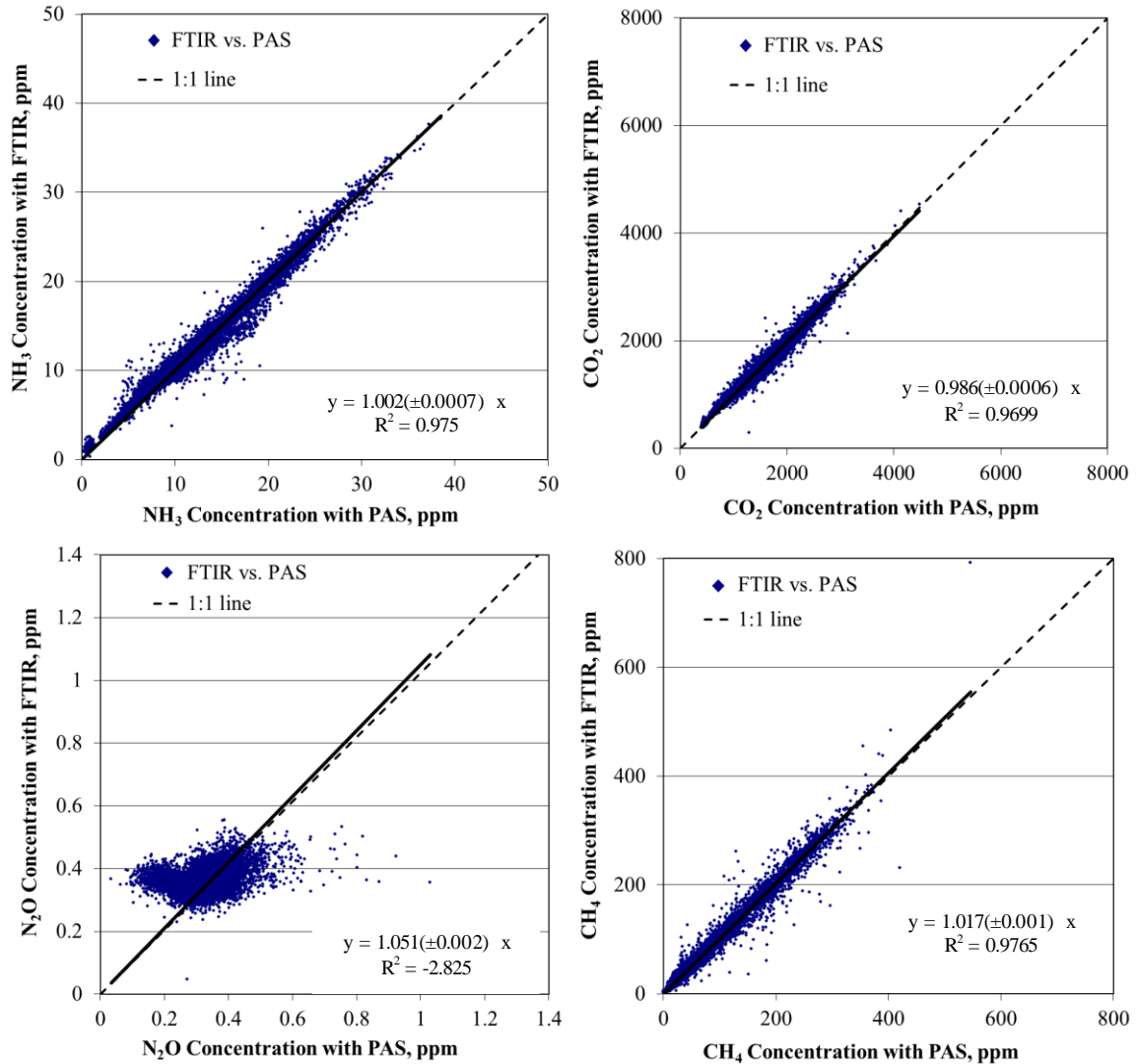


Figure 5.5. Ammonia (NH₃), carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄) concentrations measured by the FTIR vs. the PAS with best fit lines and 1:1 lines for comparison. Gas sampling time per location: 240s. The FTIR had a 16-sample integration over 60s and a flow rate of 5 LPM.

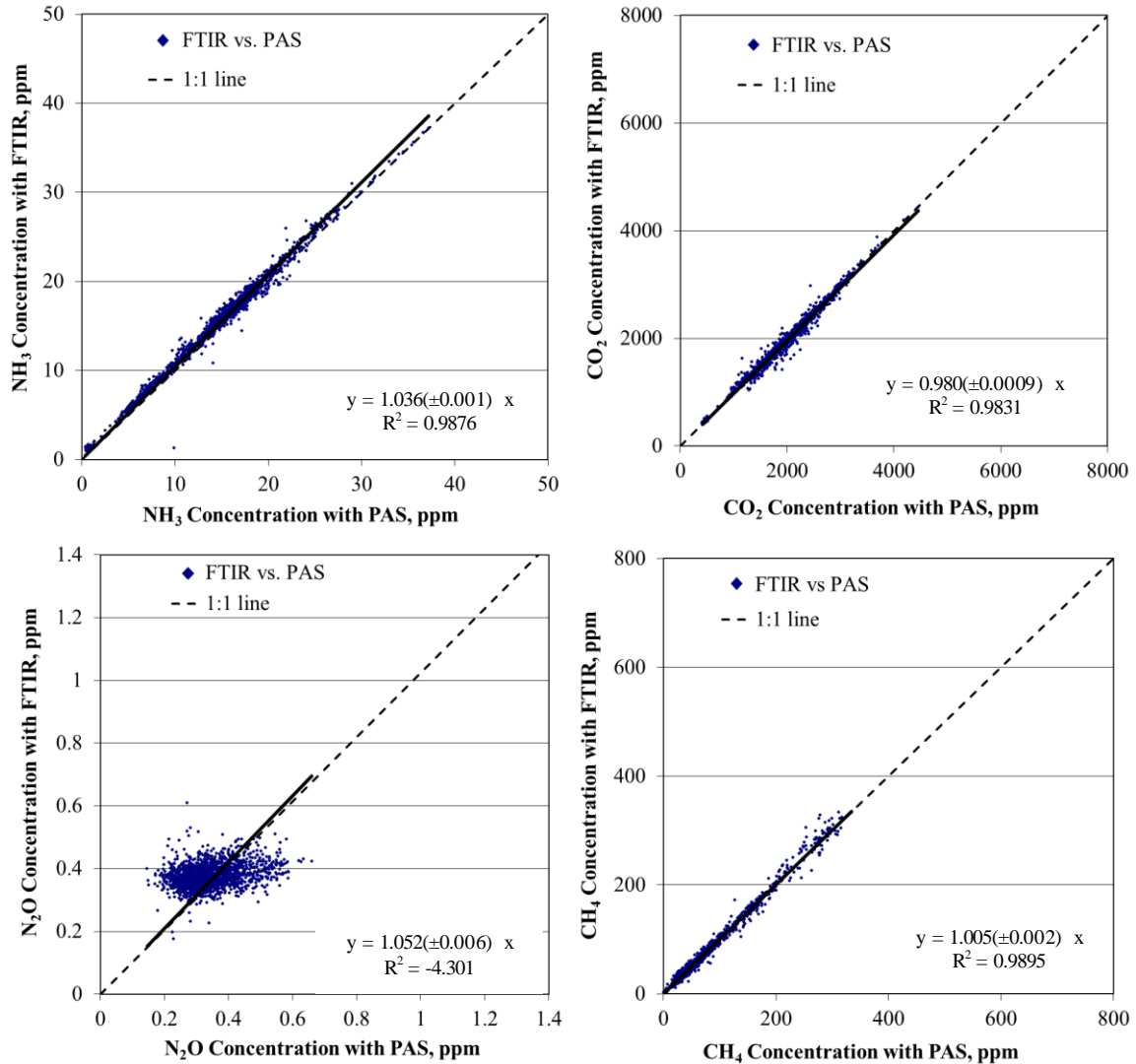


Figure 5.6. Ammonia (NH₃), carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄) concentrations measured by the FTIR vs. the PAS with best fit lines and 1:1 lines for comparison. Gas sampling time per location: 240s. The FTIR had an 8-sample integration over 30s and a flow rate of 5 LPM.

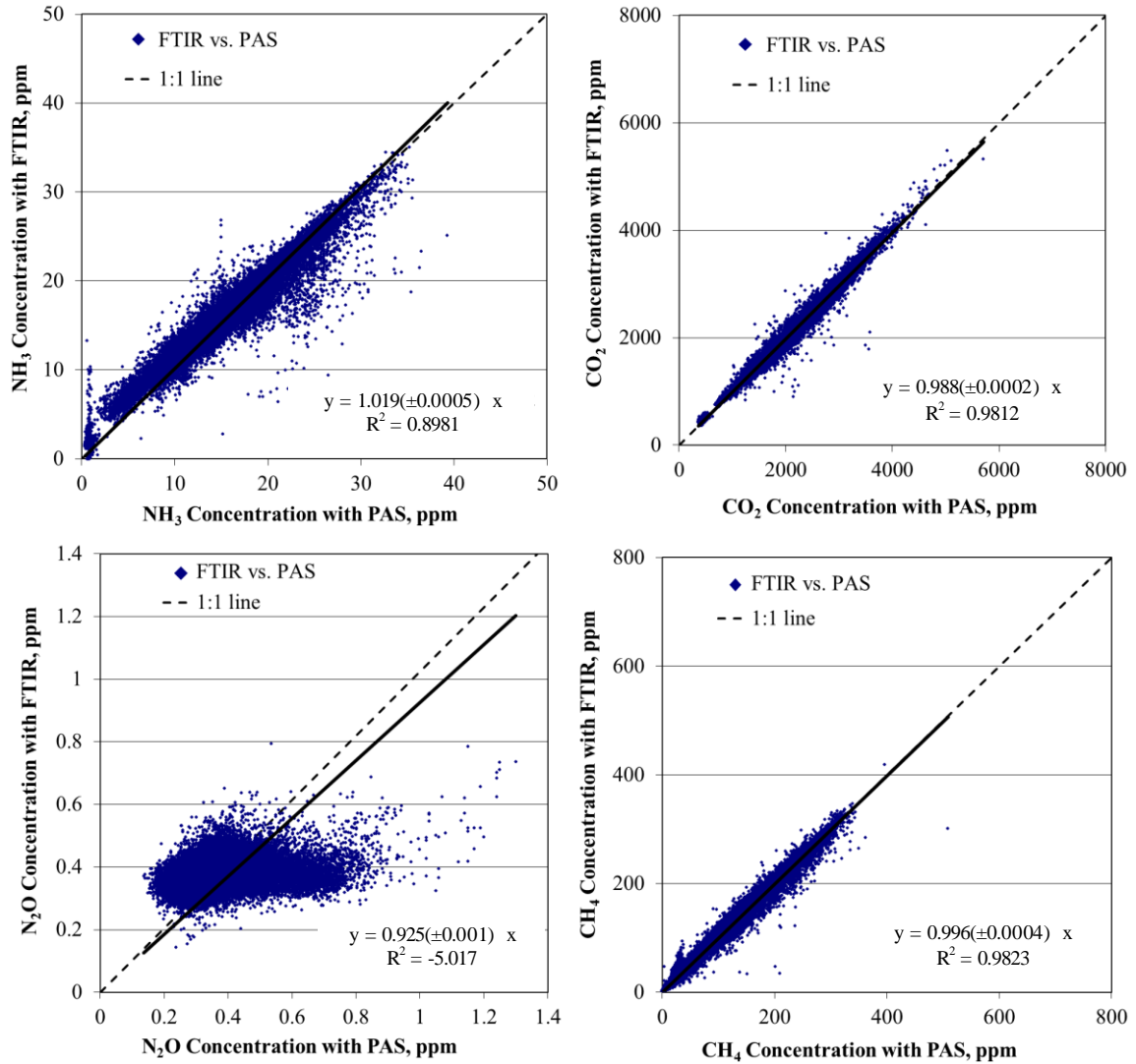


Figure 5.7. Ammonia (NH₃), carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄) concentrations measured by the FTIR vs. the PAS with best fit lines and 1:1 lines for comparison. Gas sampling time per location: 120s. The FTIR had an 8-sample integration over 30s and a flow rate of 5 LPM.

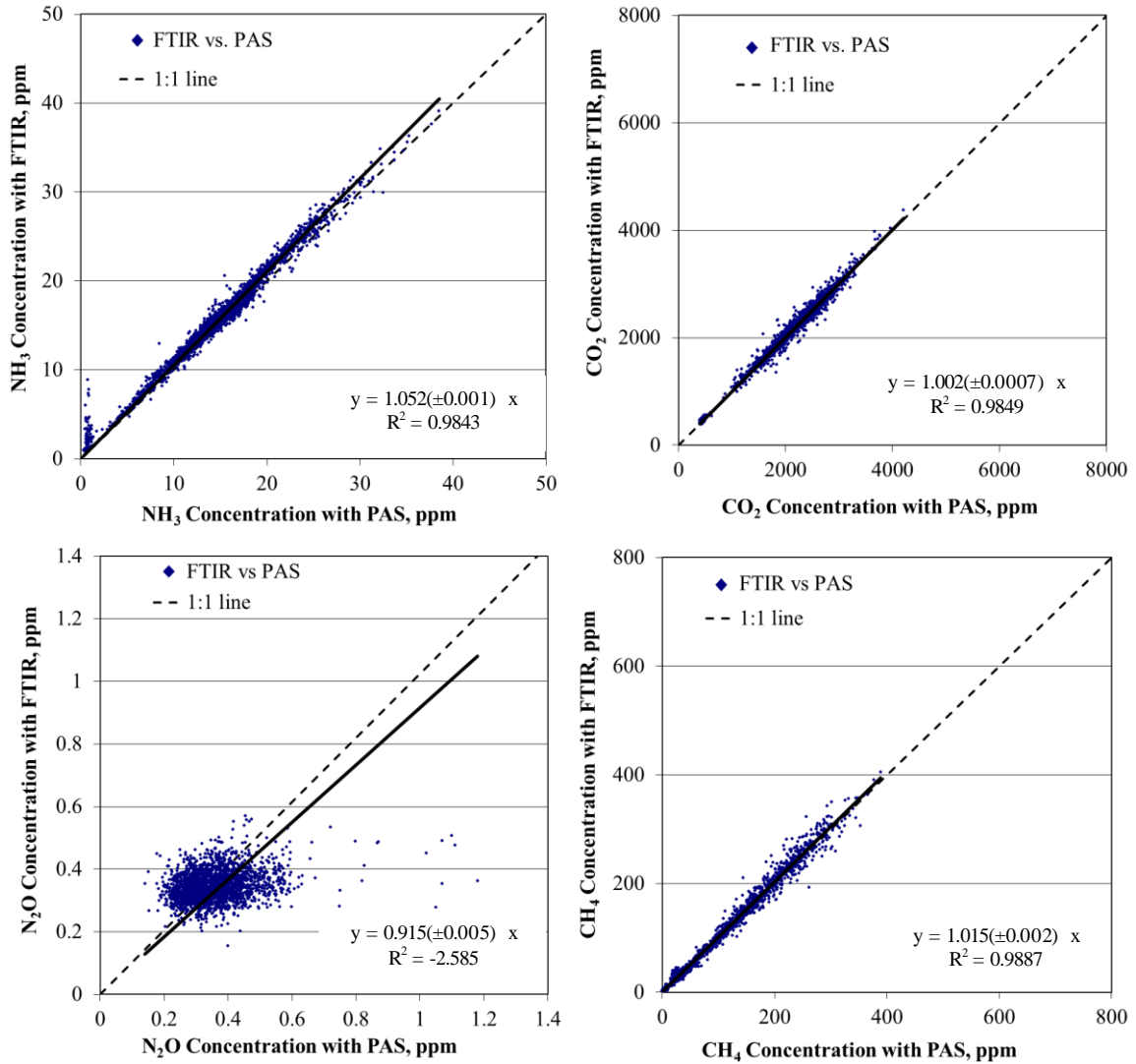


Figure 5.8. Ammonia (NH₃), carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄) concentrations measured by the FTIR vs. the PAS with best fit lines and 1:1 lines for comparison. Gas sampling time per location: 360s. The FTIR had an 8-sample integration over 30s and a flow rate of 3 LPM.

Table 5.4. Summary of linear fit parameters (SE) for FTIR vs. PAS ammonia (NH₃), carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄) concentrations for trials conducted at a swine farm with various sampling and instrument parameters. The intercept parameter was constrained to 0.

FTIR Sample Integration Time, s	Sample Duration per Location, s	Linear Fit							
		NH ₃		CO ₂		N ₂ O		CH ₄	
		m	RMSE	m	RMSE	m	RMSE	m	RMSE
60	240	1.002 (0.0007)	0.981	0.986 (0.0006)	86.082	1.051 (0.002)	0.077	1.017 (0.001)	11.456
30	240	1.036 (0.001)	0.630	0.980 (0.0009)	70.148	1.052 (0.006)	0.086	1.005 (0.002)	6.561
30	120	1.019 (0.0005)	1.521	0.988 (0.0002)	80.941	0.925 (0.001)	0.108	0.996 (0.0004)	8.936
30	360	1.052 (0.001)	0.812	1.002 (0.0007)	78.220	0.915 (0.005)	0.089	1.015 (0.002)	9.151

*All slope (m) values significantly differed from 1 (p<0.01).

The differences between the FTIR and PAS were also quantified according to the concentration levels. The relative difference between the FTIR and PAS readings were calculated using the following equation:

$$RD = \frac{(C_{FTIR} - C_{PAS})}{C_{PAS}} \times 100\% \quad (1)$$

Where RD = relative difference between FTIR and PAS concentration measurement,
%

C_{FTIR} = concentration measured by FTIR, ppm

C_{PAS} = concentration measured by PAS, ppm

The relative differences for indoor sample locations (i.e. excluding ambient samples) were then grouped according to the concentration levels. The averaged relative differences

(\pm SD) for the PAS-based concentration levels are shown in Figure 5.10. The relative differences in NH_3 measurement decrease with increasing NH_3 concentrations, except in trial 30-120 where an increase was seen when the concentration was above 25ppm. This is caused by the short sampling duration (120s) during cold weather when the indoor concentrations are elevated as a result of reduced ventilation. As will be shown also in the response time tests, the FTIR takes longer than the PAS when experiencing larger changes ($>25\text{ppm}$) in concentrations. Thus the sample location duration (120s) was insufficient for the FTIR to fully respond. The relative differences in CO_2 measurement for all concentration levels, except for 500-1000 ppm (-7.5%), were within $\pm 5\%$. Measurements of CH_4 concentrations showed good agreement, with all the relative differences within $\pm 5\%$ except for the 0-20ppm level for trial 30-120 (19.2%) and trial 60-240 (13.8%). The CH_4 percent differences either decrease or remain constant with increasing concentration. The N_2O error is smallest for the 0.3-0.4ppm level and increases as the concentration increases or decreases. The error is largest when the concentrations are near the instruments' detection limits (0-0.1ppm level). It is a challenge to accurately measure low levels of N_2O even with a properly calibrated analyzer as CO_2 and H_2O both have cross-interferences with N_2O . The low values of N_2O concentrations observed (<1 ppm) near normal atmospheric concentration levels (0.31 to 0.32 ppm) (Childers et al., 2001) make discerning a relationship between FTIR and PAS difficult. Investigation of instrument performance for a wider range of N_2O concentrations at an animal production facility would help describe the FTIR/PAS relationship.

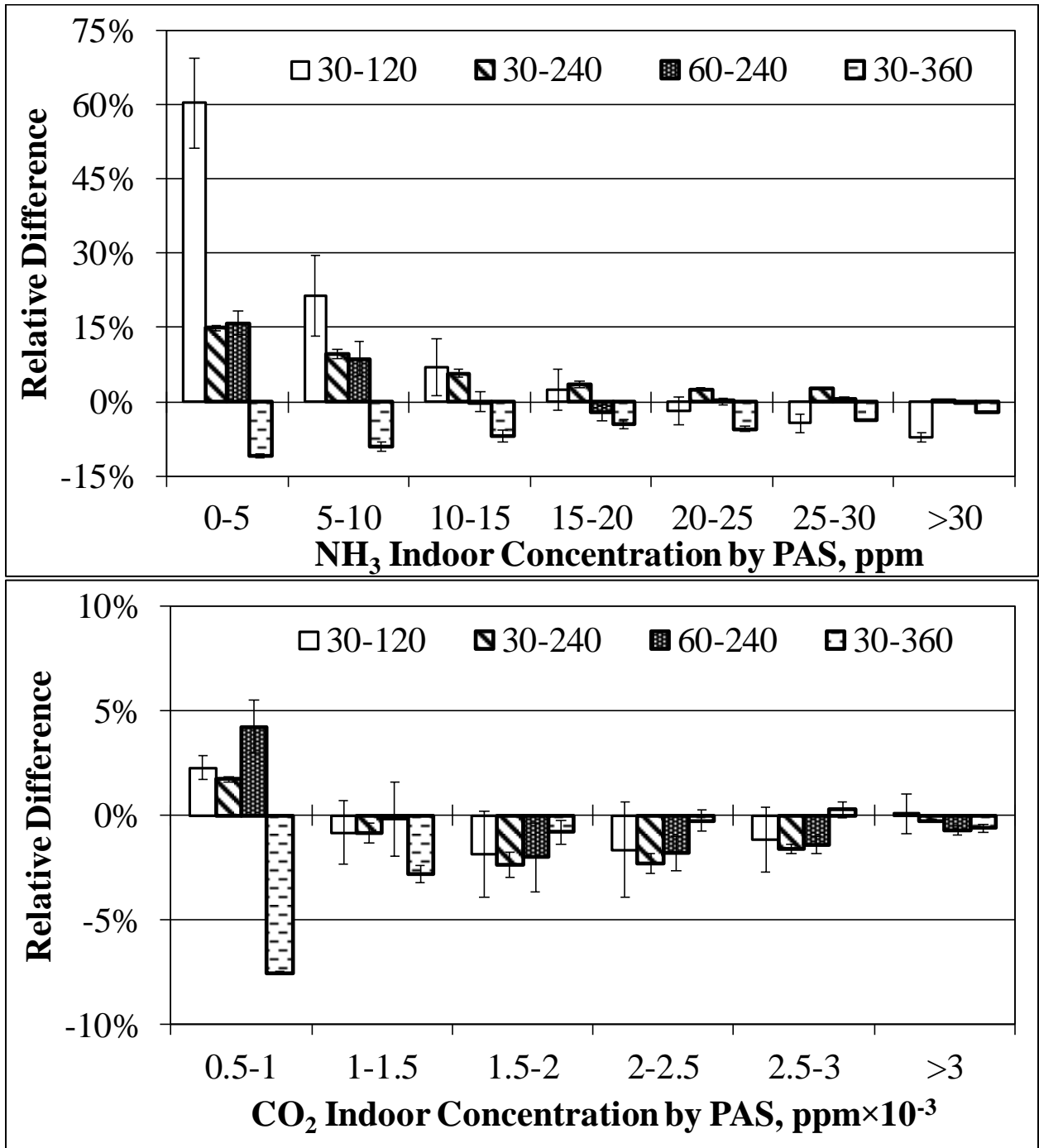


Figure 5.9. Mean percent differences (\pm SD) between PAS and FTIR concentrations for indoor locations of ammonia (NH₃), carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄) for trial parameters of 30s and 120s (30-120), 30s and 240s (30-240), 60s and 240s (60-240), and 30s and 360s (30-360) for the sample location duration and FTIR sample integration time, respectively. The percent differences were calculated as (FTIR-PAS)/PAS and averaged for concentrations ranges within the range of concentrations measured in the study.

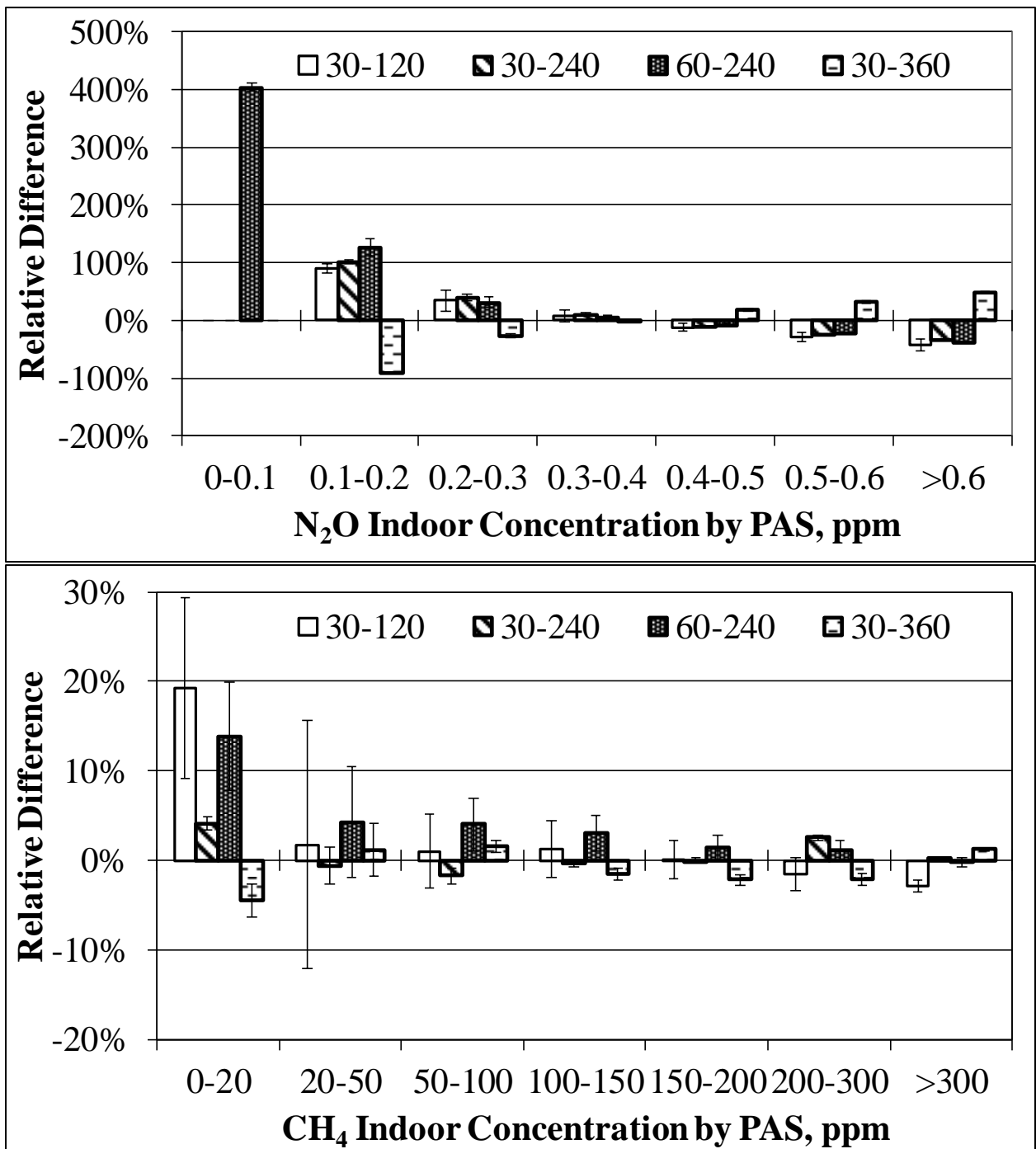


Figure 5.10 (cont). Mean percent differences (\pm SD) between PAS and FTIR concentrations for indoor locations of ammonia (NH_3), carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) for trial parameters of 30s and 120s (30-120), 30s and 240s (30-240), 60s and 240s (60-240), and 30s and 360s (30-360) for the sample location duration and FTIR sample integration time, respectively. The percent differences were calculated as $(\text{FTIR}-\text{PAS})/\text{PAS}$ and averaged for concentrations ranges within the range of concentrations measured in the study.

Performance of the two instruments for measurement of ambient concentrations was compared separately from that for indoor concentrations. The absolute differences between the FTIR and PAS for each sample were averaged by trial. The mean absolute differences (+SD) for each trial are shown in Figure 5.11. The N₂O differences were all below the detection limit of the PAS (0.066 ppm) but not the FTIR (0.008 ppm) and showed no trial effect. The difference in NH₃ measurement decreases with increasing sample duration from 120s to 240s but no change from 120s to 360s as the FTIR sample flow rate decreased from 5 to 3 LPM. The difference in CO₂ measurement was lowest for trial 30-240 (16 ppm) with the other trials being similar. The difference in CH₄ measurement shows little variation across trials (1.38 to 1.85 ppm).

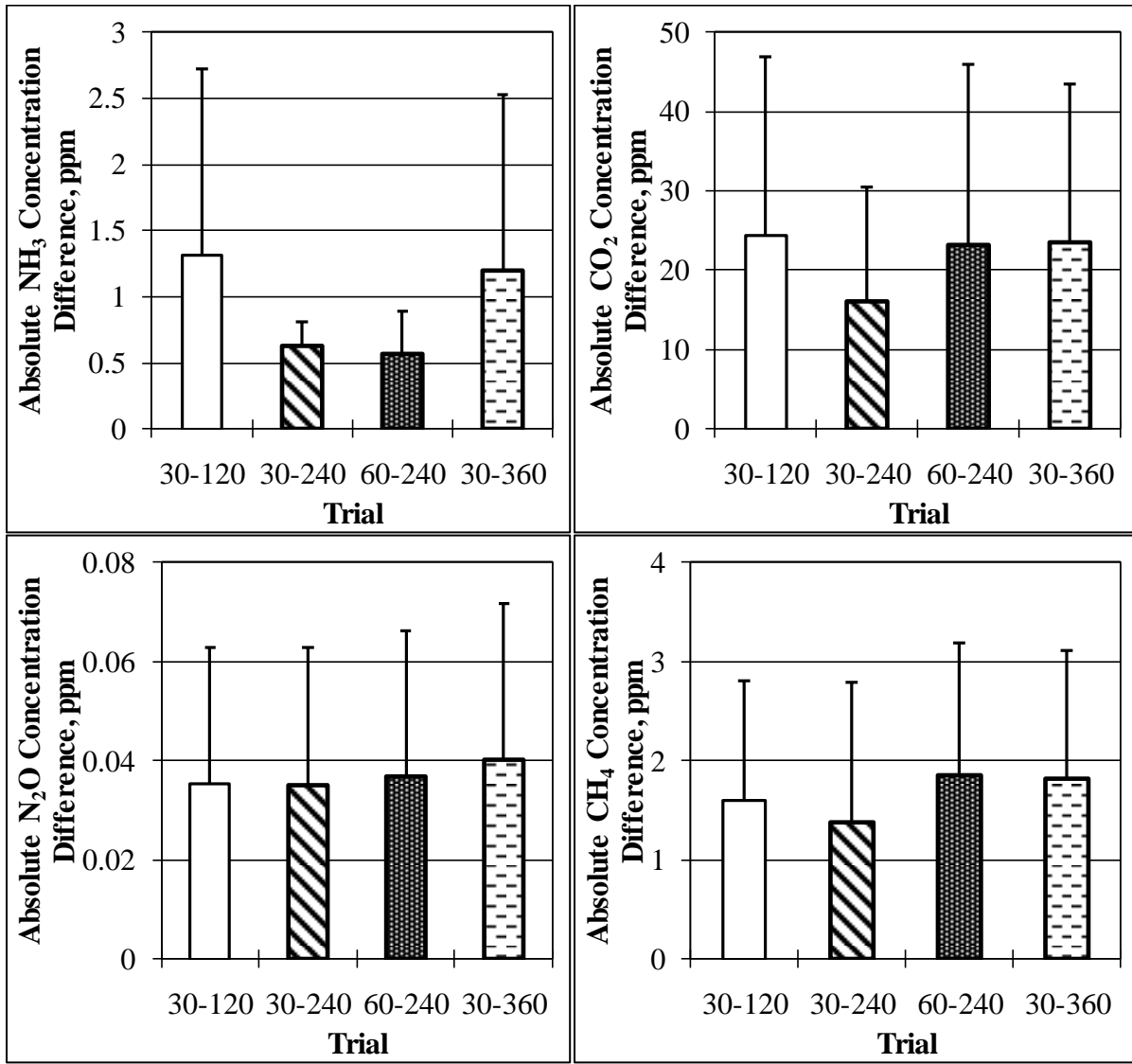


Figure 5.11. Mean of absolute differences between FTIR and PAS for ambient air samples (+SD) of ammonia (NH₃), carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄) for trial parameters of 30s and 120s (30-120), 30s and 240s (30-240), 60s and 240s (60-240), and 30s and 360s (30-360) for the indoor sample location duration and FTIR sample integration time, respectively. An ambient sample was taken every 2h with 480s sample duration.

Response Time

Figures 5.12 and 5.13 show an example of the response time tests for CH₄ for FTIR sample intervals of 30s and 60s, respectively. The concentrations for each analyzer are reported every 30s to match the sampling frequency of the PAS. The response times for all

gases are summarized in Table 5.5. NH_3 shows the largest discrepancy between PAS and FTIR (270s vs. 660s). This PAS response time has been reported before (Moody et al., 2008) when changing from low to high concentrations. The slower response of the FTIR compared to the PAS was also noticed in the field comparison results. The FTIR response was slower for CO_2 and CH_4 , but both gases were within 120s, which was the shortest sampling duration used in this study. The FTIR response to N_2O was slower than the PAS, with the FTIR at 60s sample integration having T98 of 150s, which is 30s more than fastest sampling interval used in the field. The longer FTIR responses times were expected as the FTIR has a larger sample chamber (800 cm^3 vs. 0.754 cm^3) with a lower chamber air change (AC) rate (3 to 6.25 AC vs. 110 AC per sample event) which combine to decrease the responsiveness of the FTIR.

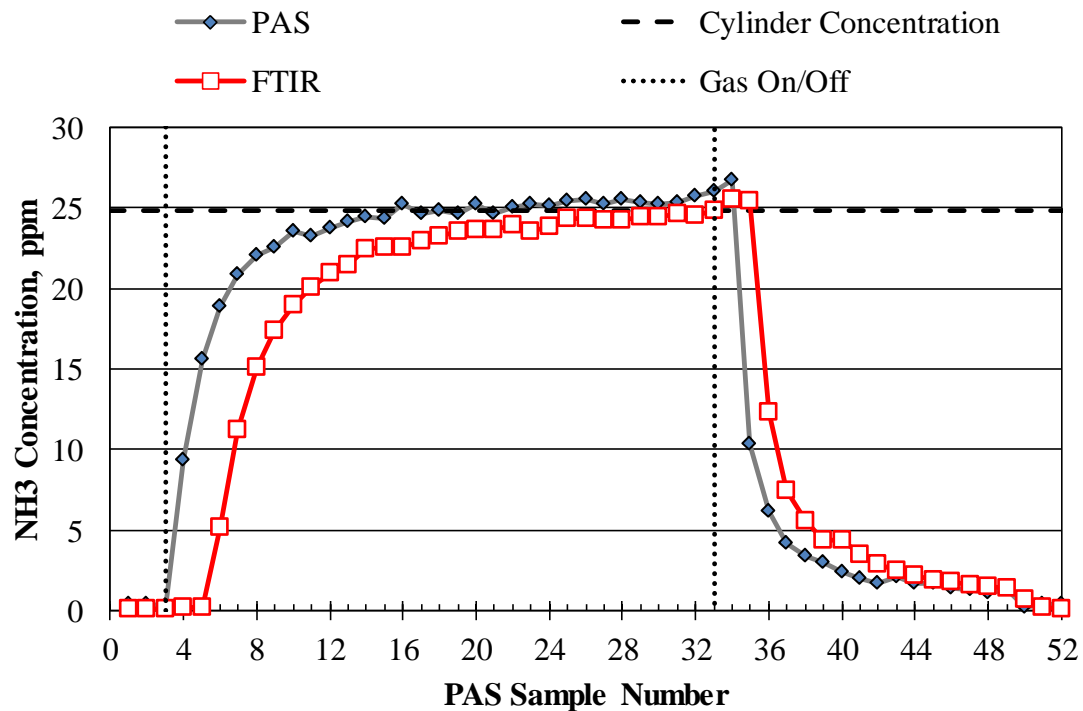


Figure 5.12. PAS and FTIR analyzer responses to exposure to 24.8 ppm NH_3 (N_2 balance) and ambient air. The PAS and FTIR both had a sample integration time of 30s.

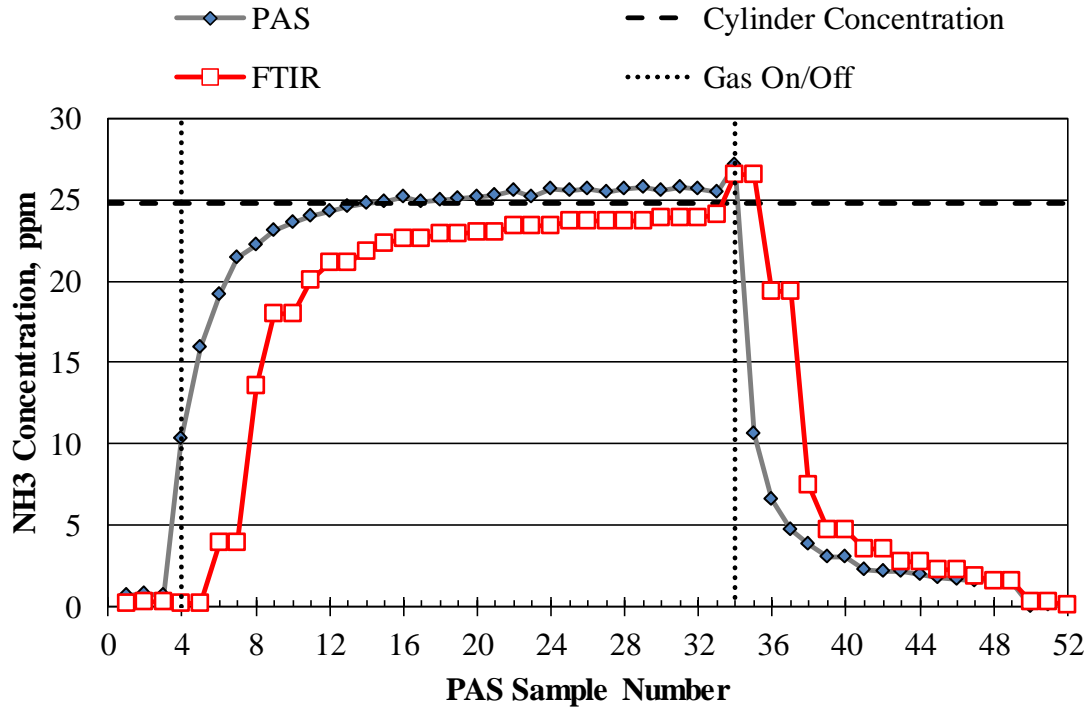


Figure 5.13. PAS and FTIR analyzer responses to exposure to 24.8 ppm NH_3 (N_2 balance) and ambient air. The PAS and FTIR had sample integration times of 30s and 60s, respectively.

Table 5.5. Response times to 98% of expected concentration (T_{98}) from ambient air to concentrations of 24.8ppm NH_3 , 4913ppm CO_2 , 5.19ppm N_2O , and 196 ppm CH_4 for the PAS and FTIR.

Instrument	Sampling Interval/ Integration Time	Response Time (T_{98} , s)			
		NH_3	CO_2	N_2O	CH_4
PAS	30 s	270	30	30	30
FTIR	30 s	660	90	120	90
	60 s	660	120	150	120

Summary and Conclusions

A commonly used PAS analyzer was compared to an FTIR analyzer at a swine facility that was already instrumented for gas concentration and emissions monitoring under a range of durations per sample location (120s, 240s, 360s) and FTIR sample integration times (30s,

60s). The analyzers were compared for agreement under field conditions and for response time to known gas concentrations in a laboratory. In general, the FTIR and PAS compared favorably. Regarding the agreement under field conditions,

- All linear regression slopes differed significantly from 1 ($p < 0.01$). However, the linear regression slopes for FTIR vs. PAS ranged from 1.002 to 1.052 for NH_3 , 0.980 to 1.002 for CO_2 , and 0.996 to 1.017 for CH_4 .
- N_2O concentrations generally were below 0.8 ppm on the PAS and below 0.6 ppm on the FTIR, but had poor agreement between the two instruments. Further investigation is needed to identify the cause of the poor agreement between instruments.
- The percent difference between FTIR and PAS indoor concentrations was generally larger at lower concentrations, shorter sample location times, and large indoor-outdoor concentration differences.
- The absolute differences between FTIR and PAS ambient concentrations remained mostly constant across trials.

The response time tests found increasing the FTIR SIT from 30s to 60s slowed the instrument response time. The FTIR's slower response time is evident, especially for NH_3 . This slower response is at least in part due to the lower measurement chamber air exchange rate for the FTIR. The FTIR chamber air exchange rate was limited by the total flow rate

available from the gas sampling system. Under circumstances where a higher flow rate is possible, the response time for the FTIR should improve. Above all, having a calibration that covers the expected range of concentrations the analyzer will be measuring and that accounts for expected cross-interferences is the most essential tool for any gas analyzer measurements.

Acknowledgements

Provision of the FTIR analyzer and technical assistance by California Analytical Instruments made the study possible.

References

Childers, J.W., E.L. Thompson, D.B. Harris, D.A. Kirchgessner, M. Clayton, D.F. Natschke, and W.J. Phillips. 2001. Multi-pollutant concentration measurements around a concentrated swine production facility using open-path FTIR spectrometry. *Atmospheric Environment* 35(11): 1923-1936.

Hayes, M.D. H. Xin, H. Li, T. A. Shepherd, Y. Zhao, and J.P. Stinn. 2013. Ammonia, greenhouse gas, and particulate matter emissions of aviary layer houses in the Midwestern United States. *Transactions of the ASABE* 56(5): 1921-1932.

Iqbal, J., M.J. Castellano, and T.B. Parkin. 2012. Evaluation of photoacoustic infrared spectroscopy for simultaneous measurement of N₂O and CO₂ gas concentrations and fluxes at the soil surface. *Global Change Biology* 19: 327-336.

Li, H., H. Xin, R.T. Burns, L.D. Jacobson, S. Noll, S.J. Hoff, J.D. Harmon, J.A. Koziel, and B.P. Hetchler. 2011. Air emissions from tom and hen turkey housed in the U.S. Midwest. *Transactions of the ASABE* 54(1): 305-314.

Li, H., H. Xin, R. T. Burns, S.A. Roberts, S. Li, J. Kliebenstein, and K. Bregendahl. 2012. Reducing ammonia emissions from high-rise laying-hen houses through dietary manipulation. *J. Air and Waste Management Association* 62(2):160-169.

Moody, L., H. Li, R.T. Burns, H. Xin, and R.S. Gates, S.J. Hoff, and D.G. Overhults. 2008. Broiler gaseous and particulate matter emission monitoring quality assurance project plan. A Special Publication of ASABE (289 pages): http://asae.frymulti.com/aqap_handbook.asp?confid=aqap2008

Nicoloso, R.S, C. Bayer, G.L. Denega, P.A. Oliveira, M.M. Correa, and L.S. Lopes. 2013. Gas chromatography and photoacoustic spectroscopy for the assessment of soil greenhouse gases emissions. *Ciencia Rural* 43(2): 262-269.

Pepple, L.M., R.T. Burns, H. Xin, H. Li, and J.F. Patience. 2011. Ammonia, hydrogen sulfide and greenhouse gas emissions from wean-to-finish swine barns fed traditional vs. a DDGS-based diet. *Proceedings of the 2011 ASABE Annual International Meeting*, Louisville, Kentucky. August 7-10, 2011.

Stinn, J.P., H. Xin, T.A. Shepherd, H. Li, and R.T. Burns. 2013. Ammonia and Greenhouse Gas Emissions of a Midwestern Swine Breeding-Gestation-Farrowing Facility. *Proceedings of the 2013 ASABE International Meeting*. Kansas City, Missouri. July 21-24, 2013.

Zhao, Y., Y. Pan, J. Rutherford, and F.M. Mitloehner. 2012. Estimation of the interference in multi-gas measurements using infrared photoacoustic analyzers. *Atmosphere* 3: 246-265.

CHAPTER 6

FINAL SUMMARY AND RECOMMENDATIONS

Four technical papers were developed from projects performed on a commercial 4,300 sow breeding-gestation-farrowing facility in Central Iowa. The facility consisted of an 1,800 head deep-pit breeding/early gestation (B/EG) barn, an 1,800 head deep-pit late gestation (LG) barn, eighteen 40-crate shallow-pit farrowing rooms, and an external above-ground manure storage tank (48.8 m diameter and 4.6 m deep). The following is a summary of the results and conclusions from the studies.

- The first paper reports ammonia and greenhouse gas (GHG) concentrations and emission rates of the facility, along with daily indoor temperatures, relative humidity (RH), and ventilation rate (VR) throughout the 29 consecutive months of monitoring period. These data enhance the knowledge of gaseous, especially GHG emissions, for U.S. sow farms. Daily indoor NH_3 , CO_2 , CH_4 , and N_2O concentrations of the breeding/gestation barns (mean \pm SD) were 9.7 (\pm 4.1) ppm, 1536 (\pm 701) ppm, 78.3 (\pm 37) ppm, and 0.30 (\pm 0.10) ppm, respectively. Daily indoor NH_3 , CO_2 , CH_4 , and N_2O concentrations of the farrowing rooms (mean \pm SD) were 12.0 (\pm 7.6) ppm, 1594 (\pm 797) ppm, 28.5 (\pm 9.8) ppm, and 0.31 (\pm 0.11) ppm, respectively. Farm-level emission rates of NH_3 , CO_2 , CH_4 , and N_2O gases (mean \pm SE) were 38.5 (\pm 9.3), 8,731 (\pm 1,666), 301 (\pm 187), and 0.24 (\pm 0.25) g $\text{AU}^{-1} \text{d}^{-1}$ (AU = animal unit, 500 kg live body mass), respectively. Daily total GHG emissions were 15.1 kg CO_2 -eq. $\text{AU}^{-1} \text{d}^{-1}$ after removing CO_2 production due to animal respiration.

Methane emissions were the largest portion of the total GHG emissions. The number of sows needed to trigger the Emergency Planning and Community Right-to-Know Act (EPCRA) reporting threshold (45.5 kg NH₃ per day) is 2702 sows. The breeding/gestation barns accounted for 66% of NH₃, 63% of CO₂, 60% of CH₄, and 45% of N₂O emissions; the farrowing barns accounted for 30% of NH₃, 35% of CO₂, 7% of CH₄, and 55% of N₂O emissions; and the external manure storage accounted for 4% of NH₃, 2% of CO₂, 33% of CH₄, and 0% of N₂O emissions. Methane emissions from the breeding/gestation barns were higher than previously reported values in the literature, but the differences in manure handling between this study (deep-pit) and past studies (shallow-pit) could be at least partially responsible for the outcome.

- The second paper reports total heat production rate (THP) which was partitioned into barn-level latent heat production rate (LHP) and barn-level sensible heat production rate (SHP) for sows in the B/EG and LG barns and lactating sows and litters in the farrowing rooms as measured during a 16-month monitoring period. The values were presented for light, dark, and time-weighted average (TWA) and compared to the ASABE Standards. These data will contribute to the updating of the standards used in the design and operation of ventilation systems for modern swine breeding/gestation and farrowing facilities. The main findings are as follows.
 - For the B/EG barn at 20°C the TWA THP, LHP, and SHP rates were, respectively, 1.80 W kg⁻¹, 0.72 W kg⁻¹, and 1.07 W kg⁻¹. Day to night THP reduction for 20°C and 25°C were, respectively, was 32% and 27%. The partitioning of TWA THP into LHP at 20°C and 25°C were, respectively, were 40% and 57%. The B/EG

barn at 20°C had changes (increases) of 28%, 68%, and 11% when compared to the ASABE Standards for THP, LHP, and SHP, respectively.

- For the LG barn at 20°C the TWA THP, LHP, and SHP rates were, respectively, 1.52 W kg⁻¹, 0.57 W kg⁻¹, and 0.94 W kg⁻¹. Day to night THP reduction for 20°C and 25°C were, respectively, were 27% and 19%. The partitioning of TWA THP into LHP at 20°C and 25°C were, respectively, 38% and 67%. The LG barn at 20°C had changes of 8%, 34%, and -3% when compared to the ASABE Standards for THP, LHP, and SHP, respectively.
- For the farrowing rooms at 25°C during week 0 the TWA THP, LHP, and SHP rates were, respectively, 3.87 W kg⁻¹, 2.05 W kg⁻¹, and 1.80 W kg⁻¹. Day to night THP reduction for 20°C and 25°C were, respectively, 6% and 9%. The partitioning of TWA THP into LHP at 20°C and 25°C were, respectively, 53% and 60%. The farrowing rooms had changes (increases) of 23%, 48%, and 11% when compared to the ASABE Standards for THP, LHP, and SHP, respectively, at a similar production stage (week 0).
- The third paper reports the results of a 12-month field study comparing heat mat vs. heat lamp for localized heating in three farrowing rooms (40 crates per room, 20 crates per treatment) over 16 farrowing/lactation cycles. The heat sources were compared by piglet performance (mortality, average weight gain or AWG), power consumption, and usage of the heat source by the piglets. The main findings are as follows.
 - AWG (±SE) for the mat and lamp raised pigs was 224 (±5.7) g/d and 220 (±5.9) g/d, respectively. The prewean mortality (±SE) for the mat and lamp raised piglets

were 7.8% ($\pm 0.4\%$) and 7.4% ($\pm 0.5\%$), respectively. No significant difference was detected in either AWG or mortality between the mat and lamp heat sources.

- Power use (\pm SE) for the mats and lamps was 0.66 (± 0.06) and 1.05 (± 0.04) kWh per kg weaned pig, respectively, hence a 36% less power for the mats ($p < 0.01$).
- The average time of non-occupancy, average daily heat source use, occupied and unoccupied events and durations were not significantly different. The average daily heat source use trends lower for 6 to 9 days of age compared to the rest of the farrowing cycle.
- The fourth paper reports the results of a 5-month field study comparing a Fourier transform infrared (FTIR) spectrometer and a photoacoustic infrared spectrometer (PAS) for measurement of gaseous concentrations at a swine breeding-gestation-farrowing facility and lab experiments comparing instrument response time. In general, the FTIR and PAS compared favorably. Main findings are as follows.
 - Regarding the agreement under field conditions, all linear regression slopes differed significantly from 1 ($p < 0.01$); however, the largest difference was for a NH_3 where the slope was 1.052. N_2O concentrations generally were below 0.8 ppm on the PAS and below 0.6 ppm on the FTIR, but had poor agreement between the two instruments.
 - The percent difference between FTIR and PAS indoor concentrations was generally larger at lower concentrations, shorter sample location times, and large indoor-outdoor concentration differences. The absolute differences between FTIR and PAS ambient concentrations remained mostly constant across trials.

- Increasing the FTIR SIT from 30s to 60s slowed the instrument response time.

Overall, findings of these studies are beneficial to the swine industry by providing an environmental assessment of a Midwestern U.S. breeding-gestation-farrowing system, as well as to the advancement of the scientific knowledge. The gaseous emissions will be helpful to the development and application of mitigation technologies. The new data on heat and moisture production rates will help updating the current ventilation design standards and allow for more precise environmental control of the production facilities. The heat source comparison demonstrates the similar results (piglet performance, piglet utilization) of both heat mat and heat lamp while indicating that further farrowing crate design modifications may be beneficial to piglet performance. The analyzer comparison demonstrates the suitability of the FTIR for animal air quality work while outlining situations that may be problematic due to the FTIR response time.

Future Research Recommendations

- Studies are needed to quantify gaseous concentrations, emission, and heat and moisture production of gestating sows in loose or group housing conditions to determine the impact of reduced stocking density and presumably higher activity levels.
- With the increase in sow size and litter size and rate of gain and the recent movement of the industry toward larger crates, expanded farrowing crates need to be investigated for their impact on piglet performance and sow and piglet well-being.
- Lab and field studies are needed to better quantify the poor agreement between the FTIR and PAS for N₂O concentration measurements.