ODOUR AND GAS EMISSIONS, ODOUR IMPACT CRITERIA, AND DISPERSION MODELLING FOR DAIRY AND POULTRY BARNS

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By

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ABSTRACT

Very limited research has been conducted to study the concentrations and emissions of odour, toxic gases (e.g., ammonia [NH_3], hydrogen sulfide [H_2S]), dust, and greenhouse gases (GHGs) from dairy and poultry barns in Canada. The major goals of this dissertation work were to study both the indoor and outdoor air pollution of a dairy, cage-layer, and broiler barn under the Canadian Prairies climate condition.

The five odour properties, including odour concentration (OC), odour intensity (OI), hedonic tone (HT), persistence, and character descriptor, were studied for all three barns. The broiler barn presented the highest OC, strongest OI and most unpleasantness (HT) followed by the layer barn and then the dairy barn. It was found that OC, OI, and HT were significantly correlated with each other ($P<0.01$); increased OC was associated with increased OI but decreased HT. Then, new odour impact criteria were developed based on the derived relationships among OC, OI, and HT, with odour concentration limits being determined under both OI and HT limits.

Seasonal concentration and emission profiles of odour, NH_3 and H_2S, GHG (carbon dioxide [CO_2], methane [CH_4], and nitrous oxide [N_2O]), and respirable dust were characterized for the dairy, broiler, and layer barns by long-term monitoring over a year, and diurnal profiles of odour and gas concentrations and emissions were identified by continuous measurements for two days in mild, warm, and cold seasons, respectively. With NH_3, H_2S, and respirable dust concentrations, the indoor air quality of the three barns in different seasons were evaluated by not only considering the occupational health effect (respiratory irritation) of these individual air pollutants, but also their additive health effect. The worst indoor air quality was observed for the broiler barn followed by the dairy barn and then the layer barn. Also, the emission factors of odour, gases, and respirable dust were acquired. The highest annual average odour and NH_3 emissions were from the layer barn (140 OU s^{-1} AU^{-1} and 1.10 mg s^{-1} AU^{-1}), followed by the broiler barn (127 OU s^{-1} AU^{-1} and 1.06 mg s^{-1} AU^{-1}) and then the dairy barn (45.9 OU s^{-1} AU^{-1} and 0.53 mg s^{-1} AU^{-1}). The annual average CO_2 and CH_4 emissions were 116 and 3.1 mg s^{-1} AU^{-1} for the dairy barn, 437 and 0.06 mg s^{-1} AU^{-1} for the broiler barn, and 435 and 0.21 mg s^{-1} AU^{-1} for the layer barn. The impact of environmental parameters (T, RH, and VR) on concentrations and emissions of odour and gases were investigated, and then prediction models for odour emission were developed depending on the environmental parameters.

To validate the performance of AERMOD for predicting odour dispersion, field odour plume measurements were conducted around the broiler barn. In consistent with previous studies, the modelled results were all greatly below the field measured results. Thus, scaling factors were generated to improve the comparison. One scaling factor was 286 by plotting all data and the other was 154 by only using the geometric mean of each odour plume. Both scaling factors achieved good agreements between model predictions and field measurements; however, the scaling factor of 154 was suggested to use due to its better performance over short distances (100-200 m). With the variable emission rates of odour, NH_3, H_2S, and respirable dust, dispersion modelling of the four air pollutants were conducted by the AERMOD dispersion model for all three barns to study their outdoor impact. Using both the recommended odour impact criteria by the Government of Saskatchewan (2012) and the developed odour impact criteria for the three barns in this study, directional setback distances were determined with the ambient threshold limits of NH_3, H_2S, and respirable dust being complied with. Additionally, odour impact criteria were found to be stricter than that of gases and respirable dust as the former always required greater setback distances than the latter.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ACGIH	American Conference of Governmental Industrial Hygienists
ADMS	Atmospheric Dispersion Modeling System
AERMET	AMS/EPA Regulatory Meteorological preprocessor
AERMOD	AMS/EPA Regulatory Model
ANOVA	Analysis of variance
ASHRAE	The American Society of Heating, Refrigerating and Air Conditioning Engineer
ASTM	The American Society for Testing and Materials
AU	Animal unit (500 kg of animal body mass)
AUSPLUME	Australian Plume dispersion model
Ave.	Average
CALPUFF	A Lagrangian Puff model
CDED	The Canadian Digital Elevation Data
CEN	The European Committee for Standardization
CH_4	Methane
CIGR	International Commission of Agricultural and Biosystems Engineering
CO_2	Carbon dioxide
d	Day
D/T	Dilutions to Threshold
EA	Early afternoon
EE	Early evening
EM	Early morning
EPA	Environmental Protection Agency
FAO	Food and Agriculture Organization
FB	Fractional bias
Fre.	Frequency
GC	Gas Chromatograph

GHG	Greenhouse gas
GLM	General linear model
H_2S	Hydrogen sulfide
HPU	Heat production unit
HT	Hedonic tone
INPUFF	Gaussian Integrated Puff model
INPUFF-2	Gaussian Integrated Puff model, version 2
IPCC	Intergovernmental Panel on Climate Change
ISCST	Industrial Source Complex-Short Term
ISCST 3	Industrial Source Complex Short Term, version 3
LA	Late afternoon
LM	Late morning
LODM	Livestock Odour Dispersion Model
N	North
N_2O	Nitrous oxide
NH_3	Ammonia
NOAA/ESRL	National Oceanic and Atmospheric Administration/ Earth System Research Laboratory
NRC	National Research Council
OC	Odour concentration
ODODIS	Odour dispersion software
OE	Odour emission
OFFSET	Odour from Feedlots-Setback Estimation Tool
OI	Odour intensity
OSHA	Occupational Safety and Health Administration
OU	Odour unit
PM	Particulate matter
ppb	Parts per billion
ppm	Parts per million
RD	Respirable dust
RH	Relative humidity

SD	Standard deviation
SF	Scaling Factor
STEL-TLV	Short-term exposure limit threshold limit value
T	Temperature
TLV	Threshold limit value
TWA-TLV	Time-weighted average threshold limit value
VDI	Verein Deutscher Ingenieure
VR	Ventilation rate
w	Week
W	West

LIST OF SYMBOLS

$(CO_2)_i$	Indoor CO_2 concentration (ppm)
$(CO_2)_o$	Outdoor CO_2 concentration (ppm)
$(CO_2)_P$	CO_2 production
ΔC	The difference of odour (OU m^{-3}) and gas (ppm) concentrations between the room incoming air and exhaust air
a, b, c	Constants, coefficients, or are used to indicate the significance of the difference in the measured items
A_0	Constant
$A_1, A_2, A_3, \ldots, A_p$	Coefficients
C	Concentration (OU m^{-3}) or detection threshold
C_m	The modelled mean concentration
C_o	An estimate of the odour detection threshold concentration (D/T)
C_p	The estimated peak concentration
D	Dilution ratio at the point where OI is being assessed
D_{best}	Best-case day
D_o	Dilution ratio at the odour threshold
D_{worst}	Worst-case day
H	The effective emission height (m)
h	Hours
h_{min}	Hours after midnight with minimum cow or birds activity
K	Odour's intensity at full strength
K and n	Constants
m	Body mass (kg)
OE_m	The modelled OE
OE_o	The observed OE
P	Days of pregnancy
Q	The source strength or emission rate

Q_{ip}	The instantaneous point source emission rate
r	Coefficient of correlation
R^2	Coefficient of determination
RH_{in}	Indoor relative humidity (%)
RH_{out}	Outdoor relative humidity (%)
T_{in}	Indoor temperature (℃)
t_m	Long-time period
T_{out}	Outdoor temperature (℃)
t_p	Short-time period
U	The mean transport velocity across the plume
u	Exponent
x, y and z	Receptor location (m)
X_1, X_2, X_3,…, Xp	Independent factors
Y	Dependent factor in Chapter 3 or egg production in Chapter 4 (kg day^{-1})
Y_1	Milk production (kg day^{-1})
σ_{FB}	Standard deviation of the fractional bias
σ_x, σ_y and σ_z	Dispersion parameters
Φ_{tot}	Total heat production (W)

CHAPTER 1
GENERAL INTRODUCTION

1.1 PROBLEM DEFINITION

In the last several decades, intensive confined housing and feeding practice around the world have been largely developed. According to the yearbook 2010 of FAO, production of chicken meat has increased from 58,017,000 tonnes in 1999-2001 to 79,596, 000 tonnes in 2009 by 37 percent, production of eggs has increased from 55,140,000 tonnes in 1999-2001 to 67,408,000 tonnes in 2009 by 22 percent, and production of world milk has increased from 579, 534,000 tonnes in 1982 to 696,554,000 tonnes in 2009 by 20 percent (FAO, 2010). Intensive livestock and poultry production is associated with odour and various air pollutant emissions, including ammonia (NH_3), hydrogen sulfide (H_2S), greenhouse gases (GHGs), particulate matter (PM), etc. (Melse et al., 2009), which could be obstacles to the development of animal industry in the future if their negative impacts on the environment are not properly solved.

Odour and gas production are complex function of bacterial degradation of organic matters which could be emitted from animal barn, animal waste management, and manure land application. Special emphasis has been imposed on potential environmental and human health effects caused by odour and gas emissions from animal operations in recent years (Schiffman, 1998). Odour and different gas emissions from animal operations have been considered to have various degree of impact ranks from global and local perspectives as given in Table 1.1 by National Research Council (NRC) (2003). For example, methane (CH_4) and nitrous oxide (N_2O) are greenhouse gases and contribute to global warming and NH_3 contributes to the formation of ambient particulate and aerosol, are of interest mainly at global level. While odour, which is on the top of the list to cause complaints about animal production, mainly has impact at local level. High levels of odours have been indicated to present negative effects on the health of workers and contribute to the friction between animal farms and residents living in the vicinity. The complaints of health symptoms from odours such as eye, nose and throat irritation, headache and drowsiness have been frequently reported (Schiffman, 1998). With the fact that nowadays people would pay more attention to their health and environment protection, governments have to impose proper regulations and guidelines to avoid odour nuisances from odour sources.

Table 1.1 Ranking of the potential importance of animal feeding operations emissions at different spatial scales (NRC, 2002).

Emissions	Global, National, Regional	Local, Property Line, Nearest Dwelling	Primary Effects of Concern
NH_3	Major*	Minor	Atmospheric deposition
N_2O	Significant	Insignificant	Global climate change
CH_4	Significant	Insignificant	Global climate change
H_2S	Insignificant	Significant	Quality of human life
PM_{10}	Insignificant	Significant	Health, haze
Odour	Insignificant	Major	Quality of life

*Rank order from high to low importance are major, significant, minor, and insignificant.

Various physical, chemical, and biological technologies have been studied to reduce odour emission (OE) from animal facilities (Schlegelmilch et al., 2005), while few of those were used by farmers because of their high cost or high maintenance requirements. A more widely used approach is to establish appropriate setback distances to separate the livestock production facilities from residences or public facilities (Yu and Guo, 2011; Guo et al., 2006). However, so far, no dispersion models can give convincing setback distance results. Effective setback distances can only be determined based on accurate source emission data, good understanding about odour properties as well as appropriate odour impact criteria.

In Canada, specifically, little is known about the OE factors and the relationships between odour properties for dairy and poultry operations, though some research has been conducted on swine barn air emissions (Wang, 2007; Sun et al., 2010). Long-term monitoring of NH_3, H_2S, and GHG were also rarely conducted. Besides, with the fact that the room air of animal barns contained over hundreds of chemical compounds (Schiffman, 1998; Ni et al., 2012), no indoor air quality index has been established based on the combined effect of these pollutants on human health. Besides indoor air quality concerns, acquiring accurate source emission data is also the first step for dispersion modelling, establishing odour and gas impact criteria and determining setback distances. Various factors have been reported to affect livestock OE, including climate, animal species, waste management, and building ventilation control, etc. Thus, directly applying the data acquired from the other regions such as the USA and Europe to Canada probably will not be scientific, especially for those regions such as Canadian Prairies where the weather changes drastically. Moreover, it has been reported that odour and gas concentrations and emissions from livestock production varied diurnally and seasonally (Sun et al., 2010; Wang, 2007). Snapshot measurements will not reflect accurate emissions of those air pollutions that probably will vary in different seasons and in different time periods, which further will affect decisions on mitigation methods and setback distances.

Hence, this study aims to quantify the concentrations and emissions of odour, toxic gases (NH_3 and H_2S), and GHG, including carbon dioxide (CO_2), CH_4, and N_2O, for a commercial dairy barn, a cage-layer barn, and a broiler barn under the Canadian Prairies climate in order to reveal their diurnal and seasonal variations, to develop odour impact criteria with odour properties being fully understood, to predict the outdoor impact of odour, NH_3, H_2S, and respirable dust emissions through dispersion modelling, and to determine setback distances using the obtained seasonal emissions and both the existing recommended and the developed odour impact criteria for the three odour sources.

1.2 LITERATURE REVIEW

1.2.1 Odour properties

In the literatures, odour was described as *"something that stimulates the olfactory system or sense of smell"* (Mackie, et al., 1998) or *"a physiological stimulus of olfactory cells in the presence of specific molecules"* (Rappert and Muller, 2005). A more detailed definition of odour was introduced by Brancher et al. (2017) that it was "*a sensation resulting from the interaction of volatile chemical species inhaled through the nose, including sulfur compounds (e.g. sulfides, mercaptans), nitrogen compounds (e.g. ammonia, amines) and volatile organic compounds (e.g. esters, acids, aldehydes, ketones, alcohols)*". Various factors have been reported to affect olfactory perception, including hormonal factors, age, exposure history, diseases, living habit, etc.

(ASHRAE, 2005). Also, there could be considerable variations between individuals regarding the perceived pleasantness or unpleasantness of a given odour as the mechanism of how odours irritate people sensory is very complex (Schiffman, 1998). Thus, odour is hard to describe, and many efforts have been taken to standardize the measurement of an odour. Generally, odour can be described by five properties (ASHRAE, 2005): odour concentration (OC), odour intensity (OI), persistence, hedonic tone (HT), and character descriptor, among which concentration and intensity are most commonly used to characterize the strength of an odour.

1.2.1.1 Odour concentration

Odour concentration is usually determined by detection threshold, which is "*the lowest level at which an odorant can be detected by a segment of the population*" (ASHRAE, 2005). Although there are also recognition threshold and annoyance threshold, which are defined as the lowest level at which an odorant can be recognized by a segment of the population and the lowest level at which concentration a sensation of annoyance will be provoked, respectively, the detection threshold is usually taken as OC in most odour research if not specifically pointed out. The most commonly used laboratory method for measuring OC is dynamic forced choice olfactometry, which is conducted with a particular dilution device (olfactometer) by presenting the odorous sample to the panel at increasing concentrations. The odour standard from European Committee for Standardization (CEN, 2003) has become the most common method in the world. Despite that olfactometry method is subjective, expensive and offers little information about chemical analysis of odorous compounds, it gives the actual human response and reflects the whole perception of odour composition and is currently the most sensitive and repeatable method (Lacey et al., 2004).

Based on the measuring method, odour unit is defined as the dilution ratio of the odorous air sample by fresh air that must be achieved so that 50% of an odour panel can detect or recognize the odour after dilution (CEN, 2003). Therefore, the OC at that detection threshold is one odour unit per cubic metre of gas at standard conditions (1 OU or 1 OU m^{-3}). In some European countries, unit of OU_E m^{-3} is used. In the USA, the unit dilutions to threshold (D/T) is used and in Korea unit OC is used. All of these units can be said conceptually equivalent to OU m^{-3}, however, different methods used in the standards may generate different results of measured OC.

1.2.1.2 Odour intensity

Intensity is a quantitative state of the degree or magnitude of the perceived odour. It can be measured only when OC is above the detection threshold. A reference substance with specified magnitude is recommended to help scale OI (ASTM standard, 1998). With this approach, the intensity of odour and intensity of a series of different known concentrations of a reference odorant can be compared. N-Butanol is the most commonly used reference because it is highly pure, stable, relatively nontoxic, its odor is neutral to the general population (neither pleasant nor unpleasant), and it has reasonably agreeable odour that is unrelated to most other odours (Mackie et al., 1998). Different n-butanol scales using n-butanol solution in water were applied. In the study of Sneath (1994), a none-referencing 6-point scale method was reported. Guo et al. (2001) and Jacobson et al. (2005) used a 5-point scale while Zhang et al. (2003, 2005) used an 8-point scale. The comparison of the non-objective scale, 5-point scale, and 8-point scale is given in Table 1.2. For the same n-butanol magnitude in water, 8-point scale achieves a lower concentration than 5-point scale, which will result in different relationships between OC and OI (Guo et al., 2006b).

Table 1.2 Measurement methods for OI.

8-point referencing scale (Zhang et al., 2003 and 2005)			5-point referencing scale (Guo et al., 2001)			Non-referencing scale (Sneath, 1994)	
OI	Odour strength	n-Butanol in water (ppm)	OI	Odour strength	n-Butanol in water (ppm)	OI	Odour strength
0	No odour	0					
1	Not annoying	120				0	No odour
2	A little annoying	240	0	No odour	0	1	Very faint
3	A little annoying	480	1	Very faint	250	2	faint
4	Annoying	960	2	Faint	750	3	distinct
5	Annoying	1940	3	Moderate	2250	4	Strong
6	Very annoying	3880	4	Strong	6750	5	Very strong
7	Very annoying	7750	5	Very strong	20250	6	Extremely strong
8	Extremely annoying	15500					

Odour dispersion models need to be assessed by field measured data. However, the output of the odour dispersion models is OC while the result of field measurement is OI. To compare the two types of odour properties, the relationship between OI and OC is critical for the conversion and for evaluating the performance of the dispersion models. Three kinds of OC-OI relationships have been reported, including Weber-Fechner law, Stevens' power law and Beidler model (Guo et al., 2006b). The best fit model was different among previous studies, which are in Table 1.3. It also has been indicated that the difference in OC-OI relationships derived for livestock sources could be significantly different (Misselbrook et al., 1993).

Table 1.3 The relationships between OC and OI in different studies.

	Odour source	OC-OI relationship	Reference
The Weber-Fechner Law $OI=K_1(\log_{10}C)+K_2$	Swine slurry	$OI=1.61(\log_{10}C)+0.45$	Misselbrook et al, 1993
	Broiler house	$OI=2.35(\log_{10}C)+0.30$	Misselbrook et al, 1993
	Swine buildings	$OI=1.57(\log_{10}C)-0.424$	Nicolai et al., 2000
	Swine manure storage	$OI=1.61(\log_{10}C)-0.519$	Nicolai et al., 2000
	Swine farms	$OI=0.928(\log_{10}C)-1.97$	Guo et al, 2001
	Dairy and beef farms	$OI=0.922(\log_{10}C)-2.068$	Guo et al. 2001
	Swine	$OI=2.19(\log_{10}C)+0.736$	Sheridan et al, 2004
	Swine	$OI=1.43(\log_{10}C)+0.78$	Feddes et al., 2006
	Swine	$OI=1.245(\log_{10}C)-0.046$	Zhang et al, 2005
	Poultry production	$OI=2.21(\log_{10}C)+0.82$	Hayes et al, 2006
Stevens' Law $OI=K(C-C_o)^n$	Two broilers farms	$Log(OI)=0.48\log(1/D-1/D_o)+1.19$ $Log(OI)=0.43\log(1/D-1/D_o)+1.15$	Jiang and Sands, 2000

OI is odour intensity; C is the detection threshold; C_o is an estimate of the odour detection threshold concentration; D is dilution ratio at the point where OI is being assessed; Do is dilution ratio at the odour threshold, K and n are constants.

1.2.1.3 Persistence, HT and character descriptor

Compared to OC and OI, much less knowledge can be found regarding odour persistence, HT, and character descriptor. Persistence tells if it's easy or not for a full-strength odorant to be diluted to below the detection threshold. It is the slope of the line representing the OC-OI relationship on a log-log scale and indicates the rate of intensity changing with dilution (Ouellette et al., 2005). As can be seen in Fig. 1.1, the same dilution would not decrease the impact on odour A and B by the same degree due to the variations of their persistence. As the perceived intensity-dilution slope is more horizontal for odour B, odour B is more persistent than odour A.

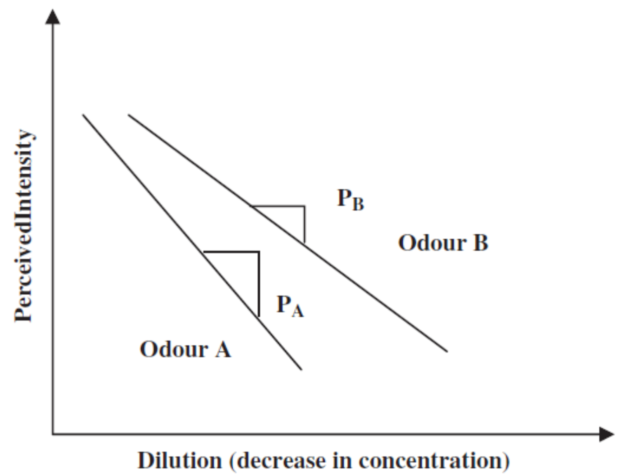

Figure 1.1 Perceived odour persistence (adapted from Ouellette et al., 2005).

Hedonic tone describes the degree of the pleasantness or unpleasantness of an odour. It is typically described by using a scale that ranges from a negative value which means unpleasant to a positive value which means pleasant. In some research a 21-point scale was used from -10 (extremely unpleasant) through 0 (neutral) to +10 (extremely pleasant) (Guo et al., 2006; McGinley et al., 2002). In the guideline of VDI 3882, a 9-point scale with values ranging from -4 (extremely unpleasant) through 0 (neither pleasant nor pleasant) to +4 (extremely pleasant) was applied (VDI, 1994). The scaling methods for HT are similar to that for OI and people may confuse the two characters easily. By definition, HT is not related to OI (ASHRAE, 2005), however, the two properties are inevitably related in perception by receptors. The relationship between HT and OI has proved complex, with a positive or negative correlation for some odorants, or even U-shaped functions or no correlation at all for other odours (Sucker et al., 2008). Liden et al. (1998) studied OI and HT using seven pyridine concentrations and found a larger variation was caused for HT than for OI when changing OC, though the statistic difference was not significant.

Character descriptor is used to describe odour using other familiar smell (such as rotten eggs, fishy, flowery, etc.) (ASHRAE, 2005). It's only used when the samples' concentrations are at or above the recognition threshold concentration. One example is "odour wheel" used by McGinley et al. (2002) in which odour is divided into eight categories, including floral, fruity, vegetable, earthy, offensive, fishy, chemical and medical. After attributing a value to each descriptor from 0-5 to describe the intensity, a spider graph will be obtained to illustrate the quality of the odour.

1.2.2 Livestock odour and gas emissions

1.2.2.1 Livestock odour emission

Odour emission is a product of OC and ventilation rate (VR). To address odour issues, there is a need to know the odour emission rate (OE) of odour as a priority before any control method can be developed and applied. Accurate and detailed source emission data is also the primary part for odour dispersion modelling.

Several studies have been conducted to measure OE from livestock production facilities. Among these studies, large variances of the results were observed. It was found that OE varied by season, weather, animal species, etc. Akdenize et al. (2012) measured OE from nine barns/rooms (four dairy barns, two pig finishing rooms, two gestation barns, and a farrowing room) during four 13-week cycles in the USA. They found that barn concentrations and emission rates presented seasonal patterns. The highest OE was observed in summer and the lowest in winter. The lowest overall barn OE was measured at the dairy barns, and the overall OE of the pig finishing rooms was lower than that of the sow gestation barns. Zhang et al. (2002) reviewed OE data published in the literature and concluded that OE varied from 0.4 to 62 OU m^{-2} s^{-1} for pig farrowing buildings and from 3 to 20 OU m^{-2} s^{-1} for gestation buildings. Gay et al. (2002) summarized OE from over 80 farms in Minnesota, and indicated that the mean OE varied from 0.25 to 12.6 OU m^{-2} s^{-1} for swine housing, from 0.32 to 3.54 OU m^{-2} s^{-1} for poultry housing, from 1.3 to 3.0 OU m^{-2} s^{-1} for dairy housing, and from 4.4 to 16.5 OU m^{-2} s^{-1} for beef feedlots. Zhang et al. (2005) investigated odour and GHG emissions from two 3000-sow farrowing operations; it was found that OE from farrowing rooms was 2-3 times higher than that from the gestation rooms (22.9 OU m^{-2} s^{-1} compared to 9.6 OU m^{-2} s^{-1}). Besides, OE was significantly lower at lower temperatures than that at higher temperature ranges (Zhang et al., 2005). Casey et al. (2006) reviewed the literatures on OE from animal waste management systems including manure storages and anaerobic lagoons; the information was limited when compared to that of animal housing.

Although various research on odour from swine production could be found, there has been relatively limited information related to odour production and emissions from poultry operations (Lacey et al, 2004). In a broiler shed, the generation of odours were resulted from biodegradation of accumulated fecal matter and were transferred into the shed air and then transported to the surrounding environment by the ventilation system (Jiang and Sands, 2000). It was found that OC varied with VR, litter moisture level, and shed design (Jiang and Sands, 2000). Carey et al. (2004) also concluded that litter moisture management was vital for odour control, and NH_3 (odorous) released from litter was negligible at litter pH below 7. Hayes et al. (2006b) measured odour and NH_3 emissions from three broiler houses, two layer houses, and two turkey houses in Ireland. It showed that the mean OE for broilers were 0.66 OU s^{-1} $bird^{-1}$ in summer, 0.33 OU s^{-1} $bird^{-1}$ in spring and 0.39 OU s^{-1} $bird^{-1}$ in winter; for layers the mean OE were 1.35 OU s^{-1} $bird^{-1}$ in summer and 0.47 OU s^{-1} $bird^{-1}$ in winter; and for turkeys the mean OE were 7.4 OU s^{-1} $bird^{-1}$ in summer and 5.7 OU s^{-1} $bird^{-1}$ in winter. Ogink and Groot Koerkamp (2001) reported OE at a range of 0.06-0.41 OU s^{-1} $bird^{-1}$ from broiler housing in the Netherlands. Robertson et al. (2002) concluded OE in the range of 20,000-33,000 OU s^{-1} for a 34,000-bird flock in UK, which meant 0.6-1.0 OU s^{-1} $bird^{-1}$.

Limited research has been conducted to reveal the diurnal and seasonal variations in livestock OC and OE. Guo et al. (2007) found large daytime variations in OC and OE from four types of swine rooms (the gestation room, farrowing room, nursery room, and finishing room). It showed that odour and gas (NH_3 and CO_2) concentrations were likely to be high in the early morning and late afternoon but no any certain pattern of OE was observed. Sun et al. (2010) indicated that the sampling month and ambient temperature significantly impacted on odour and gas concentrations and emissions of swine grower/finisher rooms. Wang (2007) monitored the diurnal and seasonal variations of OE from nursery, farrowing, and gestation rooms, and found that OC in winter was significantly higher than in mild and warm weather conditions for all three types of rooms. In addition, significant diurnal variations occurred for OE in August and April, but were not found in February. Zhao et al. (2007) measured monthly odour, H_2S, and NH_3 emissions from a dairy manure storage pond and indicated that there were large temporal variations in odour, NH_3, and H_2S emissions among various months of the year. Large diurnal and seasonal variations in OC and OE from dairy manure storage pond and from different types of swine rooms as mentioned above suggested that the representative OC and OE cannot be obtained by snapshot measurements. Besides, in Canada, although there have been a few studies on odours from swine production (Sun et al., 2010; Wang, 2007; Zhang et al., 2005), long-term monitoring of OC and OE for different poultry and dairy operations has not been conducted yet.

1.2.2.2 Livestock gas and dust emissions

Agriculture production not only contributes to NH_3, H_2S and organic compounds emissions, but also is a most major source of N_2O and CH_4 emissions (Viney et al., 2009). It is estimated that human activities in agriculture accounted for 50% of total CH_4 and 60% of N_2O emissions (IPPC, 2007), and more than 80% of NH_3 emissions (US EPA, 2007). In addition to the environmental effects, the health effects of NH_3 include eye, nose, and throat irritation at low concentrations and death at very high short-term concentrations, and of H_2S include neurological effects, immunological effects, respiratory, cardiovascular and metabolic effects and even death at very high concentrations (Copeland, 2014). Methane and N_2O are the two major GHGs. The global heating potential value within 100 years is 298 times of CO_2 for N_2O, and 25 times of CO_2 for CH_4 (IPPC, 2007). The generation of CH_4 is process of a complex microbial degradation of carbohydrates in the reticulorumen and hindgut in the presence of methanogens. The release of CH_4 was mainly attributed to enteric fermentation of ruminants and generation of N_2O was from degradation of excreted manure (Joo et al., 2015).

Large number of studies have been conducted to quantify gas emissions from livestock sources. In the USA, the National Air Emissions Monitoring Study has been carried out in 9 states to monitor NH_3, H_2S, PM and volatile organic compounds for 2 years at different barn monitoring sites (dairy, swine, broiler and layer facilities). Ammonia emission rate varies by animal species. Dairy cattle, non-dairy cattle, pigs, and poultry accounted for 11.2%, 13.2%, 8.7%, and 13.4% of total NH_3 emissions, respectively (Gay et al., 2006). Gay et al. (2006) summarized NH_3 emission rates from 66 farms in Minnesota, and reported that NH_3 emission rates varied from 0.35 to 13.0 g m^{-2} d^{-1} for swine housing, from 2.85 to 8.0 g m^{-2} d^{-1} for dairy, and from 2.2 to 4.4 g m^{-2} d^{-1} for beef feedlots; H_2S emission rates varied from 0.02 to 1.5 g m^{-2} d^{-1} for swine housing, from 0.03 to 0.35 g m^{-2} d^{-1} for poultry housing, from 0.09 to 0.25 g m^{-2} d^{-1} for dairy housing, and were about 0.15 g m^{-2} d^{-1} for beef feedlots. Usually H_2S concentrations were low in animal housing compared to CO_2 and NH_3 concentrations. Safley and Casada (1992) estimated CH_4 contributions from different livestock and poultry species and concluded that the CH_4 emission factor (in unit of kg CH_4 $animal^{-1}$ yr^{-1}) was 23 for cattle in feedlots, 70 for dairy, 20 for swine, 0.3 for caged layer and 0.09 for broiler.

There is often a desire to relate OC to a compound (such as NH_3 and H_2S) that can be easily measured using gas measurement instruments. NH_3 is generally considered to be the first step towards the generation of odorous compounds and is often used as an indicator for the microbiological processes that resulted in significant odour generation (Jiang and Sands, 2000). Amon et al. (1997) found a good relationship between NH_3 concentration and OC in a clinoptilolite-treated broiler room, but this relationship could not be confirmed in the second test. In Wang's (2007) research, NH_3, H_2S, and CO_2 emissions were measured from three types of swine rooms; the results showed that OC was positively correlated to NH_3, H_2S, and CO_2 concentrations (Wang, 2007). Blanes-Vidal et al. (2012) investigated NH_3 concentrations and odour annoyance perceived by the local residents and found that seasonal pattern of odour perception was associated with seasonal variation in NH_3 concentrations, suggesting that NH_3 level could be used as an indicator of odour annoyance in non-urban residential communities. In another study, OC was most strongly related to the sulfur containing compounds (H_2S, dimethylsulfide, dimethyldisulfide and dimethyltrisulfide) for agitated swine slurry, and significant contribution of NH_3 to OC was only found in the absence of H_2S, suggesting that H_2S could be a good indicator of the overall OC (Blanes-Vidal et al., 2009). Gostelow et al. (2001) also suggested a power-law linear relationship between concentrations of odour and H_2S, where H_2S was the only odorant. However, other odorants may contribute to the perceived odour when the H_2S concentration was low.

Particulate matter from livestock production has also been regarded as an indoor pollutant that inversely impacts on animal performance and efficiency, and workers' respiratory health. Furthermore, emitted PM outside livestock houses is also related to ecosystem and climate change (Cambra-López et al., 2010). From an occupational health point of view, dust can be classified into three major categories by size, including respirable dust, inhalable dust and total dust. Respirable dust is fraction of inhaled airborne particles that can penetrate into the gas-exchange region of the lungs (WHO, 1999). Working in livestock houses (e.g. swine, poultry) is usually associated with high dust exposure and long-term effect in lung function. In poultry houses the exposure to dust is even higher than in swine houses (Iversen et al., 2000). Cambra-Lopez et al. (2010) reviewed papers regarding PM from livestock production and found PM levels in broiler houses were the highest compared with other animal species. Besides, PM emissions were also related to housing, feeding and environmental factors (Cambra-Lopez et al., 2010).

1.2.3 Direct vs. indirect methods for VR measurement

Ventilation rate in animal barns is crucial in determining emission rate of odour and gases. Fan method and CO_2 mass balance method are the mostly commonly used direct method and indirect method, respectively, to estimate VR of animal buildings. Fan method involves measuring the rotation speed of all fans and the static pressure of the room, and then estimating the airflow rate of each fan from the fan performance curve of the fan test report supplied by the manufacture. The principle of CO_2 mass balance method is that the CO_2 gain of a room from the incoming air and CO_2 produced by the animals is equal to the CO_2 loss through the exhaust air (Albright, 1990).

Although direct fan method is usually used for mechanically ventilated buildings, considerable error will still be caused for various reasons such as loose fan belts, power supply, and dirty shutters and fan blades (Li et al., 2004). Simmons and Lott (1997) studied on the air flow reduction resulted from a shutter on a poultry-house ventilation fan. Results showed that dirt accumulation on a fan and shutter decreased fan air flows by up to 16.3% (Simmons and Lott, 1997). In a naturally or hybrid ventilated housing, or in a mechanically ventilated housing with a large number of fans, the indirect CO_2 mass balance method is much more attractive for determining the VR. The CO_2 mass balance method is based on estimating animal heat production; every 24.6 kJ of total heat is added to the environment for one litter of CO_2 is produced by animal (Albright, 1990). The possible reasons caused the unknown uncertainty for CO_2 method are: 1) the CO_2 production rates of animals were calculated using the data in the late 1950s, but the animal diets, breeds and production systems have changed over the years; and 2) only the CO_2 produced by animals was considered and the CO_2 produced by manure in the room was unknown and was assumed negligible. To solve the first problem with the CO_2 mass balance method as mentioned above, researches have taken efforts to update the CO_2 production rate and equations for total heat production from pigs, cows, poultry, etc. (CIGR, 2004), e.g., Xin et al. (2001) and Chepete (2004) studied the heat and moisture productions of modern broiler chicken raised on litter and laying hens in commercial production housing, respectively, and provided an updated database for engineering practices.

In the study of Guo et al (2006a), both fan method and CO_2 mass balance method were used to acquire the VR of different types of swine rooms; the results suggested that the fan method may have an uncertainty of about 15% due to its dust buildup and power supply variations, while the

CO_2 mass balance method had an unknown uncertainty. To evaluate the credibility of the CO_2 mass balance method, Li et al. (2004) conducted a test in a commercial laying house using manure belts with daily manure removal and used direct fan method at the same time. It indicated that the difference between the VR obtained from the two methods were not significantly different when the averaging or integration time interval was 2 hours or longer. Using the same method, Xin et al. (2009) conducted a similar study in two commercial broiler houses when supplemental heating was not in use and found no significant difference in VR between the direct and indirect methods with a measurement time over 30 minutes or greater. If not considering the CO_2 generation from the litter, the CO_2 balance method would be underestimated by 7.5%. In the study of Navaratnasamy and Feddes. (2004), it was reported that VR for livestock buildings could be measured satisfactorily using the CO_2 mass balance method. Calvet et al. (2011) indicated a 20% contribution of CO_2 generation by manure decomposition at the end of a 35-day cycle for broiler barns.

1.2.4 Livestock odour dispersion modelling

Dispersion modelling is the mathematical simulation to predict the atmospheric dispersion of air pollutants within the plume (Holmes and Morawska, 2006). Dispersion modelling involves several major aspects (Zhang et al., 2005): a) accurate source emission input; b) sufficient meteorological data; c) appropriate dispersion model for a certain source type and release scenario; and d) assess the impact of the source through post modeling analysis.

1.2.4.1 Gaussian plume models

Gaussian plume models are based on a Gaussian distribution of the plume in the vertical and horizontal directions under steady state conditions and are most widely used in assessing the impacts of air pollution from local and urban sources particularly for regulations. The Gaussian plume formula is (Arya, 1999):

$$C = \frac{Q}{2\pi \mathrm{u} \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right)\left(\exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right)\right) \quad \text{..........(1.1)}$$

Where C is the downwind concentration at the receptor location (x, y, z); Q is the source strength or emission rate; U is the mean transport velocity across the plume; σ_y and σ_z are the Gaussian plume dispersion parameters; and H is the effective emission height. Several assumptions are made in the Gaussian plume model, including: continuous emission from the source at a constant rate; no wind shear in the vertical; steady-state flow and constant meteorological conditions; constant mean transport wind in the horizontal (x-y) plane, and others. Gaussian plume dispersion models are comparatively easy to use, which made them widely used despite their limitations.

In North America, ISCST 3 is one commonly used dispersion model based on the Gaussian dispersion theory and it can be used to assess pollutant concentrations from broad variety of sources. Although numerous research has been conducted to improve the accuracy of ISCST 3 model for downwind gas and PM concentrations, using ISCST 3 to predict odour dispersion from large animal feeding operations is still a challenge (Wang et al., 2006). It can predict average downwind OC, but has difficulty in predicting peak OC and downwind OC when wind speed is higher than 6 m s^{-1} (Wang et al., 2004). AUSPLUME model is an extension of the US EPA ISC model and was developed by the Australian Environmental Protection Authority (Gardner et al., 2015); it is initially designed for flat terrain condition and is useful for small, steady-state, near-field applications. AERMOD is a Gaussian dispersion model as the replacement to ISCST 3 developed by the American Meteorological Society and the US EPA; it is designed to input hourly micrometeorological data (Yu, 2011). Compared to ISCST 3, there are improved algorithms of AERMOD (Yu, 2011), including: dispersion in both convective and stable boundary layers, plume penetration into elevated inversions, computation of vertical profile of wind, turbulence and temperature, and the advanced characterizations of the fundamental boundary layer parameters, etc.

1.2.4.2 Gaussian puff models

Puff models represent a continuous plume that consist of a number of discrete packets of pollutants (Arya, 1999). The general formula of Gaussian model is given by (Arya, 1999):

$$C=\frac{Q_{ip}}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z}\exp[-\frac{x^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}]\{\exp[-\frac{(z-H)^2}{2\sigma_x{}^2}]+\exp[-\frac{(z+H)^2}{2\sigma_z{}^2}]\} \text{ ....(1.2)}$$

Where C is the downwind concentration at the receptor location (x, y, z); Q_{ip} is the instantaneous point source emission rate; σ_x, σ_y, and σ_z are the puff-diffusion parameters; and H is the effective emission height. The puff model simulates the concentration of puff to the total concentration by a snapshot approach, and calculates the total concentration at a receptor by summarizing all nearby puffs that are averaged for all sampling steps within the basic time step (Wang et al., 2006). INPUFF-2 model is based on the Gaussian puff theory and predicts atmospheric dispersion of pollutants which released over a short time of period (Zhang et al., 2005). It can handle multiple point sources and multiple receptors simultaneously, and it also can predict the dispersion of airborne pollutants from semi-instantaneous or continuous point sources (Zhang et al., 2005). CALPUFF dispersion model is based on Lagrangian puff model and is a multi-layer, multi-species, non-steady-state puff dispersion model that designed for regulatory use (Xing, 2006). It can predict the effects of temporal and spatial variability of micrometeorological conditions on pollutant transport, transformation and removal (Henry et al., 2010). It has been proposed by the US EPA to use the CALPUFF model as a guideline model for long range transport and on a case-by-case basis for near-field applications where effects of non-steady-state may be significant.

1.2.4.3 Comparison and evaluation of dispersion models

Many researchers have applied the existing commercial air dispersion models to predict livestock odour dispersion, however, those models are initially designed for predicting industrial gas emissions, while significant differences do exist between industrial gas and livestock odour (Smith, 1993): 1) the odour source is at or near ground level; 2) there is no plume rise of livestock odour; 3) the livestock odour source may be of relatively large area extent; 4) the important receptor zone of livestock odour may be relatively close to the source of emissions; and 5) the difficulty in measuring of livestock odour emissions. Therefore, evaluations of air dispersion models in simulating livestock odour dispersion are very important to judge the credits of the modelled results and may also provide reference regarding their performance in various conditions (e.g., distance, meteorological condition) for selecting appropriate dispersion models.

Wang et al. (2006) evaluated the performance of CALPUFF model and ISCST 3 model in predicting downwind OC from a cattle feed-lot farm by taking field OC samples. The results showed that CALPUFF model could fairly well predict average downwind OC while ISCST 3 tended to underestimate downwind OC compared to the field measured concentrations, but both models failed to simulate peak OC using the constant average emission rate. Xing (2006) validated four selected air dispersion models, including ISCST 3, AUSPLUME, CALPUFF, and INPUFF 2, for predicting livestock odour. She compared the modelled results with the field measured data from University of Manitoba, University of Minnesota, and University of Saskatchewan using the OC-OI relationships from University of Manitoba and University of Alberta. The four models achieved similar agreements between modelled results and field measured results for all distances. The statistical evaluation of the model performance showed the bias of the four models all fell into the acceptable value range and no model was obviously better than others, while INPUFF 2 had better performance than CALPUFF without considering the OI level 0 after using scaling factor (also called peak-to-mean ratio) (Xing, 2006). Using similar methods to Xing's (2006) research, Li (2009) evaluated AERMOD and CALPUFF dispersion models. No significant difference was found between the agreement percentages of the modelled results and the measured results for the two models. Scaling factor could improve the agreement of modelled results and field odour results by 14.8% and 10.7% for AERMOD and CALPUFF, respectively.

Henry et al. (2010) modelled downwind OC from a swine production facility using CALPUFF and AERMOD and assessed ambient odour using Nasal Ranger, Mask Scentometer, OI rating scale (0-5 scale), and dynamic triangular forced-choice olfactometry. Through a linear regression analysis of the results, scaling factors for the two models were found and AERMOD was slightly better than CALPUFF in predicting downwind OC, but the difference was not significant. Guo et al. (2001) compared field OI measurements with modelled results to validate the INPUFF-2 dispersion model. It was found that the model could satisfactorily predict OI of 1 from a 5-point scale method up to 3.2 km away from sources under stable to slightly unstable weather conditions, however, the model underestimated moderate to strong or very strong odours during neutral or unstable weather. The reasons for underestimating strong odours included constantly changing wind direction and wind speed under windy conditions, limitation of filed measurement methods, etc. (Guo et al., 2001). Jacobson et al. (2005) validated INPUFF-2 model for predicting odour from various animal facilities through comparing to actual odour data. They also indicated that the INPUFF-2 model was capable of predicting downwind OC for low-intensity odours during stable weather conditions.

Most of the existing setback distances are determined by individual experience and judgment or by the results from neighbor surveys and odour measurement (Guo et al., 2004), limited setback distances are acquired by calculations from dispersion models. Based on the work of Jacobson et al. (2005), Guo et al. (2005) developed the OFFSET (Odour from Feedlots-Setback Estimation Tool) model to estimate the setback distances from animal production sites and compared the results with the odour complaints' distances from swine farms and odour occurrences recorded by the resident odour observers. It was found that the OFFSET model did not over-predict odour travel distances under very stable weather conditions but tended to under-predict OI for the majority of time. Piringer et al. (2007) conducted a sensitivity study using two odour impact criteria in AODM (Austrian Odour Dispersion Model) to calculate direction-dependent setback distances: 1 OU m^{-3} and 3% exceedance probability for residential areas, and 1 OU m^{-3} and 8% exceedance probability for mixed areas. Results showed that the schemes to determine atmospheric stability and peak-to-mean ratios had significant influence on separation distances. In addition, none of the above models consider the short-time fluctuations of odour although they can estimate reasonable accurate one-hour average OC for regulatory use. Yu and Guo (2011) developed a LODM (Livestock Odour Dispersion Model) model designed specifically for odour dispersion from livestock facilities, which considered the short time OC fluctuations and estimated hourly odour frequency with the input of hourly meteorological data. It proved that LODM could be used to determine different setback distances when applying different odour occurrence frequencies calculated from hourly mean OC method and hourly odour frequency method. However, this model needs to be further validated.

1.2.5 Odour impact evaluation and odour impact criteria

The mechanism of how an odorant emission leads to actual odour nuisance is quite complex, which involves various factors including the characteristics of the odour (detectability, OI, HT, persistence, annoyance potential), turbulent dispersion (wind direction, wind speed, stability of the boundary layer, etc.), exposure of the receptors (location, movement of people, time spent outdoor, etc.) and receptor characteristics (exposure history, activity during exposure episodes, etc.) (Ireland EPA, 2001). Generally, to determine whether an odour is a nuisance four principles are used in terms of "FIDO": **F**requency (the number of times an odour is detected over a specific time period), **I**ntensity (the strength or concentration of an odour), **D**uration (length of exposure), and **O**ffensiveness (HT) (Mackie et al., 1998; Sheridan, 2002; Lacey et al., 2004; Rappert and Muller, 2005). Various approaches have been applied to assess odour impact, including questionnaire method (VDI, 1997; Ireland EPA, 2001; Jiang and Sands, 2000), complaint analysis, field assessments using panels or resident observers (Guo et al., 2006), and measuring emissions at source followed by dispersion modelling (Sheridan et al., 2004; Hayes et al., 2006a). Different questionnaire techniques have been used. Ireland EPA (2001) applied the Standardized Telephone Questionnaire to measure the percentage of people annoyed in a sample of population to determine the dose-effect relationship. In Germany, a standardized questionnaire was developed (VDI, 1997). When using complaint analysis method, the data collected must be treated with caution as the absence of existed complaints does not necessarily indicate the absence of nuisance especially when there is conflict situation (Ireland EPA, 2001). Using dispersion models to predict the downwind OC based on the source OE, topography and meteorological data is a very common approach to evaluate odour impact. After the OC at the source being quantified using standard methods, OE from the source can be determined, and OC at receptors may then be estimated using reliable dispersion models.

Odour impact criteria provide reference for making decisions in land planning, designing, environmental management and regulation (Jiang and Sand, 2000). Odour impact criteria play vital roles in dispersion modelling to determine setback distances, at which a building(s) or a specific land use (which is deemed to need protection) is set back from the emission source to meet those criteria. The common expression of odour impact criterion is a specified OC limit at which an odour impact would occur with an averaging time and/or various frequencies (e.g., 98%, 99%, 99.5% and 99.9%). For example, an odour annoyance criterion of 6 odour units as a 98th percentile means a level of 6 OU m^{-3} which can be exceeded for no more than 2% of the time. There is a wide variety of odour impact criteria applied in different jurisdictions varying by the OC threshold (0.12 to 10 OU m^{-3}), by the averaging period (less than 1 second to 1 hour) and by tolerated exceedance probability (0.1% to about 35% of the time) (Sommer et al., 2014; RWDI Air Inc., 2005). The development of odour impact criteria is complex and is still a developing science.

Using laboratory measurement and a community survey, Jiang and Sands (2000) established preliminary evidence for applying a one hourly averaged OC of 5 OU m^{-3} at the 99.5th percentile as odour impact criteria for broiler farms in temperate Australia. Guo et al. (2005) used a OC of 75 OU m^{-3} and intensity 2 in OFFSET model as acceptable odour level. Ireland EPA (2001) demonstrated an odour impact criterion $C_{98,\ 1\text{-hour}} \leq 6$ OU m^{-3} for existing pig farms that hourly OC should be below 6 OU m^{-3} as a 98th percentile, and an odour impact criterion $C_{98,\ 1\text{-hour}} \leq 3.0$ OU

m^{-3} for new pig production units. Sheridan et al (2004) calculated the distinct OC (taking OI = 3 as an odour nuisance suggested by Ireland EPA [2001]) to be 4.3 OU m^{-3} using the ISCST 3 model and suggested a new odour impact criterion: $C_{98,\ 1\text{-hour}} \leq 4.3$ OU m^{-3} for pig production. Using the same method with Sheridan et al. (2004), Hayes et al. (2006a) developed a new odour impact criterion ($C_{98,\ 1\text{-hour}} \leq 9.7$ OU m^{-3}) for intensive production of broilers, layers and turkeys. Based on literature review of odour criteria in different regions, Yu and Guo (2012) proposed ambient odour criteria for different land uses in Saskatchewan with odour concentration limits from 1 OU m^{-3} to 6 OU m^{-3}, averaging period of 1 hour and annual odour occurrence-free frequency of 99.5%. By odour dispersion modelling using the AERMOD and CALPUFF models and historical odour complaints data, the recommended odour impact criteria were validated to be reasonable as the results showed the odour dispersion modelling results were consistent with the complaints received (Yu and Guo, 2012).

However, the above studies used an odour impact criterion limiting only OC or OI, while the role of HT is ignored, which directly reflects the annoyance level of odour. Odour is not a feature of a certain chemical species but a physiological reaction of humans (Schauberger and Piringer, 2012) that is commonly expressed by HT. Few methods combined HT (pleasantness or unpleasantness) with OC to estimate odour annoyance (Chaignaud et al., 2014). Besides, although various ambient odour criteria are applied in America, Australia, Europe and Asia (RWDI Air Inc., 2005), in many cases the criteria are used for wastewater treatment plants or composting facilities or for all sources while only few of them are specifically regulated for livestock odour sources. Hence, it is necessary to dig more information about livestock odour to develop an odour impact criterion based on complete understanding of odour properties.

1.3 RESEARCH GAPS

From the above literature review, the following key research gaps are outlined:

1. Most of previous studies only emphasized on OC and OI. The other odour properties, including HT, persistence and character descriptor, as well as the relationships among OC, OI and HT for livestock odour were not well understood. The existing odour impact criteria were established with a limited OC or OI, while the role of HT was ignored, which directly reflects the annoyance level of odour;

2. Little has been done for long-term indoor air quality monitoring for poultry and dairy barns in Canada. Given livestock room air is composed of hundreds of components, the indoor air quality of poultry barns and dairy barns has not been evaluated considering the combined health effect of the multiple air pollutants, as well as their possible diurnal and seasonal concentration variabilities;

3. Large diurnal and seasonal variations in odour concentrations and emission rates from livestock sources have been observed and the representative odour concentration and emission rate could not be obtained by a snapshot measurement. Monitoring of diurnal and seasonal odour concentrations and emissions for poultry and dairy barns in Canada had not been conducted. Prediction models of OC and OE for dairy and poultry barns in Canada were not developed;

4. So far, there is still a lack of sufficient data on greenhouse gas (CO_2, CH_4 and N_2O) emissions from dairy and poultry barns in different regions across Canada, and no GHG data is available for dairy and poultry barns on the Canadian Prairies;

5. The performance of AERMOD to predict odour dispersion for dairy and poultry barns on the Canadian Prairies was not evaluated;

6. No setback distances have been determined from dairy and poultry barns by dispersion modelling with data input of monthly measured emission rates as well as using odour impact criteria of recommended odour guidelines (e.g. Saskatchewan ambient odour guideline) or developed odour impact criteria under both OI and HT limits. Further, no comparison of setback distances required by odour and gas regulations or guidelines based on dispersion modelling can be found in the literature.

1.4 CURRENT STUDY

The following hypotheses, objectives, and methodology are developed based on the knowledge from the above literature review.

1.4.1 Hypotheses

In this project the following hypotheses are proposed:

1. There would be correlations between OC and OI, between OC and HT, and between OI and HT;
2. Odour, gases, and respirable dust concentrations and emissions would vary by animal species and buildings. Besides, they would also vary seasonally and diurnally by the ambient weather condition (outdoor temperature and relative humidity), by indoor environment (indoor temperature and relative humidity), and VR;
3. There would be correlations between odour and odorous gases (NH_3 and H_2S);
4. Odour and gas concentrations and emissions could be predicted by animal information and environmental parameters (indoor and outdoor temperature, indoor and outdoor relative humidity, and VR);
5. Indoor air quality indicator could be set up based on the combined occupational health effect (respiratory irritation) of NH_3, H_2S, and respirable dust for workers;
6. The impact of odour and gases as predicted by dispersion models would allow setting up setback distances to ensure the air quality of the nearby areas.

1.4.2 Objectives

Diurnal and seasonal concentration and emission profiles of odour, toxic gases (NH_3 and H_2S), and GHG (CH_4, CO_2, and N_2O) as well as seasonal concentration and emission profile of respirable dust from commercial broiler, layer, and dairy barns under the Canadian Prairie climate would be acquired and the following objectives would be obtained:

1. To study odour properties, including OC, OI, HT, character descriptor, and persistence for the three animal barns and determine odour concentration limits in odour impact criteria based on the relationships between odour properties (OC vs. OI, OC vs. HT, and OI vs. HT);
2. To evaluate the indoor air quality of the three animal barns in different seasons with the concentrations and threshold limit values of NH_3, H_2S, and respirable dust concentrations based on their occupational health effect (respiratory irritation) and develop indoor air quality indicators;
3. To acquire diurnal and seasonal odour and gas emission factors for the three odour sources

and develop statistical models for OC and OE with the knowledge of odorous gas (NH_3 and H_2S) concentrations, environmental parameters (VR, temperature, and relative humidity) as well as animal information;

4. To evaluate the performance of AERMOD for predicting livestock odour by field odour plume measurements; and
5. To conduct dispersion modelling of odour, gases (NH_3 and H_2S), and respirable dust for the study dairy and poultry barns under the Canadian Prairies climate and determine setback distances using both the regulated and newly developed odour impact criteria, which will guarantee neither the annoyance level of odour nor the threshold limits of NH_3, H_2S and respirable will be exceeded.

1.4.3 Methodology

The specific procedures to meet the goal of the study are listed below with a flow diagram displayed in Fig. 1.2:

1. Conduct a literature review to acquire background information;
2. Conduct field measurements of odour, gases, and respirable dust concentrations and emissions as well as environmental parameters (temperature, relative humidity, and VR) for a commercial dairy, layer, and broiler barn;
3. Based on the data of odour, investigate the correlations among OC, OI, and HT and determine odour threshold limits in odour impact criteria;
4. Investigate the correlations among odour, gases and environmental parameters and develop prediction models for OC and OE;
5. Evaluate the indoor air quality based on NH_3, H_2S, and respirable dust concentrations;
6. Conduct field odour plume measurements to validate the performance of AERMOD for modelling odour dispersion;
7. Conduct dispersion modelling for odour, NH_3, H_2S, and respirable dust using AERMOD and determine setback distances using the emission rates measured from step 2 and using the recommended odour impact criteria by the government as well as the developed odour impact criteria from step 3.

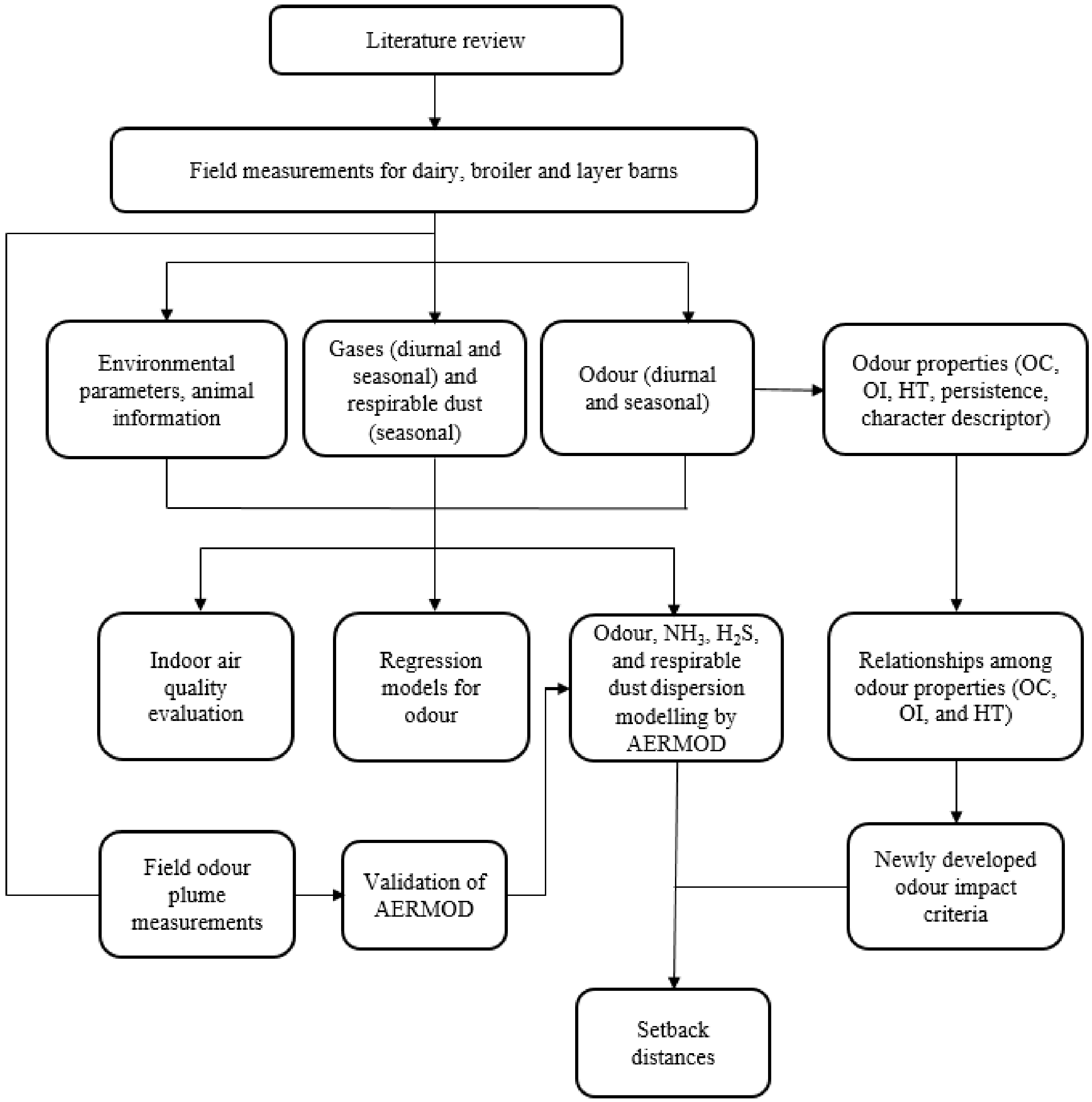

Figure 1.2 Flow diagram of the study.

1.4.4 Thesis outline

The thesis is in manuscript-based format. There are 10 Chapters (Chapter 1 to 10) and appendixes A and B. Chapter 1 gives an introduction to the thesis. Chapter 2 describes the relationships between odour properties and determination of odour concentration limits in odour impact criteria for the dairy, layer, and broiler barns. Chapter 3 presents the diurnal and seasonal variations of odour and odorous gas (NH_3 and H_2S) emissions as well as indoor air quality for the dairy barn.

Chapter 4 discusses about diurnal and seasonal variations of odour emissions, and Chapter 5 discusses about diurnal and seasonal variations of odorous gas (NH_3 and H_2S) emissions as well as indoor air quality for the broiler and layer barns. Chapter 6 and Chapter 7 focus on the diurnal and seasonal variations of GHG (CO_2, CH_4, and N_2O) emissions for the dairy barn and the two poultry barns, respectively. Chapter 8 validates the performance of AERMOD in predicting livestock odour dispersion by conducting field odour plume measurements and Chapter 9 introduces air dispersion modelling for odour, gases, and respirable dust and determination of setback distances using AERMOD for the three barns. Lastly, Chapter 10 provides an overall summary, the major conclusions, the original contributions, and some recommendations for future work. Since the respirable dust concentrations and emissions of the dairy barn were not included in the published Chapter 3 and were not suitable to put in other chapters, the results were given separately in Appendix A. The copyright permissions for using the manuscripts in this thesis are included in Appendix B.

1.5 REFERENCES

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CHAPTER 2
RELATIONSHIPS BETWEEN ODOUR PROPERTIES AND DETERMINATION OF ODOUR CONCENTRATION LIMITS IN ODOUR IMPACT CRITERIA FOR POULTRY AND DAIRY BARNS

2.1 VERSION PRESENTED IN A JOURNAL

A similar version of this chapter was published online by Science of the Total Environment in February 2018.

- Huang, D. and Guo, H. 2018. Relationships between odor properties and determination of odor concentration limits in odor impact criteria for poultry and dairy barns. Science of the Total Environment, 630, 1484-1491. https://doi.org/10.1016/j.scitotenv.2018.02.318.

2.2 CONTRIBUTION OF THE PH.D. CANDIDATE

The samples collection, lab measurements, data analysis, and manuscript writing were performed by the candidate. RLee Prokopishyn and Louis Roth helped with the instrument set-up and maintenance. Zhu Gao provided technical support as for olfactometer calibration and using. Besides, Zhu Gao, Jingjing Han, Shamim Ahamed, and Ali Motalebi participated in some of the field measurements and assisted with air sample collection. Dr. Huiqing Guo provided editorial input and suggestions on methods and data analysis.

2.3 CONTRIBUTION OF THIS PAPER TO THE OVERALL STUDY

Odour properties have not been fully studied for dairy and poultry barns. The relationships between odour properties are crucial in evaluating the performance of air dispersion models, in establishing odour impact criteria, in determining setback distances, etc. This study measured the five odour properties for the study dairy and poultry barns, based on which the relationships among odour properties were derived and odour concentration limits in odour impact criteria were determined. These results were applied in Chapter 8 to compare the field measured odour intensity with modelled odour concentration and in Chapter 9 to determine setback distances through odour and gas dispersion modelling.

2.4 ABSTRACT

Livestock odour properties have not been well understood and the role of hedonic tone (HT) in establishing appropriate odour impact criteria has not been investigated. Five odour properties, including odour concentration (OC), intensity (OI), HT, persistence, and character descriptor, were studied for odorous air from a commercial dairy barn, layer barn, and broiler barn by taking measurements in all four seasons. The seasonal OC of the dairy, layer, and broiler barns averaged 447 $\pm$162 OU m^{-3}, 583 $\pm$216 OU m^{-3}, and 766 $\pm$148 OU m^{-3}, respectively. Correspondingly, OI and HT averaged 2.7 $\pm$0.5 and -2.6 $\pm$0.5 for the dairy barn, 2.9 $\pm$0.4 and -2.9 $\pm$0.5 for the layer barn, and 3.2 $\pm$0.4 and -3.1 $\pm$0.4 for the broiler barn. Significant correlations were observed among OC, OI, and HT for all three odors ($P<0.01$). Increased OC was accompanied by increased OI but decreased HT. The relationships between OC and OI, and between OC and HT were derived in both Weber-Fechner law and Stevens' power law, while the best relationship between OI and HT turned out to be in a cubic polynomial model for the dairy-barn odour and a quadratic polynomial model for the two poultry barn odours. Based on OI-OC and HT-OC relationships in Weber-Fechner law, a reference table of OC limits was generated with 3 set values for OI (0, 1, and 2) and HT (0, -1, and -2) for all three odour sources, which may provide references in establishing appropriate odour impact criteria to meet different land use purposes. The comparison of the OC limits was made using relationships for all odour samples and for odour below 320 OU m^{-3} (OI=3), indicating no significant difference. Slightly lower OCs from the former were suggested for use in stricter odour impact criteria.

2.5 INTRODUCTION

Public concerns about odours are raised not only due to their role in predicting potential health risks, but also because odour nuisance itself may cause health symptoms (Schiffman and Williams, 2005). Neighbors of intensive livestock operations reported eye, nose, and throat irritation, headaches and drowsiness, along with other health concerns (Schiffman, 1998). Generally, odour can be described with five properties: odour concentration, odour intensity (how strong the odour is), persistence (the rate with which odour intensity decreases with dilution), hedonic tone (how much people like or dislike the odour), and character descriptor (ASHRAE, 2005). Knowledge of odour properties and relationships between odour properties has various applications, including to help establish odour control strategies and odour impact criteria, evaluate the performance of dispersion models, and determine setback distances. For example, odour dispersion models need to be evaluated by field measured data; however, the output of the odour dispersion models is OC, whereas the output of field measurement is OI. To compare the two types of output, it is critical to define the relationship between OC and OI for the conversion of the two parameters.

In relating OC and OI, three kinds of relationships are applied: the Weber-Fechner law, the Stevens' power law, and the Beidler model (Nicolai et al., 2000). The Weber-Fechner law has been used most commonly in previous studies. The reported OC-OI relationships were mainly derived for odour from swine buildings and manure management (Misselbrook et al., 1993; Nicolai et al., 2000; Guo et al., 2001; Sheridan et al., 2004; Feddes et al., 2006; Zhang et al., 2005), while there have been fewer studies done for dairy and poultry operations (Misselbrook et al., 1993; Guo et al., 2001; Hayes et al., 2006). Different methods were used, and different coefficients were derived for the models in those studies. Compared to OC and OI, there is not as much information regarding HT. Although, by definition, HT should be considered an independent odour property from OC or OI (ASHRAE, 2005), correlations between OC and HT for livestock odour do exist. Guo et al. (2005) found that HT was inversely related to OI when they conducted a one-year field odour measurement study using residents around intensive swine operations as observers. Lim et al. (2003) reported OC was inversely proportional to HT for odour from a laying hen house. Nimmermark (2011) found HT decreased with OC for pig facilities, dairy cow shed, and laying hen house. Similarly, Fournel et al. (2012) studied odour characteristics for three different cage layer housing systems, and found that the higher the OC, the more unpleasant the odour was. The categorical or scaling method for HT is similar to that for OI, thus people easily confuse the two characters (e.g., a stronger odour likely evokes higher unpleasantness). However, the relationship between HT and OI has proven to be complex, with a positive or negative correlation for some odorants, and U-shaped functions or even no correlation at all for others (Sucker et al., 2008). Lidén et al. (1998) studied OI and HT (odour annoyance) using seven pyridine concentrations.

They found that a larger variation was caused for odour annoyance than for OI when changing OC, though the statistical difference was not significant.

Odour impact criteria provide references for making decisions in land planning, designing, environmental management, and regulations on odour sources (Jiang and Sand, 2000). The concentration or intensity of odour is a crucial element when creating an odour criterion. The common expression of odour impact criterion is a specified OC or OI at which odour impact occurs for a duration of time (e.g., 10 minutes, 1 hour, etc.) and at various frequencies (e.g., 98%, 99%, 99.5% and 99.9%). For example, an odour impact criterion of 6 odour units as a 98^{th} percentile means a level of 6 OU m^{-3}, which cannot be exceeded for more than 2% of the time (mostly a year). The report by RWDI Air Inc. (2005) reviewed the various ambient OC criteria from numerous regions, including America, Australia, Europe, and Asia. In many cases, the criteria were for wastewater treatment plants, composting facilities, or for all odour sources, while few of them were established specifically for regulating livestock odour. Odour guidelines vary across Canada. In Ontario, the average OC over 10 minutes is required to be no more than 1 OU m^{-3} (Yu and Guo, 2012). In Manitoba, the maximum acceptable OC is 2 OU m^{-3} in a residential zone and 7 OU m^{-3} in an industrial zone (Government of Manitoba, 2005). In Alberta, only the representative compound is used, such as H_2S and NH_3, for odour impact management (Yu and Guo, 2012). In Saskatchewan, odour criteria vary from 1 OU m^{-3} to 6 OU m^{-3} at the 99.5% percentile and an averaging time of 1 hour for different land use purposes (Government of Saskatchewan, 2012). A low OC limit such as 1 OU m^{-3} may be too strict; thus, this may result in over-estimations for setback distance in regulation or land planning and management. To solve this problem, researchers have tried to derive an acceptable OC limit from the relationship between OC and OI.

A reference substance with specified magnitude is recommended to help scale odour intensity (ASTM Standard, 1998). With this approach, the intensity of odour and intensity of a series of different known concentrations of a reference odourant can be compared. N-Butanol (C_4H_9OH) is the most commonly used reference because it is highly pure, stable, relatively nontoxic, and has reasonably agreeable odour that is unrelated to most other odours (Mackie et al., 1998). Different n-butanol scales have been applied by researchers, including a 5-point scale (Guo et al., 2005) and an 8-point scale (Zhang et al., 2005). Table 2 gives the comparison of the two scales. A non-referencing 6-point scale method has also been used in previous studies (Misselbrook et al., 1993).

Using OI =3 in the 6-point none-referencing categorical scale (in Table 2) as a distinct odour, Jiang and Sands (2000) suggested an hourly averaged OC of 5 OU m^{-3} at the 99.5^{th} percentile as the odour impact criteria for broiler farms in temperate Australia. Guo et al. (2005) used intensity 2 (75 OU m^{-3}) in the 5-point referencing scale in OFFSET model as acceptable odour level for swine operations. In the study by Misselbrook et al. (1993), a faint odour at OI =2 of the 6-point non-referencing scale method corresponded to an OC of 8.8 to 23.4 OU m^{-3} for broiler houses. Taking OI = 3 in the same 6-point scale method, the distinct OC was 9.7 OU m^{-3} for poultry production units in the study by Hayes et al. (2006) and 4.3 OU m^{-3} for pig production units in the study by Sheridan et al. (2004). However, none of the studies considered HT, which directly reflects the receptors' acceptance and annoyance level of the odour, for determining an acceptable OC.

Hence, the objectives of this study are to: 1) compare the odour properties of commercial dairy, layer, and broiler barns in a cold region (the Canadian Prairies) by investigating the relationships among OC, OI, and HT; and 2) determine OC limits with combinations of different OI and HT values for the three different animal housings to be applied in establishing appropriate odour impact criteria for different land use purposes.

2.6 MATERIALS AND METHODS

2.6.1 Description of experimental sites

The study dairy, layer, and broiler barns are all located in or near Saskatoon, Canada, which is in a high latitude cold region with a typical Canadian Prairie climate. The two poultry barns are representative commercial broiler and layer barns in Saskatchewan, while the dairy barn is a research barn with a relatively smaller herd size compared to the average (178) in the province. The basic information of the three barns is outlined in Table 2.1. The dairy barn operates year-round and is naturally ventilated. The manure in the alley-ways is collected by automatic gutter scrapers every 3 to 4 hours and is pumped to a covered slurry tank outside of the barn, which is emptied twice a year and spread in fields. The majority of the space is a free-stall area where the study was carried out. The layer barn is a 4-tier stacked cage building. The operation cycle is one year followed by a one-week break for cleaning and disinfection. Manure drops on a conveyor belt and is removed every 3 to 4 days. In the broiler barn, the operation cycle is much shorter than the other two barns. The growth cycle is around 33 days without any manure treatment followed by a 3-week break for cleaning and disinfection before the next cycle. The long break is due to the chicken quota restriction. A mechanical ventilation system, and an automatic feeding and drinking system are used in both the broiler and layer barns, while in the dairy barn the cows are fed manually twice daily.

Table 2.1 Basic information of the study dairy, layer, and broiler barns.

	Dairy barn	Layer barn	Broiler barn
Longitude	106.62 W	106.41 W	106.61 W
Latitude	52.13 N	52.41 N	52.54 N
Animal capacity	112	35,000	33,000
Breed	Holstein	Bovan white	Cornish cross
Sampling point	1.8 m above the central area	1.5 m height, close to one exhaust fan	1.2 m height, close to one exhaust fan
Weight (kg)	755	1.56-1.98	1.86-2.25
Floor area (m^2)	3230	987	1638
Ventilation	Natural	Mechanical	Mechanical
Air inlets	37 sliding panel windows on both side-walls and the end-wall door	162, on the ceiling	96, 48 on each side wall
Fans	6 small chimney fans for winter	24 side-wall fans	6 chimney fans and 4 end-wall fans

2.6.2 Measurement schedule

The odour sampling and lab measurement work were performed between February 2015 and February 2016. The sampling point was fixed at a height of 1.8 m above the center area for the dairy barn, at a height of 1.5 m close to one exhaust fan for the layer barn and at a height of 1.2 m close to one chimney fan for the broiler barn. Two types of sampling methods were used to collect the room air samples, including seasonal sampling over the year and diurnal sampling in the cold, mild, and warm seasons, respectively. The seasonal sampling and measurements were performed within fixed time periods (including both morning hours and afternoon or early evening hours) on one day monthly from February 2015 to January 2016 for the dairy barn, from March 2015 to February 2016 for the layer barn, and during six available production cycles at the broiler barn from April 2015 to January 2016. Only worst case was considered for both layer and broiler barns to do seasonal (monthly) measurements when it was one of the last days before the manure would be removed from the layer barn in each month and one day in the last week of the growth cycles when manure was accumulated to maximum for the broiler barn. Diurnal sampling was performed continuously every three hours from 6 a.m. to 9 p.m. for two days in each season: for the dairy barn, the samples were taken in February 2015 (cold), July 2015 (warm), and October 2015 (mild);

for the layer barn, in April 2015 (mild), July 2015 (warm), and January 2016 (cold); and for the broiler barn, in April 2015 (mild), August 2015 (warm), and January 2016 (cold). The two days selected in each seasonal period for the broiler barn were in the last week of the growth cycles, while for the layer barn the two days selected were the best-case day (first day after the manure was removed from the belt) and the worst-case day (last day before the manure was removed from the belt) within the same week in each season.

For each odour measurement, four replicated air samples were collected with two of them being analyzed for OC, while the other two were analyzed for OI, HT, and character descriptor. As a result, a total of 208, 216, and 168 original full-strength air samples were collected for the dairy barn, the layer barn, and the broiler barn. Additionally, to increase data points for weak odour in order to explore the relationships of various odour properties over the full range of OC, original full-strength air samples were collected during the winter of 2015 or 2016 when OC was high, and were diluted by 2, 4, 8, 16, 32, 64, and 128 times with fresh air (four replicates were obtained for full-strength and each dilution ratio). Thus, an additional 32 air samples were acquired for each barn. Using the average results of the two replicates as one data point, there was a total of 60, 62, and 50 data points for OC, OI, and HT for the dairy barn, the layer barn, and the broiler barn, respectively.

2.6.3 measurement methods

The room air samples were collected using 10-L Tedlar air bags and were analyzed for odour properties (OC, OI, HT, and character descriptor) in the Olfactometry Laboratory at the University of Saskatchewan within 30 hours after sampling. The screening of panelists and measurements of OC were performed using a dynamic forced-choice olfactometer in compliance with CEN (2003) standard. There was a total of 18 trained panelists in the pool and 8 (a few times at least 6) random panelists making up one odour panel. The 5-point scale method (0 to 5) in Table 1.2 was applied for measuring OI using C_4H_9OH (n-butanol) as the reference (ASTM, 1998).

Hedonic tone is typically described using a scale that ranges from a negative value to refer to an unpleasant odour, to a positive value referring to a pleasant odour. In this study, an 11-point scale method was used to measure HT from -5 through 0 to +5 (0 meaning neutral, ± 1 meaning dislike or like very slightly, ± 2 meaning dislike or like slightly, ± 3 meaning dislike or like moderately,

± 4 meaning dislike or like very much, and ± 5 meaning dislike or like extremely), which is consistent with Guo et al. (2001) and Fournel et al. (2012). When an odour is diluted, the intensity decreases. Persistence is the decreasing rate of odour intensity with dilution and it follows Stevens' power law: $I = kC^p$, where I is perceived odour intensity scale reference odour concentration in ppm (which is n-butanol concentration in this study), P is persistence, C is dilution ratio, and k is the odour's intensity undiluted or at full strength (Ouellette et al., 2010). When sniffing the sampling air for measuring OI and HT, panelists were also required to use simple words to describe the character of the odour (e.g., smells like rotten eggs).

2.6.4 Data analysis

The statistical evaluation of data was performed by SPSS 22. The correlations between OC and OI and between OC and HT were indicated by a P value; $P \leq 0.05$ suggested significant correlation and $P \leq 0.01$ suggested very strong significant correlation. The OI-OC relationships and HT-OC relationships were derived in both Weber-Fechner law and Stevens' power law:

Weber-Fechner law: $\text{OI or HT} = a + b \times \log_{10}(\text{OC})$ ....(2.1)

Stevens' power law: $\text{OI or HT} = a \times \text{OC}^{b}$...(2.2)

where a and b are coefficients.

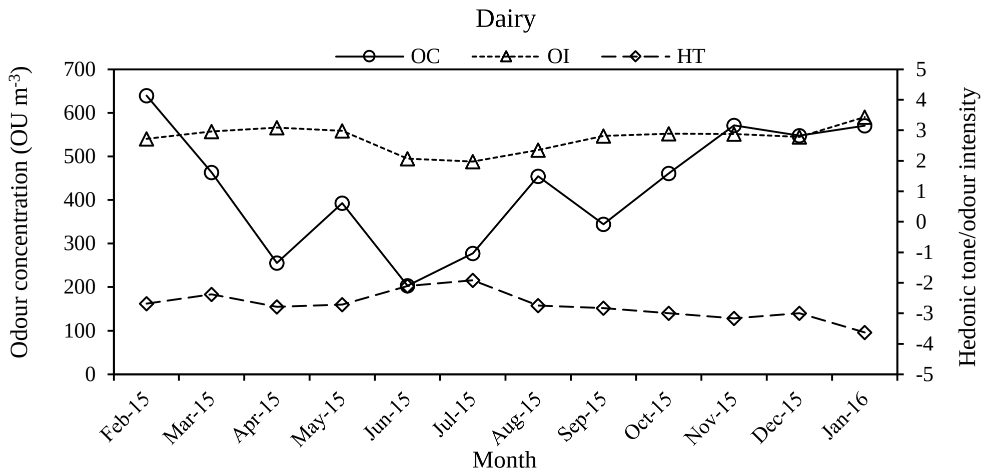
The relationships between HT and OI were investigated using curve estimation in SPSS, including linear, quadratic, logarithmic, and cubic, and so on.

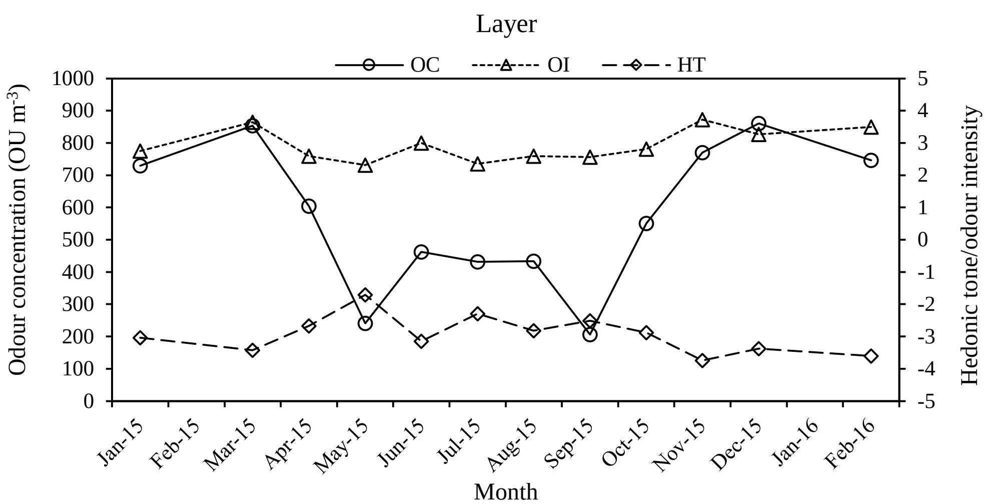
2.7 RESULTS AND DISCUSSION

2.7.1 Odour properties and relationships

2.7.1.1 Seasonal variations of OC, OI, and HT

Based on all data from seasonal measurements and diurnal measurements, it was found that higher odour concentration levels were concluded for the broiler barn than the other two barns; most data points fell within a range of 400-800 OU m^{-3} for the dairy and layer-barn odour but were within a range of 600-900 OU m^{-3} for the broiler-barn odour. Excluding the diluted samples, annual OC and HT for full-strength samples averaged 447 ± 162 OU m^{-3} and 2.7 ± 0.5 for the dairy barn, 583 ± 216 OU m^{-3} and 2.9 ± 0.4 for the layer barn, and 766 ± 148 OU m^{-3} and 3.2 ± 0.4 for the broiler barn. Excluding the diluted samples, HT averaged -2.6 ±0.5, -2.9 ±0.5, and -3.1 ±0.4, respectively, for the dairy, layer, and broiler barn. The results suggest that, overall, the broiler-barn odour appeared to have a stronger and more unpleasant smell.





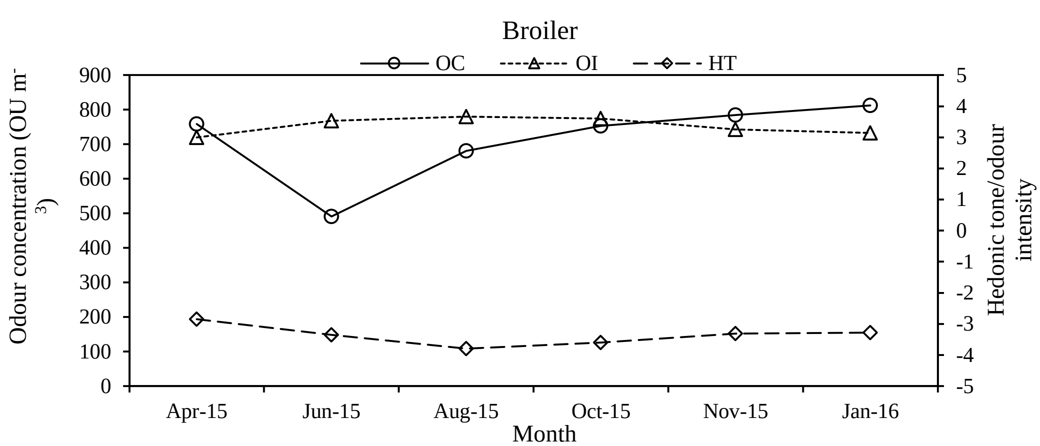


Figure 2.1 Seasonal variations of OC, OI, and HT for the dairy, layer, and broiler barns.

Using only the monthly measured results, seasonal variations of OC, OI, and HT are given in Fig. 2.1. Greater seasonal variance of OC was observed for the layer and dairy barns than the broiler barn, with OC varying between 203 and 639 OU m^{-3} for the dairy barn, between 206 and 860 OU m^{-3} for the layer barn, and between 491 and 812 OU m^{-3} for the broiler barn. Compared to OC, OI and HT changed within narrow ranges for all three barns, but still displayed seasonal difference for the dairy and layer barns. As can be seen in Fig. 2.1, for the dairy and layer barns, OC and OI generally tended to be higher, while HT was lower in the cold season than during the other seasons.

2.7.1.2 OI-OC relationships and odour persistence

All the data acquired for OI against log OC (including diluted samples) are plotted in Fig. 2.2. Overall, OI increased with OC for all three odours.

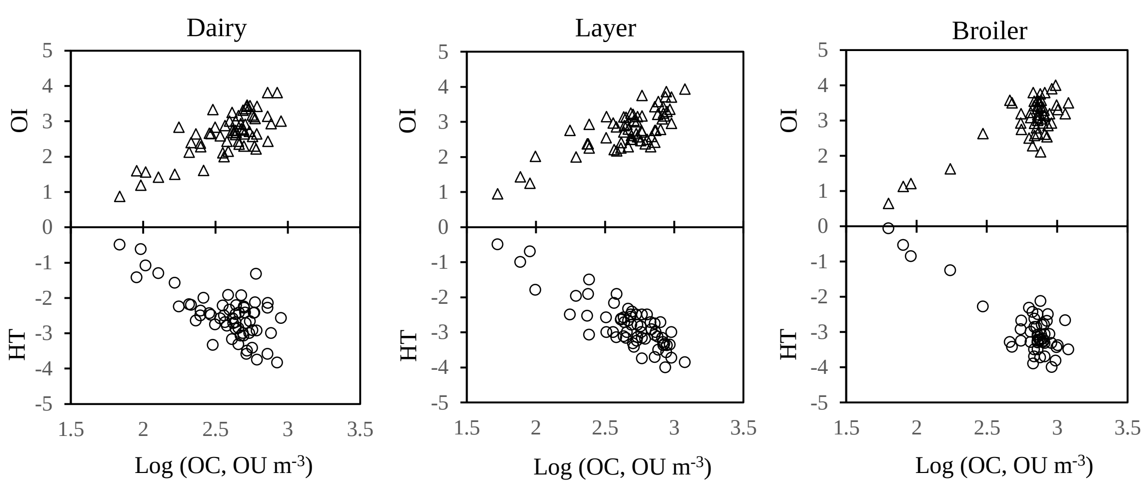


Figure 2.2 OI-log OC and HT-log OC for the dairy, layer, and broiler barns.

Statistical results also indicated significant correlations between OC and OI for all three odours ($P<0.01$). The coefficients for the derived OI-OC relationships in Weber-Fechner law and Stevens' power law are listed in Table 2.2. The Stevens' power law showed slightly better performance with slightly higher R square for all three odours, but the difference did not seem obvious. Comparing the three relationships, it was found that for the same OC, OI for the broiler-barn and dairy-barn odour would be higher than that of the layer-barn odour. This implies that, under the same odour dispersion conditions (climatic and topographic) and with the same odour emission rate of the three types of barns, at certain receptor locations the odour concentrations would be the same, but the receptor would perceive a stronger odour (OI) if the source is the broiler barn, and the perceived OI would be the lowest for the layer-barn odour. The persistence for odour from the dairy, layer, and broiler barns was -0.92, -0.78, and -1, respectively, which suggests the same dilution of the three odours would result in the greatest decrease in OI for the broiler-barn odour followed by the dairy-barn odour, and then the layer-barn odour.

Table 2.2 OI-OC and HT-OC relationships in Weber-Fechner law and Stevens' power law.

		Weber-Fechner law: OI or $HT = a + b \times \log_{10}$ (OC, OU m^{-3})			Stevens' power law: OI or $HT = a \times OC$ (OU m^{-3}) ^{b}		
		a	b	R^2	a	b	R^2
OI-OC	Dairy	-2.299	1.913	0.569	0.235	0.400	0.630
	Layer	-1.580	1.634	0.586	0.384	0.318	0.641
	Broiler	-2.794	2.074	0.632	0.134	0.476	0.753
HT-OC	Dairy	2.518	-1.945	0.475	-0.128	0.490	0.535
	Layer	2.848	-2.114	0.697	-0.136	0.484	0.705
	Broiler	4.130	-2.525	0.707	-0.008	0.904	0.723

Using the same method for measuring OC, Hayes et al. (2006) analyzed air samples from broiler, layer, and turkey units in Ireland and obtained an OI-OC relationship for poultry house odour as: $OI = 2.21 \log_{10} OC + 0.82$ ($R^2 = 0.93$), which was similar to $OI = 2.35 \log_{10} OC + 0.30$ ($R^2 = 0.84$) from Misselbrook et al. (1993) for broiler-barn odour in England. When pooling all the data measured for both layer and broiler barns in this study, the model was derived as: $OI = 1.82 \log_{10} OC - 2.08$ ($R^2 = 0.61$), which was obviously different from the results of Hayes et al. (2006) and Misselbrook et al. (1993). It should be noted that the ranking method of OI in this study was the 5-point scale method, while Misselbrook et al. (1993) and Hayes et al. (2006) used the 6-point non-referencing scale method. The distinct OC for OI = 3 was calculated to be 9.7 OU m^{-3} for poultry production units by Hayes et al. (2006), which fell within the range of 8.8-23.4 OU m^{-3} for broiler housings as reported by Misselbrook et al. (1993). However, when using OI = 3 in the 5-point scale method, which represents "distinct" as well, the distinct OC for the poultry odour in this study was 618 OU m^{-3}. This was much higher than the above two studies. One possible reason is that Misselbrook et al. (1993) and Hayes et al. (2006) observed lower OC; thus, lower OC was assigned to the same OI in their studies. In addition to the different methods used in measuring OI mentioned above, different housing and feeding practices, climate, and so on could also explain the differences in odour characteristics.

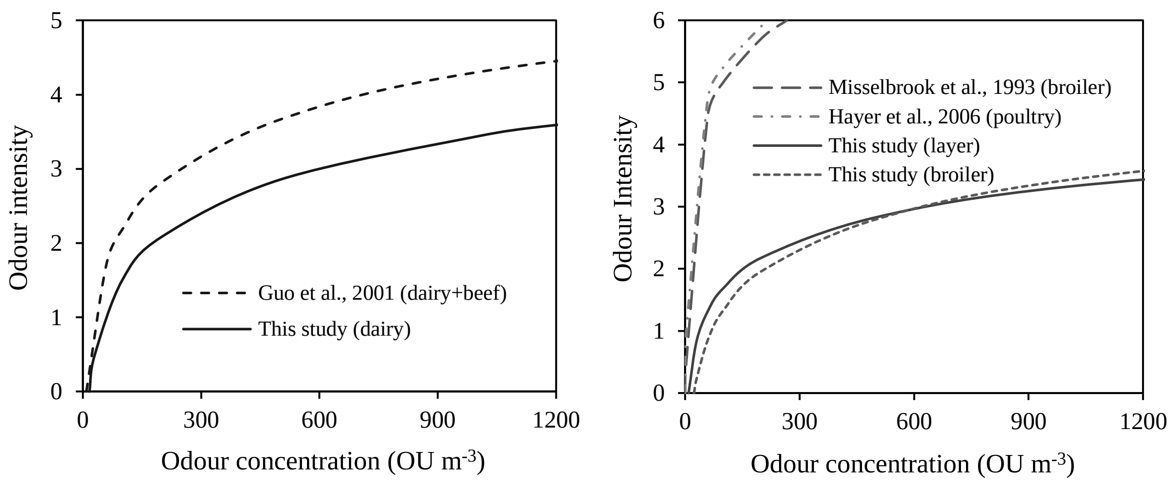


Figure 2.3 Comparison of OI-OC relationships with previous studies.

Using the same 5-point scale method for ranking OI and CEN (2003) standard for measuring OC, Guo et al. (2001) concluded an OI-OC relationship for dairy and beef farms in Minnesota: OC = 9.429 $e^{1.085OI}$ (R^2 = 0.894), rewritten as: OI = 0.922 ln (OC) - 2.068, which is very close to the OI-OC relationship: OI = 0.841 ln (OC) - 2.372 for the dairy barn in this study. However, it would generate higher OC than that of Guo et al. (2001); for example, at the same OI = 2, OC is 181 OU m^{-3} from this study compared to 83 OU m^{-3} from the study by Guo et al. (2001). The difference between these two studies is considered acceptable, as it arises mainly from different climates and housing systems. To directly compare OI-OC relationships from this study and previous studies, the equations are plotted together in Fig. 2.3.

Different character descriptors were attributed to the three odours. It is interesting to find that, when the dairy-barn odour was weak, it would present as a fishy and salty smell, which was not perceived in the odour from the poultry barns. Some of the panelists even used the word “crab” to describe the dairy-barn odour. When OC from the dairy barn was high (usually in winter), panelists would give the same word, “manure”, to describe the odour as they did for the odour of the poultry barns. Comparing the odour from the two different poultry housings, the odour from the broiler house annoyed people more by its “sour” and “sweaty” smell, which was not perceived in the layer-barn odour with its combined smell of “smoke”, “rusty”, “rotten”, and “fermentation”. It has been reported that livestock odour from dairy and poultry are complex mixtures of hundreds of compounds (Filipy, et al., 2006; Jiang and Sands, 2000; Trabue et al., 2010). Among these studies, different key components were determined, which varied from different animal species and facilities. Therefore, it could be expected that differences exist in the levels of various components emitted from the three barns, which together make up the different characteristics of the three odours. It would be helpful to identify and quantify the odourous components in the air emissions from the three barns, which could also be related to feed ingredients and mixing ratios; however, this is beyond of the scope of this study.

2.7.1.3 HT-OC relationships

The data of HT against log OC are also plotted in Fig. 2.2 for all three odours. In general, there was a trend of decreasing HT along with increasing OC for all three odours.

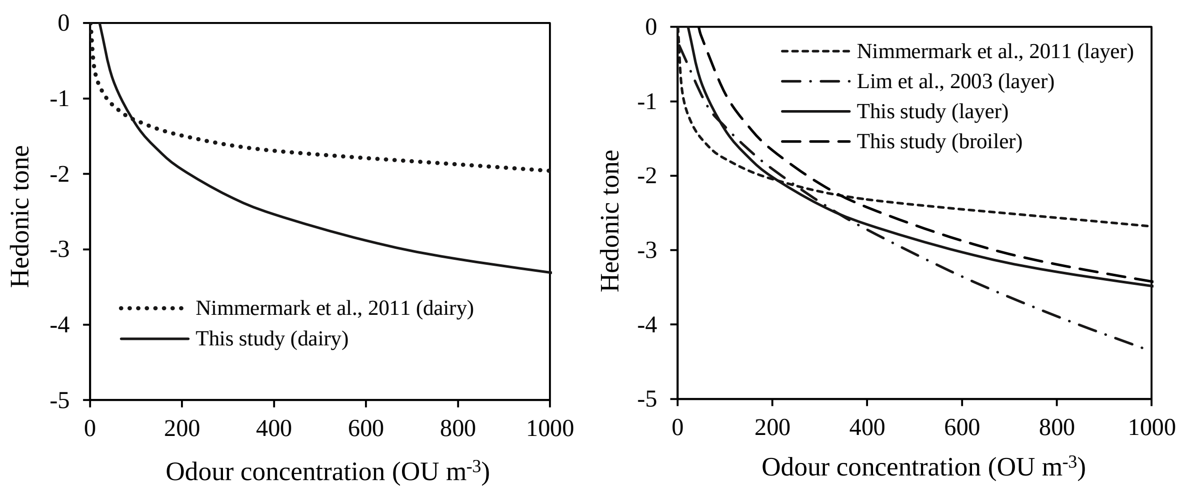


Figure 2.4 Comparison of HT-OC relationships with previous studies.

From correlation analysis, a very significant relationship was revealed between OC and HT for all three odours ($P<0.01$). The coefficients of derived regression models are given in Table 2.2. A lower negative slope was found in the HT-log OC regression model for the broiler-barn odour than for the layer-barn and dairy-barn odour, which indicates that the dislike for the broiler-barn odour increased more rapidly when OC increased than for the other two odours. Using a non-referencing 21-point scale (from -10 through 0 to +10) and Stevens’ power law, Lim et al. (2003) derived a

HT-OC relationship for a layer house (HT = -0.252 $OC^{0.513}$, R^2 = 0.70) that is comparable to the relationship derived from this study: HT = -0.136 $OC^{0.484}$ (R^2 = 0.71). Based on a 9-point scale (from -4 through 0 to 4) for ranking HT, Nimmermark (2011) studied the relationship between OC and HT for odour from pig, layer, and dairy operations. A HT of -0.5, -1, and -2 were related to an OC of 4-5 OU m^{-3}, 14-16 OU m^{-3}, and about 200 OU m^{-3}, respectively, for odour from pig and layer houses, while for odour from the dairy cow shed, a HT of -0.5, -1, and -2 corresponded to an OC of 6 OU m^{-3}, 37 OU m^{-3}, and 1100 OU m^{-3}. In this study, the corresponding OC to HT = -0.5, -1, and -2 was 37 OU m^{-3}, 67 OU m^{-3}, and 214 OU m^{-3} for the dairy barn, and was 38 OU m^{-3},66 OU m^{-3}, and 196 OU m^{-3} for the layer barn, and was 70 OU m^{-3}, 110 OU m^{-3}, and 272 OU m^{-3} for the broiler barn. Different scaling methods of HT used by these studies make it difficult to compare the results. The results from the above two studies are plotted together with this study's results in Fig. 2.4. As for the model from Lim et al. (2003) who used the 21-point scale for a layer barn, it is plotted in Fig. 2.4 by dividing the vertical scale by two. Therefore, direct comparisons between models from Lim et al. (2003) and this study for layer barns could be performed based on the 11-point scale. As shown in Fig. 2.4, when OC is below 400 OU m^{-3}, the two models give similar HT for layer-barn odour; however, when OC is above 400 OU m^{-3}, the two models begin to show significant difference.

2.7.1.4 OI-HT relationships

Significant correlations were observed between HT and OI for all three odours (P<0.01) in this study, which was consistent with Lidén et al. (1998). The correlations between OI and HT turned out to be negative for all three odours, suggesting an increase in OI was associated with a more unpleasant feeling. The HT against OI are plotted in Fig. 2.5. Using curve estimation in SPSS, the best regression model was developed as a cubic function for the dairy barn and as a quadratic function for both layer and broiler barns: for the dairy-barn odour, $HT = 2.979 - 4.980 \times OI + 1.665 \times OI^2 - 0.215 \times OI^3$ (R^2 = 0.73); for the layer-barn odour, $HT = 1.423 - 2.050 \times OI + 0.184 \times OI^2$ (R^2 = 0.86); and for the broiler-barn odour: $HT = 1.129 - 1.796 \times OI + 0.141 \times OI^2$ (R^2 = 0.92).

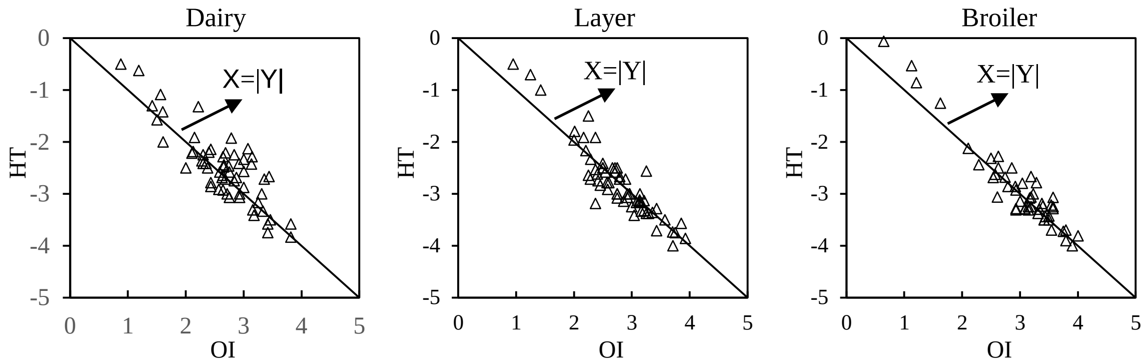


Figure 2.5 HT-OI relationships for the dairy, layer, and broiler barns.

To further discuss the difference between the variations of OI and HT along with increased OC, the ratios of OI and absolute HT (|HT|) for different odour ranges are given in Fig. 2.6. At low OC, panelists tended to give a much lower value of absolute HT compared to that of OI for all three odours, which demonstrates that weak odour from the three barns annoyed panelists at a much lower degree of unpleasantness compared to the perceived intensity. When OC is below 100 OU m^{-3}, the OI of the layer-barn odour, dairy-barn odour, and broiler-barn odour is about 1.41, 1.44, and 2.05 times absolute HT, respectively. However, when OC is above 100 OU m^{-3}, the ratios of OI to absolute HT vary within a narrow range of 0.86-1.1, 0.98-1.18, and 0.99-1.3, respectively, for the layer-barn odour, dairy-barn odour, and broiler-barn odour, showing little difference among the three odours.

A minimum ratio of OI/absolute HT is presented when OC is within the range of 600-700 OU m^{-3} for the layer-barn odour. After OC reaches above 700 OU m^{-3}, the intensity begins to gain more quickly than absolute HT, which is evidenced by panelists stating an increase of their dislike by only 11% when OC range increased from 700-800 to 900-1000 OU m^{-3}, while OI increased by 17%. For the dairy-barn odour, panelists gave similar values of OI and absolute HT when OC was within the range of 200-400 OU m^{-3}, but always perceived higher OI than absolute HT when OC increased above 400 OU m^{-3}. Compared to the layer-barn odour, the dairy-barn odour annoyed panelists less at a high OC, with an average HT of -2.8 for the dairy-barn odour compared to -3.1 for the layer-barn odour when OC was greater than 400 OU m^{-3}. For the broiler-barn odour, absolute HT was always lower than OI when OC was below 500 OU m^{-3}, but was almost the same as OI from 500 to above 900 OU m^{-3}, which is similar to the layer-barn odour when OC is above 800 OU m^{-3}.

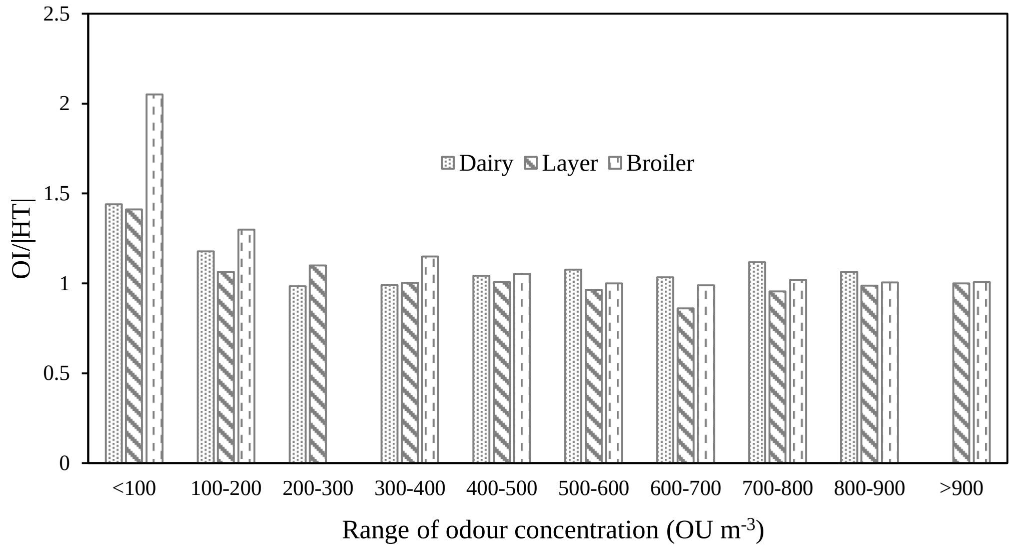


Figure 2.6 Ratios of OI/ |HT| for different odour concentration ranges.

2.7.2 Determination of OC limits for odour impact criteria

With knowledge of relationships among odour properties, we considered both OI and HT for determining acceptable OC limits using two different methods. The first method uses the relationships of OI-OC and HT-OC in Weber-Fechner law (Table 2.2) for all odour samples (including full-strength and diluted odour samples), the results of which are presented in 2.7.1.2 and 2.7.1.3. However, odour impact criteria are usually set with a very low OC, and the majority of the collected data points fell within a high OC range, thus, the first method might generate some bias when describing the relationships of OI-OC and HT-OC at a low OC. To examine the bias, a second method with OC data points below 320 OU m^{-3} (around OI = 3) was used to derive a specific OI-OC relationship and HT-OC relationship for the three odours. Therefore, a total of 14, 10, and 5 data points (each data is an average of two measurements) from the dairy, layer, and broiler barns were extracted; the models are plotted in Fig. 2.7.

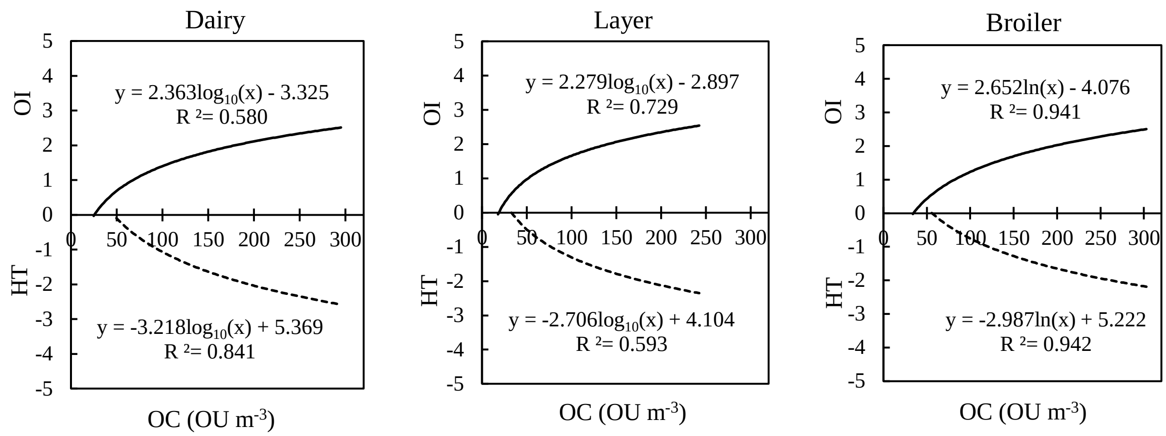


Figure 2.7 OI-OC and HT-OC relationships for odour below 320 OU m^{-3} (OI = 3).

Accordingly, the corresponding OC to given OI and HT can be estimated based on regression models. When considering odour impact criteria, a boundary limit of OI from 0 (no odour) to 2 (faint) and of HT from -2 (dislike slightly) to 0 (neutral) was set for all three odours, and reference Table 2.3 was generated where OC limits under different OI and HT for different odour sources could be found. For example, using the second method and with OI no greater than 2 and HT no less than -1, an OC limit of 77 OU m^{-3}, 95 OU m^{-3}, and 121 OU m^{-3} is determined for the layer barn, dairy barn, and broiler barn, respectively; in contrast, the first method gives 66 OU m^{-3}, 67 OU m^{-3}, and 110 OU m^{-3}, respectively.

Table 2.3 Reference table for OC (OU m^{-3}) at given OI and HT using all odour samples and using odour samples below 320 OU m^{-3} (in parenthesis).

		OI (Dairy)			OI (Layer)			OI (Broiler)		
		0	1	2	0	1	2	0	1	2
HT	0	17 (26)	21 (47)	21 (47)	9 (19)	22 (33)	22 (33)	23 (34)	45 (56)	45 (56)
	-1	17 (26)	55 (68)	67 (95)	9 (19)	38 (51)	66 (77)	23 (34)	70 (82)	110 (121)
	-2	17 (26)	55 (68)	181 (179)	9 (19)	38 (51)	156 (141)	23 (34)	70 (82)	209 (195)

Compared to the first method, which used regression models for all odour samples, the second method, specifically derived for OC below 320 OU m^{-3} (distinct odour), always results in slightly higher OC for all three odours, except for a slightly lower OC being generated where OI = 2 and

HT = -2. We suggest using the OC limits derived from the first method to give relatively stricter criteria. This reference table will help policy makers select appropriate OC limits for different land use purposes; for example, with sensitive land uses such as for a hospital, school, or concentrated residence, a strict OC limit may be applied with HT = 0 and OI = 0, while for rural areas a more permissive OC limit may be allowed.

In addition to OC limit, odour occurrence frequency and averaging time (duration of odour episodes) are also crucial factors in odour impact criteria. An odour impact criterion may be established by using a lower OC limit and a higher occurrence frequency, or a higher OC limit, but lower occurrence frequency. Sommer-Quabach et al. (2014) compared two types of odour impact criteria (one with a low OC threshold and a high tolerated exceedance probability, and the other one with a high odour threshold and a low tolerated exceedance probability) and suggested to use the higher tolerated exceedance probability for the odour impact criterion due to its higher sensitivity to site-specific meteorological data (Sommer-Quabach et al., 2014). Another essential factor, the duration of odour episodes, has not been well studied (Nicell, 2009). An odour episode with a long duration can be different from that of a short duration; for example, an odour with high intensity (concentration) over short periods is not likely to have the same impact as a low-intensity (concentration) odour over a long period. If taking frequencies into consideration, the results become more complex when there are multiple combinations of odour intensity or concentration, along with occurrence frequency and duration. Compared to the existing odour impact criteria in the regulations (e.g., 1 OU m^{-3} in Ontario), the derived OC limit from this study is higher with the lowest OC limit varying from 9 to 23 OU m^{-3} for the three barns. This may be explained by that the regulated odour impact criteria considered either the occurrence frequency or duration of odour, or both, whereas determination of OI and HT in this study were met with shorter odour exposure duration (about one minute for measuring OI and HT). Thus, more studies need to be conducted to provide related knowledge for using the newly developed odour concentration limits in establishing appropriate odour impact criteria.

2.8 CONCLUSIONS

Odour properties for three different animal housings (a commercial dairy barn, layer barn, and broiler barn) were characterized, and the relationships among OC, OI, and HT were investigated. The following are the conclusions of the study:

1) Odour concentration level was found to be higher for the broiler barn than the other two barns: seasonal OC averaged 766 ± 148 OU m^{-3} for the broiler barn compared to 447 ± 162 OU m^{-3} for the dairy barn and 583 ± 216 OU m^{-3} for the layer barn. Similarly, strong OI and more unpleasantness were also observed with the broiler-barn odour: seasonal OI and HT averaged 2.7 ± 0.5 and -2.6 ± 0.5 for the dairy barn, averaged 2.9 ± 0.4 and -2.9 ± 0.5 for the layer barn, and averaged 3.2 ± 0.4 and -3.1 ± 0.4 for the broiler barn.
2) Significant correlations between OC and OI, between OC and HT, and between OI and HT exist for all three odours. Increased OC was associated with increased OI, but decreased HT. It was found that the broiler barn and dairy barn had greater slope of OI-OC relationships than the layer barn, suggesting OI of the broiler-barn odour and dairy-barn odour would increase more quickly than that of the layer-barn odour when OC increases at the same rate. The lower negative slope from HT-OC relationship for the broiler barn implies people's dislike increased more quickly towards it than towards the other two odours when OC increased at the same rate. The relationships of OI and HT proved to be inconsistent over different OC ranges. When OC was below 100 OU m^{-3}, a much lower degree of unpleasantness (HT) was perceived by panelists than the perceived intensity scale for all three odours. However, when OC was above 100 OU m^{-3}, differences between the two became smaller and OI and HT for high OC tended to be at similar scale for all three odours.
3) The layer-barn odour is more persistent than the other two barn odours, with an odour persistence of -0.78 compared to -0.92 for the dairy-barn odour and -1 for the broiler barn-odour, which suggests the same dilution would result in a greater decrease in OI for the broiler-barn odour followed by the dairy-barn odour and then the layer-barn odour.
4) Using the OI-OC and HT-OC relationships generated, this study considered both OI and HT to determine OC limits in establishing odour impact criteria. With a boundary limit of OI from 0 (no odour) to 2 (faint odour) and of HT from -2 (dislike slightly) to 0 (neutral) considered for odour impact criteria, a reference table was generated where OC limits under different combinations of OI and HT limits could be found for the three odour sources. The estimated OC limits using OI-OC and HT-OC relationships for all odour samples and for odour below 320 OU m^{-3} (OI = 3) were compared. It turned out the difference in the estimated OC limits was insignificant; however, the slightly lower OCs derived from the

former are probably a better guideline for establishing stricter odour impact criteria. The roles of odour occurrence frequency and duration in affecting people's perception toward an odour episode need to be investigated as well and included in the odour impact criteria.

In addition, future studies are needed to identify and quantify the key components of odours from the three different animal species, and to further relate the concentrations of these components to feed ingredients and mixing ratios.

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CHAPTER 3
DIURNAL AND SEASONAL VARIATIONS OF ODOUR AND GAS EMISSIONS FROM A NATURALLY VENTILATED FREE-STALL DAIRY BARN ON THE CANADIAN PRAIRIES

3.1 VERSION PRESENTED IN A JOURNAL

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3.2 CONTRIBUTION OF THE PH.D. CANDIDATE

The samples collection, lab measurements, data analysis, and manuscript writing were performed by the candidate. RLee Prokopishyn and Louis Roth helped with the instrument set-up and maintenance. Zhu Gao provided technical support as for olfactometer calibration and using. Besides, Zhu Gao, Jingjing Han, Shamim Ahamed, and Ali Motalebi participated in some of the field measurements and assisted with air sample collection. Dr. Huiqing Guo provided editorial input and suggestions on methods and data analysis.

3.3 CONTRIBUTION OF THIS PAPER TO THE OVERALL STUDY

Diurnal and seasonal variations of odour and odorous gas concentrations and emissions for the dairy barn were presented by this study. With the data collected, the indoor air quality of the dairy barn could be evaluated using the measured concentrations of NH_3 and H_2S. Through the long-term monitoring, the diurnal and seasonal emission profiles of odour and gases were characterized, and the emission factors were quantified, which would be input in the dispersion modelling in Chapter 9 to study the outdoor impact of odour and gases for the dairy barn.

3.4 ABSTRACT

This study characterized the seasonal concentration and emission patterns of odour, NH_3, and H_2S over the course of a whole year and their diurnal patterns in cold, warm, and mild seasons for a naturally ventilated free-stall dairy barn. It was found that seasonal odour, NH_3, and H_2S emissions varied greatly: from 17.2 to 84.4 OU s^{-1} AU^{-1}, from 0.27 to 0.92 mg s^{-1} AU^{-1}, and from 3 to 105 μg s^{-1} AU^{-1}, respectively. The overall concentrations of odour and NH_3 were higher in the winter, whereas the emissions were higher in the mild and warm seasons. Diurnal variation was most significant for OE in the mild season when the ratio of maximum (279.2 OU s^{-1} AU^{-1}) to minimum value (60.5 OU s^{-1} AU^{-1}) was up to 4.6. The indoor air quality was also evaluated by considering not only the health effect of individual gases, but also the additive effect of NH_3 and H_2S. Results showed that the indoor air quality was poorest in cold seasons when NH_3 concentration could exceed the threshold limit set out in occupational health regulation, and in fact could worsen due to the additive effect of the two gases. Further, it was suggested NH_3 was a good indicator for predicting OC or OE. The impact of environmental parameters on odour and gases were also examined, and it was found VR negatively affected OC and NH_3 concentration, but positively impacted on OE and NH_3 emission. Using 70% of the total data, a multi-linear model for OE was developed as a function of VR and indoor relative humidity and was validated to be acceptable using the rest of the data.

3.5 INTRODUCTION

Intensive animal housing and feeding operations around the world have been rapidly developed and have raised public concern about their adverse impact on human health and the environment. Intensive animal production is associated with various air emissions, including NH_3 and H_2S, as well as being a general odour nuisance, leading to complaints of eye, nose, and throat irritation, headache, and drowsiness (Schiffman, 1998). At low concentrations, NH_3 and H_2S are both potential threats for respiratory irritation, neurological effects, and immunological effects, and can even result in death at very high concentrations (Copeland, 2014). Additionally, NH_3 not only contributes to eutrophication of surface water and nitrate contamination of groundwater, but also impairs atmospheric visibility through forming aerosol (US EPA, 2004).

Agriculture is the most important NH_3 emission source with the majority of NH_3 emissions being attributed to livestock production (Webb et al., 2005). In Canada, animal agriculture contributed 64% of total NH_3 emissions from a national inventory in 2002 (Carew, 2010). Several studies have been carried out to quantify air emissions from different animal sectors (Gay et al., 2003; Hayes et al., 2006); however, odour data from dairy operations are still limited (Zhu et al., 2000; Gay et al., 2003; Zhao et al., 2007; Akdeniz et al., 2012a; Mosquera et al., 2006; Rzeźnik et al., 2014). For dairy barns in Canada specifically, there are no published odour emission data, and NH_3 and H_2S emission data are also insufficient. It was indicated odour and gas emissions varied by animal species, climate, region, VR, and so on (Gay et al., 2003; Ngwabie et al., 2009), and odour and gas concentrations and emissions from animal barns would also vary diurnally and seasonally (Sun et al., 2010; Wang, 2007). Therefore, long-term measurements for different animal species, different regions (climates), and seasons are necessary to improve the air emission database involving livestock production. This first step is necessary for establishing appropriate control and mitigation strategies for odour and gas emissions. Diurnal and seasonal variations of gas emissions, including NH_3 from dairy barns, have been characterized (Saha et al., 2014); however, diurnal and seasonal odour emission patterns from dairy buildings have not been well studied. Additionally, given livestock room air is composed of hundreds of components (Ni et al., 2012), the indoor air quality of dairy barns has not been thoroughly evaluated in research studies considering the combined health effect of the multiple components, as well as their possible diurnal and seasonal concentration variabilities.

As odour measuring is time-consuming and costly, there is often a desire to relate odour to an odorous component such as NH_3 or H_2S, which are relatively easy to measure. Amon et al. (1997) reported a good relationship between OC and NH_3 concentration in a clinoptilolite-treated broiler room. Blanes-Vidal et al. (2012) found seasonal patterns of odour perception were associated with seasonal variations in NH_3 concentration in non-urban residential communities. In another study, Blanes-Vidal et al. (2009) observed OC was most strongly related to the sulfur-containing compounds, including H_2S, from agitated swine slurry. Fewer studies considered multiple factors for predicting livestock odour such as various odorants, volatile organic compounds (Hobbs et al., 2000; Akdeniz et al., 2012b), or environmental parameters (Wang, 2007).

Hence, this study was conducted at a naturally ventilated free-stall dairy barn in a cold region climate (the Canadian Prairies) aiming to 1) reveal seasonal variations of odour, NH_3, and H_2S concentrations and emissions and their diurnal variations during the cold, mild, and warm seasons; 2) evaluate indoor air quality in different seasons; 3) investigate the correlations between odour and odorous gases (NH_3 and H_2S), and the impact of environmental parameters on odour and gases; and 4) develop a prediction model for OE and validate the model.

3.6 MATERIALS AND METHODS

3.6.1 Description of the dairy barn

General introduction of the dairy barn has been introduced in Chapter 2. However, below gives the specific information. The dairy barn chosen for this study is a research dairy barn located in Saskatoon, Saskatchewan (106.6 °W and 52.1 °N). Most of the facility is a free-stall area where approximately 112 milking cows are housed. The dairy barn has a smaller average herd size compared to the provincial average (178 in Saskatchewan), but is a middle-scale barn across the whole country (Government of Canada, 2016). A photograph of the inside of the barn is provided in Fig. 3.1. The dairy breed is Holstein and the cows are routinely fed a mixed ration of barley silage and alfalfa hay, as well as concentrates with barley grain, canola meal, soybean meal, distiller's dried grains, and also a mineral-vitamin supplement. The milk production is 38 L per cow daily. The floor area is 3, 230 m^2. On the south side, 4 pens of 12 cows each are housed and milked in the parlour, while on the north side there are 52 stalls where cows are milked in an automatic milking unit, or optionally in the parlour. The automatic manure scraper is set to clean the alley ways 4 times daily. The manure and all wash water are pumped to a covered slurry tank with a capacity of 2.52 million L outside of the barn.

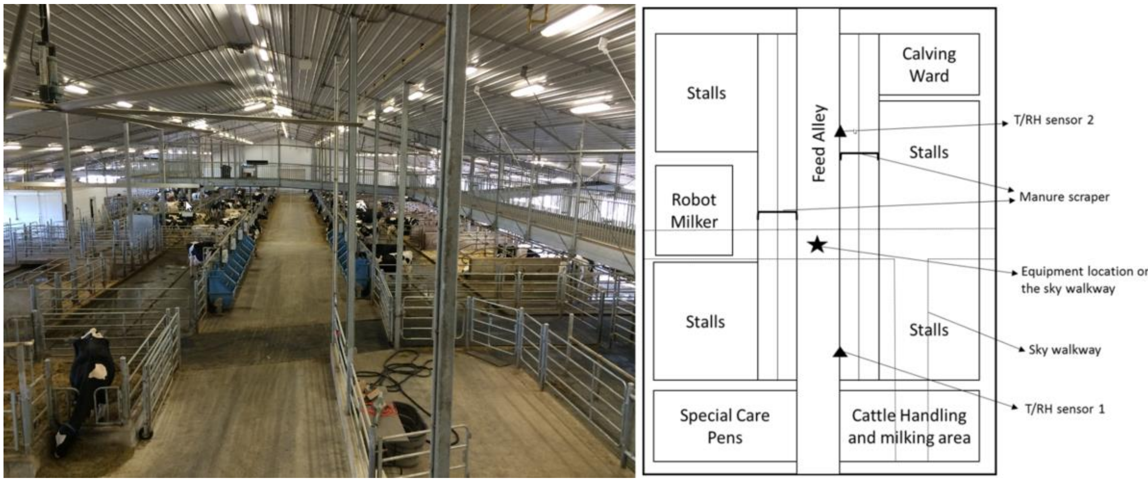

Figure 3.1 Inside view and brief schematic plan of the dairy barn.

In the mild and warm seasons, ventilation of the free-stall area is controlled by sliding window panels on the side walls, while in winter all the windows are closed and 6 chimney fans provide ventilation. On hot summer days, the end-wall door is also opened to increase ventilation. Three large-volume recirculation fans are used to keep the air temperature uniform, and a few radiant natural gas heaters are used to keep the temperatures above freezing in winter.

3.6.2 Measurement schedule

Diurnal measurements were performed for two days, respectively, in February (Feb 9th and 12th), July (Jul 21st and 23rd), and October (Oct 13th and 15th) of 2015, which represent the cold, warm, and mild seasons in Saskatoon. The two days were not consecutive due to the difficulty in setting up the odour laboratory sessions. Only day-time were considered to do measurements when outdoor activities mainly occurred and air quality was a concern to the neighbouring residents. The on-site gas sampling station was continuously measuring NH_3, H_2S, and CO_2 from 6:00 a.m. to 9:00 p.m. on each measurement day. Two air samples were collected simultaneously every 3 hours for OC measurement (from 6:00 to 9:00 a.m., from 9:00 a.m. to 12:00 p.m., from 12:00 to 3:00 p.m., from 3:00 to 6:00 p.m., and from 6:00 to 9:00 p.m.).

The seasonal sampling and measurements were conducted on one picked day each month (when the weather was typical) from February 2015 to January 2016. On each measuring day, the concentrations of NH_3 and H_2S were continuously monitored for two hours in the early morning (6:00 to 8:00 a.m.), and for another two hours in the early evening (6:00 to 8:00 p.m.). During each morning or evening sampling period, two air samples were collected for OC measurement. When the diurnal measurements were performed on February 9th, July 21st, and Oct 13th, gas concentrations during the same morning and evening periods and OC from 6:00 to 9:00 a.m. and from 6:00 to 9:00 p.m. were extracted to represent the monthly results.

3.6.3 Measurement methods

The room air was continuously drawn by an air pump from a fixed sampling point. A short Teflon tubing was used to fix the sampling height at around 1.8 m above the center area (Fig. 3.1). The air was then sent to the gas analyzers for concentration measurements. The equipment included a CO_2 sensor (K30 CO_2 sensor, CO_2 Meter, USA), a NH_3 sensor (C21 NH_3 transmitter, GFG Instrumentation, USA), and a H_2S analyzer (JEROME 631-X, Arizona Instrument Corporation, Arizona Instrument LLC, USA), which were all located on the overhead walkway as shown in Fig. 1. The measurement ranges and accuracies were 0-10000 ppm and ±3% ± 30 ppm for the CO_2 sensor, 0-100 ppm and ±5% for the NH_3 sensor, and 0.003-50 ppm and ±0.003 ppm at 0.05 ppm and ±0.03 ppm at 0.50 ppm for the H_2S analyzer. Every 5 minutes, one measurement for each of the three gas concentrations would be recorded by a data logger (CR10X, Campbell Scientific Corporation, Canada). Air samples were collected using 10-L Tedlar® air bags and were analyzed for OC in the Olfactometry Laboratory at the University of Saskatchewan. There were usually 8 or at least 6 trained panelists participating in each odour session. The screening of panelists and measurements of OC were conducted in compliance with CEN (2003) standard. Additionally, the barn's indoor temperature and relative humidity were also monitored continuously by two wireless T/RH data loggers (OM-EL-USB-2, Omega, Canada) with -35℃ to 80℃ and 0 to 100% for T and RH measurement ranges, 0.5℃ and 3.5% for T and RH accuracies, and were recorded every 5 minutes. The ambient hourly temperature and relative humidity were acquired from Environment Canada (the department of the Government of Canada with responsibility for coordinating environmental policies and programs). The maintenance and calibration of the olfactometer and gas analyzers were all performed according to their operational requirements.

3.6.4 VR and emission rate calculation

Hourly VR was estimated using a CO_2 mass balance method, which is a widely-used method for estimating VR for naturally ventilated dairy barns (Ngwabie et al., 2011; Wu et al., 2012). The equation used to calculate VR is based on per HPU, which is as follows (CIGR, 2002):

$$VR \text{ per } HPU = (CO_2)_P \times (\text{Animal activity}) / ((CO_2)_i - (CO_2)_o) \quad (3.1)$$

$$\text{Animal activity} = 1 - a \times \sin [(2 \times \pi/24) \times (h + 6 - h_{min})] \quad (3.2)$$

$$\Phi_{tot} = 5.6\ m^{0.75} + 22Y_1 + 1.6 \times 10^{-5}\ P^3 \quad (3.3)$$

where VR is in $m^3\ h^{-1}$; $(CO_2)_P$ is CO_2 production per HPU based on a 24 h period (0.185 $m^3\ h^{-1}$); $(CO_2)_i$ is indoor CO_2 concentration and $(CO_2)_o$ is outdoor CO_2 concentration in parts per million (ppm); a is a constant of 0.22 for dairy cows in free-stalls; h is the hours after midnight; h_{min} is hours after midnight with minimum cow activity, which is 2.9 (2:55 a.m.); Φ_{tot} is total heat production in W; m is body mass which is 755 kg on average for the barn; Y_1 is milk production in kg day^{-1}; and P is days of pregnancy, the effect of which was neglected in this study. To modify Φ_{tot} per HPU outside the thermoneutral zone, the following equation was used for cattle (CIGR, 2002):

$$\Phi_{tot} = 1000 + 4 \times (20 - T_{in}) \quad (3.4)$$

where T_{in} is in °C. The actual $(CO_2)_o$ on the measurement days was measured in the mild and warm seasons. To reduce the possible pollution from the open windows, $(CO_2)_o$ was measured 5 metres away from the southeast side of the dairy barn for 30 minutes at the end of the day. In the cold season, $(CO_2)_o$ was assumed to be 390 ppm (IPCC, 2013) when the ambient measurement was not applicable. Knowing the odour and gas concentrations and VR, the odour and gas emissions were calculated as follows:

$$E = VR \times \Delta C \quad (3.5)$$

where E is odour emission rate in units of OU s^{-1} AU^{-1} (odour unit per second per animal unit), OU s^{-1} m^{-2} (odour unit per second per square meter of the floor area), or OU s^{-1} cow^{-1} (odour unit per second per cow). Gas emission E is in units of mg s^{-1} AU^{-1}, mg s^{-1} m^{-2}, or mg s^{-1} cow^{-1}; VR is in $m^3\ s^{-1}$; and ΔC is the difference of odour and gas concentrations between the room incoming air and exhaust air in units of OU m^{-3} or ppm. The concentrations of odour, NH_3, and H_2S of inlet air (ambient air) were negligible compared to the indoor concentrations and were treated to be 0.

Gas emissions were calculated on an hourly basis for both diurnal and seasonal results. Therefore, each data point of gas concentrations and emissions in the figures below were the average of hourly results within the 3 hours, or the average of hourly results from the morning and evening periods. For odour emissions, 3-hour average of the diurnal results and 2-hour average from both morning and evening periods of the seasonal results were calculated for a basis.

3.6.5 Statistical data analysis

The statistical evaluation of data was performed by SPSS software 22. "Daily" effect combined the results of ambient weather, VR, animal management, and so on, while "diurnal" effect was a function of the time of day. There were two days chosen in each season with each having five diurnal levels: early morning from 6:00 to 9:00 a.m., late morning from 9:00 a.m. to 12:00 p.m., early afternoon from 12:00 to 3:00 p.m., late afternoon from 3:00 to 6:00 p.m., and early evening from 6:00 to 9:00 p.m. To examine the "diurnal" effect in each season, a GLM was performed where "daily" and "diurnal" were the two factors. The main effects of the two factors and the interaction between "daily" and "diurnal" were examined. If the interaction effect was significant, "diurnal" effect was then examined separately for each day. To do multiple comparisons, the Duncan test was selected in GLM, or a nonparametric test (Kruskal-Wallis one-way ANOVA) was selected when error variances of the data were unequal. For seasonal results, only the factor of "seasonal" was considered, and the same methods were used to examine the "seasonal" effect and perform multiple comparisons of the monthly results. The significance was indicated by P-value (0.05 level). A P-value with less than or equal to 0.05 indicated significant effect or variance. Multiple comparisons for seasonal OC and OE were not performed.

The relationships among odour, gases, and environmental parameters were indicated by Pearson correlation coefficients (r). The outcome of the results from SPSS showed two different significance levels (0.05 level and 0.01 level) for which $P \leq 0.05$ indicated significant correlation and $P \leq 0.01$ indicated very significant correlation. Using 70% of the data, randomly selected, the regression model for OE was derived as follows：

$$Y = A_0 + A_1X_1 + A_2X_2 + A_3X_3 + \ldots + A_pX_p \qquad (3.6)$$

where Y is dependent factor OE, A_0 is constant, A_1, A_2, A_3,…, A_p are coefficients, and X_1, X_2, X_3,…, Xp are independent factors including VR, T, and RH. As there may exist significant correlations among environmental parameters (e.g., VR and T_{out}), multicollinearity among the independent variables probably would occur when input all the factors to regress the model. To solve the problem, stepwise regression method was used to remove some of the highly-correlated factors. The Paired-Samples T test was performed to compare the difference between modeled results and observed results.

3.7 RESULTS AND DISCUSSION

3.7.1 Diurnal odour and gas profiles

3.7.1.1 Environmental parameters

The T_{out} varied greatly among the three seasons. The T_{in} of this dairy barn was controlled within a narrow range of 5.1 - 5.9℃ during the cold season, and was more affected by outdoor weather in the warm and mild seasons with the ranges of 19.3 - 28.0℃ and 8.6 - 16.0℃, respectively. Fig. 3.2 gives diurnal profile of VR. No significant daily difference in VR between the two days was observed in any season ($P>0.05$). Diurnal VR was significantly lower in the EM than the other periods in the cold season and was significantly higher in the afternoon during the mild season ($P<0.05$), but showed no significant difference in the warm season ($P>0.05$). There was a noticeable amount of difference for VR in the afternoon between the mild season and warm season, which was explained by the significantly positive correlation between VR and wind speed ($r = 0.63$, $P<0.01$) along with higher wind speeds during afternoons of October. Wind direction also affected where the fresh air was coming from the windows and how it mixed with the room air. The orientation of the dairy barn is northeast to southwest. Wind in October came from northwest-west (299°), which was more favorable for ventilation than the wind direction in July (from south-southwest, 200°).

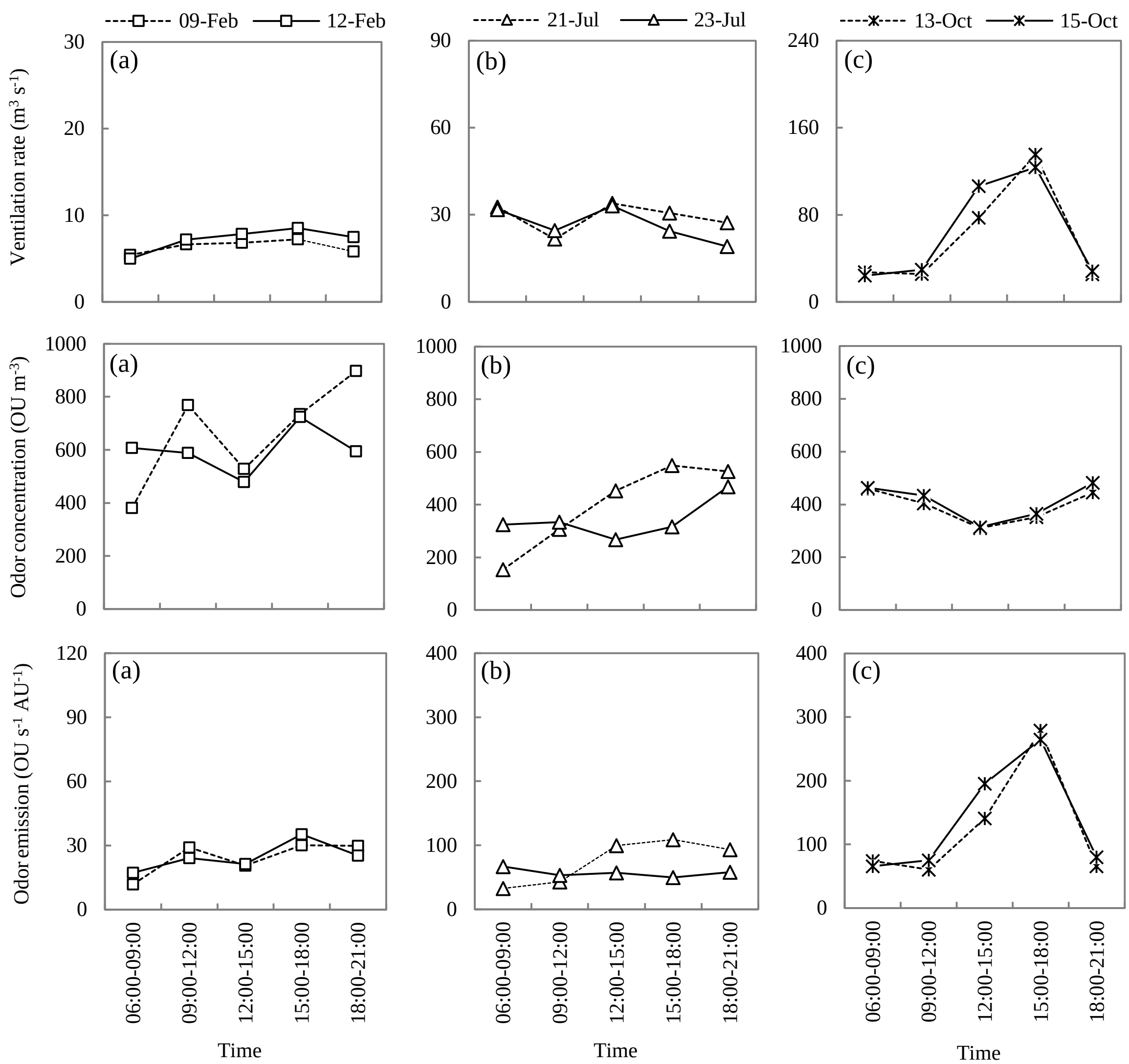

Figure 3.2 3-Hour average VR, OC, and OE in the cold (a), warm (b), and mild (c) seasons.

3.7.1.2 Odour concentrations and emissions

Diurnal 3-hour average OC and OE are presented in Fig. 3.2. The daily difference of OC or OE was not significant in any season (P>0.05). Diurnal effect was significant for OC and OE in both cold and mild seasons (P<0.05), which contradicts the conclusion of Zhu et al. (2000), who found OC and OE were both constant for a naturally ventilated dairy barn in October. This could be due to the smaller variations of VR in their study. During the cold season, diurnal OC varied differently on the two days, while OE showed highly consistent patterns on both days with being obviously low in the EM and high in the evening. No significant diurnal variance (P>0.05) was found for OC or OE during the warm season when analyzing the results from the two days together; however, great diurnal variations of OC and OE were observed on Jul 21st when OC and OE were as low as 153 OU m^{-3} and 32.5 OU s^{-1} AU^{-1}, respectively, in the EM, and as high as 549 OU m^{-3} and 109 OU s^{-1} AU^{-1}, respectively, in the LA. A higher impact of VR on OE was observed during the mild season than in the cold and warm seasons with the maximum and minimum ratio of OE being up to 4.6. Because of consistent VR variations, the OC and OE of the two days both presented highly consistent diurnal patterns with lower OC, but apparently higher OE during the entirety of the afternoon.

3.7.1.3 Ammonia concentrations and emissions

Diurnal NH_3 concentration and NH_3 emissions can be found in Fig. 3.3. Zhao et al. (2007) observed significant daily difference for NH_3 concentrations from a naturally ventilated dairy barn in summer, which was observed for both NH_3 concentration and NH_3 emission in the cold and warm seasons in this study. The T_{in}, T_{out}, and VR were all slightly lower, while the RH_{in} and RH_{out} were slightly higher on Feb 9th than on Feb 12th. This together may result in significantly higher levels of NH_3 concentration and NH_3 emission ($P<0.05$). Slightly higher VR thus lower NH_3 concentrations and emissions on Jul 21st than on Jul 23rd were observed as well. Zhang et al. (2005) and Saha et al. (2014) indicated considerable diurnal variations of NH_3 emission for naturally ventilated dairy buildings, which was also found to be true in this study. In the cold season, there were significant differences in both diurnal NH_3 concentrations and NH_3 emissions on Feb 9th ($P<0.05$). Yang et al. (2016) observed larger diurnal variations of NH_3 emission in the summer and fall at two dairy feedlots, and this pattern was confirmed in this study. In the warm season, NH_3 concentration was significantly lower in the EM on Jul 21st ($P<0.05$), but showed no significant diurnal effect on Jul 23rd ($P>0.05$). Significant diurnal variances ($P<0.05$) were found in NH_3 emission for both days with lower values in the entire morning. In the mild season, very high similarities were observed from the two curves of both NH_3 concentration and emission, with the trend of diurnal NH_3 concentration being opposite to that of NH_3 emission. Saha et al. (2014) observed the highest NH_3 emission between 1:00 p.m. and 3:00 p.m. and the lowest between 4:00 a.m. and 6:00 a.m. Similarly, this study also found NH_3 emission tended to be highest from 12:00 to 3:00 p.m. and lowest in the EM.

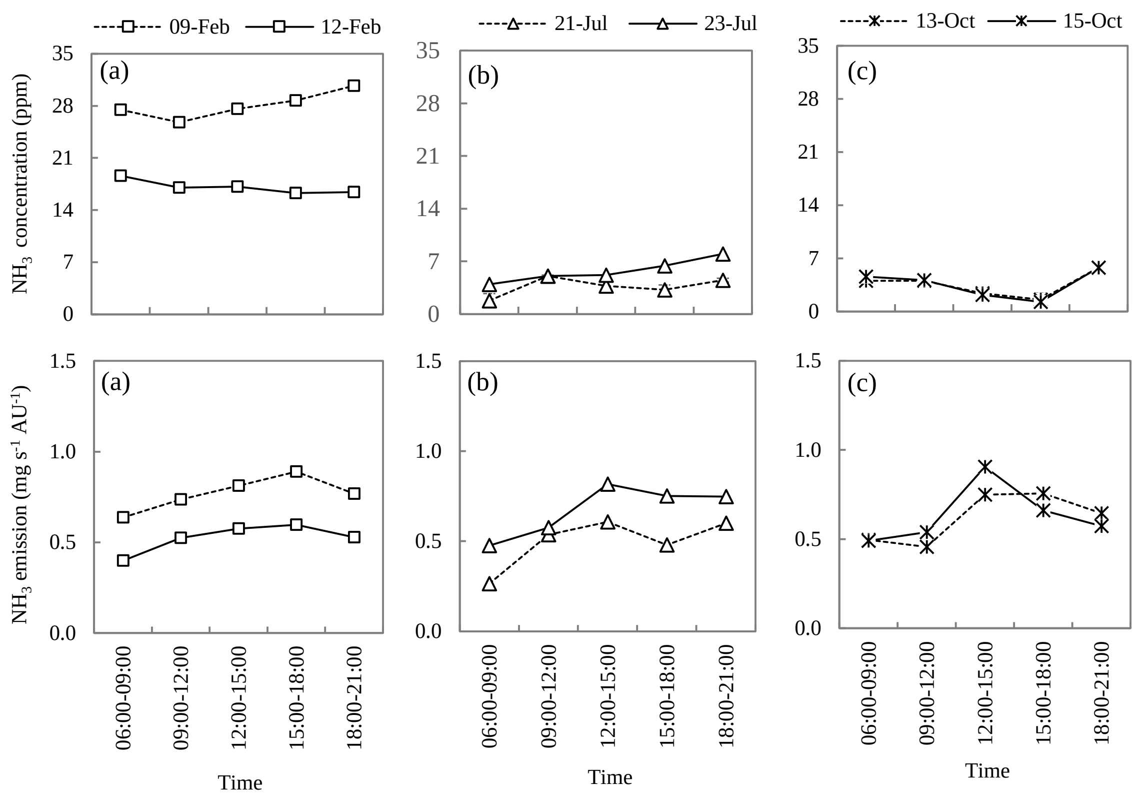

Figure 3.3 3-Hour average NH_3 concentration and emission in the cold (a), warm (b), and mild (c) seasons.

3.7.1.4 Hydrogen sulfide concentrations and emissions

Diurnal H_2S concentrations and emissions are plotted in Fig. 3.4. Due to the malfunction of the H_2S analyzer, the data of H_2S C for the whole day of Feb 12th and from 6:00 to 9:00 a.m. on Feb 9th are missing. In the cold season, significant diurnal effect was indicated by the obvious difference between H_2S C in the LM and in the EE ($P<0.05$). In the warm season, significant variance ($P<0.05$) was observed in diurnal H_2S C on Jul 21st with lower H_2S C in the EM and EE but was not found on Jul 23rd. The diurnal variations of H_2S E showed similar patterns to diurnal VR on both days with the maximum in the EA being significantly higher than the minimum in the EE ($P<0.05$). In the mild season, H_2S C and H_2S E were very low (less than 0.03 ppm and 0.01 mg s^{-1} AU^{-1}, respectively) and showed highly consistent diurnal patterns for the two days. Significant diurnal variance was concluded from both H_2S C and H_2S E ($P<0.05$), which simultaneously showed a peak in the LM and a low in the LA.

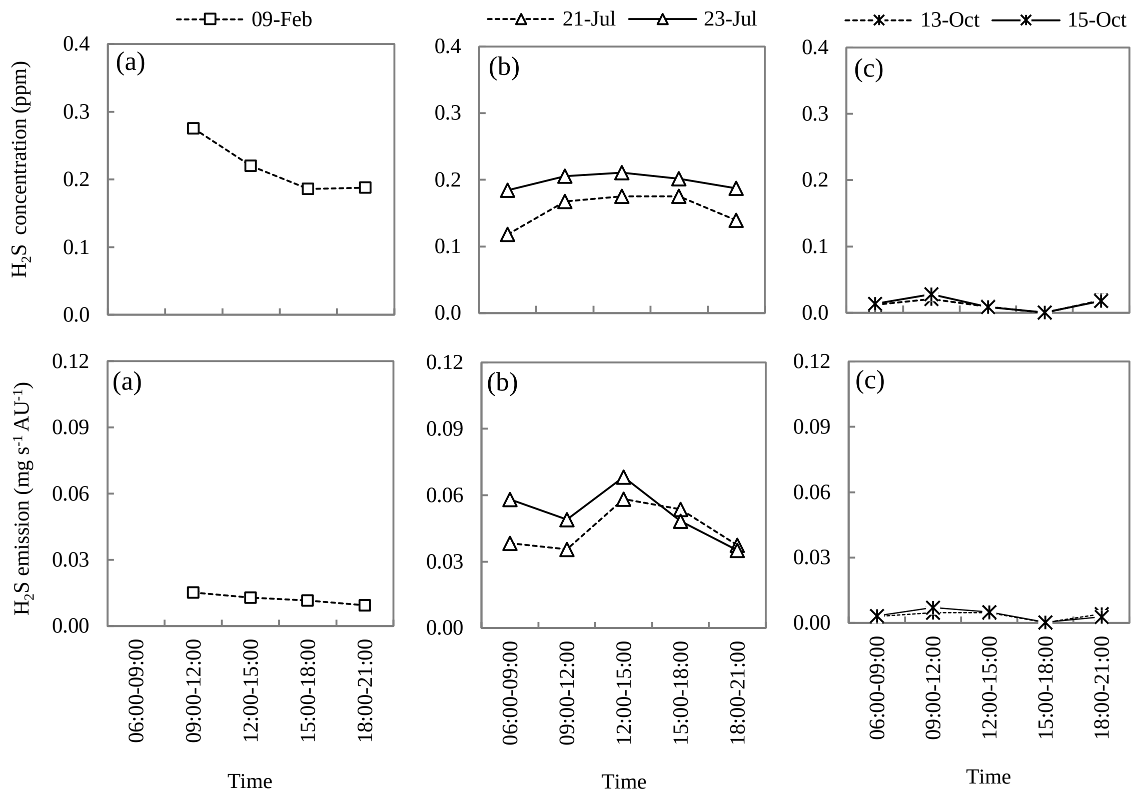

Figure 3.4 3-Hour average H_2S concentration and emission in the cold (a), warm (b), and mild (c) seasons.

Table 3.1 summarizes the minimum, maximum, and average of the diurnal results. It was found the average OC in February (cold season) was obviously higher than in July (warm season) and October (mild season), while OE was the opposite. Due to the fluctuations of VR, seasonal variations of OE could be extremely large with the average OE in October and July being 5.4 and 2.7 times that in February. Ammonia concentration was obviously high in winter and was low and similar in the warm and mild seasons. However, no such great difference was observed for NH_3 emission ($P>0.05$). Similar to OC and NH_3 concentration, H_2S concentration also showed obvious seasonality. The highest H_2S C occurred in the cold season and the lowest in the mild season. The seasonal variations of H_2S E were even greater than that of OE, with a ratio of maximum (in July) to minimum (in October) being up to 13.8. The possible great seasonal variations of odour and gas emissions suggest it is necessary to obtain detailed seasonal (such as monthly) concentration and emission profiles of odour and gases from naturally ventilated dairy barns.

Table 3.1 Descriptive statistics of 3-hour average odour, NH_3, and H_2S concentrations and emissions in the cold, warm and mild seasons.

Items	Cold			Warm			Mild		
	Min	Max	Mean (SD)	Min	Max	Mean (SD)	Min	Max	Mean (SD)
VR (m^3 s^{-1})	5.0	8.5	6.7 (1.1)^b	19.1	33.5	27.9 (5.3)^a	24.2	135.5	60.3 (45.8)^a
OC (OU m^{-3})	381	897	630 (153)^a	153	549	370 (125)^b	311	483	403 (64)^b
OE (OU s^{-1} AU^{-1})	11.7	35.0	24.3 (6.9)^b	32.5	109	66.2 (25.7)^{ab}	60.5	279.2	130.1 (86)^a
OE (OU s^{-1} m^{-2})	0.6	1.9	1.3 (0.4)	1.6	5.2	3.2 (1.2)	3.2	14.8	6.9 (4.5)
OE (OU s^{-1} cow^{-1})	17.6	52.8	36.7 (10.5)	49	165	100 (38.8)	91.4	421.5	196.5 (130)
NH_3 C (ppm)	16	31	23 (6)^a	2	8	5 (2)^b	1	6	4 (2)^b
NH_3 E (mg s^{-1} AU^{-1})	0.4	0.9	0.6 (0.2)^a	0.3	0.8	0.6 (0.2)^a	0.5	0.9	0.6 (0.1)^a
NH_3 E (μg s^{-1} m^{-2})	21.7	48.3	35.1 (8.2)	12.6	38.9	27.9 (7.7)	24.1	47.8	33.1 (7.6)
NH_3 E (mg s^{-1} cow^{-1})	0.60	1.34	0.98 (0.23)	0.40	1.23	0.88 (0.25)	0.69	1.37	0.95 (0.22)
H_2S C (ppb)	186	275	217 (42)^a	211	193	176 (29)^b	0	28	13 (9)^c
H_2S E (μg s^{-1} AU^{-1})	9.4	15.1	12.2 (2.4)^b	35.2	68.3	48.2 (11.4)^a	0.1	7	3.5 (2.1)^b
H_2S E (μg s^{-1} m^{-2})	0.5	0.8	0.7 (0.1)	1.7	3.3	2.3 (0.5)	0.01	0.4	0.2 (0.1)
H_2S E (μg s^{-1} cow^{-1})	14.2	22.9	18.5 (3.6)	53.2	103	72.8 (17.3)	0.2	10.6	5.3 (3.2)

Notes: C is concentration and E is emission; SD is standard deviation; letters a, b, and c are used to indicate the significance of the difference in the measured items among the three seasons at the 0.05 level; the same letters show the difference is not significant. The min, max, and mean were calculated from the 3-hour diurnal averages of the two days in each season.

3.7.2 Seasonal odour and gas profiles

3.7.2.1 Environmental parameters

From February 2015 to January 2016, the number of cows, T_{in}, RH_{in}, and RH_{out} changed from 102 to 116, from 6℃ to 24℃, from 49% to 91%, and from 35% to 88%, respectively. The T_{out} and VR are plotted in Fig. 3.5. It shows seasonal VR ranged from 5.0 to 69.2 m^3 s^{-1} with significant variances (P<0.05). The overall VR in winter was obviously lower than during the mild and warm seasons, excluding March when the windows were occasionally partially opened. In April, VR presented great diurnal variance, which was because the slightly higher wind speed (10 km h^{-1}) and more favorable wind direction (317°) in the early evening resulted in much higher VR than in the morning (7 km h^{-1} and 290°). It was also found that VR in August and September was significantly lower than the other warm months (P<0.05), which may be attributed to the relatively lower wind speed in August and lower T_{out} and T_{in} in September.

3.7.2.2 Odour concentrations and emissions

Figure 3.5 also gives seasonal OC and OE variations. The average OC ranged from 203 to 639 OU m^{-3}, which was within the ranges reported by Rzeźnik et al. (2014) and Mosquera et al. (2006), but higher than the 103-312 OU m^{-3} reported by Akdeniz et al. (2012a) for dairy barns with mechanical ventilation.

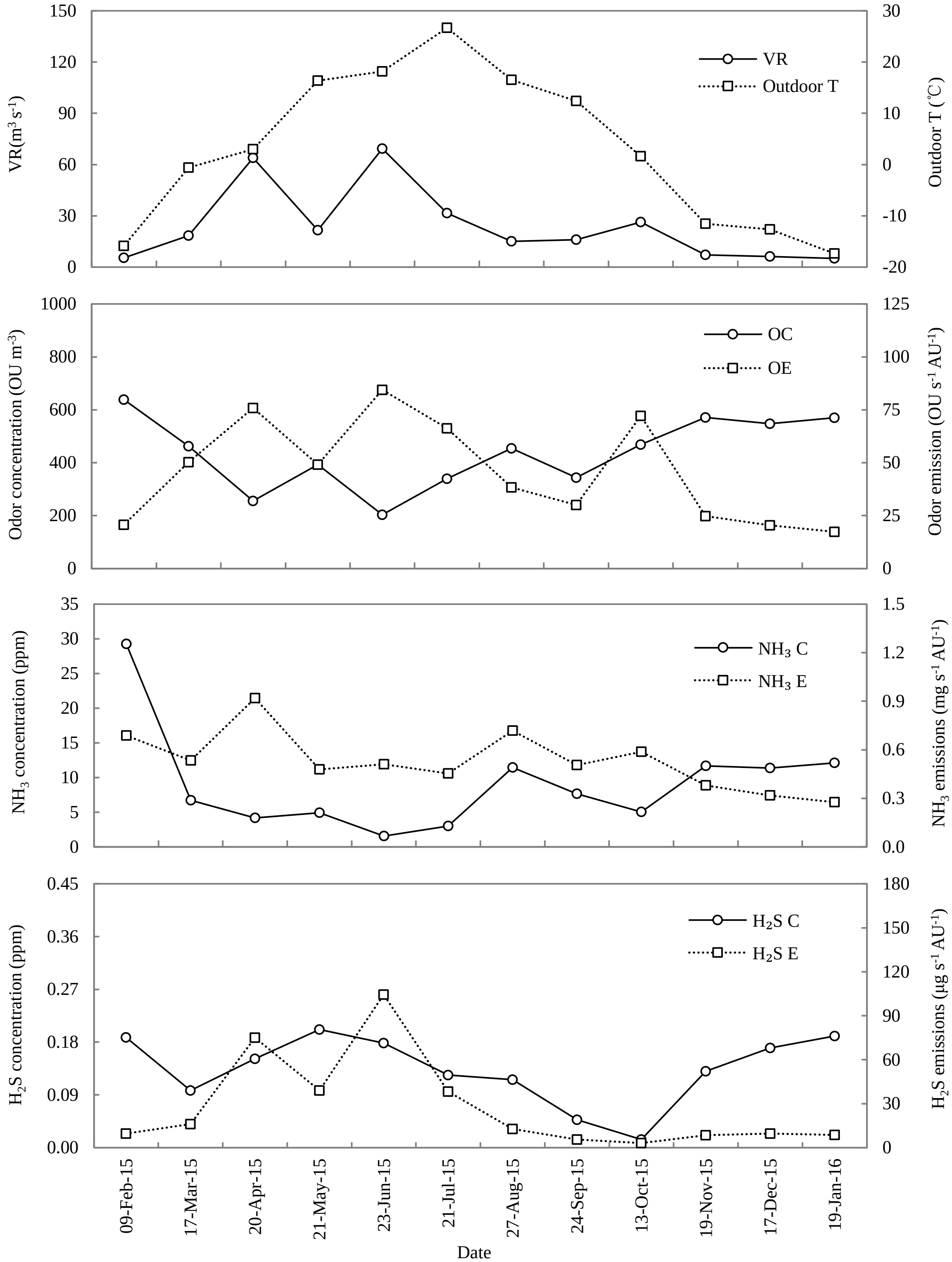

Figure 3.5 Seasonal VR and concentrations and emissions of odour, NH_3, and H_2S.

The average OC of March, June, and August was 374 OU m^{-3} and was higher than the 100 OU m^{-3} measured by Zhao et al. (2007). This can be attributed to the fact that the dairy barns Zhao et al. (2007) studied had additional wide-open ridge and cooling fans that were likely to provide more fresh air and further decrease odour and gas concentrations inside. Zhao et al. (2007) found no significant seasonal variations for OC, while the overall OC in the cold season, including November to March, was 37% higher than that in the mild and warm seasons from April to October. No obvious difference was observed between the results of the mild and warm seasons, which is consistent with the previous discussion that no significant difference existed between OC in July and October (P>0.05).

Table 3.2 Descriptive statistics of seasonal odour, NH_3, and H_2S concentrations and emissions.

Items	Min	Max	Mean ± SD
OC (OU m^{-3})	203	639	437 ± 134
OE (OU s^{-1} AU^{-1})	17.2	84.4	45.9 ± 24.2
OE (OU s^{-1} cow^{-1})	26	127.5	69.3 ± 36.6
OE (OU s^{-1} m^{-2})	0.89	4.22	2.38 ± 1.24
NH_3 C (ppm)	2	29	9 ± 7.3
NH_3 E (mg s^{-1} AU^{-1})	0.27	0.92	0.53 ± 0.18
NH_3 E (mg s^{-1} cow^{-1})	0.41	1.39	0.80 ± 0.27
NH_3 E (µg s^{-1} m^{-2})	14	50	28 ± 10
H_2S C (ppm)	0.01	0.20	0.13 ± 0.06
H_2S E (µg s^{-1} AU^{-1})	3	105	28 ± 32
H_2S E (µg s^{-1} cow^{-1})	4.7	157.8	41.5 ± 48.2
H_2S E (µg s^{-1} m^{-2})	0.16	5.23	1.42 ± 1.63

Notes: C, E and SD are abbreviations, see table 3.1. The min, max, and mean were calculated from the 12 daily averages for the 12 months.

As shown in Fig. 3.5, OE tended to be low and stable in the cold season (excluding March), but fluctuated greatly in the mild and warm seasons. Greater variations were presented in the seasonal OE than for OC. The highest OE was estimated to be 84.4 OU s^{-1} AU^{-1}, which was almost 5 times the minimum OE at 17.2 OU s^{-1} AU^{-1}. When comparing OE on a per floor area basis, the average OE was 2.38 OU s^{-1} m^{-2}, which was close to 3.30 OU s^{-1} m^{-2} reported by Maasikmets et al. (2015) for a naturally ventilated dairy barn with loose housing system in Estonia, and was higher than the results of Zhu et al. (2000) due to their high VR, and thus very low OC, but was within the range summarized by Gay et al. (2003) for 13 dairy barns in Minnesota. The average OE on a per cow basis was 69.3 OU s^{-1} cow^{-1}, which was comparable to the results of Mosquera et al. (2006). Seasonal odour and gas concentrations and emissions are summarized in Table 3.2.

3.7.2.3 Ammonia concentrations and emissions

Significant variances ($P<0.05$) existed in the seasonal NH_3 concentrations as plotted in Fig. 3.5. Similar to OC, NH_3 concentration was significantly higher in the cold season excluding August when NH_3 concentration (11 ppm) was significantly higher than in the other warm and mild months. In addition to the relatively lower VR in August compared to the overall VR over the summer, it was found both RH_{out} and RH_{in} were higher, and increasing RH_{in} and RH_{out} proved to be associated with increasing NH_3 concentration by their positive correlations ($P<0.01$). From November 2015 to January 2016 when the windows were closed, NH_3 concentration increased to above 11 ppm, but was considerably lower than the previous winter (February 2015), which may be explained by a relatively warmer winter when the windows were partially opened at times. The average NH_3 concentration was 9.1 ppm in this study, which was higher than the 2.1 ppm from Samer et al. (2012) and 6.6 ppm from Ngwabie et al. (2009); their studies had higher ventilation. On the contrary, Arcidiacono et al. (2015) reported much higher NH_3 concentration (averaged 16.6 ppm) for naturally ventilated free-stall dairy buildings in Italy, which may be explained by their lower manure removing frequency (one or two times daily) as well as the low sampling height of 10 cm above the floor. Ngwabie et al. (2009) found NH_3 concentration presented little variations during the winter months, which was also observed in this study from November 2015 to January 2016. Additionally, it was reported NH_3 concentration in May was 60% of the winter values (Ngwabie et al., 2009), while in this study the average NH_3 concentration over the summer only amounted to 39% of the winter results. The greater difference of seasonal NH_3 concentration in this study can probably be attributed to greater outdoor weather differences between Canadian Prairies summers and winters. The release of NH_3 is also directly related to the conversion of feed nitrogen to animal product (Maasikmets et al., 2015); however, no discussion could be carried out since the feed composition for this dairy barn was not analyzed.

As reported by Amon et al. (2001) and Yang et al. (2016), NH_3 emission from dairy barns varied over the course of the year, which was also observed in this study when seasonal NH_3 emission changed from 0.27 to 0.92 mg s^{-1} AU^{-1}. This finding is different from the conclusion of diurnally measured results (the variations of NH_3 emissions among February, July, and October were not obvious). Seasonal NH_3 emission averaged 0.53 mg s^{-1} AU^{-1}, which is higher than 0.21 mg s^{-1} AU^{-1} from the study of Maasikmets et al. (2015). Wu et al. (2012) found that NH_3 emission varied from 32 to 77 g d^{-1} HPU^{-1} for a naturally ventilated free-stall dairy building in Jutland. Using the same unit, seasonal NH_3 emission was in the range of 20-69 g d^{-1} HPU^{-1}, which is comparable to the result of Wu et al. (2012). If only compared the summer results, the average NH_3 emission would be 0.53 mg s^{-1} AU^{-1}, which is lower than the 2.33 mg s^{-1} AU^{-1} reported by Samer et al. (2012), but is close to the lower end of the range of 0.56 to 1.11 mg s^{-1} AU^{-1} that indicated by Fiedler and Müller (2011) (for two naturally ventilated dairy barns in Germany with more openings) and in the range of 0.36-0.78 mg s^{-1} AU^{-1} that reported by Schrade et al. (2012) (for a naturally ventilated dairy barn in Switzerland). In winter, NH_3 emission averaged 0.44 mg s^{-1} AU^{-1} and is lower than the 1.50 and 0.99 mg s^{-1} AU^{-1} that found by Samer et al. (2012) and Snell et al. (2003). When calculated by floor area, NH_3 emission averaged 28 μg s^{-1} m^{-2}, which is lower than the 43 μg s^{-1} m^{-2} that was discussed by Gay et al. (2003). Besides the VR, other factors could also be the reasons for the different NH_3 emission found in previous studies, including floor type, feeding routine, management, and so on.

3.7.2.4 Hydrogen sulfide concentrations and emissions

As can be seen from Fig. 3.5, H_2S concentration fluctuated drastically ($P<0.05$) over the year (from 0.01 to 0.20 ppm), which is higher than the results found by Zhao et al. (2007) (from 2 to 31 ppb). Different from OC and NH_3 concentration, H_2S concentration tended to be high in both cold and warm seasons (excluding September), but low in the mild season, which confirmed the conclusion from diurnal results. As for H_2S emission, it was significantly higher from April to July ($P<0.05$), but remained below 20 μg s^{-1} AU^{-1} during the other months. The range was from 3 to 105 μg s^{-1} AU^{-1}. The average H_2S emission was 1.42 μg s^{-1} m^{-2}, which is higher than 0.29 μg s^{-1} m^{-2} found by Maasikmets et al. (2015), but within the range of 1.04 to 2.89 μg s^{-1} m^{-2} as reported by Gay et al. (2003).

3.7.3 Indoor air quality evaluation

As most Canadian provinces' occupational health and safety regulations use the indoor threshold limits of NH_3 and H_2S recommended by the U.S. Occupational Safety and Health Administration (OSHA), the indoor air quality in the study barn was evaluated against OSHA threshold limits. It regulates indoor threshold limit values (TLV) of NH_3 concentration and H_2S concentration: they can be no more than 25 ppm and 1 ppm, respectively, for an 8-hourly time-weighted average (TWA-TLV), and 35 ppm and 5 ppm, respectively, for short-term exposure limits (STEL-TLV) of less than 15 minutes (ACGIH, 2010). The U.S. OSHA also suggests the effect of the mixtures should be considered as additive where the health effect and target organ or system is the same when none of the components have a value exceeding the TLV (ACGIH, 2010). That is, if the sum of $C_1/T_1+C_2/T_2+\ldots\ldots+C_n/T_n$ exceeds unity, the threshold limit of the mixture should be considered exceeded (C_1 is the observed concentration and T_1 is the corresponding threshold limit). Since NH_3 and H_2S both cause upper respiratory tract irritation, their combined effect was examined in addition to their individual impact and was described by an indicator as given in Table 3.3.

The concentrations of NH_3 and H_2S remained below the STEL-TLV in all seasons. From 9:00 a.m. to 5:00 p.m. in the warm and mild seasons with good ventilation, the TWA-TLV was not exceeded for NH_3 or H_2S, and the additive indicator was also below 1. However, the February results showed the TWA-TLV for NH_3 concentration could be exceeded in the cold season. The NH_3 concentration was below the TWA-TLV on Feb 12th, but exceeded the TWA-TLV on Feb 9th, which suggests respiratory threat when an occupant is exposed to the room air for 8 hours or longer. The combined indicator rose from 0.68 to 0.84 on Feb 12th if using the average H_2S concentration of 155 ppb during the winter (November to March) to fill in the missing data, and rose from 1.09 to 1.31 on Feb 9th, which has a substantial impact on indoor air quality as opposed to only considering the individual components.

Table 3.3 Indicator (the ratio of 8-hourly average concentration to T-TLV) of individual gas concentration levels and their combined indicator.

	Cold		Warm		Mild	
	Feb 9	Feb 12	Jul 21	Jul 23	Oct 13	Oct 15
NH_3 C	1.09	0.68	0.16	0.21	0.11	0.11
H_2S C	0.22	0.16	0.18	0.21	0.01	0.01
Combined	1.31	0.84	0.34	0.42	0.12	0.12

Notes: TWA-TLV is time-weighted average (8-hourly) threshold limit value and C is concentration.

Overall, the indoor air quality reduced from November to February when VR was small, which suggests the indoor air quality was poor during the cold season and sometimes could exceed TWA-TLV and cause respiratory irritation. Although for this dairy barn, it's not usual for workers to stay in the barn for continuous 8 hours, the results of the potential health risk in the cold season could still provide reference for the building design and operation plan of the other dairy barns, e.g., for dairy barns where long-time stay inside the barn is a possibility, it might be necessary to install an NH_3 sensor to continuously monitor the indoor concentration during the cold season and increase ventilation when necessary. Besides, indoor air quality could differ greatly among the winter or summer months, which is explained by the great variations of NH_3 concentration. The best indoor air quality was observed during the mild season, followed by the warm season; however, it should be noted that higher odour and H_2S emissions occurred during the warm and mild seasons, which would have more outdoor impact.

3.7.4 Impact of environmental parameters

Significant effect was observed for all five environmental parameters on OC ($P<0.05$), with a negative effect of T_{in}, T_{out}, and VR, and a positive effect of RH_{in} and RH_{out}. Excluding T_{in}, the other four environmental parameters all had significant impact on OE ($P<0.01$), but with an opposite effect to that on OC, suggesting the change of environmental parameters would increase one, but decrease the other.

The most related environmental parameter to OC and OE was T_{out} ($r = -0.55$, $P<0.01$) and VR ($r = 0.92$, $P<0.01$), respectively. Using curve estimation in SPSS, the best single linear regression model for OE was developed in cubic function with VR being the independent factor: OE ($OU\ s^{-1}\ AU^{-1}$) $= -0.10 + 3.25\ VR - 0.03\ VR^2 + 1.10 \times 10^{-4} \times VR^3$ ($R^2 = 0.89$), where VR is in $m^3\ s^{-1}$, or OE ($OU\ s^{-1}\ AU^{-1}$) $= 1.51 + 519\ VR - 813\ VR^2 + 493\ VR^3$ ($R^2 = 0.88$), where VR is in $m^3\ s^{-1}\ AU^{-1}$.

Environmental parameters proved to have significant impact on gases as well. Amon et al. (2001), Zhang et al. (2005), and Ngwabie et al. (2011) suggested NH_3 emission correlated with T_{in}, and Li et al. (2014) revealed NH_3 emission was strongly related to T_{out} and RH_{in}. Similar to our findings for OC, T_{in}, T_{out}, and VR all had significantly negative effects on NH_3 concentration, and RH_{in} and RH_{out} both had positive impacts on NH_3 concentration ($P<0.01$), whereas NH_3 emission was only positively correlated with VR ($P<0.01$) and negatively related to RH_{out} ($P<0.05$). The only parameter that was correlated with H_2S concentration was VR with a negative relationship ($P<0.05$). As for H_2S emission, a positive correlation between H_2S emission and T and a negative relationship between H_2S emission and RH were found, while no relationship between H_2S

emission and VR was observed. Moreover, significant correlations were also revealed among the environmental parameters, (e.g., T_{in} versus T_{out} [r = 0.94, P<0.01], RH_{in} versus RH_{out} [r = 0.79, P<0.01]), which strongly suggested the indoor thermal environment of the dairy barn was highly depending on the outdoor weather. Besides, we tried to develop a prediction model for VR based on the factors of T_{in}, T_{out}, RH_{in}, RH_{out}, difference between T_{in} and T_{out} (T_{in}-T_{out}), and difference between RH_{in} and RH_{out} (RH_{in}-RH_{out}). The best prediction model for VR was in exponential function based on the difference between T_{in} and T_{out}: VR ($m^3\ s^{-1}$) = $36.43 \times e^{-0.084\ (Tin-Tout)}$ (R^2 = 0.65), or VR ($m^3\ s^{-1}\ AU^{-1}$) = $0.22 \times e^{-0.087\ (Tin-Tout)}$ (R^2 = 0.67), where T_{in} and T_{out} are in °C.

3.7.5 Relationship between odour and odorous gases

In line with previous studies (Blanes-Vidal et al., 2012, Akdeniz et al., 2012b), significantly positive correlation was found between OC and NH_3 concentration (OC, OU m^{-3} = 141.3 ln (NH_3 concentration, ppm) + 179.5, R^2 = 0.51). On the contrary, no significant relationship was revealed between OC and H_2S concentration (P>0.05). Gay et al. (2003) reported a moderate correlation between OE and total reduced sulfur emissions (r = 0.51, P<0.05) and between OE and NH_3 emission (r = 0.48, P<0.05) for dairy housing facilities. In this study, it was found that OE was negatively related to NH_3 emission (r = 0.46, P<0.01) but not to H_2S emission (P>0.05). The results confirmed that NH_3 concentration plays a vital role in predicting OC or OE; however, H_2S cannot be an indicator in the absence of other factors.

3.7.6 Multi-linear regression model for OE and validation

The multi-linear model for OE was regressed as follows:

OE (OU $s^{-1}\ AU^{-1}$) = 76.01 + 1.25 VR ($m^3\ s^{-1}$) – 0.71 RH_{in} (%) (R^2 = 0.87)............................(3.8)

or OE (OU $s^{-1}\ AU^{-1}$) = 74.38 + 212.82 VR ($m^3\ s^{-1}\ AU^{-1}$) – 0.69 RH_{in} (%) (R^2 = 0.87)............(3.9)

The modelled OE (OE_m) from eq 3.8 and the corresponding observed OE (OE_o) are plotted in Fig. 3.6 (a). The remaining 30% of the data was used for validation. The comparison of predicted OE (OE_p) from eq 3.8 and OE_o is presented by Fig. 3.6 (b). No significant difference in the average results was observed for either group of comparisons (P>0.05).

We also used fractional bias (FB) and Pearson correlation, which are two of the general performance measures for paired statistical comparison (ASTM, 2014). Significant correlations between the paired results were found for both groups of comparisons (r > 0.88, P<0.01). The FB was 0.03 for the comparison of OE_m and OE_o, and -0.03 for the comparison of OE_p and OE_o, both of which fell into the range of -0.25<FB<0.25 (FB = 0 indicates an ideal model) suggested by ASTM (2014). The above results indicate the source odour emission model performs satisfactorily.

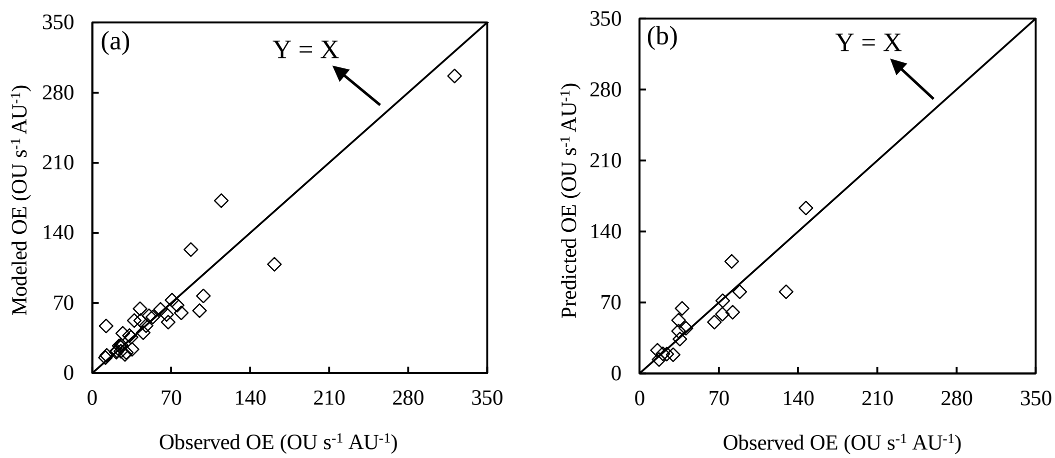

Figure 3.6 Comparison of modelled results and observed results; (a) is comparison of OE_m and OE_o using 70% of the data, and (b) is validation using the remaining 30% of the data.

3.8 CONCLUSIONS

Diurnal and seasonal variations of odour, NH_3, and H_2S concentrations were measured for a naturally ventilated free-stall dairy barn in a cold region climate (the Canadian Prairies). With this knowledge, we evaluated indoor air quality and acquired diurnal and seasonal variations of odour, NH_3, and H_2S emissions, which could be further employed to study the outdoor impact of odour and gases by dispersion modelling and provide relative references for policy makers. Our findings show:

1) Great diurnal variations of odour and gas concentrations and emissions were observed in all seasons, but especially in the mild season. Overall, higher OC and NH_3 concentration were likely to occur in the early evening from 6:00 to 9:00 p.m., while higher OE and NH_3 emission were likely to occur in the afternoon when VR was high. Odour, NH_3, and H_2S concentrations and emissions also showed great seasonal variations, with relatively higher odour and NH_3 concentrations in the winter, and higher emissions during the warm and mild seasons.

2) Considering the additive health effect of NH_3 and H_2S made a big difference for describing the indoor air quality than only considering individual gases. Based on the health effect of respiratory irritation, indoor air quality was poor and could exceed the exposure limit during the cold season.

3) Positive relationships were revealed between OC and NH_3 concentration and between OE and NH_3 emission, which agreed with previous studies. Conversely, no relationship between odour and H_2S was found. Environmental parameters presented significant, but opposite, effects on OC and OE. The most relevant environmental parameter to OC and OE was T_{out} with negative influence and VR with positive influence. The prediction model of OE was developed as a multi-linear function of VR and RH_{in}, which explained 87% of the data and was validated to be acceptable. Additionally, significant effects of environmental parameters on gas concentrations and emissions were also examined.

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CHAPTER 4
DIURNAL AND SEASONAL VARIATIONS OF ODOUR EMISSIONS FROM BROILER AND CAGE-LAYER BARNS ON THE CANADIAN PRAIRIES

4.1 VERSION PRESENTED IN CONFERENCES

Part of the results in this Chapter were presented at the CSBE/SCGAB 2015 Annual Conference and the 2016 ASABE Annual International Meeting.

- **Dandan Huang**, Huiqing Guo. 2015. Odour and gas emissions from a commercial layer barn. CSBE/SCGAB 2015 Annual Conference. Edmonton, Alberta, July 5-8. Paper No: CSBE15-22.
- **Dandan Huang**, Huiqing Guo. 2016. Seasonal odor and gas emissions from a commercial broiler barn under Canadian Prairies climate. 2016 ASABE Annual International Meeting. Orlando, USA, July 17-20. Paper No: 2461473.

4.2 CONTRIBUTION OF THE PH.D. CANDIDATE

The samples collection, lab measurements, data analysis, and manuscript writing were performed by the candidate. RLee Prokopishyn and Louis Roth helped with the instrument maintenance. Zhu Gao provided technical support for olfactometer calibration and measurement. Besides, Zhu Gao, Jingjing Han, Shamim Ahamed, and Ali Motalebi participated in some of the field measurements and assisted with air sample collection. Dr. Huiqing Guo provided editorial input and suggestions on methods and data analysis.

4.3 CONTRIBUTION OF THIS PAPER TO THE OVERALL STUDY

Similar to Chapter 3, this paper presents the results of diurnal and seasonal variations of odour concentrations and emissions for the study broiler and layer barns. Thus, the diurnal and seasonal emission profiles of odour were characterized, and the emission factors were estimated, which would be further utilized as the data input in the odour dispersion modelling for the two poultry barns in Chapters 9. The diurnal results of odour emissions of the broiler barn will be applied in Chapter 8 to validate the performance of AERMOD for predicting livestock odour dispersion.

4.4 ABSTRACT

Odour concentrations (OC) and emissions (OE) were measured for a commercial broiler barn and a cage-layer barn in a cold region (the Canadian Prairies). Seasonal odour concentration and emission profiles were plotted by monthly measurements over the course of a year from March 2015 to February 2016, and diurnal profiles were generated by two-day measurements in cold, mild, and warm seasons, respectively. Seasonal odour concentrations and emissions varied in both barns, with the highest OC but lowest OE in the cold season. The broiler barn had higher annual average OC (718 OU m^{-3}) but lower annual average OE (127 OU s^{-1} AU^{-1}) than the layer barn (574 OU m^{-3} and 140 OU s^{-1} AU^{-1}). Manure removal once every 3-4 days proved to reduce both OC and OE for the layer barn in the mild and cold seasons: OC and OE were reduced by 31% and 32% in the cold season and by 30% and 26% in the mild season after manure removal as compared to before manure removal. The influence of temperature (T), relative humidity, and ventilation rate (VR) on odour and gas concentrations and emissions were examined, and the results suggested increased outdoor T and VR were associated with decreased OC but increased OE for both barns. Finally, single linear models of OE were developed for both barns with the most related factor VR as the only variable (R^2 = 0.91 for the broiler barn and 0.74 for the layer barn).

4.5 INTRODUCTION

As reported by the 2010 yearbook of FAO, from 1999-2001 to 2009, chicken meat production has increased by 37% and egg production has increased by 22% (FAO, 2010). Intensive animal production is associated with odour and various gas emissions, which are produced by bacterial degradation of organic matters. Odorants and chemicals impact on human beings in many ways, which may even occur at below odour threshold concentrations (Nimmermark, 2004). High levels of odour have already been proven to present various effects on the health of workers and contribute to the friction between animal farms and residents living in the vicinity (Schiffman, 1998).

There is limited information related to odour concentration (OC) and odour emission (OE) from poultry operations, despite that much research has been carried out for swine operations (Lacey et al., 2004). Gay et al. (2003) summarized odour and gas emission rates from over 80 farms in Minnesota and found odour and gas emissions varied by animal species. Akdeniz et al. (2012) indicated that OC and OE from animal buildings presented seasonal patterns. Fournel et al. (2012) found both OE and hedonic tone (degree of pleasantness or unpleasantness) were affected by manure treatment for cage-layer housing systems; the manure belt system reduced OE and hedonic tone considerably as compared to the deep-pit system. In a broiler barn, OC also varied with ventilation rate (VR), litter moisture level, and building design (Jiang and Sands, 2000). Amon et al. (1997) observed that OC increased with bird age. Similarly, Gates et al. (2008) found that ammonia (odorous gas) emissions increased with bird age from near zero at the beginning of the flock to maximum at the end, which is consistent with Jiang and Sands (2000) and Lin et al. (2010).

In Canada, specifically, only a few studies quantified OE for swine operations (Sun et al., 2010; Wang, 2007; Zhang et al., 2005), while rarely data could be found for other animal species, including poultry. Navaratnasamy and Feddes (2004) conducted short-term measurements of OC and OE for broiler, turkey, and layer houses in the Canadian Prairies climate. A bench-scale study was performed by Fournel et al. (2012) to compare OE from different cage-layer housing systems. The data of OE from different poultry housings needs to be updated. In addition, possible seasonal and diurnal OE variations for livestock barns have been revealed (Akdenize et al., 2012; Sun et al., 2010; Wang, 2007; Zhu et al., 2000). This need to be considered in experimental design to improve the accuracy of the emission factor as well as to provide solid reference to further assess outdoor odour impact on the surrounding areas.

Hence, this study measured OC and OE for a commercial broiler barn and a cage-layer barn in a cold region (the Canadian Prairies) with the following objectives: 1) to reveal the seasonal variations of OC and OE over the course of a year; 2) to study the diurnal variations of OC and OE in different seasons (cold, mild, and warm seasons); and 3) to investigate the impact of environmental parameters, including VR, temperature (T), and relative humidity (RH), on OC and OE for the two barns as well as the influence of manure removal on OC and OE for the layer barn.

4.6 MATERIALS AND METHODS

4.6.1 Description of the broiler and layer barns

This study was conducted at a typical commercial broiler barn (106.61 W, 52.54 N) and cage-layer barn (106.41 W, 52.41 N) in north of Saskatoon, Saskatchewan, Canada. The broiler barn has a floor area of 1638 m^2 (18 m wide × 91 m long) and could house 33, 000 birds. The barn is mechanically ventilated by 6 chimney variable speed fans evenly distributed along the ridge as well as 4 end-wall fans, which are only working to increase VR for cooling on hot summer days. Besides, 4 recirculation fans are used to mix the room air. There are 96 air inlets symmetrically installed on the side walls (24 air inlets × 2 rows × 2 walls), which are controlled automatically according to the requirement of VR. The growth cycle for each flock is around 33 days followed by 3 weeks of cleaning and disinfection before the next flock starts. The 3-week break is because of quota control by the local industry. Birds are raised loosely on the floor covered with litter. No manure collection is performed during production cycles. For the 6 flocks within the measuring period (March 2015 to February 2016), the number of birds on the measurement days varied between 27,851 and 31,387, the bird age varied between 29 and 35 days, and the bird weight ranged within 1.86-2.25 kg.

The layer barn is a 4-tier stacked cage building with belt manure system. The dimension is 12 m wide ×81 m long (986 m^2) with a capacity of 35,000 birds. The barn is also mechanically ventilated by 4 variable speed fans and 20 single speed fans on one side wall (as shown in Fig. 4.1 (c)). A total of 172 air inlets (two rows) are installed on the ceiling. One batch of birds are raised in the barn for one year followed by one-week break for cleaning and disinfection. Manure drop on the belt and are cleaned to outside every 3-4 days. March 2015 was the last month of the old batch with 33922 birds, 1.98 kg of average weight, and 70 weeks old. A new batch was placed in April, which aged at 22 weeks and weighted at 1.56 kg on average. From April 2015 to February 2016, the number of birds decreased from 39,760 to 39,321, and the bird weight kept increasing and reached maximum 1.87 kg in December and then decreased slightly till the end of measurement.

Figure 4.1 Outside and inside view of the two barns; (a) and (b) are the broiler barn and (c) and (d) are the layer barn.

4.6.2 Sampling and measurement methods

The sampling point for the broiler barn was fixed at a height of 1.2 m, located close to a chimney fan. As manure was accumulating from the beginning to the end of each cycle, and birds' weight was continuously increasing, it was considered that in the last week of each flock the indoor air quality would be the worst, so the sampling and measurement were conducted to get the worst-case scenario. Two types of sampling and measurement were performed. Firstly, to acquire the seasonal profiles, odour sampling was performed between 8 a.m. and 4 p.m. for one day of the last week for each flock, which were in April, June, August, October, November, and January, respectively. The CO_2 concentration was also measured to estimate ventilate rate. Secondly, to obtain the diurnal profiles, odour sampling was conducted between 6 a.m. and 9 p.m. for two days in the last week of each flock in April, August, and January, which represented typical mild, warm, and cold seasons in Saskatoon, respectively. Seasonal measurements were not performed during the months when diurnal measurements were conducted, instead, the results from one of the two days in each of the three seasons were extracted to represent seasonal results. To assume the seasonal variations in OC and OE were not attributed to different bird age for the broiler barn, the results on April 16th, August 4th, and January 21st were extracted to be included in the seasonal data set for odour and gases when bird age and weight were similar to the other months.

The sampling point for the layer barn was fixed at a height of 1.5 m close to one exhaust fan, which was working throughout the year. The last day before manure removal from the belt should have the highest odour and gas concentrations so was named the worst-case day while the first day after the manure removal should have the least odour and gas concentrations so was named the best-case day. Seasonal measurements were only performed on worst-case days from 10:00 a.m. to 4:00 p.m.; one worst-case day in each month from March 2015 to February 2016. Diurnal measurements were conducted from 6:00 a.m. to 9:00 p.m. for two days in each of April (mild season), July (warm season), and January (cold season), including both a best-case day and worst-case day (within the same week). The results on Apr 28th, Jul 30th, and Jan 14th were used to consist of seasonal profiles as they were the worst-case days for diurnal measurements.

During the sampling periods mentioned above, continuous air sampling was performed and analyzed by a CO_2 sensor (K30 CO_2 sensor, CO_2 Meter, USA) with measurement range of 0-10000 ppm and accuracy of ±30 ppm ±3%. Every five minutes one data of CO_2 concentration was recorded by a data logger (CR10X, Campbell Scientific Corporation, Canada). Two replicate air samples were collected by 10-L Tedlar air bags for seasonal odour measurements in both morning (around 9:00 a.m. for the broiler barn and 11:00 a.m. for the layer barn) and afternoon at around 3 p.m., with a total of 4 odour samples on each measuring day. For diurnal OC measurement, two replicate air samples were collected every 3 hours at 6 a.m., 9 a.m., 12 p.m., 3 p.m., 6 p.m., and 9 p.m. with a total of 12 samples for each measuring day. The collected air samples were transported back for OC measurement in Olfactometry Laboratory at University of Saskatchewan within 30 hours. The odour measurement procedures, including calibration of olfactometer and screening of panelists, followed the CEN (2003) standard with generally 8 or at least 6 panelists consisting of one odour panel.

Additionally, the T_{in} and RH_{in} were continuously monitored by T/RH data loggers (OM-EL-USB-2, Omega, Canada) with measurement ranges of -35℃ to 80℃ and 0 to 100%, respectively and accuracies of 0.5℃ and 3.5%, respectively. The T_{out} and RH_{out} were obtained from Environment Canada (Government of Canada, 2016).

4.6.3 Ventilation rate and emission rate calculation

In this study, a CO_2 mass balance method was used to estimate VR rather than the fan method for both barns due to the numerous fans for the layer barn and difficulty of monitoring the performance of the large chimney fans for the broiler barn. The calculation of hourly VR was by the following series of equations (CIGR, 2002):

$$\text{VR per HPU} = (CO_2)_P \times (\text{relative animal activity}) / ((CO_2)_i - (CO_2)_o) \quad (4.1)$$

$$\text{Relative animal activity} = 1 - a \times \sin[(2 \times \pi/24) \times (h + 6 - h_{min})] \quad (4.2)$$

$$\Phi_{tot} = 10.62\ m^{0.75} \text{ for broilers or } \Phi_{tot} = 6.28\ m^{0.75} + 25\ Y \text{ for laying hens} \quad (4.3)$$

where VR is in $m^3\ h^{-1}$; $(CO_2)_P$ is CO_2 production per HPU based on a 24-h period (0.185 $m^3\ h^{-1}$); $(CO_2)_i$ is indoor CO_2 concentration and $(CO_2)_o$ is outdoor CO_2 concentration, in ppm; a is 0.08 for broilers and 0.61 for layers; h is the hours after midnight; h_{min} is hours after midnight with minimum animal activity, which is not defined for broilers by CIGR (2002) and is assumed to be 0 but is -0.1 for layers (11: 55 p.m.); Φ_{tot} is total heat production under thermoneutral conditions (20℃), in W; m is bird body mass, in kg; and Y is egg production (0.05 kg day^{-1} for consumer eggs). The actual $(CO_2)_o$ on the measurement days was measured in the warm and mild seasons and was assumed to be 390 ppm (IPCC, 2013) in the cold season. To modify Φ_{tot} per HPU outside the thermoneutral zone, the following equation was used for poultry (CIGR, 2002):

$$\Phi_{tot} = 1000 + 20 \times (20 - T_{in}) \quad (4.4)$$

where T_{in} is indoor T, in ℃. Knowing concentrations and VR, the emissions were calculated as follows:

$$E = VR \times \Delta C \quad (4.5)$$

where E is emission rate in OU s^{-1} AU^{-1} (odour unit per second per animal unit), OU s^{-1} $bird^{-1}$ or OU s^{-1} m^{-2} (odour unit per second per square meter of floor area), VR is in $m^3\ s^{-1}$, and ΔC is the difference of OC between the room inlet air and exhaust air, in unit of OU m^{-3} or parts per million (ppm). The concentrations of odour in the room inlet air (ambient air) were negligible compared to the indoor concentrations and were treated to be 0.

For OE, 20-minute averages around the sampling time were used to generate the diurnal profiles in the figures of the Results part while 2-hour averages from both morning and evening periods were calculated as a basis for the seasonal results.

4.6.4 Statistical data analysis

The statistical data analysis was performed using SPSS 22 (IBM, USA). A P-value was used to indicate the significance of correlations between OC or OE and environmental parameters ($P \leq 0.05$ indicates a significant correlation and $P \leq 0.01$ indicates a very significant correlation). To compare the differences of diurnally measured results (odour concentrations and emissions) from the cold, mild, and warm seasons, the results of the two days in each season were pooled together to consist of one group. A General Linear Model was applied where Duncan test was performed to conduct multiple comparisons among the three seasons.

4.7 RESULTS AND DISCUSSION

4.7.1 Diurnal odour and gas profiles

4.7.1.1 Broiler barn

Diurnal profiles of VR, OC, and OE for the broiler barn are given in Fig. 4.2. Overall, the average VR was highest in August (the warm season), followed by April (the mild season) and then January (the cold season). For both days in the mild season, diurnal VR varied with being obviously higher in the afternoon and lower in the early morning (6:00 a.m.). There observed a sharp increase in VR from around 2:00 p.m. on April 16th compared to April 14th. This is because the T_{in} was over-high in the afternoon of April 16th thus the 4 end-wall fans were starting to run from around 2:00 p.m., which provided more air circulation. On August 4th, diurnal VR displayed a similar varying pattern to that in the mild season, being low in the early morning and slightly rising after, but with overall higher levels. On August 6th, VR obviously decreased from 3:00 p.m. and reached a low at 9:00 p.m. compared to that on August 4th, which is due to the rain on August 6th and the T_{out} decreased from 3:00 a.m. The largest variations of diurnal VR were observed in the mild season (maximum 50 m^3 s^{-1} and minimum 9 m^3 s^{-1}) when the difference between the minimum T_{out} in the early morning and maximum T_{out} in the afternoon reached 22℃. Diurnal VR was relatively constant on both days in the cold season within a range of 8-11 $m^3\ s^{-1}$.

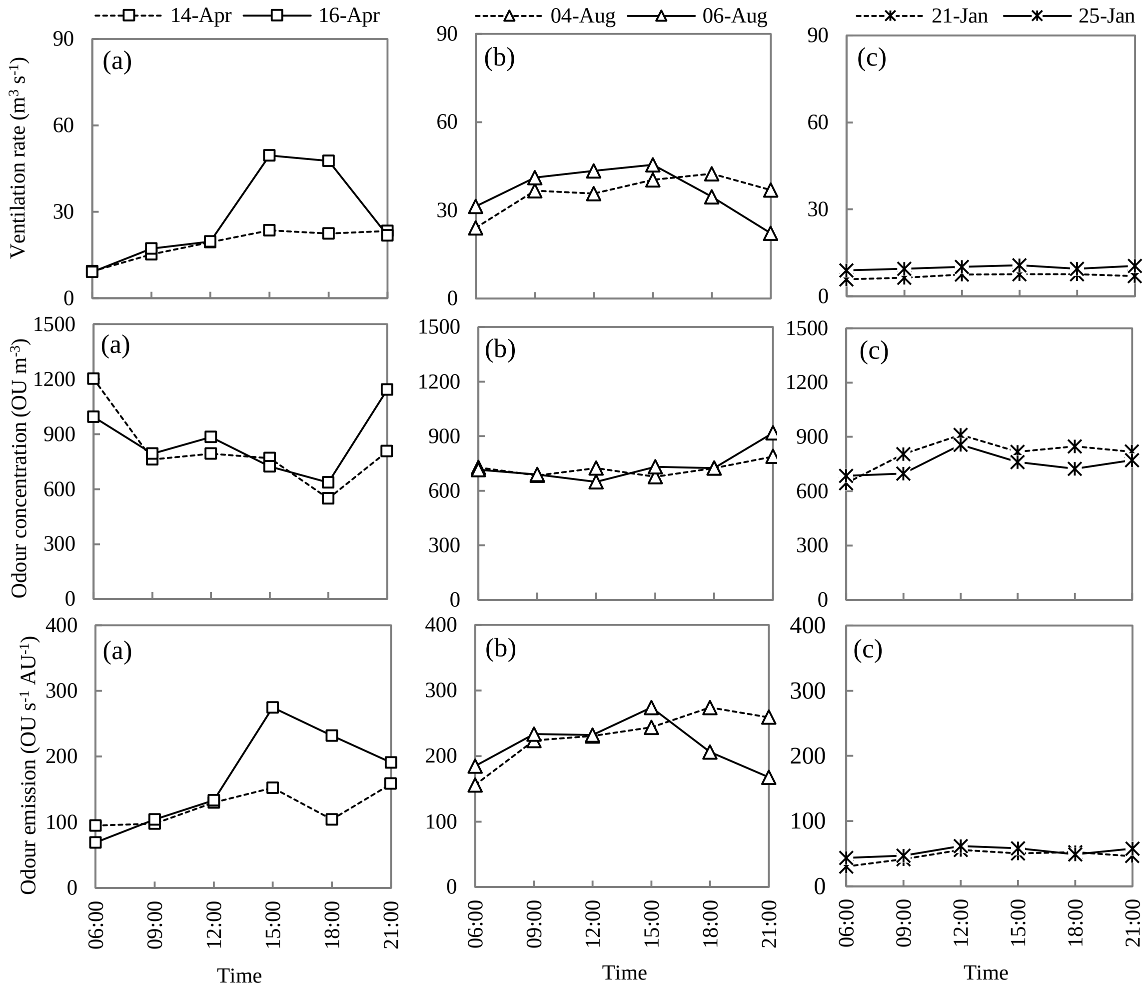

Figure 4.2 Diurnal variations of VR, OC, and OE for the broiler barn in the mild (a), warm (b), and cold (c) seasons.

As for diurnal profiles of OC in the mild season from Fig. 4.2 (a), similar varying patterns in the two days could be found; OC was high at 6:00 a.m. when VR was low and decreased along with increasing T_{out} and VR till late afternoon (6:00 pm), and then seemed to increase after. On April 14th, OC was as high as 1203 OU m^{-3} at 6:00 a.m. and reduced to 549 OU m^{-3} at 6:00 p.m. Such big diurnal difference was not observed during the warm and cold seasons. In the warm season, although the weather and VR apparently differed, the difference between OC of the two days were not obvious; however, on August 6th OC slightly increased from 3:00 p.m. and an abrupt peak occurred at 9:00 p.m. due to the decreased VR within the same period. Zhu et al. (2000) monitored diurnal trends of odour from a broiler building in late September and found that OC was very constant during the day, which is in agreement with the results of this study in the warm and cold seasons, but not in the mild season.

It was observed that OE showed similar diurnal patterns to that of VR in all seasons. In the mild season, OE had a peak at around 3:00 p.m. and still maintained high levels in the early evening. Due to the larger diurnal variations of VR, OE on April 16th presented greater variations than that on April 14th, with the maximum OE of up to 275 OU s^{-1} AU^{-1} at 3:00 p.m. and the minimum 69 OU s^{-1} AU^{-1} at 6:00 a.m. In the warm season, if disregarding the period of 6:00-9:00 p.m. on Aug 6th (when the impact of rainy weather was significant), it was found that OE was low in the early morning and high within 3:00-9:00 p.m., but with overall higher emission level compared to that in the mild season. Such great diurnal variations of OE were not observed in the cold season, when OE were observed within a low range of 30-63 OU s^{-1} AU^{-1}. The minimum, maximum, mean, and standard deviation of the diurnal results are summarized in Table 4.1.

Table 4.1 Summary of min, max, and mean of diurnal results in the three seasons for the broiler barn.

	Mild			Warm			Cold		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
OC (OU m^{-3})	549	1203	838 (192)[a]	649	919	729 (69)[a]	645	911	779 (79)[a]
OE (OU s^{-1} AU^{-1})	69	275	145 (61)[a]	156	274	224 (39)[a]	30	61	49 (8)[b]
OE (OU s^{-1} $bird^{-1}$)	0.29	1.15	0.58 (0.26)	0.59	1.12	0.88 (0.15)	0.13	0.29	0.22 (0.05)
OE (OU s^{-1} m^{-2})	6	22	11 (5)	11	20	16 (3)	2	5	4 (1)

Notes: The numbers in parenthesis are standard deviation; letters a, b, and c are used to indicate the significance of the difference in the measured item among the three seasons at the 0.05 level; the same letters mean the difference is not significant. The min, max, mean, and SD were calculated from using point data (20-minute averages around each fixed sampling time for odour samples) for odour.

4.7.1.2 Layer barn

Diurnal profiles of VR, OC, and OE for the layer barn are shown in Fig. 4.3. Similar to the broiler barn, diurnal VR changed apparently in both mild and warm seasons even with greater variations. In the mild season, diurnal VR gradually raised and tended to reach peaks in the early afternoon within 12:00 to 3:00 p.m. and then gradually reduced till the end of the measurement, which resembles the diurnal curves of T_{out}. In the warm season, the ratio of maximum to minimum VR was up to 4 on the worst-case day. However, due to the rain and cooler weather on Jul 28th, VR on the best-cast day was much lower compared to the worst-case day and presented relatively flat curve from 9:00 a.m. to 6:00 p.m. In the cold season, diurnal VR were quite similar for the two days and varied within a low narrow range of 5.8-10.7 $m^3 s^{-1}$.

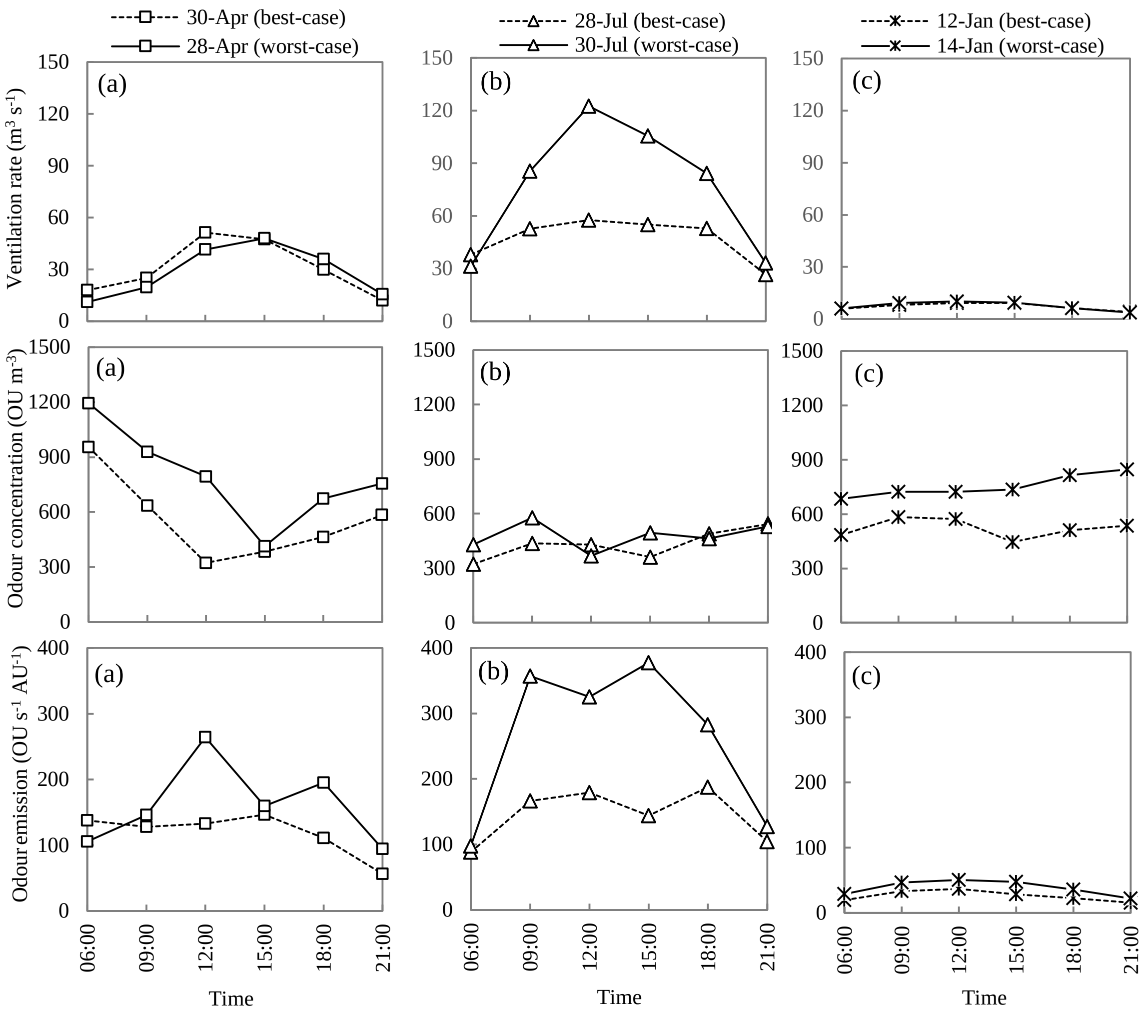

Figure 4.3 Diurnal variations of VR, OC, and OE for the layer barn in the mild (a), warm (b), and cold (c) seasons.

Diurnal OC varied slightly within 15% and 26% from the average, respectively for the cold and warm seasons. In the mild season, great variations in diurnal OC was observed on both days; the highest OC in the early morning was almost 3 times of the lowest OC in the early afternoon (12:00 to 3:00 p.m.). Diurnal OE was obviously influenced by diurnal VR in all seasons, displaying lows in the early mornings and evenings but increased during the day, with two peaks and greater fluctuations in the mild and warm seasons. Table 4.2 summarized the average and standard deviation of diurnal results for both best-case day and worst-case day as well as the overall mean of the best-case and worst-case days in each season for the layer barn.

Table 4.2 Summary of average diurnal OC and OE on the best-case days and worst-case days and overall mean in the three seasons for the layer barn.

	Mild			Warm			Cold		
	D_{best}	D_{worst}	$Mean_{overall}$	D_{best}	D_{worst}	$Mean_{overall}$	D_{best}	D_{worst}	$Mean_{overall}$
OC	558	794	676	431	477	454	523	755	639
(OU m^{-3})	(228)	(261)	(264)^{a}	(81)	(74)	(78)^{b}	(53)	(63)	(133)^{a}
OE	119	161	140	145	261	203	26	39	32
(OU s^{-1} AU^{-1})	(33)	(63)	(52)^{b}	(41)	(120)	(105)^{a}	(8)	(12)	(12)^{c}
OE	0.37	0.50	0.44	0.50	0.91	0.71	0.10	0.14	0.12
(OU s^{-1} $bird^{-1}$)	(0.10)	(0.20)	(0.16)	(0.14)	(0.42)	(0.37)	(0.03)	(0.04)	(0.04)
OE (OU s^{-1} m^{-2})	15 (4)	20 (8)	18 (7)	20 (6)	37 (17)	29 (15)	4 (1)	6 (2)	5 (2)

Notes: D_{best} is the best-case day and D_{worst} is the worst-case day; the numbers in parenthesis are standard deviation; letters a, b, and c are used to indicate the significance of the difference in the measured item among the three seasons at the 0.05 level (the same letters mean the difference is not significant). The mean and SD were calculated from using point data (20-minute averages around each fixed sampling time for odour samples).

Removing manure to outside by belt-transportation could greatly reduce both OC and OE in the mild and cold seasons. As can be seen in Fig. 4.3, OC was lower on the best-case days, which was 523 OU m^{-3} and 558 OU m^{-3}, respectively, in the cold and mild seasons compared to 755 OU m^{-3} and 794 OU m^{-3} on the worst-case days, with reduction ratios of 31% and 30% by manure removal, respectively. Similarly, OE was also reduced by manure removal in the mild and cold seasons from 161 to 119 OU s^{-1} AU^{-1} (reduced by 26%) and from 39 to 26 OU s^{-1} AU^{-1} (reduced by 32%), respectively. This agrees with the results found by Fournel et al. (2012) that a cage-layer housing with manure belt systems could reduce OE between 37-42% compared to a cage-layer house with deep-pit system. Although OC and OE on the best-case day (431 OU m^{-3} and 145 OU s^{-1} AU^{-1}) were also lower than the worst-case day (477 OU m^{-3} and 261 OU s^{-1} AU^{-1}) in the warm season, the reduction ratio needs to be validated as the VR on the worst-case day was much higher than the best-case day (89 m^3 s^{-1} compared to 51 m^3 s^{-1}), which may be a major reason for the higher OE on the worst-case day in the warm season. Therefore, in the cold season when odour and gas concentrations are high, frequent manure removal may improve the air quality. In addition, it is recommended to increase frequency of manure removal for the layer barn in the mild and warm seasons when OE is high and odour impact on the adjacent land use may be the highest in a year.

4.7.2 Seasonal odour and gas profiles

Seasonal patterns of environmental parameters (including T_{in}, T_{out}, and VR) as well as OC and OE are plotted in Fig. 4.4 and Fig. 4.5 for the broiler barn and the layer barn, respectively. Over the course of the year, the ambient T varied considerably from below -30℃ in the winter to above 30℃ in the summer; however, only the average T_{out} for the measured hours during the day were calculated to relate to odour when air samples were collected. It appears seasonal VR followed the patterns of T_{out} for both barns, being high in the mild (April and October) and warm seasons (May to September) and low in the cold season (November to March), within a range of 7-36 $m^3 s^{-1}$ for the broiler barn and a range of 10-120 $m^3 s^{-1}$ for the layer barn. As the result, the T_{in} was controlled within a narrow range of 22℃ to 26℃ for the broiler barn and of 19℃ to 26℃ for the layer barn. Besides, RH_{out} varied greatly from minimum of 19% to maximum of 85%, while RH_{in} ranged from 48% in June to 71% in January for the broiler barn, and from 27% in May to 63% in February for the layer barn.

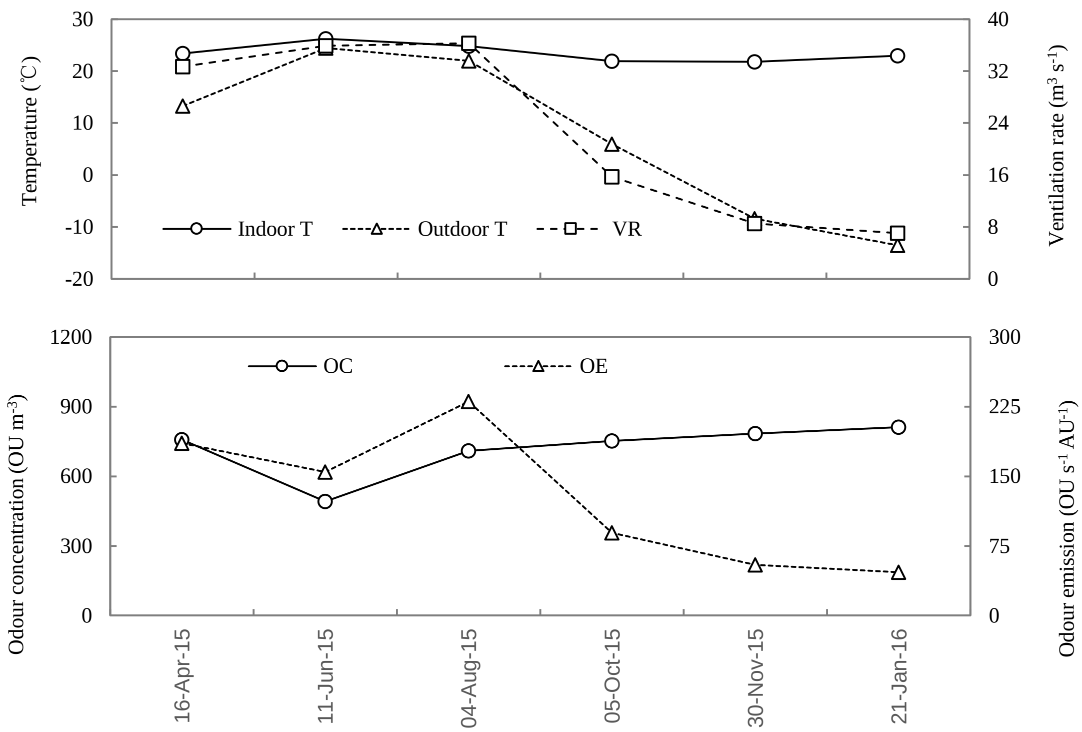

Figure 4.4 Seasonal variations of environmental parameters, OC, and OE of the broiler barn.

Odour concentrations and emissions varied between 491 and 812 OU m^{-3} (averaged 718 OU m^{-3}) and between 47 and 231 OU s^{-1} AU^{-1} (averaged 127 OU s^{-1} AU^{-1}) for the broiler barn. The annual OC was lower but the annual OE was higher for the layer barn, which had a seasonally varying OC of 260-860 OU m^{-3} (averaged 574 OU m^{-3}) and varying OE of 50-370 OU s^{-1} AU^{-1} (averaged 140 OU s^{-1} AU^{-1}). It was found that OC from the layer barn showed more apparent seasonality than the broiler barn, with much higher OC in the winter (791 OU m^{-3}) than in the mild season (578 OU m^{-3}) and the warm season (355 OU m^{-3}). In addition, the seasonal OC tended to fluctuate against VR for the layer barn as shown in Fig. 4.5 (e.g., being high when VR was low in the winter and being low when VR was high in the summer), which indicated a possible significant impact of VR on OC. Compared to the layer barn, OC from the broiler barn was relatively stable for most of the months except June when OC was much lower. As a combined result of OC and VR, OE presented great seasonal variations for both barns, following the trends of seasonal VR with higher emissions in the warm and mild seasons than the cold season. The variation was up to 82% and 164% difference from the average for the broiler barn and layer barn, respectively. The average OE in the summer, winter, and mild season was 193, 51, and 137 OU s^{-1} AU^{-1}, respectively for the broiler barn and was 202, 65, and 177 OU s^{-1} AU^{-1}, respectively for the layer barn.

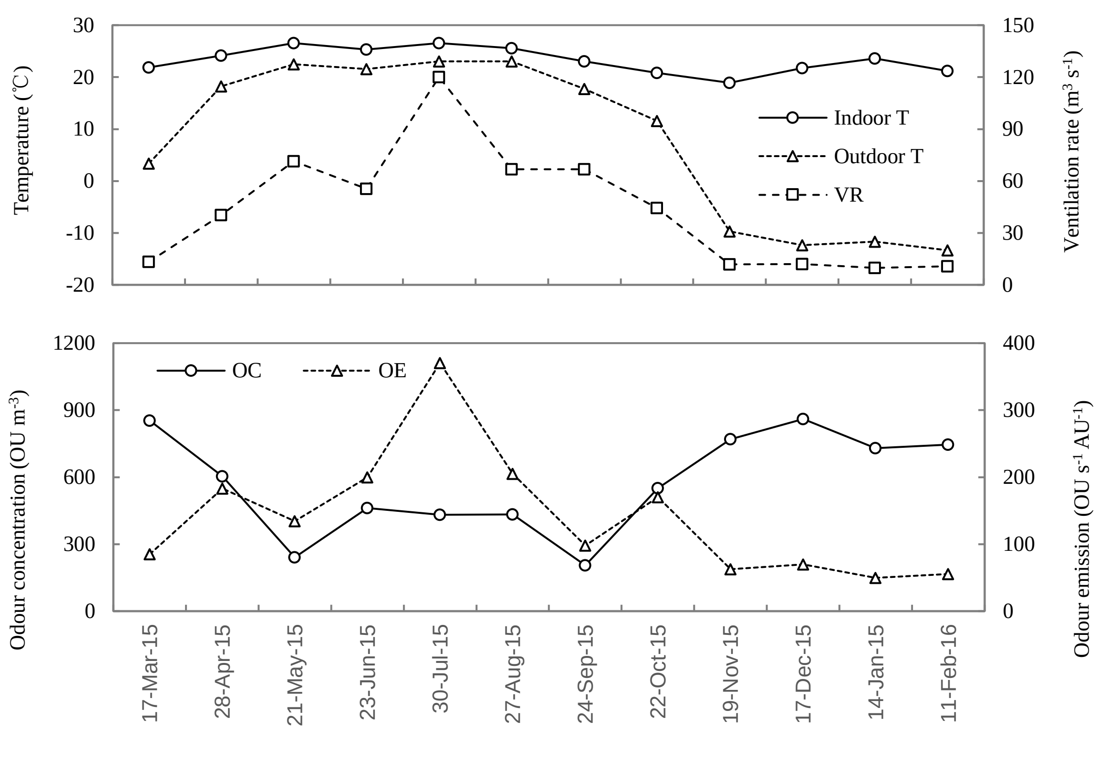

Figure 4.5 Seasonal variations of environmental parameters, OC, and OE of the layer barn.

The seasonal OC and OE with different units are all listed in Table 4.3. Amon et al. (1997) found a maximum OC of 2080 OU m^{-3} in week 6 for a broiler house, while the broiler barn in this study had a shorter operation period (5 weeks) and a lower maximum OC (491-812 OU m^{-3}). The overall daily means of OC and OE were reported to be 316 OU m^{-3} and 28.3 OU s^{-1} AU^{-1}, respectively by Lim et al. (2000) for a high-rise laying house with 250, 000 hens and daily manure scraping from March to May. The daily OC for the layer barn from March to May was higher at 566 OU m^{-3}, which resulted in a much higher average OE (134 OU s^{-1} AU^{-1}). Relatively higher OE for the broiler barn was observed as well as compared to the broiler housings in USA. Gay et al. (2003) concluded a mean OE of 0.17 to 9.47 OU s^{-1} m^{-2} for all types of broiler housings, including loose and caged. If converted to the same unit, the average OE based on floor area was 9.36 OU s^{-1} m^{-2} in this study, which is comparable to the upper limit from Gay et al. (2003). Ogink and Groot Koerkamp (2001) reported an overall lower OE of 0.16 OU s^{-1} m^{-2} for broiler housings and of 0.35 OU s^{-1} $bird^{-1}$ for caged-layer housings with manure belt in the Netherlands. Hayes et al. (2006) measured OE from three broiler barns and two layer housings in Ireland, and reported OE of 0.66 OU s^{-1} $bird^{-1}$ in summer and 0.39 OU s^{-1} $bird^{-1}$ in winter for the broiler barns, and of 1.35 OU s^{-1} $bird^{-1}$ in summer and 0.47 OU s^{-1} $bird^{-1}$ in winter for the layer barns. In this study, the average OE in summer and winter were 0.72 and 0.22 OU s^{-1} $bird^{-1}$, respectively, for the broiler barn, and 0.69 and 0.24 OU s^{-1} $bird^{-1}$, respectively, for the layer barn, with comparable OE from the broiler barn but lower OE from the layer barn in both summer and winter compared to the results of Hayes et al. (2006). The spring OE for the broiler barn was 0.78 OU s^{-1} $bird^{-1}$, which is much higher than 0.33 OU s^{-1} $bird^{-1}$ in the study by Hayes et al. (2006). This can be explained by the relatively warm spring in Saskatoon thus higher VR for the broiler barn.

In Canada, Navaratnasamy and Feddes (2004) measured OE at 0.44 OU s^{-1} $bird^{-1}$ from a broiler barn and 0.56 OU s^{-1} $bird^{-1}$ from a layer barn in summer (both on the Canadian Prairies). A higher average OE of 0.72 and 0.69 OU s^{-1} $bird^{-1}$ in summer were obtained for the broiler barn and layer barn, respectively by this study. The difference is probably attributed to the much greater birds density for the broiler and layer barns in this study: the birds density is 19 and 40 bird/m^2, respectively, for the broiler barn and layer barn in this study compared to 14 and 7 bird/m^2, respectively, for the broiler barn and layer barn in the study by Navaratnasamy and Feddes (2004). Fournel et al. (2012) reported a mean OE of 0.16 OU s^{-1} $bird^{-1}$ for a cage layer building through bench-scale experiments during an 8-week period. The layer barn presented a much higher OE

(0.18-1.29 OU s^{-1} $bird^{-1}$), which also likely resulted from a much greater birds density in this study than 10 bird/m^2 in the study by Fournel et al. (2012). It should be noted that all the comparisons for layer barns were performed by using the results under the worst case in this study. Since 30% and 31% of the OC and 26% and 32% of the OE could be reduced by manure removal in the mild and cold seasons (no reduction ratio of OC or OE in the warm season was calculated in this study), respectively, we took an average of 30.5% and 29% as reduction ratios for estimating OC and OE under the best case for the layer barn. Thus, the annual average OE should be adjusted to get a representative average between best condition and worst condition as given in Table 4.3. It turned out the OE of the layer barn was still at a high level compared to the above studies.

Table 4.3 Summary of seasonal OC and OE of the broiler and layer barns.

	Broiler			Layer (worst-case)			
Items	Min	Max	Average ± SD	Min	Max	Average ± SD	Adjusted average
OC (OU m^{-3})	491	812	718 ± 116	206	860	574 ± 224	486
OE (OU s^{-1} AU^{-1})	47	231	127 ± 75	50	370	140 ± 93	120
OE (OU s^{-1} $bird^{-1}$)	0.20	0.87	0.51 ± 0.28	0.18	1.29	0.49 ± 0.32	0.42
OE (OU s^{-1} m^{-2})	3.51	15.78	9.36 ± 5.29	7.29	52	19.57 ± 12.83	16.73

Notes: SD is standard deviation.

4.7.3 Impact of environmental parameters

The correlation coefficients for odour against environmental parameters are listed in Table 4.4. It suggests T and VR played vital roles in determining OC and OE for both barns, which is in line with the results by Lim et al. (2003). Increased T_{in} and VR were both found to significantly decrease OC for the two barns ($P<0.01$). As for the layer barn, OC was also negatively related to T_{out} ($P<0.01$). More significant influence from T and especially from VR were observed for OE from both two barns. The positive correlations in Table 4.4 indicate increased T_{out} and VR were associated with increased OE. Overall, VR was the most critical factor to negatively impact on OC but positively affect OE for both barns. Additionally, strong positive correlation between T_{out} and VR was indicated ($P<0.01$, $r > 0.85$) for both barns, which explained the high consistency between VR varying patterns and T_{out} varying patterns from previous discussed results. Very little or no influence of RH_{in} was found for OC for the layer barn, which is different from the conclusion of Nimmermark and Gustafsson (2005) that increasing RH was associated with increasing OC for a layer housing with loose housing system. It is probably due to the floor housing systems used for the laying hens in the study of Nimmermark and Gustafsson (2005), which had large exposed surface of manure and litter for odour and gas generations, thus the effect of relative humidity level in the room air has more impact on manure decomposing.

Table 4.4 Correlations between OC or OE and environmental parameters.

	Broiler barn					Layer barn				
	T_{in}	T_{out}	RH_{in}	RH_{out}	VR	T_{in}	T_{out}	RH_{in}	RH_{out}	VR
OC	-0.47**	-0.28	0.12	0.01	-0.41**	-0.42**	-0.52**	0.20	0.30*	-0.61**
OE	0.08	0.84**	-0.22	-0.25	0.95**	0.38**	0.76**	-0.50**	-0.52**	0.86**

Notes: ** indicates correlation is significant at the 0.01 level and * indicates correlation is significant at the 0.05 level.

Similarly, no significant impact of RH on OC or OE was found for the broiler barn, either, which may be because RH_{in} for the broiler barn with no manure removal always was relatively high (48%-71% for seasonal RH_{in}) despite the great variations of RH_{out}, therefore, OC and OE for the broiler barn maintained a high level and did not reflect the impact of the seasonal variations of RH_{out}. Significant negative correlation between RH and OE was indicated for the layer barn (P<0.01). This may be explained by that generally higher OE occurred in the summer for the layer barn when RH_{out} and RH_{in} were both lower compared to the other seasons, while lower OE was found in the cold season when RH_{out} and RH_{in} were both higher.

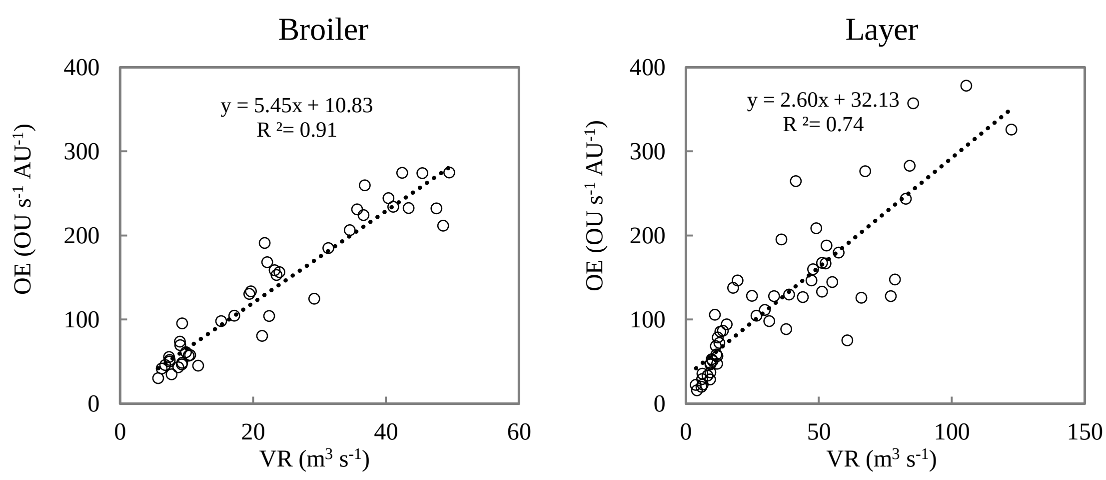

Figure 4.6 Relationships between OE and VR for both barns.

Using all data, single linear models of OE were regressed for the two barns with VR as the only factor and were plotted in Fig. 4.6. It suggested a very good performance for the regression model of the broiler barn, which explained 90.7% of the data. As for the layer barn, the R square was lower but was still fair (R^2>0.7). The two prediction models could be utilized to estimate OE by only measuring VR for other similar layer and broiler barns on the Canadian Prairies.

4.8 CONCLUSIONS

Diurnal and seasonal variations of odour concentrations and emissions were characterized for a commercial broiler barn and cage-layer barn under the Canadian Prairies climate. The following findings are summarized:

1) The broiler barn displayed higher annual averages of OC but lower OE than the layer barn. The annual average concentrations and emissions of odour were 718 OU m^{-3} and 127 OU s^{-1} AU^{-1} for the broiler barn and were 574 OU m^{-3} and 140 OU s^{-1} AU^{-1} for the layer barn. Seasonal odour concentrations and emissions varied for both barns; OC was higher in the cold season, but OE was higher in the mild and warm seasons. Relatively greater variations of both OC and OE were observed for the layer barn than the broiler barn.
2) Diurnal OC displayed greater variations and more clear trends in the mild season than the warm and cold seasons, being high in the early morning and early evening, while being low in the afternoon. As for diurnal OE, it tended to follow the diurnal changes of T_{out} and VR, with much greater fluctuations observed in the mild and warm seasons than the cold season. In the mild and warm seasons, diurnal OE occurred one peak between 3:00 p.m. and 9:00 p.m. for the broiler barn, while occurred two peaks within the period of 9:00 a.m. to 6:00 p.m. for the layer barn.
3) Manure removal by belt transportation proved to efficiently reduce OC and OE for the layer barn in both mild and cold seasons, with reduction ratios of 31% and 30% for OC, respectively, and with reduction ratios of 26% and 32% for OE, respectively. Thus, it suggests increasing manure removing frequency for the layer barn during the mild season and may also the warm season when OE is high and odour complaints could occur, and also in the cold season to improve the indoor air quality when odour concentrations are high (which indicates higher gas concentrations). Influence of region (climate) on OC and OE were proved in comparing the results with previous studies. The two barns both tended to have high OC and OE levels compared to the poultry barns in USA and European countries. Birds density also showed potential impact on OC and OE when comparing studies across Canada.

4) The impact of the five environmental parameters (including indoor and outdoor T, indoor and outdoor RH, and VR) on OC and OE were investigated. Increased T_{out} and VR were found to negatively relate to OC but positively correlate with OE for both barns ($P<0.01$). Especially in the mild and warm seasons, when T_{out} could vary greatly during the day, changes of diurnal VR apparently reflected in the diurnal OE. Finally, regression models were derived for predicting OE with the most relevant factor VR being the only variable

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CHAPTER 5
DIURNAL AND SEASONAL VARIATIONS OF ODOROUS GAS EMISSIONS FROM BROILER AND CAGE-LAYER BARNS ON THE CANADIAN PRAIRIES

5.1 VERSION PRESENTED IN CONFERENCES

Part of the results in this Chapter were presented at the CSBE/SCGAB 2015 Annual Conference and the 2016 ASABE Annual International Meeting.

- **Dandan Huang**, Huiqing Guo. 2015. Odour and gas emissions from a commercial layer barn. CSBE/SCGAB 2015 Annual Conference. Edmonton, Alberta, July 5-8. Paper No: CSBE15-22.
- **Dandan Huang**, Huiqing Guo. 2016. Seasonal odor and gas emissions from a commercial broiler barn under Canadian Prairies climate. 2016 ASABE Annual International Meeting. Orlando, USA, July 17-20. Paper No: 2461473.

5.2 CONTRIBUTION OF THE PH.D. CANDIDATE

The samples collection, lab measurements, data analysis, and manuscript writing were performed by the candidate. RLee Prokopishyn and Louis Roth helped with the instrument set-up and maintenance. Zhu Gao, Jingjing Han, Shamim Ahamed, and Ali Motalebi participated in some of the field measurements and assisted with air sample collection. Dr. Huiqing Guo provided editorial input and suggestions on methods and data analysis.

5.3 CONTRIBUTION OF THIS PAPER TO THE OVERALL STUDY

Similar to Chapter 3, this paper presents the diurnal and seasonal variations of odorous gas (NH_3 and H_2S) concentrations and emissions as well as the seasonal variations of respirable dust concentrations and emissions for the broiler and layer barns. Thus, the indoor air quality of the two barns could be evaluated based on the measured NH_3, H_2S, and respirable dust concentrations. As for the study on the outdoor impact, the emission factors of NH_3, H_2S, and respirable dust were estimated based on their diurnal and seasonal concentration profiles, which would be further utilized as the data input in the dispersion modelling for the two barns in Chapter 9.

5.4 ABSTRACT

Ammonia (NH_3), hydrogen sulfide (H_2S), and respirable dust concentrations and emissions were measured for a commercial broiler barn and a cage-layer barn in a cold region (the Canadian Prairies). Seasonal gas and respirable dust concentration and emission profiles were plotted by monthly measurements over the course of a year between March 2015 and February 2016, and diurnal gas concentration and emission profiles were generated by two-day measurements in cold, mild, and warm seasons, respectively. Seasonal gas and respirable dust concentrations and emissions varied in both barns. The broiler barn presented higher annual average NH_3, H_2S, and respirable dust concentrations but lower gas emissions based on per animal unit than the layer barn. In the cold and mild seasons, manure removal once every 3-4 days proved to reduce NH_3 concentrations by 61% and 89%, respectively, and NH_3 emissions by 62% and 90%, respectively. The indoor air quality for both barns were evaluated and quantified using air quality index by considering not only the health effect (respiratory irritation) of individual air pollutants (NH_3, H_2S, and respirable dust), but also their additive effect. The results indicated that the indoor air quality of the broiler barn was very poor in the cold season with both the 8-houlry and 15-minute exposure limits of NH_3 being exceeded and the combined indicators being more than 2 times of the limit level. The correlations between gas concentrations or emissions and environmental parameters were investigated, and the results suggested significant negative impact of outdoor temperature (T_{out}) and ventilation rate (VR) on NH_3 concentrations for both barns, and also significant negative influence of T_{out} and VR on NH_3 emissions for the broiler barn but positive impact of T_{out} on NH_3 emissions for the layer barn.

5.5 INTRODUCTION

Livestock production is the most important agriculture source of ammonia (NH_3). Ammonia not only impairs atmospheric visibility through forming aerosol, but also contributes to eutrophication of surface water and nitrate contamination of groundwater (US EPA, 2004). Besides its environmental effects, NH_3 also negatively impacts on respiratory health (Wood et al., 2015). Livestock production is also associated with hydrogen sulfide (H_2S) and dust emissions. It said H_2S is potential threat for neurological effects, immunological effects, and respiratory irritation at low concentrations (Copeland, 2014). Particulate matter (PM) from livestock production has also been regarded as an indoor pollutant, which inversely impacts animal performance and efficiency, and famers' respiratory health. Furthermore, emitted PM outside livestock houses is also related to ecosystem and climate change (Cambra-López et al., 2010).

Due to that gas and dust concentrations are influenced by various factors, including building design, temperature (T), manure handling system, animal diet, animal numbers and sizes, etc., large variations in gas and dust emissions from animal production were found (Schmidt, et al., 2002). In USA, the National Air Emissions Monitoring Study (NAEMS) had been carried out in 9 states to monitor NH_3, H_2S, PM and volatile organic compounds for 2 years at different barn monitoring sites (dairy, swine, broiler and layer facilities) (Bereznicki et al., 2012). Gay et al. (2003) summarized NH_3 flux rates from 66 farms in Minnesota and reported that NH_3 emissions were higher from swine facilities than that from beef, dairy, and poultry facilities, and NH_3 emissions from lay housings were about three times higher than the emissions from broiler facilities (Gay et al., 2003). Besides, they also found that total reduced sulfur (defined as the summation of all gaseous unoxidized sulfur compounds, among which H_2S is the majority constituent) emissions from layer housings fell within a much wider range (0.08-9.15 $\mu g\ s^{-1}\ m^{-2}$) than that of the broiler barns (0.16-1.28 $\mu g\ s^{-1}\ m^{-2}$) (Gay et al., 2003). Working in livestock houses is usually associated with high dust exposure and long-term decline in lung function. In poultry houses the exposure to dust is even higher than in swine houses (Iversen et al., 2000). In a review paper regarding PM from livestock production by Cambra-López et al. (2010), it was found that PM levels in broiler houses were highest compared with other animal species, and PM emissions were also related to housing and feeding type, environmental factors besides animal species. Based on its aerodynamic diameter (a cumulative log-normal curve having a median aerodynamic diameter of 4 μm), respirable dust is "fraction of inhaled airborne particles that can penetrate beyond the terminal bronchioles into the gas-exchange region of the lungs" (WHO, 1999).

In Canada, studies concerning NH_3, H_2S, and PM concentrations and emissions from poultry production are still very limited (Roumeliotis et al., 2010; Fournel et al., 2012; Navaratnasamy and Feddes, 2004). There is a need for more research information on NH_3, H_2S, and PM emissions from different sites across Canada. Thus, this study measured NH_3, H_2S, and respirable dust concentrations and emissions for a commercial broiler barn and a cage-layer barn in a cold region (Canadian Prairies) with the following objectives: 1) to characterize the seasonal variations of NH_3, H_2S, and respirable dust concentrations and emissions over the course of a year; 2) to reveal the diurnal variations of NH_3 and H_2S concentrations and emissions in different seasons (cold, mild, and warm seasons); 3) to evaluate the indoor air quality; and 4) to investigate the impact of environmental parameters, including ventilation rate (VR), T, and relative humidity (RH), on gas concentrations and emissions for the two barns as well as the influence of manure removal on gas concentrations and emissions for the layer barn.

5.6 MATERIALS AND METHODS

5.6.1 Description of the broiler and layer barns

The study broiler barn and cage-layer barn are located in Northern Saskatoon, Canada, both of which are typical commercial broiler and layer barns in Saskatchewan. The basic information of the two barns can be found in Table 5.1.

Table 5.1 Description of the study broiler and layer barns

	Broiler barn	Layer barn
Location	106.61 W, 52.54 N	106.41 W, 52.41 N
Operation cycle	Around 33 days for each flock and 3-week break	Around 1 year and 1-week break
Animal capacity	Around 33,000	Around 35,000
Breed	Cornish cross	Bovan white
Dimension	1638 m^2 (18 m wide × 91 m long)	986 m^2 (12 m wide × 81 m long)
Ventilation	Mechanical, 6 chimney fans and 4 end-wall fans	Mechanical, 24 side-wall fans
Air inlets	96, 48 on each side wall	162, on the ceiling
Manure removal	No manure removal during production cycles	Every 3 or 4 days by belt transportation

The broiler barn is mechanically ventilated by 6 chimney variable speed fans evenly distributed along the ridge as well as 4 end-wall fans (only working for hot hours in summer). There are also 4 recirculation fans to mix the room air. The air inlets are symmetrically installed on the side walls and controlled automatically according to the requirement of VR. The growth cycle for each flock is around 33 days followed by 3 weeks of cleaning and disinfection. The 3-week break is due to quota control by the local industry. Birds are raised loosely on the floor covered with litter. No manure collection is performed during each production cycle. A total of 6 flocks were available for the measurements between March 2015 and February 2016. Over the measuring flocks, the number of birds varied between 27,851 and 31,387, the bird age varied between 29 and 35 days, and the bird weight ranged within 1.86-2.25 kg.

The layer barn is a 4-tier stacked cage building using belt manure system. The barn is also mechanically ventilated by 4 variable speed fans and 20 single speed fans on one side wall. A total of 172 air inlets (two rows) are installed on the ceiling. One batch of birds are raised in the barn for one year followed by one-week break for cleaning and disinfection. Manure drop on the belt and would be cleaned to outside every 3 or 4 days. March 2015 was the last month of the old batch with 33922 birds, 1.98 kg of average weight, and 70 weeks old. In April, a new batch was placed which aged at 22 weeks and weighted at 1.56 kg on average. From April 2015 to February 2016, the birds number decreased from 39,760 to 39,321, and the bird weight kept increasing and reached maximum 1.87 kg in December and decreased slightly till the end of measurement.

5.6.2 Sampling and measurement methods

For the broiler barn, as manure was accumulating during production cycles and birds' weight was also maximum in the last week, sampling and measurements were conducted in the last week of flocks when the indoor air quality would be the worst (worst-case scenario). Two types of sampling were performed, including seasonal sampling and measurement for one day of each flock in April, June, August, October, November, and January, respectively, and diurnal sampling and measurements for two days in the last week of each flock in April, August, and January, which represented typical mild, warm, and cold seasons in Saskatoon, respectively. The sampling point for the broiler barn was fixed at a height of 1.2 m, located close to a chimney fan. For seasonal sampling and measurements, NH_3 and H_2S concentrations of the broiler barn were continuously monitored from 8 a.m. to 4 p.m. on the measuring day by an NH_3 sensor (C21 NH_3 transmitter, GFG Instrumentation, USA) with measurement range of 0-100 ppm and accuracy of ±5%, and an H_2S analyzer (JEROME 631-X, Arizona Instrument Corporation, Arizona Instrument LLC, USA) with measurement range of 0.003-50 ppm and accuracies of ±0.003 ppm at 0.05 ppm and ±0.03 ppm at 0.50 ppm. Simultaneously, to estimate VR, carbon dioxide (CO_2) concentrations were also continuously measured by an CO_2 sensor (K30 CO_2 sensor, CO_2 Meter, USA) with measurement range of 0-10000 ppm and accuracy of ±30 ppm ±3%. Every five minutes one data for each of the three gases was recorded by a data logger (CR10X, Campbell Scientific Corporation, Canada). All instruments were maintained and calibrated according to their operational requirements. For diurnal sampling and measurements, the three gas concentrations were continuously measured from 6 a.m. to 9 p.m. on two days in the three seasons, respectively. Seasonal measurements were not performed during the months when diurnal measurements were conducted, instead, the results from one of the two days in each of the three seasons were extracted to represent seasonal results. To assume the seasonal variations in gas concentrations and emissions were not attributed to different bird age for the broiler barn, the results on April 16th, August 4th, and January 21st were exacted to consist of seasonal profiles when bird age and weight were similar to the other months.

For the layer barn, it was defined that the last day before manure removal was the worst-case day when gas concentrations should be the highest and the first day after manure removal was the best-case day when gas concentrations should be the least. The sampling point was fixed at a height of 1.5 m close to one exhaust fan, which was working throughout the year. Seasonal measurements were only performed from 10:00 a.m. to 4:00 p.m. on one worst-case day in each month from March 2015 to February 2016. Diurnal measurements were conducted from 6:00 a.m. to 9:00 p.m. for two days during the same week in each of April (mild season), July (warm season), and January (cold season), including both a best-case day and worst-case day. The results on Apr 28th, Jul 30th, and Jan 14th were used to generate seasonal profiles as they were the worst-case days for diurnal measurements.

For both barns, respirable dust was sampled and measured in compliance with NMAM 0600 (NIOSH, 1998) by Aluminum cyclones with three-piece cassette and tared 37-mm, 5-μm PVC filters (SKC, Inc., PA, USA) when both seasonal and diurnal measurements were performed. Two samplings for respirable dust concentration were collected continuously for 2 hours in both morning (8 to 10 a.m.) and afternoon (2 to 4 p.m.) on the measuring days. Respirable dust concentration was determined by gravimetrical method and the weight difference was measured by a precise microbalance (the lowest measured value is 0.00001g). The results were expressed in unit of mg m^{-3}. Besides, the indoor T (T_{in}) and RH (RH_{in}) were continuously monitored by T/RH data loggers (OM-EL-USB-2, Omega, Canada) with measurement ranges of -35℃ to 80℃ and 0 to 100%, respectively and accuracies of 0.5℃ and 3.5%, respectively. The outdoor T(T_{out}) and RH (RH_{out}) were obtained from Environment Canada.

5.6.3 Ventilation rate and emission rate calculation

A CO_2 mass balance method was used to estimate VR with the following series of equations (CIGR, 2002):

VR per HPU = $(CO_2)_P$ × (relative animal activity) / $((CO_2)_i - (CO_2)_o)$....................................(5.1)

Relative animal activity = $1 - a \times \sin[(2 \times \pi/24) \times (h + 6 - h_{min})]$..(5.2)

$\Phi_{tot} = 10.62\ m^{0.75}$ for broilers or $\Phi_{tot} = 6.28\ m^{0.75} + 25\ Y$ for laying hens............................(5.3)

where VR is in $m^3\ h^{-1}$; $(CO_2)_P$ is CO_2 production per HPU based on a 24-h period (0.185 $m^3\ h^{-1}$); $(CO_2)_i$ is indoor CO_2 concentration and $(CO_2)_o$ is outdoor CO_2 concentration, in ppm; a is 0.08 for broilers and 0.61 for layers; h is the hours after midnight; h_{min} is hours after midnight with minimum animal activity, which is not defined for broilers by CIGR (2002) and is assumed to be 0 but is -0.1 for layers (11: 55 p.m.); Φ_{tot} is total heat production under thermoneutral conditions (20℃), in W; m is bird body mass, in kg; and Y is egg production (0.05 kg day^{-1} for consumer eggs). The actual $(CO_2)_o$ on the measurement days was measured in the warm and mild seasons and was assumed to be 390 ppm (IPCC, 2013) in the cold season. To modify Φ_{tot} per HPU outside the thermoneutral zone, the following equation was used for poultry (CIGR, 2002):

$\Phi_{tot} = 1000 + 20 \times (20 - T_{in})$...(5.4)

where T_{in} is in ℃. Knowing concentrations and VR, the emissions were calculated as follows:

$E = VR \times \Delta C$...(5.5)

where E is gas or respirable dust emission in units of mg s^{-1} AU^{-1}, mg s^{-1} m^{-2}, or mg s^{-1} $bird^{-1}$; VR is in $m^3\ s^{-1}$; and ΔC is the difference of gas concentrations between the room inlet air and exhaust air, in unit of ppm. The concentrations of NH_3 and H_2S of inlet air (ambient air) were negligible compared to the indoor concentrations and were treated to be 0.

Gas emissions were calculated on an hourly basis for both diurnal and seasonal results. Therefore, each data point of gas concentrations and emissions in the figures in the Results part were the average of hourly results within the 3 hours, or the average of hourly results from the morning and evening periods.

5.6.4 Statistical data analysis

The statistical data analysis was performed using SPSS 22 (IBM, USA). A P-value was used to indicate the significance of correlations between gas concentration or emission and environmental parameters ($P \leq 0.05$ indicates a significant correlation and $P \leq 0.01$ indicates a very significant correlation). To compare the differences of diurnally measured gas concentrations and emissions from the cold, mild, and warm seasons, the results of the two days in each season were pooled together to consist of one group. A General Linear Model was applied where Duncan test was performed to conduct multiple comparisons among the three seasons.

5.7 RESULTS AND DISCUSSION

5.7.1 Diurnal concentration and emission profiles

5.7.1.1 Broiler barn

The 3-hour average VR and NH_3 concentrations and emissions in the three seasons for the broiler barn are plotted in Fig. 5.1. The average VR was 26 m^3 s^{-1}, 40 m^3 s^{-1}, and 10 m^3 s^{-1}, respectively, in April (the mild season), August (the warm season), and January (the cold season). In the mild season, VR was low in the early morning (6:00 a.m.) but increased during the day. On April 16th, there was an abrupt increase in VR from around 2:00 p.m., which was not observed on April 14th. This is due to that the 4 end-wall fans were starting to run from around 2:00 p.m. on April 16th because of the over-high T_{in} in the afternoon, which greatly increased VR. In the warm season, VR showed a similar diurnal varying curve on August 4th to that in the mild season (low in the early morning and gradually raised after). Compared to diurnal VR on August 4th, VR continuously decreased from 3:00 p.m. to 9:00 p.m. on August 6th, which is explained by that there was rain on August 6th and the T_{out} decreased from 3:00 a.m. The largest diurnal variations of VR were observed in the mild season with maximum 50 m^3 s^{-1} and minimum 9 m^3 s^{-1} when the diurnal variations of T_{out} were also greatest (the difference between the minimum T_{out} in the early morning and maximum T_{out} in the afternoon was up to 22℃). Diurnal VR fell within a narrow range of 8-11 m^3 s^{-1} on the two days in the cold season.

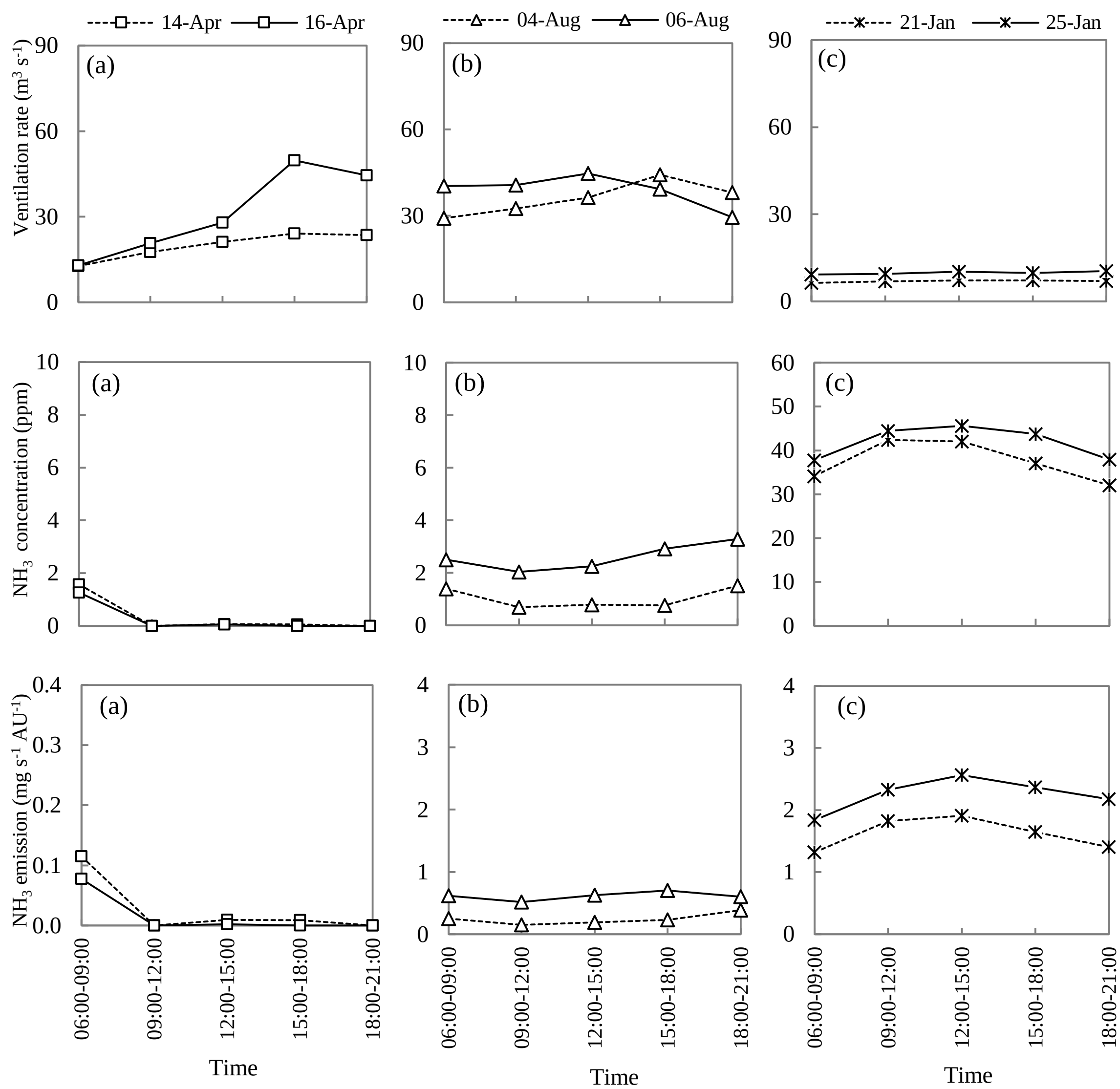

Figure 5.1 3-Hour average VR and NH_3 concentrations and emissions of the broiler barn in the mild (a), warm (b), and cold (c) seasons.

In the mild season, NH_3 concentration was below 2 ppm in the early morning and could not be detected from around 8 a.m. till the end of the measurement. Hence, NH_3 emission was only measurable in the early morning. In the warm season, both VR and NH_3 concentrations remained stable thus large variance was not observed in NH_3 emissions. Roumeliotis et al. (2010) found that hourly NH_3 emission from broiler barn could change significantly in summer time so that discrete measurements can not reflect diurnal trends. In this study, it was found that NH_3 emission in the summer was likely to be lowest during the time of 9 a.m. to 12 p.m. and increased in the afternoon.

In the cold season, VR was stable during the day while NH_3 concentration pattern showed a parabolic shape with relatively low NH_3 concentration in the early morning from 6 to 9 a.m. and in the early evening from 6 to 9 p.m., which resulted in similar diurnal NH_3 emission patterns. These results do not agree with Zhu et al. (2000) who found that NH_3 concentrations in fall time (late September) was relatively low in the early morning at 7 a.m. and remained constant during the day time. The diurnal varying range of NH_3 concentration reported by Zhu et al. (2000) was from 9 to 13 ppm, which was lower than 32 to 46 ppm in the winter but was higher than 0-2 and 1-3 ppm in the mild and warm seasons as found by this study. Diurnal NH_3 emission showed patterns in consistent with that of NH_3 concentrations for all three seasons, with lows and peaks of emission occurring at the same time as that of concentration. Calvet et al. (2011) reported NH_3 emissions at 5.03 μg bird^{-1} s^{-1} in summer and 6.65 μg bird^{-1} s^{-1} in winter in the fifth week of the growing cycles for a broiler barn located in eastern region of Spain. The average NH_3 emission from this broiler was lower in the summer but was higher in the winter than the results of Calvet et al. (2011) mainly due to the concentration difference.

Table 5.2 Summary of min, max, mean, and standard deviation of diurnal results in the three seasons for the broiler barn.

	Mild			Warm			Cold		
	Min	Max	Mean (SD)	Min	Max	Mean (SD)	Min	Max	Mean (SD)
NH_3 C (ppm)	0	2	0 (1)^b	1	3	2 (1)^b	32	46	40 (5)^a
NH_3 E (mg s^{-1} AU^{-1})	0	0.11	0.02 (0.04)^b	0.15	0.70	0.43 (0.21)^b	1.31	2.53	1.92 (0.41)^a
NH_3 E (μg s^{-1} bird^{-1})	0	0.43	0.08 (0.16)	0.57	2.86	1.71 (0.88)	5.48	12	8.69 (2.36)
NH_3 E (μg s^{-1} m^{-2})	0	8	2 (3)	10	52	31 (16)	98	217	156 (42)
H_2S C (ppb)	19	145	66 (51)^b	2	89	32 (30)^b	226	401	328 (63)^a
H_2S E (μg s^{-1} AU^{-1})	4	33	17 (11)^b	1	43	16 (15)^b	21	41	31 (7)^a
H_2S E (μg s^{-1} bird^{-1})	0.01	0.12	0.07 (0.04)	0.00	0.16	0.06 (0.05)	0.09	0.20	0.14 (0.04)
H_2S E (μg s^{-1} m^{-2})	0.28	2.36	1.28 (0.75)	0.07	2.97	1.08 (0.99)	1.17	3.54	2.34 (0.90)

Notes: C is concentration; E is emission; SD is standard deviation; and letters a, b and c are used to indicate the significance of the difference in the measured item among the three seasons at the 0.05 level (the same letters mean the difference is not significant). The min, max, mean, and SD were calculated from the diurnal 3-hour results of the two days in each season.

As given in Table 5.2, H_2S concentrations and emissions were very low compared to NH_3 concentrations and emission. In both mild and warm seasons, H_2S concentrations were obviously higher for one day than the other, the reason for which could not be found. In the cold season, diurnal H_2S concentrations and emissions varied similarly on both days; remained high and stable in the morning from 6 a.m. to 12 p.m. and decreased gradually till the end of the measurement.

Similar to NH_3 emission, H_2S emission seemed to be more affected by concentration rather than VR and showed similar trends as diurnal H_2S concentrations in all three seasons.

5.7.1.2 Layer barn

Diurnal 3-hour average VR and NH_3 concentrations and emissions in the three seasons for the layer barn are given in Fig. 5.2. The average VR was highest in the warm season (70 m^3 s^{-1}), followed by the mild season (34 m^3 s^{-1}) and then the cold season (8 m^3 s^{-1}). Similar to the broiler barn, diurnal VR was found to vary more greatly in both mild and warm seasons. In the mild season, VR gradually increased from 6:00 a.m. and reached a peak in the early afternoon within 12:00 to 3:00 p.m. and then gradually decreased till 9:00 p.m., which followed the diurnal pattern of T_{out}. In the warm season, there was a large diurnal variance in the VR on the worst-case day with the ratio of maximum to minimum up to 4, while relatively lower and flat curve of diurnal VR from 9:00 a.m. to 6:00 p.m. was observed on the best-case day due to the rain and cooler weather. In the cold season, VR displayed consistent diurnal patterns for the two days within a low narrow range of 5.8-10.7 m^3 s^{-1}.

Overall, NH_3 concentrations were highest in the cold season and lowest in the warm season. The highest NH_3 emissions were observed in the mild season when comparing the worst-case days, while no significant difference was found for best-case days of the three seasons. In the mild season, NH_3 concentrations tended to be high in the early morning (6:00 a.m. to 9:00 a.m.) and the early evening (6:00 p.m. to 9:00 p.m.) on both best-case and worst-case days when VR was low. In the warm season, NH_3 concentration was low and constant. In the cold season, NH_3 concentrations gradually increased from the early morning to the evening on the worst-case day, while was stable on the best-case day. As for NH_3 emission, great diurnal variations were found for worst-case days in the mild season and cold season, both with a peak occurring in the early afternoon. This partially agrees with Alberdi et al. (2016) who found the diurnal patterns of NH_3 emissions for a layer barn did not differ between the seasons, all with a peak occurring around the noon time.

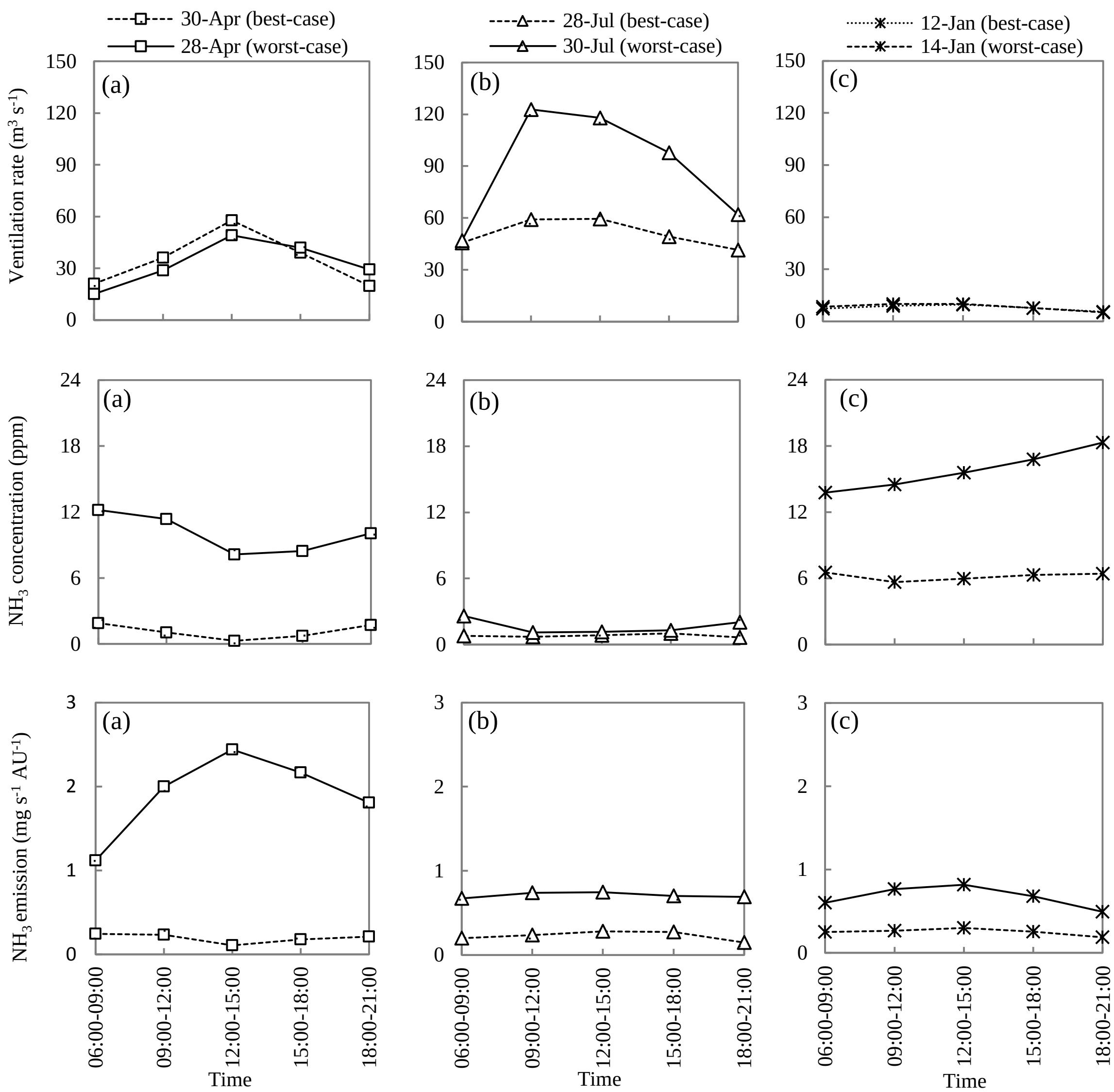

Figure 5.2 3-hour average VR and NH_3 concentrations and emissions of the layer barn in the mild (a), warm (b), and cold (c) seasons.

It was found that removing manure from the belt greatly reduced NH_3 concentrations and emissions in the mild and cold seasons (Fig. 5.2). The reduction rate was 61% and 89%, respectively, in the cold and mild seasons for NH_3 concentrations, and 62% and 90%, respectively, in the cold and mild seasons for NH_3 emissions. Nicholson et al. (2004) also found twice weekly belt-scraping reduced NH_3 emissions by 50% compared with weekly cleaning for a layer house. Similar to that of the broiler barn, H_2S concentrations and emissions of the layer barn were also very low and were not plotted. The statistical description of the data can be found in Table 5.3. It was found that the highest H_2S concentrations and emissions were in the warm season followed by the mild season and then the cold season. Similarities were observed in diurnal varying patterns of H_2S concentrations and emissions in the mild and warm seasons, with an overall decreasing trend of H_2S concentrations during the day and with one peak occurring for H_2S emissions on both best-case and worst-case days. Additionally, manure removal also reduced H_2S concentrations and emissions in the mild season, with reduction ratios of 95% and 96% for H_2S concentrations and emissions, respectively. However, the reduction ratios of 13% and 50% for H_2S concentrations and emissions by manure removal in the warm season need to be further validated due to the great variance of VR between the best-case day and worst-case day.

Table 5.3 Summary of mean of diurnal results on the best-case days and worst-case days and overall mean in the three seasons for the layer barn.

	Mild			Warm			Cold		
	D_{best}	D_{worst}	Mean	D_{best}	D_{worst}	Mean	D_{best}	D_{worst}	Mean
NH_3 C	1	10	6	1	2	1	6	16	11
(ppm)	(0.2)	(1.2)	$(5)^b$	(0.1)	(0.7)	$(1)^c$	(0.4)	(1.8)	$(5)^a$
NH_3 E	0.19	1.91	1.05	0.23	0.71	0.47	0.25	0.67	0.46
(mg s^{-1} AU^{-1})	(0.05)	(0.50)	$(0.96)^a$	(0.05)	(0.04)	$(0.26)^b$	(0.04)	(0.13)	$(0.24)^b$
NH_3 E	0.60	5.96	3.28	0.80	2.46	1.63	0.93	2.48	1.71
(µg s^{-1} $bird^{-1}$)	(0.17)	(1.56)	(3)	(0.19)	(0.13)	(0.89)	(0.15)	(0.48)	(0.88)
NH_3 E	24	241	133	32	99	66	37	99	68
(µg s^{-1} m^{-2})	(7)	(63)	(122)	(8)	(5)	(36)	(6)	(19)	(35)
H_2S C	1	28	16	49	56	53	4	0	1
(ppb)	(2)	(6)	$(0)^b$	(6)	(6)	$(9)^a$	(7)	(0)	$(5)^c$
H_2S E	0.5	11	6	27	55	41	0.34	0.02	0.18
(µg s^{-1} AU^{-1})	(0.7)	(3)	$(6)^b$	(6)	(22)	$(21)^a$	(0.62)	(0.03)	$(0.45)^b$
H_2S E	0.00	0.03	0.02	0.10	0.19	0.14	0.00	0.00	0.00
(µg s^{-1} $bird^{-1}$)	(0.00)	(0.01)	(0.02)	(0.02)	(0.08)	(0.07)	(0.00)	(0.00)	(0.00)
H_2S E	0.06	1.35	0.70	4	8	6	0.05	0.00	0.03
(µg s^{-1} m^{-2})	(0.08)	(0.39)	(0.73)	(1)	(3)	(3)	(0.09)	(0.00)	(0.07)

Notes: C is concentration and E is emission; D_{best} is the best-case day and D_{worst} is the worst-case day; the numbers in parenthesises are standard deviation (SD); letters a, b and c are used to indicate the significance of the difference in the measured item among the three seasons at the 0.05 level (the same letters mean the difference is not significant). The mean and SD for D_{best} and D_{worst} were calculated from the diurnal 3-hour results.

5.7.2 Seasonal concentration and emission profiles

Seasonal patterns of environmental parameters (including T_{in}, T_{out}, and VR) and gas concentrations and emissions are plotted in Fig. 5.3 for the broiler barn and Fig. 5.4 for the layer barn.

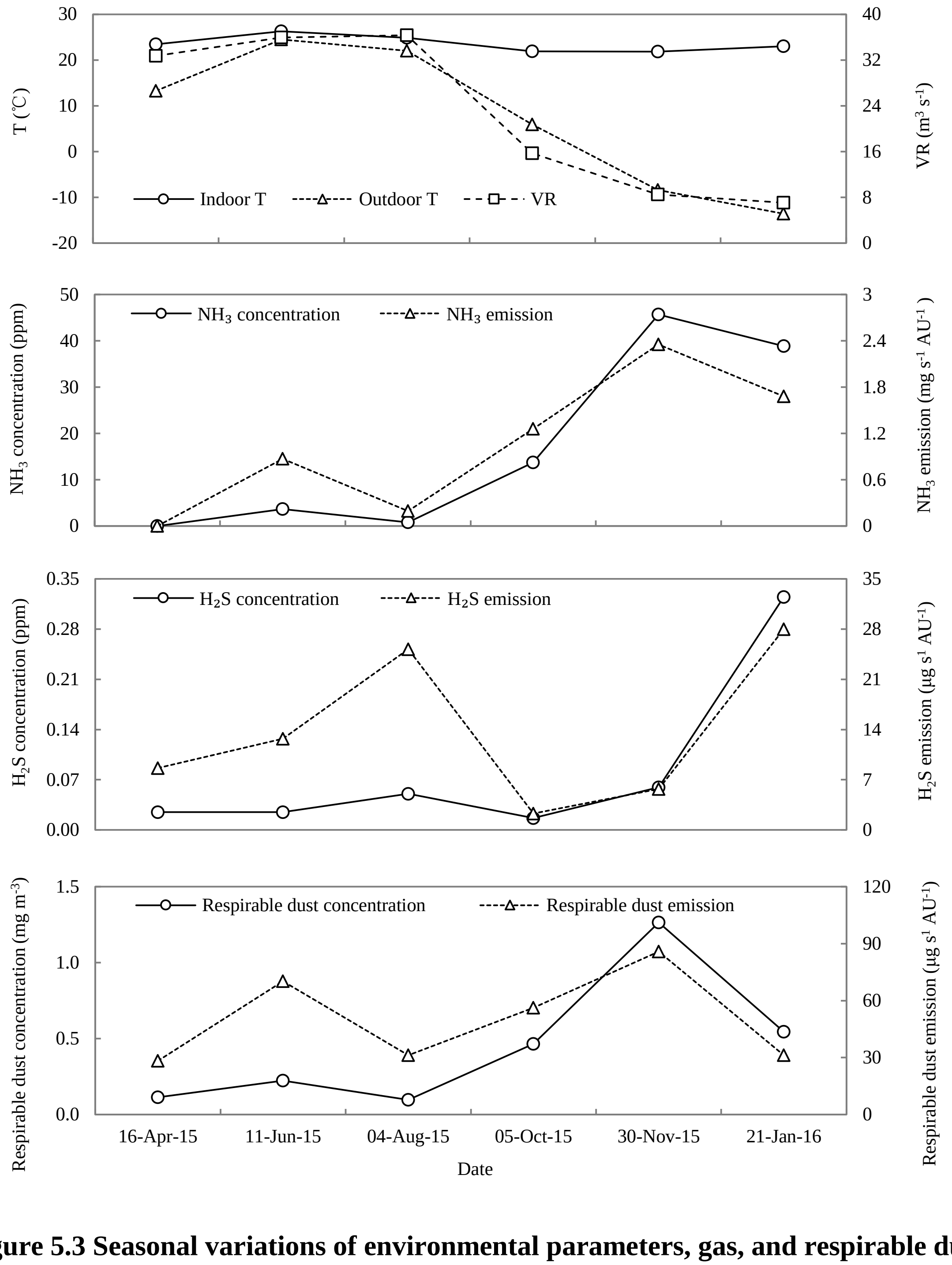

Figure 5.3 Seasonal variations of environmental parameters, gas, and respirable dust concentrations and emissions of the broiler barn.

Throughout the year, the T_{out} changed greatly from below -30℃ to above 30℃; however, only the average T_{out} for the measured hours during the day were used to relate to gas concentrations and emissions. Seasonal VR ranged from 7 to 36 $m^3 s^{-1}$ for the broiler barn and from 10 to 120 $m^3 s^{-1}$ for the layer barn, both following the pattern of T_{out} with higher level in the mild (April and October) and warm seasons (May to September). As the result, the T_{in} fell within a narrow range of 19℃ to 26℃ for the layer barn and 22℃ to 26℃ for the broiler barn. In addition, RH_{out} also varied greatly from minimum of 19% to maximum of 85%, while RH_{in} ranged from 27% in May to 63% in February for the layer barn and from 48% in June to 71% in January for the broiler barn.

Seasonal NH_3 concentrations varied within ranges of 1-20 ppm for the layer barn and of 0-46 ppm for the broiler barn, with obviously higher NH_3 concentration level in the cold season than in the warm season. The NH_3 emissions changed between 0.45 and 2.30 mg s^{-1} AU^{-1} for the layer barn, and between 0 and 2.35 mg s^{-1} AU^{-1} for the broiler barn. Seasonal effect was proven to be significant for both NH_3 concentration and NH_3 emission ($P<0.05$). The emissions of NH_3 displayed opposite trends to NH_3 concentrations for the layer barn, with higher averages in the mild and warm seasons than that in the cold season. Lin et al. (2012) also found higher daily NH_3 emission in summer than in winter for a high-rise layer facility in California. However, due to the much increased NH_3 concentrations in the entire winter (above 35 ppm), seasonal variations of NH_3 emissions from the broiler barn were dominated by NH_3 concentrations with higher emissions occurring in the winter as well.

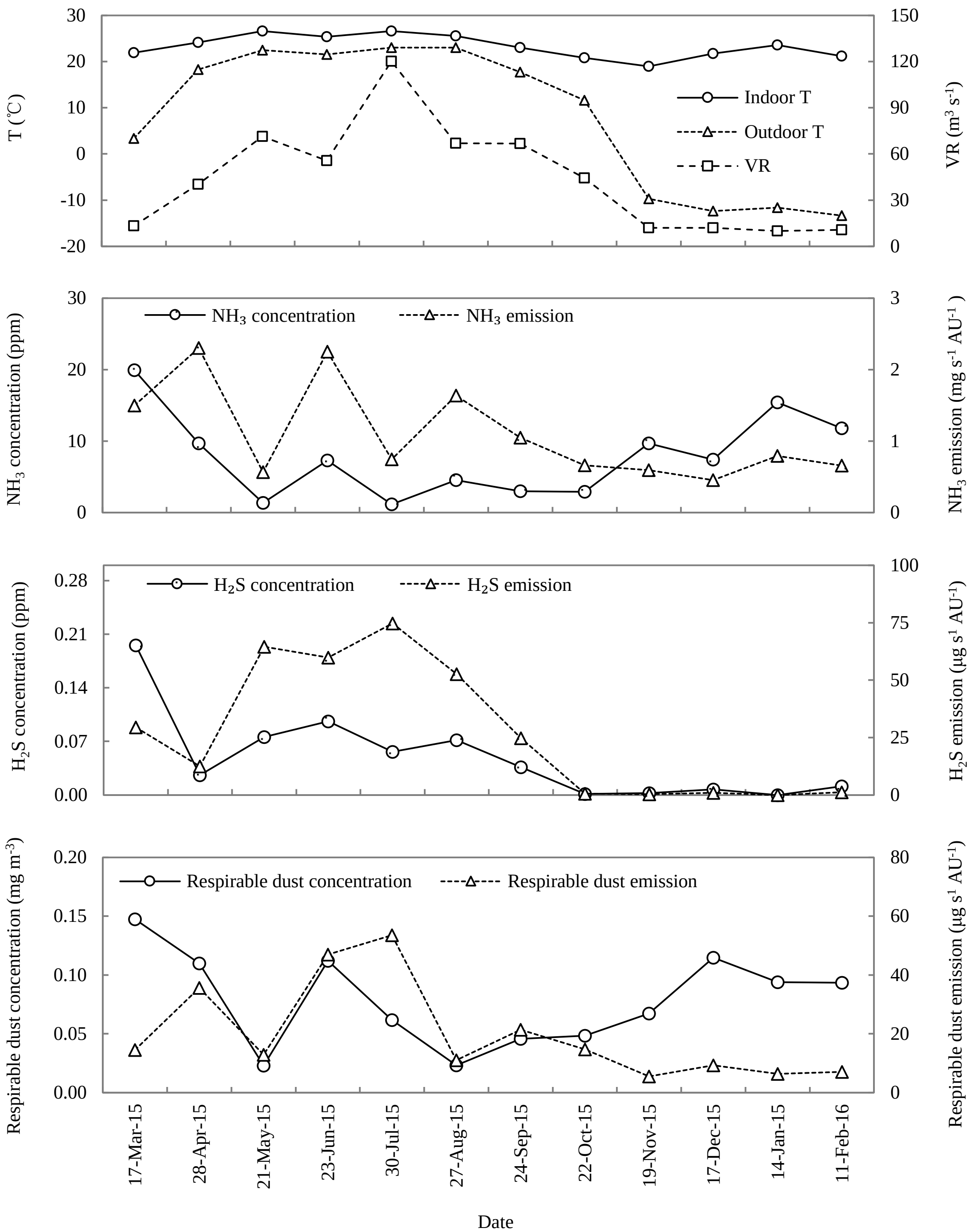

Figure 5.4 Seasonal variations of environmental parameters, gas, and respirable dust concentrations and emissions of the layer barn.

The overall annual mean NH_3 concentration for the broiler barn was 17 ppm, which was a little lower than that of Wathes et al. (1997) who reported an average NH_3 concentration at 24 ppm for broiler houses in UK. They observed that maximum hourly NH_3 concentration exceeded 40 ppm, which also occurred for the broiler barn in November in this study. Guiziou et al. (2005) measured a range of 0.8-32 ppm for NH_3 concentration from broiler houses in France and Redwine et al. (2002) observed NH_3 concentrations between 2 and 45 ppm from broiler houses in Texas, USA. However, the ranges they reported were all from the whole growth cycles. This study observed below 4 ppm of NH_3 concentration in the mild (April) and warm seasons (June and August), which was different from the result of Casey et al. (2010) who measured over 20 ppm of NH_3 concentration in May from a broiler house in south-central Kentucky. That difference may be explained by the higher VR for the broiler barn in this study than that in the study of Casey et al. (2010) (averaged 35 m^3 s^{-1} in the mild and warm seasons compared to 23 m^3 s^{-1} in May) and also by the long growing period (49 days or longer) of birds in the study of Casey et al (2010). It was also suggested that manure moisture is an important factor to influence NH_3 emissions, and in poultry houses high moisture content in the litter is usually associated with higher NH_3 concentrations and emissions (Meda et al., 2011), which was confirmed by this study where positive correlation between NH_3 concentration and indoor RH for this broiler barn was observed ($P<0.05$). The outdoor and indoor RH were relatively low in the mild and warm seasons compared to the cold season, especially in April and August only 35.7% and 41% of RH_{in} were observed while 68.8% and 70.8% of RH_{in} were measured in November and January. It was expected that the litter moisture content was less in drier room air, which would result in less NH_3 generation. The average daily NH_3 emission factor for summer (June and August flocks), winter (November and January flocks), and for annual was 0.53 mg s^{-1} AU^{-1}, 2.02 mg s^{-1} AU^{-1} and 1.06 mg s^{-1} AU^{-1}, respectively, which was lower than the warmer season result (1.09 mg s^{-1} AU^{-1}) while was higher than the cooler season result (0.76 g day^{-1} AU^{-1}) of Roumeliotis et al (2010). Gay et al. (2003) reported a range of 17-107 μg s^{-1} m^{-2} for NH_3 emission flux from broiler barns. In this study, the average NH_3 emission flux was calculated to be 80 μg s^{-1} m^{-2} and was within that range.

Seasonal variations of NH_3 emissions were also significant for the layer barn, which is in line with what Alberdi et al. (2016) found for a cage layer facility (52, 000 hens) under Oceanic climate conditions with a manure removal frequency of around every 3 days. An average NH_3 emission of 144.9 mg d^{-1} $bird^{-1}$ (1.68 μg s^{-1} $bird^{-1}$) in summer and of 90.3 mg d^{-1} hen^{-1} (1.05 μg s^{-1} $bird^{-1}$) in winter was reported by Alberdi et al. (2016), both were lower than the results in this study when using the monthly measured results acquired only on worst-case days (4.30 μg s^{-1} $bird^{-1}$ in summer and 3.02 μg s^{-1} $bird^{-1}$ in winter). However, if using the diurnal results in Table 5.3 for averages of best-case and worst-case results for the layer barn, the summer averages and winter averages were found to be comparable to the results of Alberdi et al. (2016). Since NH_3 emissions were reduced greatly by manure removal in the mild and cold seasons as discussed above, a correction factor of 0.62 and 0.90 was used to adjust the seasonal results from the worst-case measurements in the cold and mild seasons, respectively, while the summer results were not adjusted as the effect of manure removal was not clear in the warm season. The adjust NH_3 emission values for annual averages are given in Table 5.4. From a bench-scale study, Fournel et al. (2012) found the average NH_3 emission over the 8 weeks from March to May 2010 and June to August 2010 was 32 g $year^{-1}$ $bird^{-1}$ (1 μg s^{-1} $bird^{-1}$) for "manure belt-natural drying" system and was 24.2 g $year^{-1}$ $bird^{-1}$ (0.77 μg s^{-1} $bird^{-1}$) for "manure belt-forced air drying" system. The average NH_3 emission (5 μg s^{-1} $bird^{-1}$) and adjusted emission (4.79 μg s^{-1} $bird^{-1}$) within the same periods for the layer barn in this study was both much higher with a much greater birds density of 40 birds m^{-2} than 10 birds m^{-2} in the study of Fournel et al. (2012).

Table 5.4 Summary of seasonal NH_3, H_2S, and respirable dust concentrations and emissions of the broiler and layer barns.

	Broiler			Layer (worst-case)			
Items	Min	Max	Mean (SD)	Min	Max	Mean (SD)	Adjusted mean
NH_3 concentration (ppm)	0	46	17 (20)	1.1	19.9	7.8 (5.8)	5.7
NH_3 emission (mg s^{-1} AU^{-1})	0	2.35	1.06 (0.90)	0.45	2.30	1.10 (0.66)	0.89
NH_3 emission (μg s^{-1} $bird^{-1}$)	0	10.59	4.52 (4.01)	1.70	7.52	3.85 (2.15)	3.10
NH_3 emission (mg s^{-1} m^{-2})	0	0.18	0.08 (0.07)	0.07	0.30	0.15 (0.08)	0.12
H_2S concentration (ppb)	17	325	84 (120)	0	196	48 (57)	/
H_2S emission (μg s^{-1} AU^{-1})	2.31	28	13.77 (10.55)	0	74.79	26.80 (28.84)	/
H_2S emission (μg s^{-1} $bird^{-1}$)	0.01	0.12	0.06 (0.04)	0	0.26	0.09 (0.10)	/
H_2S emission (μg s^{-1} m^{-2})	0.18	2.10	1 (0.75)	0	10.51	3.67 (3.95)	/
Respirable dust concentration (mg m^{-3})	0.10	1.26	0.45 (0.44)	0.02	0.15	0.08 (0.04)	/
Respirable dust emission (μg s^{-1} AU^{-1})	58	85	50 (24)	53	5	20 (16)	/
Respirable dust emission (μg s^{-1} $bird^{-1}$)	0.003	0.045	0.016 (0.016)	0.001	0.004	0.002 (0.001)	/
Respirable dust emission (μg s^{-1} m^{-2})	0.06	0.77	0.28 (0.27)	0.02	0.15	0.08 (0.04)	/

Notes: SD is standard deviation. The data for the layer barn were acquired only on worst-case days.

Compared to NH_3, H_2S concentrations and emissions were low for both barns and were much less reported in literatures. Lim et al. (2003) found the average H_2S concentrations and emissions were 19.7 ppb and 2.5 μg s^{-1} AU^{-1} for a 250,000 hen, high-rise laying house from March to May 2002 in USA, compared to 99 ppb and 36 μg s^{-1} AU^{-1} in this study. Lin et al. (2012) indicated that the average daily mean NH_3, H_2S, and respirable dust emissions were 0.95 g d^{-1} $bird^{-1}$ (11 μg s^{-1} $bird^{-1}$), 1.27 mg d^{-1} $bird^{-1}$ (0.015 μg s^{-1} $bird^{-1}$), and 33.4 mg d^{-1} $bird^{-1}$ (0.39 μg s^{-1} $bird^{-1}$) for a high-rise layer house (32,500 hens) in USA. The average NH_3 and respirable dust emissions for the layer barn in this study were lower while the average H_2S emission were higher (see Table 5.4) than the results of Lin et al. (2012). Lin et al. (2012) also observed higher respirable dust emission in summer than in winter; however, the conclusion is the opposite in this study, which might be due to the high air ventilation in summer for the study layer barn. Comparing the seasonal gas and respirable dust concentrations and emissions of the broiler barn and layer barn, it was found that the broiler barn generated higher concentrations of all three air pollutants, but lower emissions (based on per AU) except respirable dust, which suggests possible poorer indoor but lower outdoor air pollution for the broiler barn than the layer barn.

5.7.3 Indoor air quality evaluation

Knowing the gas and respirable dust concentrations, the indoor air quality was evaluated considering not only the concentration levels of individual pollutants but also the possible additive health effect of these mixtures. The U.S. Occupational Safety and Health Administration regulated the exposure limit values of different air pollutants based on their health effect, including NH_3, H_2S, and respirable dust (ACGIH, 2010). As NH_3, H_2S, and respirable dust all cause respiratory irritation, their health effect should be considered as additive (ACGIH, 2010). Therefore, we used an air quality indicator to describe the health impact of each gas, which is the ratio of the gas concentrations to its exposure limit. The sum of the combined air quality indicator of NH_3, H_2S, and respirable dust represents their additive health effect on respiratory system. The 8-hourly time-weighted average (TWA-TLV) for NH_3 and H_2S are 25 ppm and 1 ppm, respectively, and short-term exposure limit (STEL-TLV) less than 15 minutes are 35 ppm and 5 ppm, respectively (ACGIH, 2010). An exposure limit of 3 mg m^{-3} for respirable dust was set without specifying whether it is TWA-TLV or STEL-TLV and was used as TWA-TLV in this study (ACGIH, 2010). The 8-hourly averages of air quality Index were calculated using data from 9 a.m. to 5 p.m. for NH_3 and H_2S, and from using the averages of morning results and afternoon results for respirable dust from the diurnal measurements in the three seasons and the results were listed in Table 5.5.

Table 5.5 Indicator (the ratio of 8-hourly average concentration to TWA-TLV) of individual air pollutant concentration levels and their combined indicator.

		Mild		Warm		Cold	
		Apr 14	Apr 16	Aug 04	Aug 06	Jan 21	Jan 25
Broiler barn	NH_3 C	0.00	0.00	0.03	0.09	1.64	1.76
	H_2S C	0.13	0.02	0.07	0.01	0.22	0.37
	Respirable dust	0.02	0.04	0.03	0.03	0.18	0.15
	Combined	0.15	0.06	0.13	0.13	2.04	2.28
		Mild		Warm		Cold	
		April 30 (best-case)	April 28 (worst-case)	July 28 (best-case)	July 30 (worst-case)	Jan 12 (best-case)	Jan 14 (worst-case)
Layer barn	NH_3 C	0.03	0.38	0.03	0.05	0.24	0.62
	H_2S C	0.00	0.03	0.05	0.06	0.01	0.00
	Respirable dust	0.04	0.04	0.02	0.02	0.03	0.06
	Combined	0.07	0.45	0.10	0.13	0.28	0.68

Notes: C is concentration.

For the broiler barn, H_2S and respirable dust concentrations were below the TWA-TLV and STEL-TLV for all seasons. In both mild and warm seasons, NH_3 concentration remained below the TWA-TLV as well as the STEL-TLV, however, it was above 30 ppm for the entire two days in the cold season, which exceeded the TWA-TLV and even higher than the STEL-TLV for the entire day of November 30th and Jan 25th, and for the whole period of from 9 a.m. to 6 p.m. on Jan 21th. Therefore, it can be concluded that the indoor air quality based on the health effect of respiratory irritation was acceptable in the mild and warm seasons but was very poor in the cold season exceeding both TWA and STEL of NH_3 and the combined indicator for NH_3, H_2S, and respirable dust was very high. For the layer barn, none of the individual air pollutant concentrations exceeded the TWA-TLV or STEL-TLV in any season. The combined air quality indicator of these three air pollutants were also below 1. However, the air quality of the worst-case days in both cold season and mild season was much poorer than that of the warm season, as given in Table 5.5. Besides, the indoor air quality was much improved by manure removal in both mild and cold seasons by comparing the air quality indicators.

5.7.4 Impact of environmental parameters

The correlation coefficients for gases against environmental parameters are all listed in Table 5.6. it was found that T_{out} and VR were the two most related factors to both NH_3 concentrations and emissions with negative correlations for the broiler barn (P<0.01). Similar findings were found for the layer barn as well, except that no significant impact of VR on NH_3 emission were found (P>0.05). Significant negative effect of T_{out} and VR on H_2S concentrations were also indicated for the broiler barn (P<0.01), while H_2S concentration were positively related to T_{out} and VR for the layer barn. Much less influence of the environmental parameters on H_2S emission was observed for the broiler barn, including T_{out} and VR, which agrees with Lin et al. (2012) who also found the H_2S emission was not related to ambient temperature. Ni et al. (2012) found the impact of temperature and VR on H_2S concentrations were not as obvious as NH_3 concentrations for high-rise and manure-belt layer hen houses, and this study had similar findings.

Table 5.6 Correlations between gas concentrations or emissions and environmental parameters.

	Broiler barn					Layer barn				
	T_{in}	T_{out}	RH_{in}	RH_{out}	VR	T_{in}	T_{out}	RH_{in}	RH_{out}	VR
NH_3 C	0.05	-0.89**	0.42**	0.55**	-0.71**	-0.14	-0.60**	0.37**	0.27*	-0.62**
NH_3 E	0.06	-0.76**	0.47**	0.61**	-0.57**	0.29*	0.36**	-0.31*	-0.38**	0.23
H_2S C	0.23	-0.80**	0.25	0.40**	-0.66**	0.20	0.45**	-0.27*	0.18	0.36**
H_2S E	0.50**	-0.26	-0.10	0.03	-0.23	0.51**	0.64**	-0.34*	-0.37**	0.82**

Notes: C is concentration in ppm for gases; and E is emission in mg s^{-1} AU^{-1} for NH_3 and μg s^{-1} AU^{-1} for H_2S. ** indicates correlation is significant at the 0.01 level and * indicates correlation is significant at the 0.05 level.

5.8 CONCLUSIONS

Diurnal and seasonal variations of NH_3 and H_2S concentrations and emissions were identified for a commercial broiler barn and cage-layer barn in the Canadian Prairies climate. Seasonal respirable dust concentrations and emissions were also measured. The following findings are summarized:

1) The broiler barn displayed higher annual averages of NH_3, H_2S, and respirable dust concentrations and higher annual averages of respirable dust emissions than the layer barn. The annual average emissions of NH_3, H_2S, and respirable dust were 1.06 mg s^{-1} AU^{-1}, 13.77 μg s^{-1} AU^{-1}, and 50 μg s^{-1} AU^{-1}, respectively, for the broiler barn, and were 1.10 mg s^{-1} AU^{-1}, 26.80 μg s^{-1} AU^{-1}, and 20 μg s^{-1} AU^{-1}, respectively, for the layer barn. For the broiler barn, NH_3 concentrations and emissions, and H_2S and respirable dust concentrations were all higher in the cold season, while no specific varying patterns of H_2S and respirable dust emissions were found. For the layer barn, NH_3 and respirable dust concentrations were

both relatively higher in the cold season, while higher NH_3 and respirable emissions were observed in the mild and warm seasons. The concentrations and emissions of H_2S of the layer barn were highest in the warm season and were very low in the cold season excluding March.

2) Indoor air quality was evaluated using a quantified indicator by considering not only the health effect of the three individual air pollutants (NH_3, H_2S, and respirable dust) but also their additive effect on respiratory system. It showed the indoor air quality of the broiler barn could be an issue in the cold season as both the 8-hourly and 15-minute exposure limits of NH_3 were exceeded, and the greater combined indicator suggested the situation could be worse.
3) Manure removal by belt transportation proved to efficiently reduce NH_3 concentrations and emissions. In the mild and cold seasons, NH_3 concentrations were reduced by 89% and 61%, respectively, and NH_3 emissions were decreased by 90% and 62%, respectively.
4) The impact of the five environmental parameters (including indoor and outdoor T, indoor and outdoor RH, and VR) on gases were investigated. It was found that T_{out} and VR were the two most related factors to NH_3 and H_2S concentrations and emissions, Negative impact of T_{out} and VR on NH_3 concentrations for both barns and on NH_3 emissions for the broiler barn was indicated, while positive effect of T_{out} and no significant impact of VR on NH_3 emissions was suggested for the layer barn.

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CHAPTER 6
DIURNAL AND SEASONAL VARIATIONS OF GREENHOUSE GAS EMISSIONS FROM A NATURALLY VENTILATED FREE-STALL DAIRY BARN ON THE CANADIAN PRAIRIES

6.1 VERSION PRESENTED IN A JOURNAL

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6.2 CONTRIBUTION OF THE PH.D. CANDIDATE

The samples collection, data analysis, and manuscript writing were performed by the candidate. The measurements of CO_2 were performed by the candidate while samples were sent to the Soil Laboratory at University of Saskatchewan for CH_4 and N_2O measurements. RLee Prokopishyn and Louis Roth helped with the instrument set-up and maintenance. Besides, Zhu Gao and Jingjing Han participated in some of the field measurements and assisted with air sample collection. Dr. Huiqing Guo provided editorial input and suggestions on methods and data analyses.

6.3 CONTRIBUTION OF THIS PAPER TO THE OVERALL STUDY

Diurnal and seasonal variations of GHG concentrations and emissions of the dairy barn were introduced in this paper. The emission factors of CO_2, CH_4, N_2O, and total GHG were obtained and the CH_4 emission factor was compared with that estimated in the inventory for dairy. Comparisons of the results with that of previous studies were conducted and the impact of environmental parameters (indoor and outdoor T, indoor and outdoor RH, and VR) on GHG concentrations and emissions were examined.

6.4 ABSTRACT

The emissions of CO_2, CH_4, and N_2O were quantified for a naturally ventilated free-stall dairy barn in the Canadian Prairies climate through continuous measurements for a year from February 2015 to January 2016, with VR estimated by a CO_2 mass balance method. The results were categorized into seasonal emission profiles with monthly data measured on a typical day, and diurnal profiles in cold (January), warm (July), and mild seasons (October) of all three gases. Seasonal CO_2, CH_4, and N_2O concentrations greatly fluctuated within ranges of 593-2433 ppm, 15-152 ppm, and 0.32-0.40 ppm, respectively, with obviously higher concentrations in the cold season. Emission factors of the three gases were summarized: seasonal N_2O emission varied between 0.5-10 μg s^{-1} AU^{-1} with lower emission in the cold season, while seasonal CO_2 and CH_4 emissions were within narrow ranges of 112-119 mg s^{-1} AU^{-1} and 2.5-3.5 mg s^{-1} AU^{-1}. The result suggested a lower enteric CH_4 emission for dairy cows than that estimated by Environment Canada (2014). Significant diurnal effects ($P<0.05$) were observed for CH_4 emissions in all seasons with higher emissions in the afternoons and evenings. The total GHG emission, which was calculated by summing the three GHG in CO_2 equivalent, was mainly contributed by CO_2 and CH_4 emissions and showed no significant seasonal variations ($P>0.05$), but obvious diurnal variations in all seasons. In comparison with previous studies, it was found that the dairy barn in a cold region climate with smaller vent openings had relatively higher indoor CO_2 and CH_4 concentrations, but comparable CO_2 and CH_4 emissions to most previous studies. Besides, VR, temperature, and relative humidity all significantly affected the three gas concentrations with the outdoor temperature being the most relevant factor ($P<0.01$); however, they showed less or no statistical relations to emissions.

6.5 INTRODUCTION

Agriculture production is a large source of N_2O and CH_4 emissions (Aneja et al., 2009); and livestock production is a major contributor to GHG emissions in agriculture. According to Steinfeld et al (2006), about 18% of global GHG emissions were caused by livestock production in some way. In Europe, it was indicated that dairy accounted for the largest livestock-related GHG emissions followed by beef, and together the two sectors emitted more than 70% of GHG emissions from livestock production (Lesschen et al., 2011). In the United States, it was reported that dairy cattle and all livestock contributed 0.55% and 2.75% of total anthropogenic GHG emissions, respectively (US EPA, 2012). In Canada, agriculture accounted for 27% and 70% of the national CH_4 emission and N_2O emission, with a contribution of 62% of total agricultural emissions from livestock emissions, and the largest contributor to GHG emissions in livestock section is beef followed by dairy cattle (Environment Canada, 2014).

Canada has committed to reducing its total GHG emissions to 17% below the 2005 level by 2020 (Environment Canada, 2014). Though the emission factor has been estimated in the inventory based on 2006 IPCC guideline for different sources, doubt to the accuracy of the estimated data has been raised by researchers (VanderZaag et al., 2014). The inventory itself has reported an uncertainty of up to 21% for enteric CH_4 emission (Environment Canada, 2014). Thus, the inventory results need to be evaluated. Besides, large variations existed in GHG emissions among different countries, which were partially due to differences in animal production systems, feed types, and nutrient use efficiencies by animals (Lesschen et al., 2011), as well as climate differences. Therefore, there is a need to collect data of GHG emissions at both national and regional levels.

Limited measurements have been carried out to quantify CH_4 and N_2O emissions from dairy facilities. Joo et al. (2015) measured CO_2, CH_4, and N_2O from two naturally ventilated free-stall dairy barns in the USA and investigated the impact of the three related parameters: T, RH, and VR. Saha et al. (2014) revealed the seasonal and diurnal variations of CH_4 emissions from a naturally ventilated dairy building in German. Ngwabie et al. (2014) measured CO_2, CH_4, and N_2O emissions with animal activity and air temperature from February to May for a naturally ventilated dairy building in Sweden. Zhu et al. (2014) estimated CH_4 and N_2O emissions based on their diurnal patterns from a dairy barn in China. In Canada, Ngwabie et al. (2014) measured CH_4, N_2O, and NH_3 emissions from a commercial free-stall dairy barn in Southern Ontario; however, they only considered spring and autumn time. Two other dairy farms in Eastern Ontario were studied by VanderZaag et al. (2014) in autumn and spring, where the whole farm CH_4 emission was quantified, and enteric CH_4 emission and the contribution of manure removal in affecting CH_4 emission were estimated. So far, there is still a lack of sufficient data on CH_4 and N_2O emissions from dairy barns in different regions across Canada, and no GHG data is available for dairy barns in the Canadian Prairies, which is a cold region in Western Canada. For naturally ventilated dairy buildings specifically, which are significantly affected by local climate, acquiring complete profiles of diurnal and seasonal variations in GHG emissions is essential to improve the emission database and modify the estimated results in inventory, to compare the results from different regions, and to further develop proper policy and mitigation strategies.

Hence, this study was conducted at a naturally ventilated free-stall dairy barn in the Canadian Prairies climate aiming to 1) reveal the diurnal variations in cold, warm, and mild seasons and seasonal variations throughout a year for the concentrations and emissions of CO_2, CH_4, and N_2O, and total GHG emissions; 2) compare with the enteric CH_4 emission factor estimated in the inventory (Environment Canada, 2014); 3) compare with the dairy barns from different regions or countries; and 4) examine the influence of parameters (T, RH, and VR) on the three GHG concentrations and emissions.

6.6 MATERIALS AND METHODS

6.6.1 Description of the dairy barn

The dairy barn was located in Saskatoon, Saskatchewan (106.62 ºW and 52.13 ºN), with northeast-southwest orientation. The floor was solid, and the area was 3, 230 m^2 with around 112 cows housed, within the normal range of 68-178 cows of dairy farms across Canada (Government of Canada, 2016). The display of the inside is given in Fig. 3.1. In the free-stall area, 4 pens of 12 cows each were housed on the south side of the barn and were milked in parlour, while 52 stalls were on the north side where cows were milked in the robotic milker or optionally in the parlour. The milk production was averaged at 38 L cow^{-1} day^{-1}. Cows were fed twice daily; one was around 9:30 a.m. and another around 3:00 p.m. The automatic gutter scraper was programmed to clean the alley ways 4 times daily. Manure and all wash water were pumped to a covered slurry tank outside every other day.

The barn was naturally ventilated by adjusting sliding window panels on the side walls in the mild and warm seasons. To increase ventilation, the end-wall door was open on warm days in summer. In the cold season, all the windows and doors were closed, and 6 small ceiling exhaust fans were running for ventilation. Besides, there were 3 large-volume recirculation fans installed in the milking parlour area for mixing the room air. Radiant natural gas heaters were used to keep the temperature above freezing in the cold season when necessary.

6.6.2 Sampling and measurement methods

There were two types of sampling work performed on the overhead walk-way inside the barn. The sampling point was fixed by Teflon® tubing at a height of 1.8 m above the center area of the floor, as labeled in Fig. 3.1. The first one was monthly sampling under typical weather condition of Saskatoon for giving the gas emission profiles throughout the year, which was carried out for one selected day (when the weather was typical) in each of the 12 months from February 2015 to January 2016. Due to that cow activity (eating, walking, excretion, milking, etc.) was observed to be low in the early morning, but relatively higher in the late afternoon and early evening, we did sampling in both the early morning and early evening periods considering the impact of cow activity on the generation of GHG. Thus, on those sampling days, CO_2 concentration was measured continuously on site for two hours from 6:00 to 8:00 a.m. and for another two hours from 6:00 to 8:00 p.m. by an CO_2 sensor (K30 CO_2 sensor, CO_2 Meter, USA), with the range of 0-10000 ppm and accuracy of $\pm$ 30 ppm $\pm$3 % of measured value. Every 5 minutes one measured value was recorded by a data logger (CR10X, Campbell Scientific Corporation, Canada). Two replicate air samples during the same morning period and another two during the same evening period were collected using Tedlar® air bags around 7:00 a.m. and 7:00 p.m. for a duration of 30 minutes, and were transported to the Soil Laboratory at University of Saskatchewan for measurements of CH_4 and N_2O concentrations by GC method. The average of the morning and afternoon results were used to represent the daily mean.

The second one was diurnal sampling for selected two days in the months of February 2015, July 2015, and October 2015, which represented the cold, warm, and mild seasons in Saskatoon. On these sampling days, five diurnal periods were categorized for CH_4 and N_2O measurements, including 6:00 a.m. to 9:00 a.m., 9:00 a.m. to 12:00 p.m., 12:00 p.m. to 3:00 p.m., 3:00 p.m. to 6:00 p.m., and 6:00 p.m. to 9:00 p.m. The concentration of CO_2 was continuously monitored from 6:00 a.m. to 9:00 p.m., while for each of the five diurnal periods, two replicate air samples were collected for a duration of two and a half hours (half an hour for washing bags) and analyzed for CH_4 and N_2O concentrations. The CO_2 sensor was maintained regularly and was calibrated every three months. The GC was calibrated before each measurement. The T_{in} and RH_{in} were also monitored continuously by two wireless T/RH data loggers (OM-EL-USB-2, Omega, Canada) with -35℃ to 80℃ and 0 to 100% RH measurement ranges, and ±0.5℃ and ±3.5% RH accuracies. The two sensors were installed at the same height of 1.8 m above the floor as the gas sampling point, with one at one-third length of the feed alley (center zone of the barn) and the other at two-thirds (as shown in Fig.3.1). The data of outdoor T_{out} and RH_{out} were downloaded from the website of Environment Canada.

6.6.3 VR and emission rate calculation

VR was estimated by a CO_2 mass balance method based on per heat production unit (HPU) (1000 W total heat produced by the livestock) as follows (CIGR, 2002):

VR per HPU = $(CO_2)_P$ × (Relative animal activity) / $((CO_2)_i - (CO_2)_o)$....................................(6.1)

where VR is VR in $m^3\ h^{-1}$; $(CO_2)_P$ is CO_2 production rate per HPU based on a 24 h period (0.185 $m^3\ h^{-1}$) and is adjusted by relative animal activity to an hourly basis; $(CO_2)_i$ is indoor CO_2 concentration and $(CO_2)_o$ is outdoor CO_2 concentration in ppm. The relative animal activity is estimated by an equation of time of day. The total heat production is a function of body mass (755 kg on average), milk production (38 L per cow daily), and days of pregnancy (the effect of which was ignored), and is modified by an equation of T_{in} when the indoor temperature is outside the thermoneutral zone (20℃). The equations were all from CIGR (2002). The description of the method could also be found in the study of Ngwabie et al. (2011). Knowing gas concentrations and VR, the gas emissions were calculated as follows:

$E = VR \times \Delta C$..(6.2)

where E is emission rate, mg s^{-1} AU^{-1} (milligram per second per animal unit), mg s^{-1} cow^{-1} (milligram per second per cow), or mg s^{-1} m^{-2} (milligram per second per square meter of floor); VR is VR of the room, $m^3\ s^{-1}$; and ΔC is the difference of gas concentrations between the room inlet air and exhaust air, ppm (part per million). The $(CO_2)_o$ was measured in the mild and warm seasons where it was around 5 meters away from the southeast side of the dairy barn for 30 minutes at the end of the day, and was assumed to be 390 ppm in the cold season (IPCC, 2013) when T_{out} was below the operating temperature range of the CO_2 sensor (0℃ to 50℃). The ambient concentrations of CH_4 and N_2O were not measured and values from IPCC (2013) were used: 1.8

ppm for ambient CH_4 concentration and 0.32 ppm for ambient N_2O concentration. Hourly CO_2 emission was used as a basis, while 3-hour average emissions for the diurnal results or 2-hour average emissions for the seasonal results of both CH_4 and N_2O emissions were calculated as a basis. The total GHG emission in CO_2 equivalent was estimated by summarizing CO_2 emissions, CH_4 emissions multiplied by 25 (IPCC, 2007), and N_2O emissions multiplied by 298 (IPCC, 2007). In addition, it should be noted that in using the CO_2 mass balance method to calculate VR and CO_2 emission, it assumes steady state and no accumulation or loss of CO_2 in the dairy barn during the calculation hours. Thus, CO_2 emission is modeled from a function of CO_2 production rate and total heat production (CIGR, 2002).

6.6.4 Statistical data analysis

We used SPSS software 22 to do the statistical evaluation of the data. Diurnal variances were analyzed separately for the three months. Five diurnal levels were considered, including early morning (6:00 to 9:00 a.m.), late morning (9:00 a.m. to 12:00 p.m.), early afternoon (12:00 to 3:00 p.m.), late afternoon (3:00 to 6:00 p.m.), and early evening (6:00 to 9:00 p.m.). The main effects of the two factors "daily" and "diurnal", and the interaction effect between the two factors were examined. "Daily" combined the results of ambient weather, VR, animal management, and so on, and "diurnal" effect was a function of the time of day. Diurnal variances were analyzed separately for each day if the interaction effect was significant ($P \leq 0.05$). Multiple comparisons of diurnal results were performed by Duncan test in General Linear Model or by nonparametric test (Kruskal-Wallis test) when error variances of the data were unequal. The method was the same for multiple comparisons of monthly results to examine the "seasonal" effect. Besides, comparisons of the diurnally measured results among the three months (February, July, and October) were conducted by Duncan test in One-Way ANOVA using 3-hour average data.

Pearson correlations among gases and parameters were investigated and were indicated by a coefficient (r). There were two different significance levels from the outcome of the results: $P \leq 0.05$ indicates significant correlation and $P \leq 0.01$ indicates very significant correlation. Single linear model was used to develop the relationships among the three gas concentrations.

6.7 RESULTS AND DISCUSSION

6.7.1 Seasonal GHG concentration and emission profiles

Table 6.1 summarizes the number of cows, VR, and environmental parameters (including T_{in}, T_{out}, RH_{in}, RH_{out}, wind speed, and wind direction) from February 2015 to January 2016. Seasonal VR varied significantly ($P<0.05$) with a range of 5-69.2 $m^3\ s^{-1}$. Overall, VR in the mild (April and October) and warm (May to September) seasons were higher than in the cold season (November to March), with an average value of 45.6 and 30.7 $m^3\ s^{-1}$ compared to 8.4 $m^3\ s^{-1}$. There were two peaks appeared in the seasonal VR profile, which were in April and June. In addition to animal activity and T_{out}, it was suggested that wind speed and wind direction were also essential factors to affect diurnal VR patterns (Ngwabie et al., 2014; Joo et al., 2015). For the dairy barn from April to October, window panels were open fully, thus the effects of wind speed and direction were obvious. In April, the wind speed from 6:00 to 8:00 a.m. was only 5.7 km h^{-1}, but increased by almost 5 times to 32 km h^{-1} in the early evening, which resulted in great variance of diurnal VR and finally gave a much higher average VR than the other months (excluding June). The high VR in June probably was attributed to the favorable wind direction, though the wind speed was fair (the long side of the barn was almost perpendicular to wind direction).

Table 6.1 Cows number, environmental parameters, and VR from Feb 2015 to Jan 2016.

Date	Cows number	T_{out} (℃)	T_{in} (℃)	RH_{out} (%)	RH_{in} (%)	Wind speed (km h^{-1})	Wind direction (degree)	VR ($m^3\ s^{-1}$)
09-Feb-15	116	-16	6	83	91	9.7	97	5.4^{e}
17-Mar-15	115	-1	7	75	79	9.8	223	18.4^{cd}
20-Apr-15	116	3	8	61	62	18.8	117	64^{ab}
21-May-15	111	16	18	35	49	10.7	208	21.6^{bcd}
23-Jun-15	107	18	20	59	64	8.5	303	69.2^{a}
21-Jul-15	102	27	24	50	72	19.5	148	31.5^{ab}
27-Aug-15	112	17	21	85	82	5.0	140	15.1^{d}
24-Sep-15	116	12	17	87	82	10.0	140	16^{d}
13-Oct-15	113	2	10	77	66	13.5	253	26^{bc}
19-Nov-15	109	-12	7	88	82	15.8	285	7.1^{e}
17-Dec-15	111	-13	6	76	84	16.7	313	6.2^{e}
19-Jan-16	111	-17	7	88	89	8.0	203	5^{e}

Notes: for VR, letters a, b, and c indicate the significance of the difference in the same column at the 0.05 level, and same letters indicate the difference is not significant.

Seasonal gas concentration and emission profiles are all given in Fig. 6.1. The seasonal concentrations of CO_2 and CH_4 showed highly consistent patterns, both varying greatly with obviously higher values in the cold season from November to February than the other months. On the contrary, the emissions of CH_4 and CO_2 remained with small variations.

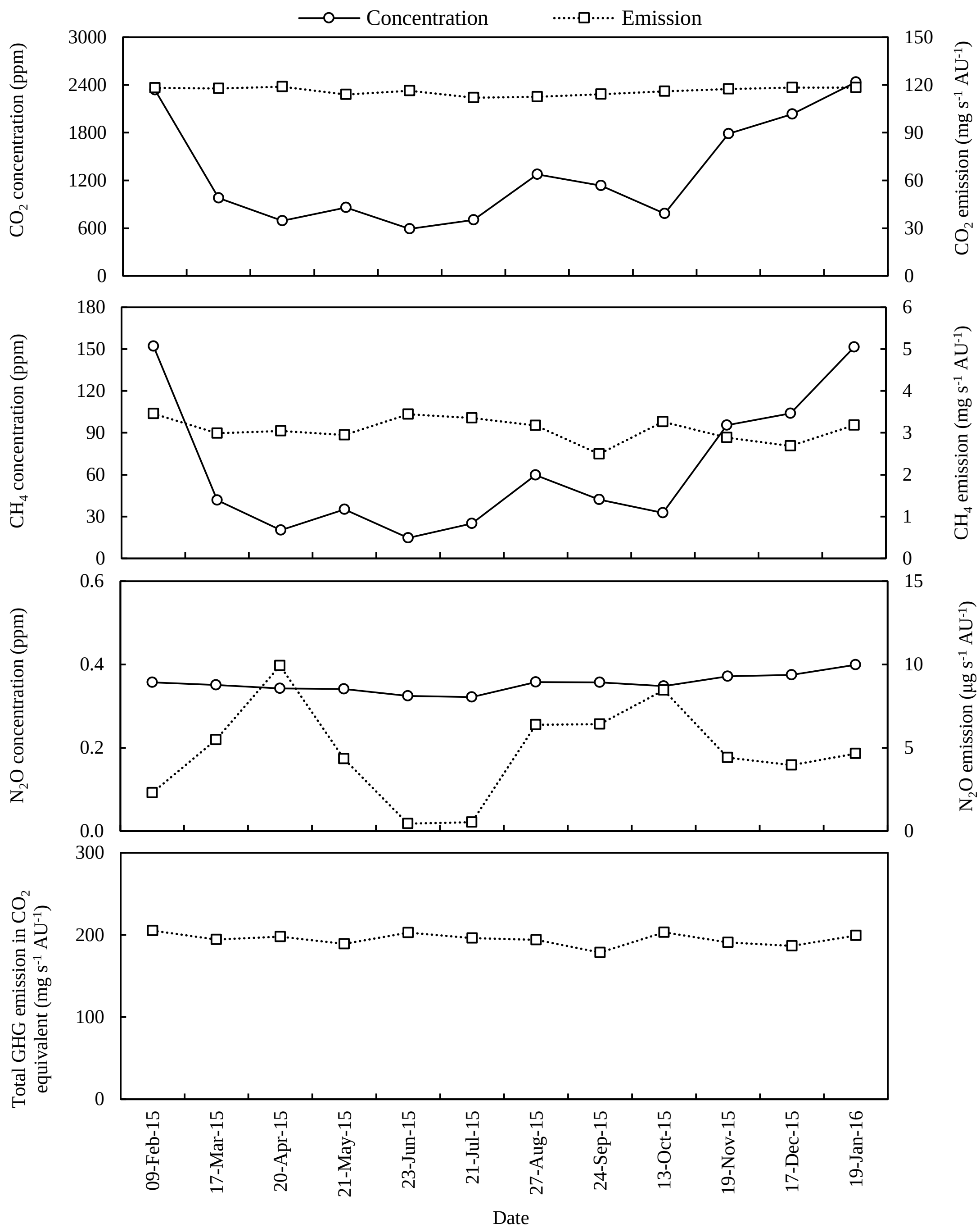

Figure 6.1 Seasonal variations of GHG concentrations and emissions.

Ngwabie et al. (2009) found little variations in indoor concentrations of CH_4 and CO_2 during the winter season, which was agreed by this study excluding March when windows were open partially and VR was apparently higher than the other winter months. As indicated by Amon et al. (2001) and Saha et al. (2014), the seasonal effect was insignificant for CH_4 emission for dairy housings in Austria and Germany. Gao et al. (2011) pointed out that the seasonal variations of CH_4 emission from dairy feedlot might be within 10%. The results in the study were in line with the above studies, with great variances observed for seasonal CH_4 concentrations, but not for seasonal CH_4 emissions (see Table 6.2). The seasonal CH_4 emissions varied within 19% from the seasonal average that was calculated from monthly emissions. The CH_4 emission factor for the whole dairy barn, contributed by both enteric fermentation and decomposition of excreted manure, was 145.9 kg head^{-1} year^{-1}. If only considering enteric CH_4 emission for dairy cows, the result suggests an lower value than 155.1 kg head^{-1} year^{-1} that estimated by Environment Canada (2014).

Table 6.2 Descriptive statistics of seasonal GHG concentrations and emissions.

Items	Min	Max	Mean ± standard deviation
CO_2 concentration (ppm)	593	2433	1301 ± 671
CO_2 emission (mg s^{-1} AU^{-1})	112	119	116 ± 2
CO_2 emission (mg s^{-1} cow^{-1})	169	179	175 ± 4
CO_2 emission (mg s^{-1} m^{-2})	5.3	6.4	6.1 ± 0.3
CH_4 concentration (ppm)	15	152	65 ± 49
CH_4 emission (mg s^{-1} AU^{-1})	2.5	3.5	3.1 ± 0.3
CH_4 emission (mg s^{-1} cow^{-1})	3.8	5.2	4.6 ± 0.4
CH_4 emission (mg s^{-1} m^{-2})	0.14	0.19	0.16 ± 0.01
N_2O concentration (ppm)	0.32	0.40	0.35 ± 0.02
N_2O emission (μg s^{-1} AU^{-1})	0.5	10	5 ± 3
N_2O emission (μg s^{-1} cow^{-1})	1	15	7 ± 4
N_2O emission (μg s^{-1} m^{-2})	0.02	0.54	0.25 ± 0.15
Total GHG emission in CO_2 equivalent (mg s^{-1} AU^{-1})	178	205	194 ± 7
Total GHG emission in CO_2 equivalent (mg s^{-1} cow^{-1})	269	310	294 ± 11
Total GHG emission in CO_2 equivalent (mg s^{-1} m^{-2})	9	11	10 ± 1

The N_2O concentrations were only slightly above ambient concentration with seasonal fluctuation within 5%. No specific seasonal pattern was found for N_2O emissions, despite that N_2O emissions tended to increase when it changed from winter to mild season and tended to go back to low level when it turned from warm season to winter again. However, N_2O emissions varied greatly in the warm season and could be lower than that in the winter due to low N_2O concentrations. Compared to CO_2 and CH_4 emissions, N_2O emissions were very low. As for total GHG emissions, an average contribution of 59.8%, 39.5%, and 0.7% was attributed to CO_2, CH_4, and N_2O emissions, respectively. Thus, the total GHG emissions were dominated by CO_2 and CH_4 emissions with no significant seasonal effect observed ($P>0.05$).

6.7.2 Diurnal GHG concentration and emission patterns

Diurnal 3-hour average CO_2, CH_4, and N_2O concentration patterns are given in Fig. 6.2. Due to the variations of T_{out}, the VR patterns of the three seasons differ significantly from each other, being relatively low and stable in the cold season, high and stable in the warm season, and high and fluctuating much in the mild season. In February, all the windows were closed due to the cold weather, thus the air exchange was minimized. As discussed above, wind speed and wind direction are also crucial factors to explain the variations of VR. Wind direction in the mild season was from northwest to southeast which was perpendicular to the long side of the dairy barn where the window panels were installed. Besides, on both days in the mild season, wind speed increased greatly from the early morning to the afternoon and decreased in the evening, which probably explained the great diurnal variations of VR.

The concentrations of the three gases were all significantly higher in the cold season than in the mild and warm seasons ($P<0.05$). The lowest concentrations of CO_2 and CH_4 both occurred in the mild season and the minimum N_2O concentration was found in the warm season. Similar to our findings for seasonal results, high consistency was observed between diurnal patterns of CH_4 concentration and CO_2 concentration with greater diurnal variations in both cold and mild seasons as compared to the warm season. Significant difference was not found in 3-hour average CO_2 concentrations in either cold season or warm season ($P>0.05$), but existed in 3-hour average CO_2 concentration in the mild season with significantly lower value in the entire afternoon than the other diurnal periods ($P<0.05$). Diurnal N_2O concentrations were quite stable and fell within a low level of 0.32-0.37 ppm in all seasons. Statistical descriptions of the diurnal data are all listed in Table 6.3.

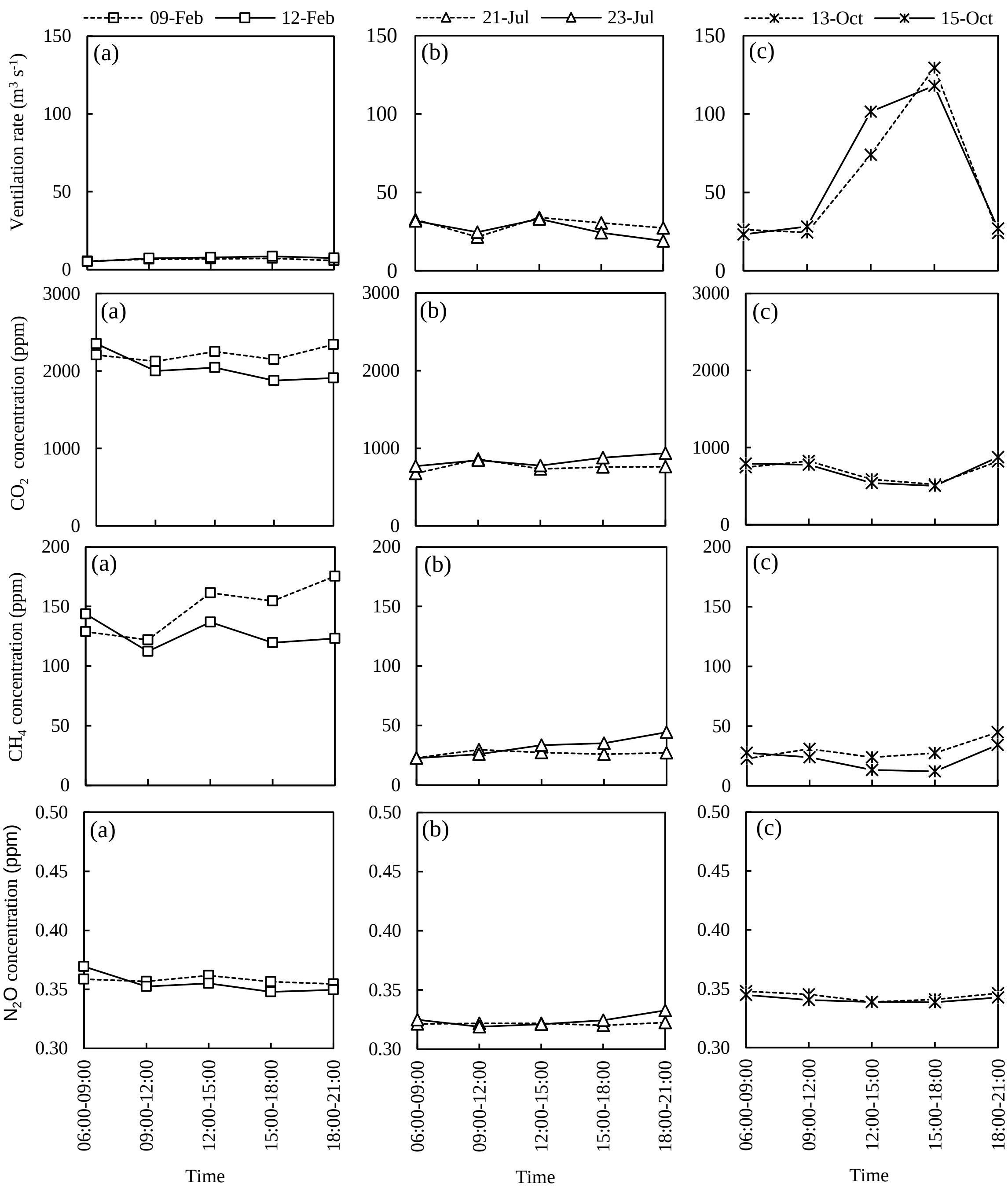

Figure 6.2 3-Hour average VR and GHG concentrations in the cold (a), warm (b), and mild (c) seasons, respectively.

Diurnal 3-hour average CO_2, CH_4, and N_2O emissions are plotted in Fig. 6.3. Diurnal CO_2 emissions presented highly consistent sinusoidal diurnal patterns for the two measurement days in all three seasons, which was due to the sinusoidal model used to estimate relative animal activity (CIGR, 2002), and also because the average cow body mass and milk production were the same in calculating VR. In brief, the sinusoidal patterns of diurnal CO_2 emissions resulted from the CO_2 mass balance method used for calculating VR (CIGR, 2002).

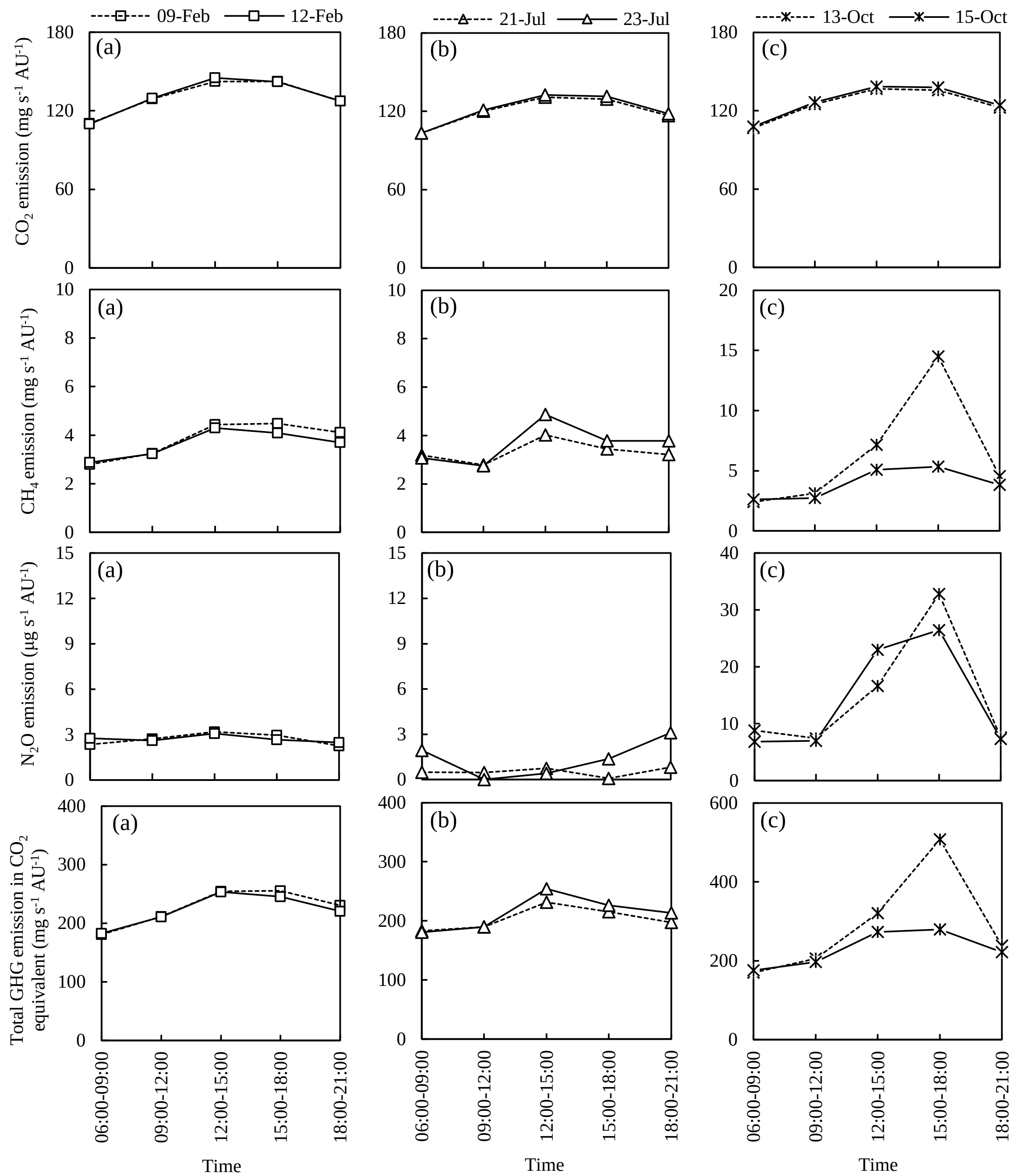

Figure 6.3 3-Hour average GHG emissions in the cold (a), warm (b), and mild (c) seasons, respectively.

Diurnal CH_4 emissions tended to display similar patterns to that of VR in all seasons but opposite to that of concentrations, with higher emission levels of CH_4 in afternoons and evenings.

Significant diurnal CH_4 emission variations were also reported by Gao et al. (2011) and Zhu et al. (2014). In their studies, three emission peaks were observed starting at around 5:00 a.m., 11:30 a.m., and 4:00 p.m., which were related to the feeding activity. Similarly, Negwabie et al. (2011) indicated that diurnal CH_4 emission had two peaks at 9:00 a.m. and 5:00 p.m., which were probably related to the feeding routine as well. While in this study, no obvious evidence indicated that feeding activity (feeding two times per day, one was around 9:30 a.m. and the other around 3:00 p.m.) would affect diurnal CH_4 emissions. In line with Saha et al. (2014) who found the highest CH_4 emission between 12:00 and 3:00 p.m., the peak also appeared between 12:00 and 3:00 p.m. in both cold and warm seasons, but tended to occur later between 3:00 and 6:00 p.m. in the mild season. Joo et al. (2015) reported that diurnal CH_4 and CO_2 emissions from naturally ventilated dairy barns showed peaks and lows at the same time, which was also agreed by this study. No significant difference was found in either CO_2 emissions or CH_4 emissions among the three months using 3-hour average data, which confirmed the previous finding that seasonal effect is insignificant for CO_2 or CH_4 emissions ($P>0.05$).

Due to low VR in the cold season and low N_2O concentration in the warm season, diurnal N_2O emissions in both seasons remained below 4 μg s^{-1} AU^{-1} with relatively constant diurnal N_2O emissions in the cold season and no clear pattern of diurnal N_2O emissions in the warm season. The highest N_2O emission turned out to be in the mild season when diurnal N_2O emissions tended to show great variations and similar varying pattern to that of VR. Diurnal N_2O emission was relatively low in both morning and evening and increased greatly during the whole afternoon with a peak occurring between 3:00 and 6:00 p.m., and then decreased until the end of the measurement. This is in line with Zhu et al. (2014) who noticed that N_2O emission decreased from late evening to early morning and then increased until the late afternoon. The diurnal trends of total GHG emissions in CO_2 equivalent in the three seasons are also plotted in Fig. 6.3. It was noted that CH_4 emissions in CO_2 equivalent were comparable to CO_2 emissions, with 54.7% contribution to total GHG emissions from CO_2 and 44.5% from CH_4, whereas N_2O emissions contributed little to total GHG emissions (0.8%). Thus, diurnal total GHG emissions varied in consistent with CO_2 and CH_4 emissions, occurring low in the morning and high in the afternoon and evening for all seasons, and with the greatest diurnal variations in the mild season (the ratio of maximum to minimum is 3) due to the considerable variations in CH_4 and N_2O emissions.

Table 6.3 Descriptive statistics of diurnal 3-hour average GHG concentrations and emissions.

	Cold			Warm			Mild		
Items	Min	Max	Mean + SD	Min	Max	Mean + SD	Min	Max	Mean + SD
Outdoor T (℃)	-17	-11	-14 ±2[c]	14	28	24 ±5[a]	0	14	8 ±5[b]
VR (m^3 s^{-1})	5.0	8.5	6.8 ±1.1[b]	19.1	33.5	27.9 ±5.3[a]	24.2	135.5	60.3 ±45.8[a]
CO_2 C (ppm)	1878	2356	2127 ±168[a]	676	935	800 ±78[b]	503	875	699 ±144[b]
CO_2 E (mg s^{-1} AU^{-1})	110	145	131 ±13[a]	103	133	121 ±11[a]	107	139	126 ±12[a]
CO_2 E (mg s^{-1} cow^{-1})	166	219	197 ±20	160	210	190 ±15	161	209	191 ±18
CO_2 E (mg s^{-1} m^{-2})	5.9	7.9	7.1 ±0.7	5	6.6	6 ±0.5	5.6	7.3	6.7 ±0.6
CH_4 C (ppm)	112	175	138 ±21[a]	23	45	30 ±7[b]	12	45	26 ±10[b]
CH_4 E (mg s^{-1} AU^{-1})	2.8	4.5	3.7 ±0.6[a]	2.7	4.9	3.5 ±0.6[a]	2.4	14.5	5.1 ±3.6[a]
CH_4 E (mg s^{-1} cow^{-1})	4.2	6.8	5.6 ±1	4.1	7.3	5.3 ±1	3.6	22	7.8 ±5.4
CH_4 E (mg s^{-1} m^{-2})	0.15	0.24	0.2 ±0.03	0.13	0.23	0.17 ±0.03	0.13	0.77	0.27 ±0.19
N_2O C (ppb)	348	369	356 ±6[a]	319	333	323 ±4[c]	339	348	342 ±3[b]
N_2O E (μg s^{-1} AU^{-1})	2	3	3 ±0.3[b]	0	3	1 ±1[b]	7	33	14 ±10[a]
N_2O E (μg s^{-1} cow^{-1})	3.4	4.8	4.1 ±0.5	0	4.7	1.4 ±1.5	10	50	22 ±15
N_2O E (μg s^{-1} m^{-2})	0.12	0.17	0.15 ±0.02	0	0.15	0.04 ±0.05	0.36	1.73	0.76 ±0.51
Total GHG in CO_2 equivalent (mg s^{-1} AU^{-1})	181	255	225 ±28[a]	186	261	213 ±23[a]	170	508	259 ±100[a]
Total GHG in CO_2 equivalent (mg s^{-1} cow^{-1})	273	385	339 ±43	280	394	322 ±35	256	767	391 ±151
Total GHG in CO_2 equivalent (mg s^{-1} m^{-2})	10	14	12 ±2	3	11	7±3	9	27	14 ±(5)

Notes: C is concentration and E is emission; SD is standard deviation; letters a, b and c indicate the significance of the difference in the measured item among the three seasons at the 0.05 level (same letters mean the difference is not significant).

6.7.3 Comparison of the results with other studies

The results of CO_2, CH_4, and N_2O concentrations and emissions from previous published studies for naturally ventilated dairy barns are listed in Table 6.4. It was found that CO_2 and CH_4 concentrations were comparable to Ngwabie et al. (2009) for a naturally ventilated dairy building in Switzerland and Ngwabie et al. (2014) for a dairy barn in Ontario, Canada, but were higher than most previous studies. The difference between the results from this study and the previous studies can probably be attributed to the different climate conditions and different building design. The dairy barns from the studies of Joo et al. (2015), Wu et al. (2012), and Saha et al. (2014) all had large sidewall curtains and ridge openings, as well as one fully open end. In the study of Zhu et al. (2014), open lots were described for the dairy barn where lower CH_4 and N_2O concentrations were measured. In the study of Samer et al. (2012), much higher VR was reported (456 $m^3 s^{-1}$ in summer and 428 $m^3 s^{-1}$ in winter) as a result of larger curtains, ridge slot, gates, as well as doors compared to this study, which explained its relatively lower CO_2, CH_4, and N_2O concentrations in both summer and winter seasons.

Table 6.4 Comparison of GHG (CO_2, CH_4, and N_2O) concentrations and emissions from different naturally ventilated dairy barns.

Source	Concentration (ppm)			Emission			Season	Country
	CO_2	CH_4	N_2O	CO_2 (mg s^{-1} AU^{-1})	CH_4	N_2O		
Joo et al. (2015)	443-789	0-39.4	0.25-0.39	61-124	0.77-2.92 mg s^{-1} AU^{-1}	3-29 µg s^{-1} AU^{-1}	May, Jul, Sep	USA
Wu et al. (2014)	559-1066	17.2-43.6	0.33-0.47	None	3 mg HPU^{-1} s^{-1}	None	Sep-Dec&May-Jul	Denmark
Negwabie et al. (2009)	535-1480	4-77	0.29-0.39	None	2.5-3.61 mg s^{-1} AU^{-1}	None	Dec-Mar&May	Sweden
Negwabie et al. (2011)	960±210	39.4±16.9	0.26±0.04	None	3±0.64 mg s^{-1} AU^{-1}	None	Feb-May	Sweden
Negwabie et al. (2014)	1000±335	68±39	0.47±0.08	None	1.25-9.58 mg s^{-1} AU^{-1}	0.1-36 µg s^{-1} AU^{-1}	Spring	Canada
Negwabie et al. (2014)	685±119	35±13	0.39±0.04	None	0.83-8.92 mg s^{-1} AU^{-1}	0-34 µg s^{-1} AU^{-1}	Fall	Canada
Zhu et al. (2014)	None	2.1-8.5	0.34-0.62	None	3.89-5.31 mg s^{-1} cow^{-1}	0.42-0.78 mg s^{-1} cow^{-1}	May to Aug	China
Gao et al. (2011)	None	2-10	None	None	3.94 mg s^{-1} cow^{-1}	None	Fall	China
Gao et al. (2011)	None	2-10	None	None	3.59 mg s^{-1} cow^{-1}	None	Winter	China
Cortus et al. (2015)	None	0-200	0.26-0.52	None	3.36 mg s^{-1} AU^{-1}	8 µg s^{-1} AU^{-1}	All seasons	USA
Samer et al. (2012)	455	15	0.27	898	10.6 mg s^{-1} AU^{-1}	0.53 mg s^{-1} AU^{-1}	Summer	Germany
Samer et al. (2012)	536	13	0.45	979	7.69 mg s^{-1} AU^{-1}	0.80 mg s^{-1} AU^{-1}	Winter	Germany

As for emission, different units were used in those studies and we converted them in units of mg s^{-1} AU^{-1} or mg s^{-1} cow^{-1} depending on the original data format in order to be consistent with this study for comparison purpose. The observed CH_4 emission in this study is comparable to the results of majority of the studies, with the range within that reported by Negwabie et al (2009), Negwabie et al. (2014), Saha et al. (2014), and Zhu et al. (2014), and with the average close to the results of Negwabie et al. (2011), Cortus et al. (2015), and Gao et al. (2011), but is a little higher than that of Joo et al. (2015) and obviously lower than Samer et al. (2012). The N_2O emission was much less compared to CH_4 emission. It is within the ranges of Joo et al. (2015) and Negwabie et al. (2014), but is lower than that of Zhu et al. (2014) and Samer et al. (2012). The average N_2O emission is approximate to the result of Cortus et al. (2015). Only a few of the reviewed papers reported CO_2 emission together with CH_4 and N_2O emissions. The seasonal CO_2 emission from using VR estimated by CO_2 mass balance method (CIGR, 2002) is much lower than that of Samer et al. (2012) using the same method, while is within the range reported by Joo et al. (2015) who used three-dimensional ultrasonic anemometers for measuring VR. Besides, Samer et al. (2012) observed slightly higher CO_2 emission in the winter than in the summer. Similarly, CO_2 emission from November to March (118 mg s^{-1} AU^{-1}) was slightly higher than that from May to September (114 mg s^{-1} AU^{-1}), but the difference was not significant ($P>0.05$).

6.7.4 Relationships between GHG concentrations

In line with Amon et al. (2001), Ngwabie et al. (2009), and Rong et al. (2014), CO_2 concentration and CH_4 concentration were highly correlated with each other ($r = 0.98$, $P<0.01$), which was explained by that the two gases were generated from a similar source or process including either enteric fermentation or respiration in ruminants (Joo et al., 2015). The reported ratios of CH_4 and CO_2 in previous studies need to be validated for dairy barns in the Canadian Prairies as various factors affect GHG production and emission, including animal housing, animal species and feed, local climate, etc. It was found the ratio of CH_4 concentration to CO_2 concentration was 0.04, which is a little lower than 0.08 that concluded by Ngwabie et al. (2009) and Rong et al. (2014), but is close to 0.05 from the study of Wu et al. (2015). Besides, N_2O concentration was examined to be positively correlated with both CO_2 concentration ($r = 0.78$, $P<0.01$) and CH_4 concentration ($r = 0.73$, $P<0.01$). The single linear relationships between CH_4 and CO_2 concentrations and between N_2O and CO_2 concentrations are given in Fig. 6.4. The relationships could provide reference to estimate CH_4 concentration and N_2O concentration by only knowing CO_2 concentration as it is relatively easier to be measured.

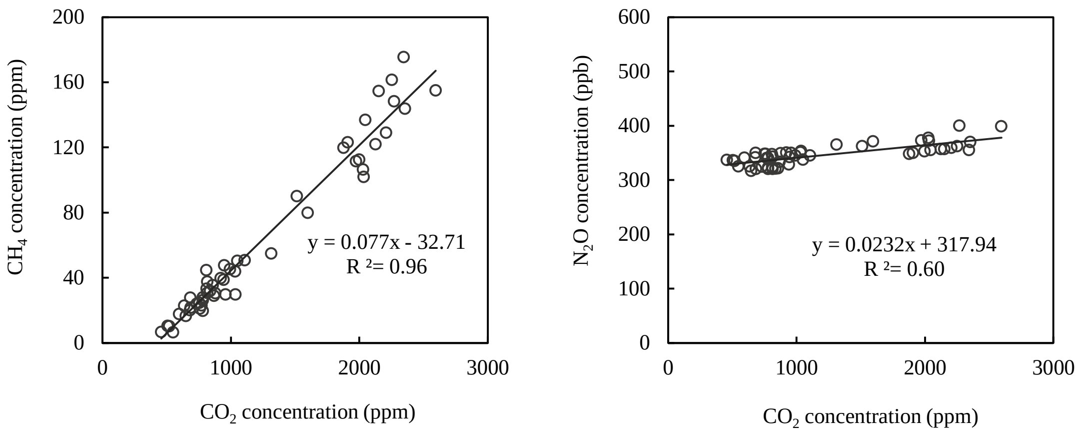

Figure 6.4 Relationships between GHG concentrations.

6.7.5 Relationships between GHG (concentrations and emissions) and environmental parameters

The concentrations of CO_2, CH_4, and N_2O were all significantly related to VR and environmental parameters (T and RH) ($P<0.01$). The greatest influence on the three gas concentrations was observed from T_{out} ($r>0.78$). Increasing T_{out} was associated with lower concentrations of all three gases, which was due to the higher VR resulted from the increased T_{out} thus more dilution for indoor gas concentrations. On the contrary, positive effects from RH_{in} and RH_{out} were observed on all three gas concentrations. As CO_2 and CH_4 of the dairy barn are mainly produced from enteric fermentation and cow respiration, the reason for RH affecting the two gas concentrations is probably that indoor RH, as one thermal factor, affects the performance and behavior of dairy cows (Joo et al., 2015), thus the gas generation and releasing.

As the indoor thermal environment (T and RH) of the naturally ventilated dairy barn is highly depending on the outdoor thermal condition, the statistical relationships between gas emissions and outdoor weather condition (T_{out} and RH_{out}) could reflect how the GHG emissions were related to the local climate for the dairy barn in a cold region and might be further utilized to predict GHG emissions. It was found that RH_{out} was the only factor to relate to CO_2 emission and CH_4 emission with negative correlations ($P<0.01$). As for N_2O emission, it was negatively correlated with RH_{in} ($P<0.05$) and more influenced by VR with a positive correlation ($r = 0.79$, $P<0.01$).

6.8 CONCLUSIONS

Diurnal and seasonal concentration and emission patterns of GHG (CO_2, CH_4, and N_2O) were presented for a naturally ventilated free-stall dairy barn in a cold region climate (the Canadian Prairies). Using the measured results, the enteric CH_4 emission factor estimated by Environment Canada (2014) was evaluated, comparison with other dairy barns in different climates (regions) were conducted, and influence of VR and environmental parameters (T and RH) on GHG concentrations and emissions were examined. We have the following findings:

1) Seasonal CO_2, CH_4, and N_2O concentrations varied greatly over the year with higher concentrations in the cold season than that in the warm and mild seasons. Significant seasonal variations were observed for N_2O emission, but not for CO_2 and CH_4 emissions. Great diurnal variations existed for both CO_2 and CH_4 emissions in all seasons, which were low in the morning and high in the afternoon and evening. The vast majority of total GHG emissions (99.3%) were contributed by CO_2 and CH_4 emissions thus total GHG emissions presented no significant seasonal variations, but obvious diurnal variations similar to that of CO_2 and CH_4 emissions in all seasons (the maximum is up to 3 times of minimum in the mild season). Besides, CH_4 concentration patterns were highly consistent with CO_2 concentration patterns for both diurnal results and seasonal results;

2) The emission factor of CH_4 measured for the dairy barn suggested a lower CH_4 emission for enteric fermentation than the inventory result (Environment Canada, 2014);

3) This dairy barn in a cold region climate with smaller vent openings had relatively higher indoor CO_2 and CH_4 concentrations, but comparable CO_2 and CH_4 emissions to most of the dairy barns in other regions;

4) The three GHG concentrations were negatively related to T_{in}, T_{out} and VR, and positively correlated with RH_{in} and RH_{out}. The most relevant parameter to GHG concentrations was T_{out}. The emissions showed less correlations with the parameters than the concentrations: CO_2 and CH_4 emissions were only negatively related to RH_{out}, and for N_2O emission, it was negatively related to RH_{in} and positively related to VR with more influence.

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CHAPTER 7
DIURNAL AND SEASONAL VARIATIONS OF GREENHOUSE GAS EMISSIONS FROM A COMMERCIAL BROILER BARN AND CAGE-LAYER BARN ON THE CANADIAN PRAIRIES

7.1 CONTRIBUTION OF THE PH.D. CANDIDATE

The samples collection, data analysis, and manuscript writing were performed by the candidate. The measurements of CO_2 were performed by the candidate while samples were sent to the Soil Laboratory at University of Saskatchewan for CH_4 and N_2O measurements. RLee Prokopishyn and Louis Roth helped with the instrument set-up and maintenance. Besides, Zhu Gao and Jingjing Han participated in some of the field measurements and assisted with air sample collection. Dr. Huiqing Guo provided editorial input and suggestions on methods and data analyses.

7.2 CONTRIBUTION OF THIS PAPER TO THE OVERALL STUDY

Similar to Chapter 6, this paper presents the diurnal and seasonal variations of the three GHG concentrations and emissions, including CO_2, CH_4, and N_2O, for the study layer and broiler barns. Based on the diurnal and seasonal emission profiles, the emission factors of the three GHG and total GHG for the two poultry barns were quantified. Besides, the influence of environmental parameters (indoor and outdoor T and VR) on the three GHG emissions were investigated and comparisons of the results between the two barns and with the previous studies were conducted.

7.3 ABSTRACT

Emission factors of the three greenhouse gases (GHG), including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), were acquired for a commercial broiler barn and cage-layer barn in the Canadian Prairies climate. Between March 2015 and February 2016, two types of measurements were conducted, which were seasonal measurements throughout the year for the

layer barn and over 6 flocks for the broiler barn, and diurnal measurements in the mild, warm, and cold seasons, respectively. The emissions of CO_2 tended to be constant for both barns, while considerable seasonal effect was observed for N_2O emissions of the broiler barn, and for CH_4 and N_2O emissions of the layer barn, both with higher emissions in the mild and warm seasons than that in the cold season. Because CH_4 and N_2O emissions were very low compared to CO_2 emissions, seasonal total GHG emissions were also stable for both barns. Diurnal CO_2 and total GHG emissions were comparatively stable for the broiler barn but varied in all three seasons for the layer barn with peak emissions during 9:00 a.m. and 3:00 p.m. Thus, seasonally measured CO_2 emissions over middle hours of the daytime were over-high to represent the daily results for the layer barn, and correction factors (from -20.9% to -22.5%) were obtained from the diurnal CO_2 emission trends. These factors were also applicable to modify total GHG emissions. Besides, the difference of GHG concentrations and emissions between best-case (the first day after manure removal) and worst-case conditions (the last day before manure removal) was not obvious for the layer barn. By correlating environmental parameters with GHG emissions, changes of temperature and ventilation rate were likely to have more impact on N_2O emission for the broiler barn and more impact on CH_4 emissions for the layer barn, both with positive correlations.

7.4 INTRODUCTION

Animal production not only contributes to air pollutant emissions such as ammonia, hydrogen sulfide, and organic compounds, but also is an important agricultural source of greenhouse gases (GHG). In poultry barns, carbon dioxide (CO_2) is mostly derived from animal respiration, followed by aerobic fermentation of the excreta and other litter residues. Methane (CH_4) is produced by fermentation of organic matter including animal feces and waste feed whereas nitrous oxide (N_2O) is related to the agricultural nitrogen cycle and is produced in the nitrification and denitrification process in the management of manure and after its application to agricultural soils (Calvet et al., 2011). In Canada, it was reported that broiler and layer production were major poultry sources of GHG emissions with 54% and 33% of contribution in poultry industry, respectively (Vergé et al., 2009). Between 1981 and 2006, GHG emissions from the Canadian poultry industry has been increased by 40% (Vergé et al., 2009).

Methane and N_2O emissions from different livestock and poultry sectors have been estimated in various countries based on IPCC (2007) guidelines, including European countries (Lesschen et al., 2011; Cederberg at al., 2009), USA (EPA, 2011), Canada (Vergé et al., 2009), and China (Liang et al., 2013). Through these studies, it was found that poultry production contributed less compared to beef and dairy, which is due to that poultry production has low N_2O and CH_4 emissions although its CO_2 emission is considerable. However, validation of the modelled GHG emission factors of the inventory was rarely performed and very limited field measurements have been conducted to acquire accurate GHG emission factors from poultry production. Data concerning GHG emissions from poultry houses remain scarce.

Several factors were reported to impact on GHG emissions from poultry production, including dietary manipulations, manure moisture, bird age and weight, floor management, indoor conditions, ventilation rate (VR), etc. (Meda, et al., 2011). Besides, the possible influence of climate on GHG emissions should also be taken into consideration because it affects the indoor temperature (T_{in}) and VR of poultry housing (Meda, et al., 2011). Measurements from different production sites and climates are needed to improve the emission databases, which would provide scientific evidence for poultry industries and regulatory agencies (NRC, 2002). Identifying seasonal and diurnal GHG emission patterns are also crucial for establishing cost-effective measurement protocols and mitigation techniques that focus in these periods when emissions are higher.

Hence, this study conducted long-term measurement of GHG emissions (CO_2, CH_4 and N_2O) from a commercial broiler barn and a commercial cage-layer barn on the Canadian Prairies with the following objectives: 1) to quantify the emission factors of CO_2, CH_4, N_2O, and total GHG with their seasonal variations and diurnal variations in different seasons; 2) to investigate the influence of manure removal on GHG emissions for the layer barn; and 3) to study the impact of T and VR on the GHG emissions.

7.5 MATERIALS AND METHODS

7.5.1 Description of the broiler and layer barns

The study sites included a typical commercial cage-layer barn (106.41 W, 52.41 N) and broiler barn (106.61 W, 52.54 N) in Northern Saskatoon, Canada. The floor area of the broiler barn is 1638 m^2 (18 m wide × 91 m long) with an animal capacity of 33, 000 birds. The broiler barn is mechanically ventilated by 6 chimney fans distributed along the ridge. The 4 end-wall fans are only working on hot summer days to increase VR for cooling. There are also 4 recirculation fans to mix the room air. A total of 96 air inlets, which were symmetrically installed on the side walls (24 air inlets × 2 rows × 2 walls), are controlled automatically according to the requirement of VR. As for the broiler barn, the production cycle for each flock is around 33 days. Between the flocks is a 3-week break for cleaning and disinfection (the 3-week break is due to quota restriction by the local industry). The floor is covered with litter. Birds are raised loosely on the floor and manure is not treated during production cycle. The layer barn is a 4-tier stacked cage building. The floor area is 986 m^2 with 12 m wide and 81 m long, which could house maximum 35,000 birds. The layer barn is also mechanically ventilated by 20 single speed fans and 4 variable speed fans, all installed on the same side wall. There is a total of 172 air inlets (two rows) on the ceiling. The production cycle for one batch is one year followed by one-week break for cleaning and disinfection. Belt manure system is used in the layer barn and manure removal is performed every 3-4 days.

7.5.2 Sampling and measurement methods

The sampling point was fixed at a height of 1.2 m (close to a chimney fan) for the broiler barn, and at a height of 1.5 m (close to one exhaust fan, which was working throughout the year) for the layer barn. For the broiler barn, manure was continuously accumulating during each production cycle, and birds' weight was increasing as well, so the sampling and measurement were conducted in the last week of each flock when the indoor air quality would be the worst, to get the worst-case scenario. For the layer barn, the last day before manure removal from the belt should have the highest gas concentrations so was named the worst-case day while the first day after the manure removal should have the least gas concentrations so was named the best-case day. There were two types of sampling and measurement work. The first one was to acquire the seasonal GHG concentration and emission profiles. For the broiler barn, air samples were collected within both fixed morning hours (8:00-10:00 a.m.) and afternoon hours (2:00- 4:00 p.m.) on one day of the last week for each flock. A total of 6 flocks were available, which were in April, June, August, October, November, and January, respectively. For the layer barn, seasonal measurements were performed for fixed morning hours (10:00 a.m.-12:00 p.m.) and afternoon hours (2:00-4:00 p.m.) only on worst-case days; one worst-case day in each month from March 2015 to February 2016. The second one was to obtain the diurnal profiles, which was conducted from 6 a.m. to 9 p.m. for two days in the last week of each flock in April (mild season), August (warm season), and January (cold season), respectively, for the broiler barn, and from 6:00 a.m. to 9:00 p.m. for two days in each of April (mild season), July (warm season), and January (cold season) for the layer barn, including both a best-case day and worst-case day (within the same week). Seasonal measurements were not performed during the months when diurnal measurements were conducted, instead, the diurnal results on April 16th, August 4th, and January 21st were exacted to represent seasonal results for the broiler barn when bird age and weight were similar to the other months, and the results on Apr 28th, Jul 30th, and Jan 14th were used to consist of seasonal profiles for the layer barn as they were the worst-case days.

During the sampling periods mentioned above, CO_2 concentrations were continuously measured by a CO_2 sensor (K30 CO_2 sensor, CO_2 Meter, USA) with measurement range of 0-10000 ppm and accuracy of ±30 ppm ±3%; every five minutes one data of CO_2 concentration was recorded by a data logger (CR10X, Campbell Scientific Corporation, Canada). For seasonal CH_4 and N_2O measurements, two replicate air samples were collected by 10-L Tedlar air bags in both morning (around 9:00 a.m. for the broiler barn and 11:00 a.m. for the layer barn) and afternoon at around 3 p.m., with a total of 4 air samples on each measuring day for both barns. For diurnal CH_4 and N_2O measurements, two replicate air samples were collected every 3 hours at 6 a.m., 9 a.m., 12 p.m., 3 p.m., 6 p.m., and 9 p.m., with a total of 12 samples for each measuring day. The collected air samples were extracted and injected into vacuum tubes and were sent to the Soil Laboratory at University of Saskatchewan for CH_4 and N_2O concentration measurements by a Gas Chromatography (GC) method. The calibration was performed for the CO_2 sensor every three months and for the GC before each test. Additionally, two wireless T/RH data loggers (OM-EL-USB-2, Omega, Canada) continuously monitored T_{in} and indoor RH (RH_{in}) for both barns, with measurement ranges of -35℃ to 80℃ and 0 to 100%, and accuracies of ±0.5℃ and ±3.5%. The outdoor T (T_{out}) and RH (RH_{out}) were downloaded from the website of Environment Canada.

7.5.3 Ventilation rate and emission rate calculation

To estimate VR, a CO_2 mass balance method was used for both barns rather than fan method, which is because of the numerous fans (24 in total) for the layer barn and difficulty of monitoring the performance of the 6 large chimney fans for the broiler barn. The following series of equations from the CIGR (2002) report were used for the calculation of hourly VR:

$$\text{VR per HPU} = (CO_2)_P \times (\text{relative animal activity}) / ((CO_2)_i - (CO_2)_o) \qquad (7.1)$$

$$\text{Relative animal activity} = 1 - a \times \sin[(2 \times \pi/24) \times (h + 6 - h_{min})] \quad (7.2)$$

$$\Phi_{tot} = 10.62\ m^{0.75} \text{ for broilers or } \Phi_{tot} = 6.28\ m^{0.75} + 25\ Y \text{ for laying hens} \quad (7.3)$$

where VR is in $m^3\ h^{-1}$; $(CO_2)_P$ is CO_2 production per HPU based on a 24-h period (0.185 $m^3\ h^{-1}$); $(CO_2)_i$ is indoor CO_2 concentration and $(CO_2)_o$ is outdoor CO_2 concentration, in ppm; a is 0.08 for broilers and 0.61 for layers; h is the hours after midnight; h_{min} is hours after midnight with minimum animal activity, which is not defined for broilers by CIGR (2002) and is assumed to be 0 but is -0.1 for layers (11: 55 p.m.); Φ_{tot} is total heat production under thermoneutral conditions (20℃), in W; m is bird body mass, in kg; and Y is egg production (0.05 kg day^{-1} for consumer eggs). To modify Φ_{tot} per HPU outside the thermoneutral zone, the following equation was used for poultry (CIGR, 2002):

$$\Phi_{tot} = 1000 + 20 \times (20 - T_{in}) \quad (7.4)$$

where T_{in} is in ℃. Knowing gas concentrations and VR, the emissions were calculated as follows:

$$E = VR \times \Delta C \quad (7.5)$$

where E is emission rate in units of mg s^{-1} AU^{-1}, mg s^{-1} m^{-2}, or mg s^{-1} $bird^{-1}$; VR is in $m^3\ s^{-1}$; and ΔC is the difference of gas concentrations between the room inlet air and exhaust air, in unit of ppm. The $(CO_2)_o$ was measured in the mild and warm seasons for both barns by continuous 30-minute measurements after the indoor measurements were finished, but was assumed to be 390 ppm (IPCC, 2013) in the cold season because T_{out} was below the operating temperature range of the CO_2 sensor (0℃ to 50℃). The ambient concentrations of CH_4 and N_2O were not measured and values of 1.8 ppm and 0.32 ppm were used for ambient CH_4 concentration and N_2O concentration, respectively according to IPCC (2013).

Gas emissions were calculated on an hourly basis for seasonal results. Therefore, each data point of seasonal GHG emissions in the figures (the Results part) were the average of hourly results from the morning and evening periods. For diurnal profiles, 20-minute averages around the sampling time were used so only point data were acquired to generate the diurnal variations.

7.5.4 Statistical data analysis

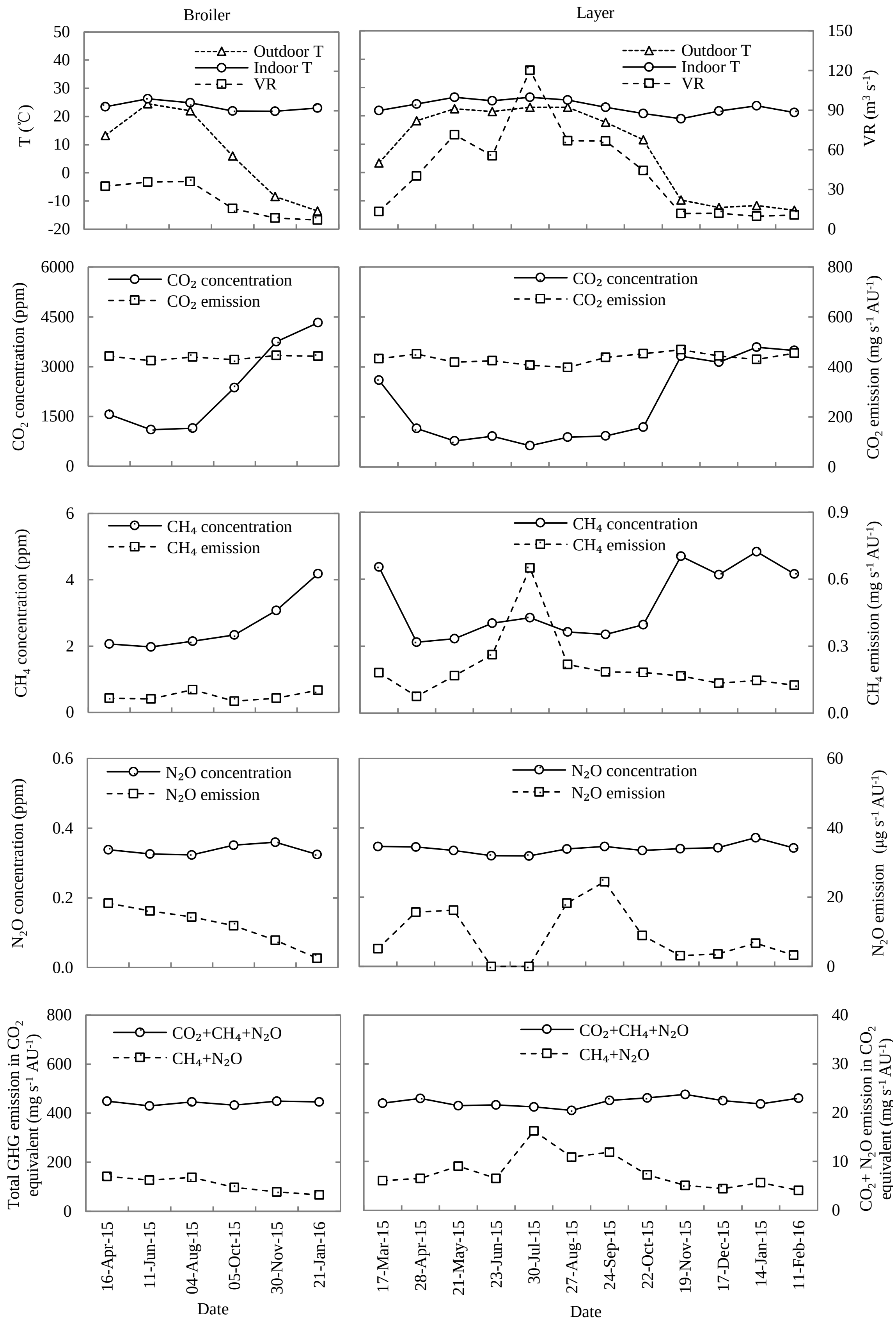
To compare the difference among diurnally measured results from the three seasons, all diurnal results of the two days for the broiler barn were pooled together for each season and were analyzed by Duncan test for multiple comparison using a GLM in SPSS 22 (IBM, USA). The same method was applied in comparing the difference among the three seasons under either best-case condition or worst-case condition for the layer barn. Additionally, Independent-Samples T test was performed to investigate the difference caused by manure removal between best-case days and worst-case days for the layer barn. The significance for the above analyses were indicated by a P value at the 0.05 level ($P \leq 0.05$ indicates a significant correlation). To study the impact of environmental parameters (T and RH) on GHG emissions, a correlation matrix was developed by SPSS 22 with the environmental parameters and GHG emissions as input, where $P \leq 0.05$ indicates a significant correlation and $P \leq 0.01$ indicates a very significant correlation.

7.6 RESULTS AND DISCUSSION

7.6.1 Seasonal GHG concentration and emission profiles

For these measurement days over the 6 flocks of the broiler barn, the birds age varied between 29 and 35 days, the birds number varied between 27,851 and 31,387, and the birds weight ranged from 1.86 to 2.25 kg. For the layer barn, March was the last month of the old batch with 33,922 birds, 1.98 kg of average weight and 70 weeks old. From April a new batch of birds were placed which aged at 22 weeks and weighted at 1.56 kg. From April 2015 to February 2016, the birds number decreased from 39,760 to 39,321, and the bird weight kept increasing and reached maximum 1.87 kg in December but decreased slightly till the end of measurement.

Seasonal patterns of environmental parameters (including T_{in}, T_{out}, and VR), and gas concentrations and emissions are shown in Fig. 7.1. Though the ambient T varied greatly from below -30℃ in the winter to 30℃ in the summer, only the average over the measured hours of the day was plotted for T_{out}. Seasonal VR presented a variation pattern following that of T_{out}, which ranged from 7 $m^3 s^{-1}$ in the winter (January) to 36.33 $m^3 s^{-1}$ in the summer (August) for the broiler barn and ranged from 9.82 $m^3 s^{-1}$ in the winter (January) to 120.17 $m^3 s^{-1}$ in the summer (July) for the layer barn. Seasonal T_{in} was controlled within a narrow range of 22℃ to 26℃ for the broiler barn and of 19℃ to 27℃ for the layer barn. Besides, seasonal RH_{out} fluctuated from 19% to 85%. Seasonal RH_{in} varied less but at higher level for the broiler barn in the range of 48% - 71% compared to 27% - 63% for the layer barn.



Broiler
Layer
Outdoor T
Indoor T
VR
T (℃)
VR (m3 s-1)
CO2 concentration
CO2 emission
CO2 concentration (ppm)
CO2 emission (mg s-1 AU-1)
CH4 concentration
CH4 emission
CH4 concentration (ppm)
CH4 emission (mg s-1 AU-1)
N2O concentration
N2O emission
N2O concentration (ppm)
N2O emission (µg s-1 AU-1)
CO2+CH4+N2O
CH4+N2O
Total GHG emission in CO2 equivalent (mg s-1 AU-1)
CO2+ N2O emission in CO2 equivalent (mg s-1 AU-1)
16-Apr-15
11-Jun-15
04-Aug-15
05-Oct-15
30-Nov-15
21-Jan-16
17-Mar-15
28-Apr-15
21-May-15
23-Jun-15
30-Jul-15
27-Aug-15
24-Sep-15
22-Oct-15
19-Nov-15
17-Dec-15
14-Jan-15
11-Feb-16
Date

Figure 7.1 Seasonal variations in environmental parameters and GHG (CO_2, CH_4, and N_2O) concentrations and emissions.

Due to the great variations of outdoor weather and VR, seasonal CO_2 concentration varied greatly from 1,097 to 4,322 ppm for the broiler barn and from 639 to 3,594 ppm for the layer barn, with higher level in the winter (when VR was low) than the mild and warm seasons for both barns. Seasonal CH_4 concentrations presented consistent variation pattern to CO_2 concentrations, increasing to around 4 ppm in the winter and decreasing to around 2 ppm in the summer for both barns. Seasonal N_2O concentration fell within a narrow range of 0.32-0.36 ppm for the broiler barn, and of 0.32-0.37 ppm for the layer barn. Only slightly higher N_2O concentrations were observed in the winter. Compared to CO_2 concentration, CH_4 and N_2O concentrations were both quite low, which agreed with Wathes et al. (1997) who found CH_4 and N_2O concentrations were only slightly above ambient levels for broiler and layer houses.

Alberdi et al. (2016) measured GHG emissions from a cage layer facility under Oceanic climate conditions. They found that CO_2 emissions did not show seasonality. In this study, seasonal CO_2 emissions also tended to be stable within small differing variations of 3% and 9% from the unity for the broiler barn and the layer barn, respectively. Similarly, seasonal effect seemed to be not obvious for CH_4 emissions, either, for the broiler barn, which is in line with what Roumeliotis et al. (2010) reported for a commercial broiler barn in Ontario, Canada. However, significant seasonal influence was observed for CH_4 emission for the layer barn with slightly higher emission observed in the warm season than the mild and cold seasons ($P<0.05$). This seasonality was mainly caused by a sharp peak of seasonal CH_4 emission in July, which was due to the very high VR measured when all the fans were running.

Due to low CH_4 and N_2O concentrations, the emission levels of CH_4 and N_2O were considerably low compared to CO_2 emissions. However, it should be noted that the global warming potential of CH_4 and N_2O are much higher than that of CO_2 with 25 times and 298 times of CO_2, respectively (IPCC, 2007). The average CH_4 emission rate for the broiler barn is 0.06 mg s^{-1} AU^{-1} for the 6 flocks, which is much lower than 2.41 mg s^{-1} AU^{-1} reported by Roumeliotis et al. (2010) for 4 flocks, who also found their emission rate was much higher than previous studies. Burns et al. (2008) reported an overall CH_4 emission rate of 1.04 mg s^{-1} AU^{-1} for all 12 flocks from two broiler houses (6 flocks in each house) in western Kentucky, which was apparently higher than the result of this study. This might be because the two broiler barns Burns et al. (2008) studied only had one cleanout of the litter (manure) over the year thus gas concentrations and emissions could be accumulated. The average CO_2 emission is 435.09 mg s^{-1} AU^{-1} from this layer barn comparing to 325.23 mg s^{-1} AU^{-1} for a layer facility in California (Lin et al., 2012). The seasonal CH_4 emission averages at 0.21 mg s^{-1} AU^{-1} or 63.86 mg d^{-1} $bird^{-1}$ for the layer barn, which is close to 72.05 mg d^{-1} $bird^{-1}$ summarized by Fournel et al. (2012) for a layer barn in Quebec, Canada, and is slightly lower than 81.7 mg d^{-1} $bird^{-1}$ reported by for organic laying hen husbandry in Netherlands both with manure belt transportation (Dekker, et al., 2011).

Seasonal N_2O emissions gradually decreased with decreasing VR from April to January for the broiler barn. As for the layer barn, N_2O emission was relatively constant in the cold season (November to March) and remained below 10 μg s^{-1} AU^{-1} but varied greatly in the mild and warm seasons from 0 to 24 μg s^{-1} AU^{-1} because of the combined effect of N_2O concentration and VR. Because the measured N_2O concentrations in June and July were very close to the ambient level (0.32 ppm), N_2O emissions were considered to be 0 for the two months. The average N_2O emissions in the mild and warm seasons (12 μg s^{-1} AU^{-1}) were obviously higher than in the cold season (4 μg s^{-1} AU^{-1}). This contradicts with the findings of Alberdi et al. (2016) that N_2O emissions tended to be higher in the winter. The annual N_2O emission from this broiler barn is estimated to be 0.31 g $bird^{-1}$ $year^{-1}$ or 0.09 kg $bird^{-1}$ $year^{-1}$ in CO_2 equivalent, which is much lower than 0.51 kg $bird^{-1}$ $year^{-1}$ reported by Burns et al. (2008). The average monthly N_2O emission for the layer barn is 2.65 mg d^{-1} $bird^{-1}$, which is lower than 4.50 mg d^{-1} $bird^{-1}$ reported by Alberdi et al. (2016), 3.12 mg d^{-1} $bird^{-1}$ from Dekker et al (2011), and 7.10 mg d^{-1} $bird^{-1}$ indicated by Fournel et al. (2012). The obviously lower N_2O emission in June than the other warm months (May to September) was resulted from the lowest N_2O concentration and VR measured.

Given the high CO_2 emissions and low CH_4 and N_2O emissions, the majority (>98%) of total GHG emissions was contributed by CO_2 emissions for both barns. As a result, the total GHG emission pattern followed that of CO_2 emission pattern with no significant seasonal variances ($P>0.05$).

7.6.2 Diurnal GHG concentration and emission profiles

Diurnal measurements were conducted in April, August, and January for the broiler barn, and in April, July, and January for the layer barn. The bird information on these days are listed in Table

7.1. For the layer barn, Apr 28th, Jul 30th, and Jan 25th were worst-case days and Apr 30th, Jul 28th, and Jan 21th were best-case days.

Table 7.1 Birds number, age, and weight on sampling days in the three seasons.

	Broiler						Layer		
	Mild		Warm		Cold		Mild	Warm	Cold
	Apr 14	Apr 16	Aug 04	Aug 06	Jan 21	Jan 25	Apr 28&30	Jul 28&30	Jan 12&14
Number	31,387	31,287	29,853	29,815	29,421	29,263	39,760	39,672	39,402
Age	29 d	31 d	29 d	31 d	31 d	35 d	22 w	35 w	59 w
Weight (kg)	1.891	2.089	1.878	2.037	2.091	2.396	1.564	1.743	1.841

Notes: d means day, and w means week

7.6.2.1 Broiler barn

In agreement with seasonal results, it was found that diurnal VR was relatively low and stable in the cold season, while presented obvious diurnal variations in the warm and cold seasons. In the mild season, the T_{out} varied greatly from as low as -2°C in the early morning to up to 20°C in the afternoon. As a result, diurnal VR was low in the early morning and gradually increased with the increased T_{out} and tended to show a plateau from the late afternoon (3 p.m.) till the end of the measurement for April 14th. Diurnal VR from 6 a.m. to 12 p.m. on April 16th showed the similar routine to that of April 14th, but began to soar from 3 p.m. until 6 p.m., which was due to the over heat stress inside the broiler barn in the afternoon thus the 4 end-wall fans were running from around 2 to 6 p.m. After that, diurnal VR fell back to the same level as April 14th at 9 p.m. In the warm season, it was observed that diurnal VR on August 4th presented similar variation pattern to that of April 14th with almost 2 times of average VR on April 14th. On the contrary, diurnal VR on August 6th gradually increased from 6 a.m. to 3 p.m. and reduced significantly from 3 to 9 p.m., which was explained by that it was raining on August 6th and the cool air decreased the T_{in} and lowered the requirement of VR.

Diurnal gas concentrations for the broiler barn are summarized in Table 7.2. Being affected by VR, CO_2 concentrations showed obvious diurnal effect in the mild season. It was decreasing from the early morning to the afternoon along with increased T_{out} and VR but increased from the early evening when T_{out} and VR decreased. As a combining result of CO_2 concentration and VR, diurnal CO_2 emissions occurred to be constant (around 400 mg s^{-1} AU^{-1}) for all seasons. From Table 7.2, it seemed that diurnal impact was not obvious for CH_4 or N_2O concentrations. Diurnal CH_4 concentrations remained stable at around 2 ppm in the mild season and increased slightly but still below 2.30 ppm in the warm season and was maximum in the cold season within a range of 3.22-4.60 ppm. Diurnal N_2O concentrations were even more stable than CH_4 concentration, falling within a narrow range of 336-345 ppb in the mild season, of 317-330 ppb in the warm season, and of 323-344 ppb in the cold season.

Table 7.2 The average 3-hourly diurnal CO_2, CH_4, and N_2O concentrations in the three seasons for the broiler barn.

	Mild			Warm			Cold		
	CO_2 (ppm)	CH_4 (ppm)	N_2O (ppb)	CO_2 (ppm)	CH_4 (ppm)	N_2O (ppb)	CO_2 (ppm)	CH_4 (ppm)	N_2O (ppb)
06:00	3274	2.05	345	1458	2.28	323	4195	3.64	325
09:00	2167	2.10	339	1170	2.18	328	4105	4.28	327
12:00	1859	2.04	337	1156	2.26	325	3784	4.34	325
15:00	1273	2.06	336	1075	2.17	319	3591	3.76	324
18:00	1256	2.01	336	1133	2.13	319	3591	3.88	336
21:00	1571	2.05	341	1348	2.18	321	3476	3.80	326
Mean	1900^{b}	2.05^{b}	339^{a}	1223^{b}	2.20^{b}	323^{b}	3790^{a}	3.95^{a}	327^{b}

Notes: a, b and c indicate the significance of the difference for each item; same letters mean not significant.

Different from CO_2 emissions, CH_4 and N_2O emissions presented great diurnal variations in both mild and warm seasons when diurnal VR varied more significantly. In the mild season, CH_4 and N_2O emissions were mainly affected by VR thus displayed similar diurnal trends to VR. In the warm season, both concentrations and VR played vital roles in shaping diurnal CH_4 and N_2O emission patterns. Though no clear diurnal patterns could be summarized, the apparent influence of concentrations and VR was still found on emissions, e.g., diurnal CH_4 emission was decreasing from 3:00 p.m. to 9:00 p.m. on Aug 6th when VR was decreasing, and diurnal N_2O emission were observed to be 0 within 3:00-6:00 p.m. on both days in the warm season when N_2O concentrations were measured to be the ambient level. Diurnal effect also seemed to be obvious for CH_4 emission in the cold season, which was indicated by that the ratio of maximum value could be 2.5 times of the minimum value but was not proved for N_2O emission.

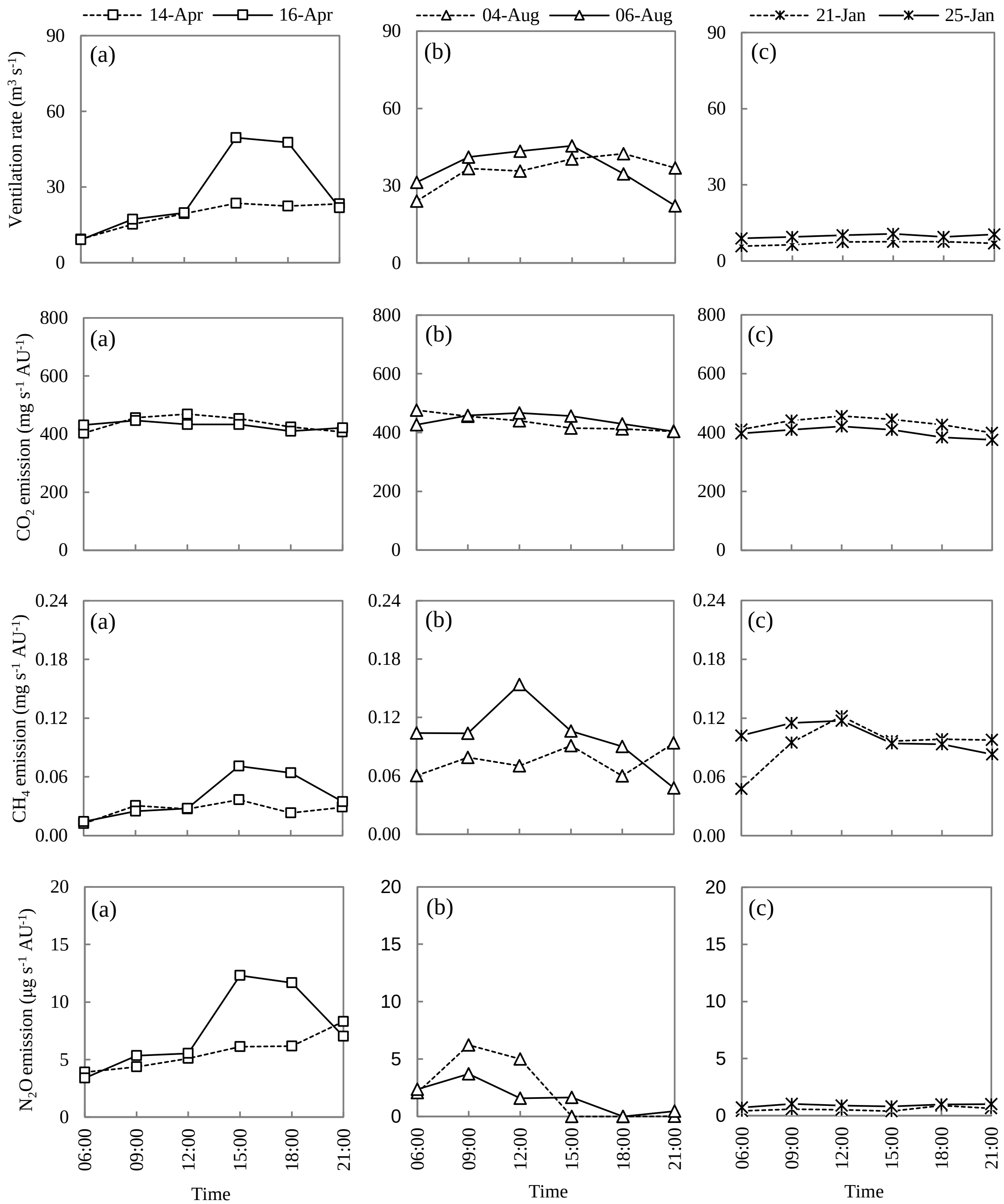


Figure 7.2 Diurnal variations in VR and GHG (CO_2, CH_4, and N_2O) emissions for the broiler barn in the mild (a), warm (b), and cold (c) seasons.

7.6.2.2 Layer barn

In consistent with the broiler barn, there also observed relatively low and constant VR in the cold season, but higher and more fluctuating VR in the mild and warm seasons. It was found that VR showed highly consistent diurnal trends for the two days in both mild and cold seasons. Though varying with different extent, similarity was still observed in diurnal VR patterns in the warm and mild seasons, both of which presented downward parabola with a peak occurred within 12:00-3:00 p.m. However, obvious difference was observed in VR between the two days in the warm season, with significantly higher VR on July 30th than July 28th, which was explained by that it was raining on July 28th and the T_{out} was lower.

Table 7.3 The average of diurnal CO_2, CH_4, and N_2O concentrations in the mild, warm, and cold seasons for the layer barn.

		Mild			Warm			Cold		
		CO_2 (ppm)	CH_4 (ppm)	N_2O (ppb)	CO_2 (ppm)	CH_4 (ppm)	N_2O (ppb)	CO_2 (ppm)	CH_4 (ppm)	N_2O (ppb)
Best-case	06:00	1533	2.21	350	961	2.90	317	3980	4.38	366
	09:00	1537	2.22	342	984	2.85	315	4046	4.32	362
	12:00	1002	2.09	343	997	2.91	315	3989	4.94	360
	15:00	978	1.91	342	949	2.99	316	3599	4.55	360
	18:00	1042	2.41	339	791	2.74	318	3629	4.40	362
	21:00	1368	2.17	344	850	3.19	318	3214	4.70	365
	Mean	1243^{ab}	2.17^{b}	344^{ab}	922^{b}	2.93^{ab}	316^{b}	3743^{a}	4.55^{a}	362^{a}
Worst-case	06:00	2250	2.33	344	1108	3.27	321	3865	4.16	360
	09:00	1860	2.19	340	751	2.69	318	3654	4.13	358
	12:00	1148	2.08	347	651	2.83	319	3719	4.96	359
	15:00	934	2.15	343	648	2.87	319	3554	4.69	384
	18:00	904	2.17	344	621	2.55	319	3700	4.79	360
	21:00	1148	2.15	346	757	2.63	321	3553	5.28	360
	Mean	1374^{ab}	2.18^{b}	344^{ab}	756^{b}	2.81^{ab}	320^{b}	3674^{a}	4.67^{a}	363^{a}

Notes: a, b and c indicate the significance of the difference for each item; same letters mean not significant.

No diurnal effect was proved for CH_4 and N_2O concentrations (Table 7.3) of the layer barn, either. Diurnal CH_4 emission had apparently greater variations in the warm season than the other two seasons, which was attributed to the greater diurnal VR variations. As for diurnal N_2O emission, it varied greatly in the mild season followed by the cold season, with peaks occurring within 12:00-3:00 p.m., while was observed as zero emission in the warm season. Different from the broiler barn, diurnal CO_4 emissions of the layer barn seemed to be more affected by VR and presented a similar patter to that of VR with obvious diurnal variances. Diurnal CO_2 emissions showed highly consistent diurnal patterns in the three seasons and greater diurnal variations for the layer barn than the broiler barn. From 6:00 a.m. to 12:00 p.m., CO_2 emission increased gradually and reached a peak at 12 p.m. when usually VR was maximum, and then gradually decreased after 12 p.m. till the end of the measurement along with decreased VR. The average diurnal CO_2 emissions were similar in the three seasons which is given in Table 7.5.

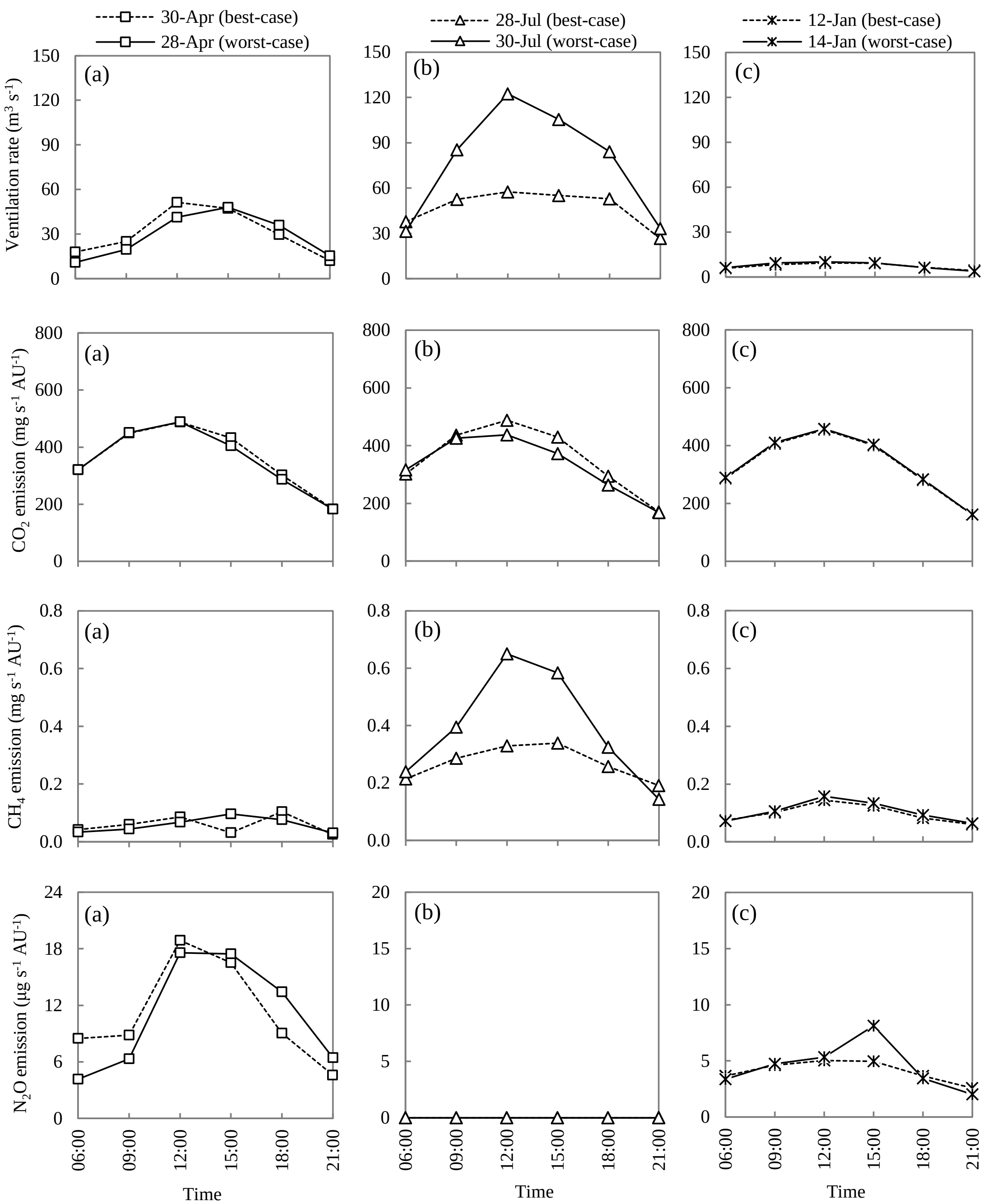


Figure 7.3 Diurnal variations in VR and GHG (CO_2, CH_4, and N_2O) concentrations and emissions for the layer barn.

Comparing the gas concentrations on best-case day and worst-case day, no significant effect of removing manure on reducing CO_2, CH_4, and N_2O concentration was found for any of the three seasons ($P>0.05$). No significant difference in CO_2, CH_4, and N_2O emissions was caused by removing manure, either ($P>0.05$), which agreed with Dekker et al. (2011) who found CH_4 and N_2O emissions for aviary systems was not affected by the presence of manure on the belt. This finding suggests that CO_2 production from manure for this layer barn with frequent manure removal (every 3 or 4 days) did not have significant contribution to the whole CO_2 production and may could be neglected compared to CO_2 production from bird respiration, which further demonstrates the credibility of the CO_2 mass balance method used in estimating VR.

7.6.3 Summary of the results

Table 7.4 and Table 7.5 summarize seasonal and diurnal concentrations and emissions of CO_2, CH_4, and N_2O as well as total GHG in different units for both barns.

Table 7.4 Summary of seasonal GHG emissions for the broiler and layer barns (worst-case conditions).

	Broiler			Layer		
	Min	Max	Mean ± SD	Min	Max	Mean ± SD
CO_2 C (ppm)	1097	4322	2372 ± 1378	639	3594	1892 ± 1217
CO_2 E (mg s^{-1} AU^{-1})	423	445	437 ± 8.91	399	469	435 ± 21
CO_2 E (mg s^{-1} $bird^{-1}$)	1.57	2.00	1.80 ± 0.16	1.35	1.74	1.55 ± 0.14
CO_2 E (mg s^{-1} m^{-2})	28.85	34.48	31.92 ± 2.28	54.39	69.74	61.46 ± 5.09
CH_4 C (ppm)	1.98	4.18	2.63 ± 0.86	2.12	4.82	3.29 ± 1.05
CH_4 E (mg s^{-1} AU^{-1})	0.04	0.10	0.06 ± 0.02	0.08	0.65	0.21 ± 0.15
CH_4 E (μg s^{-1} $bird^{-1}$)	0.14	0.41	0.25 ± 0.10	0.24	2.27	0.74 ± 0.51
CH_4 E (μg s^{-1} m^{-2})	3.98	7.37	5.39 ± 1.42	9.50	91.30	29.38 ± 20.55
N_2O C (ppb)	323	360	337 ± 15	319	371	340 ± 14
N_2O E (μg s^{-1} AU^{-1})	0.48	8.66	4.74 ± 2.98	0	24.43	8.79 ± 7.97
N2O E (μg s^{-1} $bird^{-1}$)	0.002	0.04	0.02 ± 0.01	0	0.09	0.03 ± 0.03
N_2O E (μg s^{-1} m^{-2})	0.04	0.68	0.35 ± 0.24	0	3.54	1.23 ± 1.11
Total GHG (mg s^{-1} AU^{-1})	425	448	439 ± 9	410	474	443 ± 19
Total GHG (mg s^{-1} $bird^{-1}$)	1.58	2.02	1.81 ± 0.16	1.40	1.76	1.59 ± 0.13
Total GHG (mg s^{-1} m^{-2})	29	35	32 ± 2	57	71	63 ± 5

Notes: SD means standard deviation; a, b, and c indicate the significance of the difference for each item and same letters mean not significant.

It should be noted that the emission data listed in Table 7.4 was only from the worst-case conditions for both barns. As discussed above, manure removal did not significantly impact on CO_2, CH_4, and N_2O emissions for the layer barn (P>0.05), thus the emission data from worst-case conditions could also represent the overall average for the layer barn. The following discussion were based on the emissions using per animal unit basis. It was found that the total GHG emissions from seasonal measured results for the two barns were quite similar due to their similar CO_2 emissions (the majority of total GHG emissions was contributed by CO_2 emission), though obviously lower CH_4 and N_2O emissions from the broiler barn than the layer barn was observed. This is due to the much lower VR for the broiler barn in the mild and warm seasons.

In agreement with the seasonal results, great contribution of CO_2 emissions to the total diurnal GHG emissions was observed for the layer and broiler barn with 98.6% and 99.3% for all seasons. The average CO_2 emission and total GHG emission for all seasons from diurnally measured results was 345 and 350 mg s^{-1} AU^{-1} for the layer barn, which was 20.7% and 21% lower than the average results of monthly measurements. This was explained by that seasonal measurement was only performed for 2 hours in the late morning and 2 hours in the afternoon for the layer barn when CO_2 emission was relatively high (according to its diurnal patterns), while the diurnal result was an average of CO_2 emissions from all the diurnal periods, which further suggested that snapshot measurement would cause considerable error in estimating CO_2 emissions for the layer barn but not for the broiler barn. However, with the knowledge of diurnal CO_2 emission patterns in each season, the seasonal CO_2 emission was able to be modified due to its highly consistent diurnal patterns observed in all seasons. The correction factors were calculated to be -21%, -20.9%, and -22.5%, respectively, for the monthly measured results of the mild, warm, and cold seasons. The above conclusions also work for modifying the monthly total GHG emissions as the vast majority of GHG emissions were CO_2 emissions.

Table 7.5 Summary of diurnal GHG emissions in the mild, warm, and cold seasons for the broiler (worst-case condition) and layer barns (including best-case and worst-case conditions).

		Mild			Warm			Cold			All
		Min	Max	Mean ± SD	Min	Max	Mean ± SD	Min	Max	Mean ± SD	seasons
Broiler	CO_2 (mg s^{-1} AU^{-1})	404	469	$433^a \pm 21$	412	476	$437^a \pm 25$	370	452	$410^a \pm 25$	427
	CH_4 (mg s^{-1} AU^{-1})	0.01	0.07	$0.03^b \pm 0.02$	0.05	0.15	$0.09^a \pm 0.03$	0.05	0.12	$0.10^a \pm 0.02$	0.07
	N_2O (μg s^{-1} AU^{-1})	3.39	12.3	$6.60^a \pm 2.85$	0	6.21	$1.92^b \pm 2.09$	0.39	1.04	$0.73^b \pm 0.23$	3
	GHG_{total} (mg s^{-1} AU^{-1})	405	471	$435^a \pm 21$	406	478	$440^a \pm 26$	373	455	$413^a \pm 25$	429
Layer	CO_2 (mg s^{-1} AU^{-1})	182	489	$359^a \pm 109$	168	488	$342^a \pm 107$	161	458	$333^a \pm 104$	345
	CH_4 (mg s^{-1} AU^{-1})	0.03	0.10	$0.06^b \pm 0.03$	0.14	0.65	$0.33^a \pm 0.15$	0.06	0.16	$0.10^b \pm 0.03$	0.16
	N_2O (μg s^{-1} AU^{-1})	4.16	18.9	$11^a \pm 5.47$	0	0	0^c	2.02	8.12	$4.29^b \pm 1.58$	5.09
	GHG_{total} (mg s^{-1} AU^{-1})	185	496	$364^a \pm 110$	172	496	$350^a \pm 109$	163	463	$337^a \pm 105$	350

Notes: SD is standard deviation; a, b, and c indicate the significance of the difference for each item and same letters mean not significant.

7.6.4 Correlations between GHG emissions and environmental parameters

The statistical correlations between environmental parameters and GHG emissions are given in Table 7.6. Significant positive correlations between VR and T_{out} (r>0.8, P<0.01) were observed for both barns. For the broiler barn, T and VR seemed to have more impact on N_2O emission than CO_2 and CH_4 emissions; the strong positive correlations suggest increased T_{out} and VR were associated with increased N_2O emissions (P<0.01). More influence of T and VR on CH_4 emissions were suggested for the layer barn; T_{in}, T_{out} and VR were all positively related to CH_4 emissions.

Table 7.6 Correlations between GHG emissions and environmental parameters.

	Broiler			Layer		
	CO_2 E (mg s^{-1} AU^{-1})	CH_4 E (mg s^{-1} AU^{-1})	N_2O E (μg s^{-1} AU^{-1})	CO_2 E (mg s^{-1} AU^{-1})	CH_4 E (mg s^{-1} AU^{-1})	N_2O E (μg s^{-1} AU^{-1})
T_{in} (℃)	-0.402**	NA	NA	NA	0.318*	NA
T_{out} (℃)	NA	NA	0.811**	NA	0.427**	0.318*
VR (m^3 s^{-1})	NA	0.314*	0.895**	NA	0.778**	NA

Notes: E is emission; ** means correlation is significant at the 0.01 level (2-tailed) and * means correlations is significant at the 0.05 level (2-tailed); NA means not significant.

7.7 CONCLUSIONS

This study quantified the emission factors of the three GHG (CO_2, CH_4, and N_2O) and the total GHG for a commercial broiler barn and cage-layer barn in the Canadian Prairies climate with their seasonal and diurnal variations being characterized by long-term measurement. The following conclusions are summarized:

1) For both barns, CO_2 and CH_4 concentrations were higher in the cold season than the mild and warm seasons, while N_2O concentration was relatively stable. Seasonal effect was not obvious for CO_2 emissions for both barns but was considerable (P<0.05) for N_2O emissions of the broiler barn, and for CH_4 and N_2O emissions of the layer barn, with higher emissions in the mild and warm seasons. The emissions of CH_4 and N_2O were very low compared to CO_2 emissions. As the vast majority (>98%) of total GHG emission was attributed to CO_2 emissions, monthly total GHG emissions remained constant for both barns. Comparing the results with that of previous studies, it was found that the CH_4 emission of the broiler barn with cleanout of manure for each flock was greatly lower than broiler barns with only one

cleanout of manure for all flocks within a year, while the layer barn presented comparable CO_2 and CH_4 emissions to other layer barns at different locations or under different climate conditions.

2) Based on the diurnal results in the three seasons, the emission factors of CO_2, CH_4, N_2O and total GHG for all seasons were 428 mg s^{-1} AU^{-1}, 0.07 mg s^{-1} AU^{-1}, 3 μg s^{-1} AU^{-1}, and 431 mg s^{-1} AU^{-1} for the broiler barn, compared to 345 mg s^{-1} AU^{-1}, 0.16 mg s^{-1} AU^{-1}, 5.09 μg s^{-1} AU^{-1}, and 350 mg s^{-1} AU^{-1} for the layer barn. Diurnal variations were obvious for CO_2 concentration in the mild season but were not for CH_4 or N_2O concentrations in any season. Diurnal CO_2 and total GHG emissions were relatively constant for the broiler barn, but were varying with highly consistent diurnal patterns in all seasons for the layer barn, with highs occurring within 9:00 a.m.-3:00 p.m.
3) With the diurnal trends for the layer barn, seasonally measured CO_2 emissions over middle hours of a day were found to be over-high to represent the daily results. Thus, correction factors of -21%, -20.9%, and -22.5% for modifying seasonally measured CO_2 emissions in the months of the mild, warm, and cold seasons were acquired for the layer barn, which would also work for modifying total GHG emissions. Besides, manure removal for the layer barn did not show obvious efficiency in reducing GHG concentrations or emissions. Therefore, the GHG emission factors acquired from worst-case conditions for the layer barn could represent general GHG emissions.
4) Changes of T and VR seemed to have more impact on N_2O emission than on CO_2 and CH_4 emissions for the broiler barn. Increased T_{out} and VR were indicated to increase N_2O emissions ($P<0.01$). For the layer barn, more influence of T and VR were suggested for CH_4 emissions as T_{in}, T_{out}, and VR were all found to positively correlate with CH_4 emissions ($P<0.05$).

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CHAPTER 8
VALIDATING THE PERFORMANCE OF AERMOD FOR LIVESTOCK ODOUR DISPERSION

8.1 CONTRIBUTION OF THE PH.D. CANDIDATE

The emission data collecting, odour plume measurement, dispersion modelling, data analysis, and manuscript writing were performed by the candidate. Zimu Yu and Zhu Gao provided technical support as for AERMOD model set-up. Dr. Huiqing Guo provided editorial input and suggestions on methods and data analyses.

8.2 CONTRIBUTION OF THIS PAPER TO THE OVERALL STUDY

This chapter introduces the validation of the performance of AERMOD in simulating livestock odour dispersion through field odour plume measurements for the study broiler barn. Diurnal odour emission (OE) measured in the summer for the broiler barn (Chapter 4) was used as data input for the modelling and the relationship between odour concentration (OC) and odour intensity (OI) acquired in Chapter 2 was used to convert the field measured OI to OC or convert the modelled OC to OI. As the results, scaling factors were generated to adjust modelled results to similar level as the field measured results for comparisons, and the evaluations of AERMOD for predicting OC over different distances were also given. Thus, the credibility of the modelled results in Chapter 9 could be validated by the results from this Chapter.

8.3 ABSTRACT

Field odour plume measurement was conducted around a broiler barn under the Canadian Prairies climate condition and flat terrain condition to validate the performance of AERMOD model for predicting ambient odour dispersion. The measured odour intensities (OIs) were converted to

odour concentrations (OCs) by the OC and OI relationship established earlier for the same broiler barn in Chapter 2, and were compared with the corresponding modelled OCs. It was found that the modelled hourly OCs were all greatly lower than the field measured odour results from short-term measurements (10-minute). Two scaling factors were generated to adjust the model predictions, which were the slopes of the linear relationships by plotting modelled OC against field measured OC, one was 286 from using all the data points and the other was 154 from using the geometric mean of each odour plume. Results showed that field measurements and model predictions achieved acceptable agreement by using both scaling factors, 76% for the scaling factor of 286 and 81% for 154. The scaling factor of 154 was suggested to use due to that it greatly improved the performance of AERMOD for predicting OC over short distances (100-200 m) as well as generated smaller paired difference and better paired sample correlations compared to 286.

8.4 INTRODUCTION

Many researchers have applied the commercial air dispersion models to predict livestock odour dispersion, to assess odour impact on the communities and to determine setback distances. AERMOD is one of the most commonly used model with added or improved algorithms designed to replace ISCST3 (Industrial Source Complex) (US EPA, 2003). However, these dispersion models, including AERMOD, are initially designed for predicting industrial air pollutant dispersions. Significant differences do exist between industrial gases and odour, especially livestock odour (Smith, 1993), e.g., odour source is at or near ground level, no or little plume rise mainly due to small difference of room temperature and ambient temperature, the source may be of relatively large area extent, and the important receptor zone may be relatively close to the source of emissions. Only a few models, including AODM, ODODIS and LODM, were specifically designed for odour dispersion from agricultural sources, nevertheless, these models use the same air dispersion theories as the other dispersion models (Guo et al., 2006; Yu, 2010). In addition, odour concentration (OC) is measured by detection threshold which is the dilution ratio of odorous air by fresh air rather than a mass concentration that used for gas concentration, therefore, evaluations of these models are very important to judge the credits of the modelled results (Xing, 2007; Li, 2009).

Field odour plume measurement is a widely-used method to validate model validity. In comparing model predictions to field measurements, researchers have found under-estimated performance of the commercial dispersion models in predicting livestock odour (Zhu et al., 2000; Guo et al., 2001; Guo et al., 2006). Zhu et al. (2000) attributed the possible reasons to the assumptions employed by the models, including OC is in unit of OU m^{-3} instead of mass unit input in the modelling, disregard of chemical and biological reactions during odour dispersion, as well as the complex composition of odour might make its dispersion different from a single gas dispersion for which is the commercial models have been designed. In addition to the inherent drawbacks existed in the dispersion models in predicting odour dispersion, another important explanation is that dispersion models usually calculate hourly mean OC while field odour measurements were conducted for a short term with one odour measurement occurring only within a few seconds for a duration of 10 minutes (Guo et al., 2001). The 10-min average measured OC were then taken as hourly average values to compare with modelled hourly average OC. Therefore, to compare the modelled results over a long-term to the field measured results over a short-term, the modelled odour concentrations need to be adjusted by using a "peak-to-mean ratio" or "scaling factor" (Guo et al., 2006; Schulte et al., 2007; Karageorgos et al., 2010; Brancher et al., 2017). Smith (1973) proposed the following equation to transform the modelled half-hour mean concentrations to instantaneous concentrations: $C_p/C_m = (t_m/t_p)^u$, where C_p is the estimated peak concentration for a short time period, t_p, C_m is the modelled mean concentrations for a long period, t_m. The exponent u varied between 0.35 to 0.65 depending on the atmospheric stability (Smith, 1973; Schauberger and Piringer, 2004). Koppolu et al. (2004) reported that scaling factors from 0.2 to 3900 may be needed to adjust the modelled odour results to short-term values, depending on the source type (point, area, or volume) and the facility type.

Guo et al. (2001) compared field measured odour intensity (OI) with modelled results to validate the INPUFF-2 dispersion model. It was found that the model could satisfactorily predict OI up to 3.2 km away from sources under stable to slightly unstable weather conditions, however, the model underestimated moderate to strong or very strong odours during neutral or unstable weather. Wang et al. (2006) compared CALPUFF model and ISCST 3 model in predicting downwind OCs from cattle feedlots by field OC measurements (ambient odour samples were collected from both upwind and downwind of the source and were analyzed for OC in the lab). The results showed that CALPUFF model could fairly well predict average downwind OC but ISCST 3 tended to underestimate downwind OC compared to the measured results, and both models (using the constant average emission rate) failed to simulate peak OC. Schulte et al. (2007) conducted odour dispersion for a swine facility using AERMOD. They found the ambient odour levels measured by a Nasal Ranger® were generally lower than the predicted values by AERMOD. Scaling factors of 1.66-3.12 were determined from the slope of the linear relationship between modelled results and observed results to adjust the modelled odour levels to the observed levels. Xing (2006) validated four selected air dispersion models, including ISCST 3, AUSPLUME, CALPUFF and INPUFF 2, for predicting livestock odour and found their performances were poor by direct comparison with field measurements. No model was obviously better than others. After scaling factors were generated for CALPUFF (8.3 for barn and 11.4 for the manure storage) and INPUFF2 (8.3 for barn and 11.4 for the manure storage), the agreement of the modeled predictions and the field measurements were increased by 4% to 24%. Using similar methods to Xing's (2006) research, Li (2009) evaluated AERMOD and CALPUFF dispersion models using field odour data and found no significant difference between the percentages of the agreement of the two modelled results and the measured result; scaling factors can improve the agreement of modelled results and all field odour results by 14.8 and 10.7% for AERMOD and CALPUFF respectively. Henry et al. (2010) modelled downwind OCs from a swine production facility using CALPUFF and AERMOD dispersion models and assessed ambient odour using Nasal Ranger, Mask Scentometer, OI Rating Scale (0-5 scale), and dynamic triangular forced-choice olfactometry. Through a linear regression analysis of the results, scaling factors for the two models were acquired and AERMOD was slightly better than CALPUFF in predicting downwind OC, but the difference was not significant. Zhou (2010) measured odour emissions (OEs) and downwind odour plumes for two swine farms in southern Manitoba, and used three different dispersion models (ISCST3, AUSPLUME, and INPUFF-2) to predict odour dispersion for the two farms. They found adequate agreement between modelled results and field measurements for downwind distances of 500 and 1000 m, but relatively low percentage for 100 m for all three models.

Based on the above results, no conclusion could be drawn that these air dispersion models can be used to satisfactorily predict livestock odour dispersion in all situations, or a certain model is always better than the other models. Besides, scaling factor plays a vital role in comparing model predictions over a long-term averaging period (mostly 1 hour) to field measurements over a short term (a few seconds to 10 minutes), which likely varies among different studies depending on the measurement methods of OC, the OI ranking methods, OC and OI relationships, the dispersion models and modelling methods, etc. Thus, there is a need to evaluate the credibility of dispersion models used for livestock odour and determine the scaling factor for a specific study or similar kinds of studies (including similar methods, meteorological conditions, terrain conditions, etc.). This study is aiming to validate the performance of AERMOD for livestock odour dispersion under Canadian Prairies climate and flat terrain condition by field odour plume measurements around a broiler barn, as well as obtain scaling factors to make modelled hourly average values comparable to short-term (10-minute) average values.

8.5 MATERIALS AND METHODS

8.5.1 Study site

This study was conducted for a broiler barn, which located in Hepburn, Saskatoon, Canada (106.61^{o}W and 52.54^{o}N). The broiler barn is mainly surrounded by agricultural land, grassland, and lakes, as shown in Fig. 8.1, with no obvious other odour sources within a distance of 1 km. The other details for the broiler barn can be found in Chapter 4.

Figure 8.1 Surrounding areas of the broiler barn (Google earth, 2017).

8.5.2 Downwind odour plume measurement

Plume measurements were conducted for two days in the last week of one flock of the broiler barn in summer 2016, including Aug 31st and Sep 2nd. Five trained and experienced odour panelists performed field odour measurements in compliance with VDI standard (2006). There were 4 measurement periods each day: early morning (7:00-9:00 a.m.), late morning (10:00 a.m.-12:00 p.m.), afternoon (2:00-4:00 p.m.), and early evening (6:00-8:00 p.m.). During each measurement period, 3-4 measuring sessions were performed with one session lasting for 10 minutes. During each 10-min measurement session, the 5 panelists stood leeward of the broiler barn in a line which was perpendicular to the wind direction and spread out with 5-20 m distance between each other and recorded the OI and their positions (longitude and latitude coordinates). With the instruction of the panel leader, panelists took off air masks (which is used to protect their noses from fatigue) and sniffed odour simultaneously every 10 seconds, as well as hedonic tone (HT) and character descriptor when odour was detected. Therefore, 60 observations were collected by each panelist at the end of each 10-min session.

Table 8.1 Corresponding OC range to the 5-Point reference scale for OI measurement (ASTM, 1998).

OI	Odour strength	N-butanol in water (ppm)	Broiler odour	
			Concentration (OU m^{-3})	Concentration range for OI ± 0.5 (OU m^{-3})
0	No odour	0	0	<15
1	Very faint	250	68	15-160
2	Faint	750	292	160-467
3	Moderate	2250	685	467-948
4	Strong	6750	1255	948-1607
5	Very strong	20250	2006	1607-2451

The plume measurements were always started from a far distance where panelists began to detect odour and moved to closer distances to the broiler barn. Wind direction was checked by a bubble maker at the beginning and the end of each 10-min session and was used as the actual wind direction in dispersion modelling. Before performing each odour session for OI measurement, panelists' noses were calibrated by standard n-butanol samples made in accordance with the 5-point scale method (ASTM, 1998) in Table 8.1.

8.5.3 Relationship between OC and OI

To compare the field measured results with modelled results, the field measured OI should be converted to OC or vice versa. Thus, the relationship between OC and OI needs to be obtained for this conversion. From previous study (Chapter 4) for characterizing the seasonal and diurnal variations of OC and OE for the broiler barn within the period of Apr 2015 to Jan 2016, a total of 50 data points of OC and OI were acquired over 6 available flocks to investigate the relationship between OC and OI, with one data point representing the average of two replicates. The OC-OI relationships were developed and fully introduced in Chapter 2.

8.5.4 Configuration for AERMOD

AERMOD modelling system needs three major data sets as input before it could calculate OC at various receptors around the broiler barn, including source OE, meteorological data, and terrain data. Odour emissions from livestock barns could show obvious diurnal patterns (Wang, 2007). Thus, to acquire diurnal variations of OE in typical summer season for the broiler barn, continuous diurnal measurements of OC and OE were conducted from 6 a.m. to 9 p.m. for two days on Aug 4^{th} and Aug 6^{th}, 2015, respectively. Every three hours, two replicate room air samples were collected and measured for OC at the Olfactometry Laboratory at University of Saskatchewan in compliance with CEN (2003) standard. The methods for calculating VR and OE were described in Chapter 4. Considering that field plume measurements were conducted on typical sunny days in summer for the broiler barn and there was rain on Aug 6^{th}, 2015, only the variable hourly OE measured on Aug 4^{th}, 2015 were input as source emissions.

Table 8.2 Hourly OE in typical summer season for the broiler barn.

Hour of day	05:00-06:00	06:00-08:00	08:00-09:00	09:00-11:00	11:00-12:00	12:00-14:00	14:00-15:00	15:00-17:00	17:00-18:00	18:00-20:00
OE (OU S^{-1})	17484	21295	25105	25480	25854	26606	27358	29057	30756	29908

The broiler barn was treated as "volume" source type in the modelling, thus the emissions in the unit of OU s^{-1} were applied. As OE was measured at discrete hours, an average of the two adjacent data points was used for the hours between (Table 8.2). The meteorological data for Aug 31^{st} and Sep 2^{nd}, 2016 when field plume measurements were conducted were used in the dispersion modelling, including hourly surface weather data from the Government of Canada (2016), and upper air sounding data downloaded from GLASGOW weather station (NOAA/ESRL Radiosonde Database, 2016) (no upper air sounding data is available in Canada), which is the nearest weather station to Saskatoon (as suggested to use by Government of Saskatchewan, 2012). As for the terrain data input, the 1:50, 000 Canadian Digital Elevation Data from Geobase Canada (2017) was utilized.

8.6 RESULTS AND DISCUSSION

8.6.1 Field measured and modelled results

Due to that wind speed on Sep 2nd, 2016 was low (sometimes calm) and the major wind direction was not favorable for panelists to find suitable standing places in the downwind of the broiler barn, only the results from Aug 31st, 2016 were used. Thus, a total of 14 odour plume measurements on Aug 31st, 2016 were conducted with a total of 70 data points being collected at various discrete receptors (one data point is the average of all the 60 recordings for one 10-minute session from one panelist); however, only 66 data points were used as four of them were deleted due to the wrong coordinates recorded. The statistical description of the field measured OI and modelled OCs for all 14 plumes are listed in Table 8.3.

Table 8.3 Statistical description of field measured OI and modelled OC.

Plume #	Time	Average Distance (m)	Field measured OI							Modelled OC (OU m^{-3})			
			Min	Max	Ave	Nonzero ave	S.D.	Peak	Fre. (%)	Min	Max	Ave	S.D.
1	7:35-7:45 a.m.	531	0.02	0.27	0.14	0.6	0.12	1.5	3-47	8×10^{-4}	10×10^{-4}	9×10^{-4}	6×10^{-5}
2	8:00-8:10 a.m.	329	0.04	1.41	0.71	1.02	0.51	3	5-100	0.26	0.29	0.28	0.01
3	8:29-8:39 a.m.	211	1.02	1.54	1.27	1.86	0.22	4	33-97	0.52	0.65	0.55	0.07
4	10:12-10:22 a.m.	602	0.22	0.81	0.45	0.86	0.26	2	33-67	1×10^{-3}	8×10^{-3}	3×10^{-3}	2×10^{-3}
5	10:36-10:46 a.m.	389	0.44	1.37	0.74	1.04	0.36	3	60-85	4×10^{-3}	6×10^{-3}	5×10^{-3}	1×10^{-3}
6	10:58-11:08 a.m.	258	0.66	1.54	1.12	1.42	0.34	4	55-98	0.18	0.48	0.37	0.15
7	11:23-11:33 a.m.	151	0.88	1.70	1.21	1.46	0.35	4	68-78	0.90	1.15	1.03	0.14
8	2:09-2:19 p.m.	694	0.11	0.18	0.15	0.65	0.03	1.5	18-52	0.03	0.04	0.03	0.01
9	2:33-2:43 p.m.	605	0.05	0.31	0.20	0.63	0.11	1.5	10-48	0.03	0.09	0.07	0.02
10	3:07-3:17 p.m.	380	0.50	1.05	0.67	1.18	0.23	3	40-67	0.05	0.59	0.20	0.22
11	3:27-3:37 p.m.	267	0.52	0.90	0.75	1.19	0.16	3	47-83	0.28	0.37	0.34	0.04
12	5:51-6:01 p.m.	441	0.08	0.27	0.17	0.70	0.08	2.5	12-35	4×10^{-3}	13×10^{-3}	9×10^{-3}	3×10^{-3}
13	6:13-6:23 p.m.	376	0.58	1.50	0.83	1.18	0.39	3	55-86	3×10^{-3}	3×10^{-3}	3×10^{-3}	1×10^{-4}
14	6:50-7:00 p.m.	279	0.42	0.74	0.53	1.15	0.13	3.5	35-58	5×10^{-3}	6×10^{-3}	6×10^{-3}	5×10^{-4}

Notes: Min is minimum, Max is maximum, Ave is average, S.D. is standard deviation, and Fre. is odour detection frequency. The values of Min, Max, Ave, Nonzero ave and S.D are calculated based on the 10-minute averages of all five panelists. The peak value is based on all data recording of the five panelists. Fre. is the ratio of nonzero value numbers and total numbers during the 10-minute session; the range is for the five panelists.

Besides, Fig. 8.2 is one example to show the modelled odour plume (hourly OC contour) for the 12th hour (11:00 a.m.-12:00 p.m.) as well as the locations of the panelists distributed for the two periods of the hour when they did field measurements. It should be pointed out that the period of 10:58-11:08 a.m. was treated to be within the 12th hour (11:00 a.m.-12:00 p.m.) when conducting dispersion modelling. Additionally, one receptor within the period of 11:23-11:33 a.m. was deleted due to the wrong coordinate recording. As the result, a total of 9 receptors, 5 within 10:58-11:08 a.m. and 4 within 11:23-11:33 a.m., are displayed in Fig. 8.2. For the 12th hour, the wind come from the southeast direction (290 °), thus, odour reaches all receptors as predicted by AERMOD.

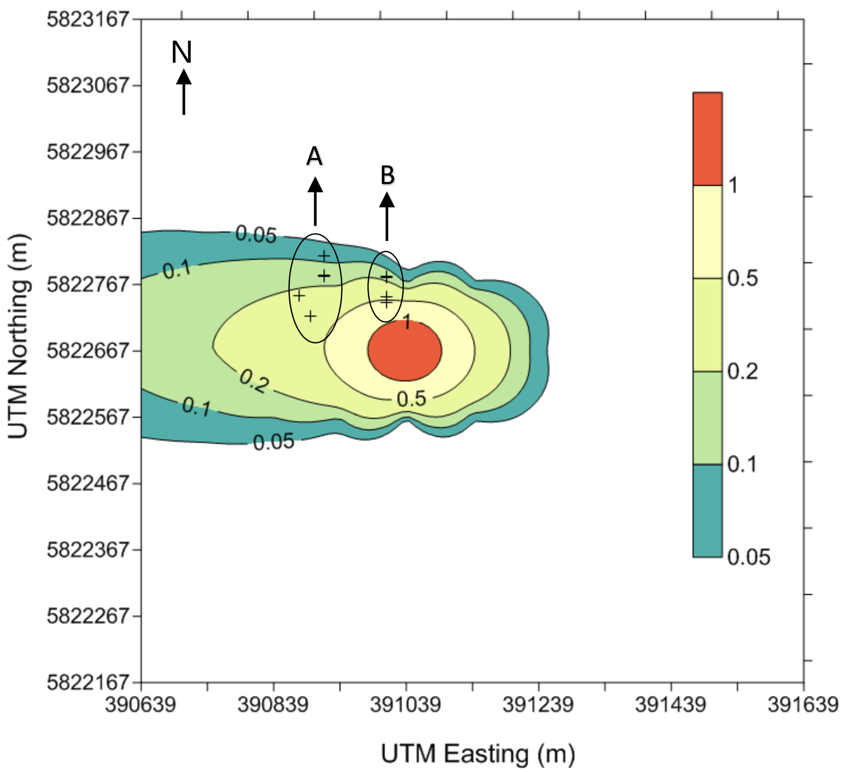

Figure 8.2 Modelled odour plume (OC is in unit of OU m^{-3}) for the 12th hour on August 31st; the symbols "+" are receptors; A is within 10:58-11:08 a.m. and B is within 11:23-11:33 a.m.

8.6.2 OC-OI relationship

Three kinds of relationships have been used by researchers in relating OC and OI, including the Weber-Fechner law, the Stevens' power law, and the Beidler model (Nicolai et al., 2000). In Chapter 2, the relationship between OC and OI for the broiler barn was investigated using both

Weber-Fechner law and Stevens' power law, with slightly better performance for the latter, but the difference was not obvious. In this paper, the OC-OI relationship, OI = $0.1344OC^{0.4756}$, derived from the Stevens' power law was applied to the conversion between field measured OI and modelled OC, as shown in Fig. 8.3. As being discussed in Chapter 2, the OC-OI relationship developed for the broiler barn generated higher OC for the same OI than the very limited previous studies, e.g., the OC for OI=1 is 68 OU m^{-3} in this study while is only 1.21 OU m^{-3} in the study by Hayes et al. (2006). This difference is considered to be reasonable as Hayes et al. (2006) used a 6-point non-referencing scale method for ranking OI while 5-point referencing scale method was used in this study. Additionally, different odour characteristics could also be caused by different housing and feeding practice, climate, etc.

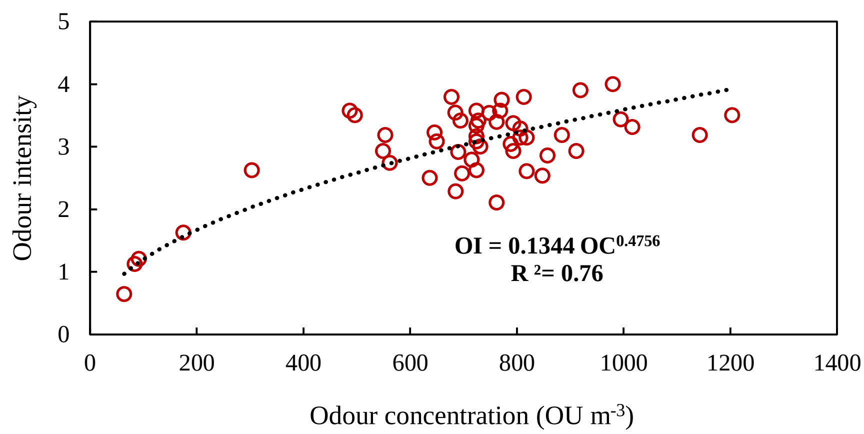

Figure 8.3 Relationship between OC and OI for the broiler barn.

8.6.3 Comparison of field measured and modelled results

8.6.3.1 Direct comparison of field measured and modelled results

To do comparison, the average of converted OI from model predictions and converted OC from field measurements by using the OC-OI relationship from Fig. 8.3 are given in Table 8.4. In addition, the average of converted OI from adjusted model predictions by using different scaling factors (which is discussed later in Section 8.6.3.2) are also given in Table 8.4 for comparison.

Table 8.4 The field measured OI and converted field OC (OU m^{-3}), and the modelled OC and converted modelled OI.

Plume #	Time	Average Distance (m)	Converted field OC		Modelled OC			Field measured OI		Converted modelled OI		
			Average	Geomean	Average	Average (Using SF of 286)	Geomean (Using SF of 154)	Average	Geomean	Average	Average (Using SF of 286)	Geomean (Using SF of 154)
1	7:35-7:45 a.m.	531	1.76	0.41	9×10^{-4}	0.25	0.13	0.14	0.09	0.005	0.07	0.05
2	8:00-8:10 a.m.	329	49	13	0.28	81	43	0.71	0.45	0.07	1.08	0.81
3	8:29-8:39 a.m.	211	116	110	0.55	159	85	1.27	1.26	0.10	1.49	1.11
4	10:12-10:22 a.m.	602	16	9	3×10^{-3}	1	0.43	0.45	0.39	0.009	0.13	0.09
5	10:36-10:46 a.m.	389	45	31	5×10^{-3}	1.47	0.77	0.74	0.69	0.011	0.16	0.12
6	10:58-11:08 a.m.	258	94	80	0.37	105	52	1.12	1.08	0.08	1.21	0.90
7	11:23-11:33 a.m.	151	109	96	1.03	296	158	1.21	1.02	0.14	2.01	1.50
8	2:09-2:19 p.m.	694	1.31	1.21	0.03	8	4.25	0.15	0.15	0.02	0.36	0.27
9	2:33-2:43 p.m.	605	2.82	1.53	0.07	19	9.37	0.20	0.16	0.04	0.53	0.40
10	3:07-3:17 p.m.	380	32	26	0.20	58	21	0.67	0.64	0.06	0.84	0.63
11	3:27-3:37 p.m.	267	38	35	0.34	96	52	0.75	0.73	0.08	1.18	0.88
12	5:51-6:01 p.m.	441	2.04	1.39	9×10^{-3}	2.53	1.28	0.17	0.16	0.014	0.21	0.15
13	6:13-6:23 p.m.	376	55	40	3×10^{-3}	1	0.44	0.83	0.77	0.008	0.12	0.09
14	6:50-7:00 p.m.	279	19	17	6×10^{-3}	2	0.90	0.53	0.51	0.012	0.17	0.13

Notes: SF is scaling factor; average and geomean (geometric mean) are calculated based on the 10-minute averages of the five panelists for the field measured results and from hourly averages of the receptors for the modelled results.

Fig. 8.4 plots the converted field measured OC and modelled hourly OC by using all 66 data points of the 14 plumes and using the geometric mean for each odour plume. It was found that the field measured results were all significantly higher than the modelled results, which has already been reported and discussed (Zhu et al., 2000; Guo et al., 2001; Guo et al., 2006).

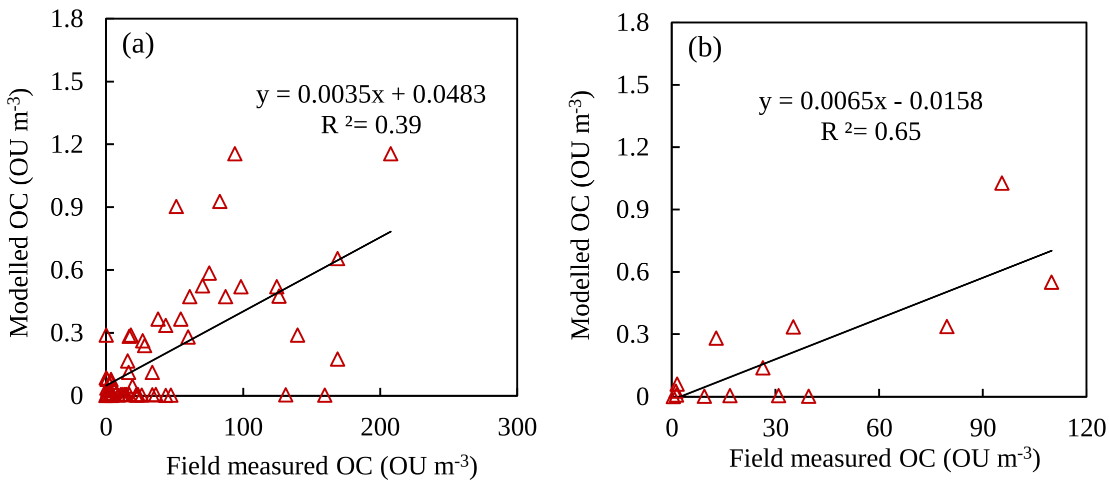

Figure 8.4 Direct comparison of field measured OC and modelled OC using all data points from the 14 plumes (a) and using the geometric mean for each plume (b).

8.6.3.2 Evaluation of AERMOD by using scaling factor

Henry et al. (2010) suggested to use linear regression method to determine a scaling factor from the slope of the relationship. Using all 66 pairs of data, a significant linear relationship ($P<0.05$) was derived between modelled OC and field measured OC as given in Fig. 8.4 (a). Therefore, a scaling factor of 286 (1/0.0035) was determined from the slope of the relationship to adjust the modelled OC. The comparisons between the field measured results and adjusted modelled results are given in Fig. 8.5 (a). Compared to direct comparison, the modelled OC were adjusted to the similar numerical level as the field measured results, which suggested the effectiveness of the scaling factor. In the study of Schulte et al. (2007), scaling factors from 1.66 to 3.12 were determined to adjust modelled odour levels by AERMOD to field measured levels measured by Nasal Ranger® for a swine facility located in Iowa state. On the contrary, Xing et al. (2006) found no improvement of the performance of dispersion models by using scaling factor, which may be explained by the different scaling methods used for ranking OI on the field and different relationships acquired between OC and OI, thus the converted modelled results from the study of Xing et al. (2006) were not consistently higher or lower than the field measured results.

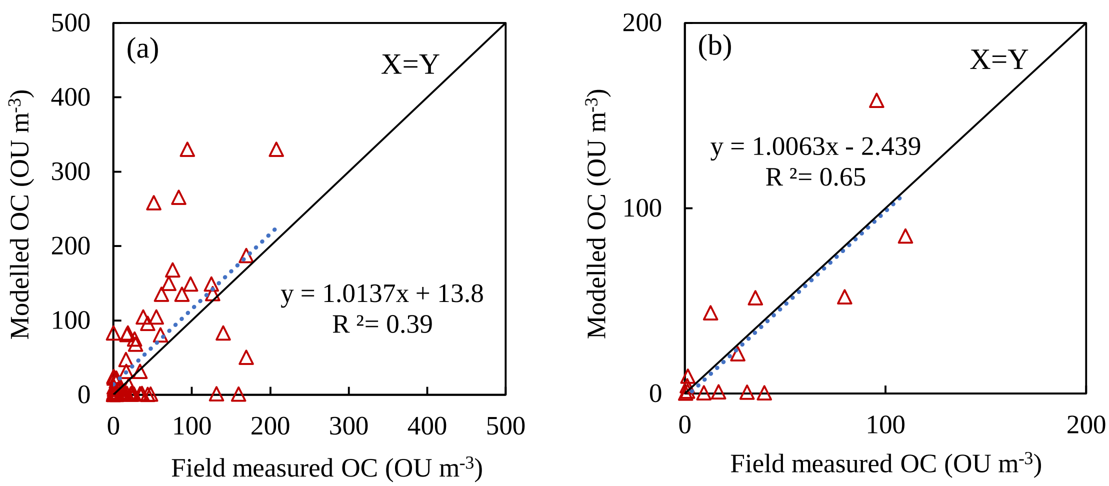

Figure 8.5 Comparison of field measured OC and modelled OC using the scaling factor of 286 (a) and 154 (b).

Moreover, Guo et al. (2001) found that when OI was high, it was difficult for panelists to distinguish a moderate or strong odour, especially when the odour was offensive. At such times, the panelists might likely over estimate the odour intensity, which resulted in higher converted odour concentration than the modelled results. In this study, it was also found that for the same odour plume, the variance of the OI that the five panelists perceived could be very large. Taking odour plume #2 as an example, the field measured average OI over the 10 minutes varied greatly from 0.04 to 1.41 among the five panelists, while the modelled OC were within a narrow range of 0.26-0.29 OU m^{-3} with also relatively constant converted OI. Such great variance in the perceived OI is likely to cause big error in generating the scaling factor for comparing the field measurements and modelled predictions. To reduce the bias, another scaling factor was generated, which is 154 (1/0.0065), by comparing the geometric means of the field measured OC from all five panelists for each 10-minute odour session and the geometric means of the modelled hourly OC for the five receptors. Thus, a total of 14 pairs of data were acquired and were plotted in Fig. 8.4 (b). A significantly improved R square (R^2 = 0.65) was obtained for the linear relationship between field measured results and modelled results. The comparisons of adjusted modelled OC by using the scaling factor of 154 and the corresponding field measured OC are shown in Fig. 8.5 (b).

To acquire the agreement between the two groups of data, the same method from the study of Xing (2006) and Li (2009) was used for comparison based on the intensity results, who considered that each measured intensity values covered ± 0.5 range. Thus, if the predicted OI is within ± 0.5 range of the measured intensity, the pair of data points agree. The corresponding OC range for each OI within ± 0.5 range is given in Table 8.1, e.g., intensity 1 ± 0.5 covers OC from 15 to 160 OU m^{-3}. As listed in Table 8.5, when using the scaling factor of 286, the overall agreement percentage is 76%, with the low agreement between the data found for the distance of 100-200 m. The results indicate very good agreement between the results for the distances of 400-800 m, which suggests that AERMOD performs better for predicting OC at distances above 400 m than predicting OC at short distances less than 400 m, especially within 200 m. This finding is in line with Zhou et al. (2010) who found adequate agreement between modelled results of three different dispersion models (ISCST3, AUSPLUME, and INPUFF-2) and field measurements for downwind distances of 500 and 1000 m, but relatively low agreement for 100 m. It was found that the overall agreement was slightly increased from 76% to 81% by using the scaling factor of 154 instead of 286. Especially for the distance of 100-200 m, the agreement was greatly improved to 80% compared to 40% from using the scaling factor of 286.

Table 8.5 Agreement between field measured and modelled OI using different scaling factors.

	Use the scaling factor of 286			Use the scaling factor of 154		
Distance (m)	Total No. of paired data	Agreement No. of paired data	Agreement Percentage	Total No. of paired data	Agreement No. of paired data	Agreement Percentage
100-200	5	2	40%	5	4	80%
200-300	19	16	84%	19	17	89%
300-400	19	11	58%	19	12	63%
400-500	3	3	100%	3	3	100%
500-600	9	8	89%	9	7	78%
600-700	10	9	90%	10	10	100%
700-800	1	1	100%	1	1	100%
Overall	66	50	76%	66	54	81%

In conclusion, using the field measured results to evaluate AERMOD in predicting OC, acceptable performance of AERMOD was observed in this study using the scaling factor of 286, but it seemed to be unable to predict OC well for short distances within 200 m. However, using the scaling factor of 154, the performance of AERMOD could be slightly improved from overall, and greatly improved for short distances within 200 m.

8.6.3.3 Statistical evaluation of AERMOD using an ASTM-Standard guide

Besides the above methods used, a standard guide reported by ASTM was also utilized to evaluate the performance of atmospheric dispersion models from a statistical point of view (ASTM, 2015). Seven different statistical parameters were reported and described by the standard, including bias, normalized mean square error, the coefficient of correlation, the fraction of prediction with a factor of two of observations, the absolute fractional bias, the geometric mean variance and the geometric mean bias (ASTM, 2015). In this study the coefficient of correlation, bias (mean difference), fractional bias and standard deviation of the fractional bias are used as overall evaluation. The fractional bias (FB) and standard deviation (σ_{FB}) of the fractional bias are defined as:

$$FB = \overline{FB_i} \quad (8.1)$$

$$\sigma_{FB}{}^2 = \overline{(FB_i - FB)^2} \quad (8.2)$$

Where $FB_i = \frac{2(P_i - O_i)}{(P_i + O_i)}$; the subscript "i" in the above equations refer to paired values and the "overbar" indicates an average; O_i is used to represent the observed value, and P_i is used to represent the corresponding model's prediction value. The FB is symmetrical and bounded varying between -2.0 (extreme under-prediction) and +2.0 (extreme over-prediction) and 0 for an ideal model. The value of FB of perfect model prediction is 0, meaning free from bias. A low variance in FB can be taken as indicating confidence in the model prediction. The acceptable range of FB for a model is from -0.67 to +0.67. Value of the FB of -0.67 is equivalent to model under-prediction by a factor of two, while +0.67 is equivalent to over-prediction by a factor of two.

As can be seen in Table 8.6, the values of FB for the three groups of comparisons proved that AERMOD performed poorly from direct comparison of field measurements and model predictions (FB = -1.89), while indicated it was acceptable when using either of the two scaling factors as the FB both fell within the range of -0.67 to 0.67. Though FB value was closer to 0 for the paired results using the scaling factor of 286 than 154, it could not be taken on its own as an indication of good model performance. It was found that the FB_i for paired values were not consistently positive or negative, thus over-predictions could cancel out under-predictions and gave a low average of FB_i, which may give a false impression of model performance (McHugh et al., 1999). Hence, other statistical parameters would need to be considered together to evaluate the model performance. Significant correlations were indicated for all three groups of comparisons (P<0.01), with the strongest correlation found between field measured OC and adjusted modelled OC by using the scaling factor of 154. It was also found that the mean difference between field measurements and modelled predictions was significant (P<0.01) when conducted direct comparison, while was insignificant (P>0.05) when using the scaling factors of 286 or 154 to adjust the modelled OC. The mean difference and standard deviation of the mean difference between the paired results were both greatly reduced by using the scaling factor of 154 compared to using the scaling factor of 286.

Table 8.6 Results of performance measures for paired statistical comparison.

	No. of paired samples	Paired differences			Paired samples correlations		FB	σ_{FB}
		Mean difference (OU m^{-3})	S. D.	Sig.	r	Sig.		
Field OC vs. modelled OC	66	39.83	50	0.00	0.626	0.00	-1.89	0.43
Field OC vs. modelled OC×286	66	-14.35	63	0.07	0.626	0.00	-0.07	1.32
Field OC vs. modelled OC×154	14	2.23	27	0.76	0.809	0.00	-0.35	1.19

Notes: S.D. is standard deviation, sig. is significance, r is correlation coefficient, FB is fractional bias, and σ_{FB} is standard deviation of the fractional bias.

8.7 CONCLUSIONS

To validate the performance of AERMOD for predicting odour distribution for a commercial broiler barn under Canadian Prairies climate condition and flat terrain condition, field odour plume measurements were conducted in the downwind of the broiler barn at distances from 100 m to 800 m. The OC at these discrete receptors were then modelled by AERMOD with the input of diurnally measured OE data. Using the relationship between OC and OI investigated for the broiler barn, field measured OI could be converted to OC and compared to modelled predictions, or vice versa. The findings are as follows:

1) Direct comparison of field measured results and modelled results showed the modelled hourly OC were all greatly lower than the field measured OC over the 10-minute odour plume measurements; however, consistent under-prediction by AERMOD and significant correlation ($P<0.05$) between the field measurements and model predictions suggested possible effectiveness of scaling factor in making the hourly model predictions comparable to 10-minuite field measured results;
2) Using all data points of the 14 odour plumes and the geometric mean of each plume, scaling factors of 286 and 154 were developed, respectively, to adjust the model predictions. It was found that the field measurement and model prediction achieved good agreement by using both scaling factors (76% for the scaling factor of 286 and 81% for 154). However, the scaling factor of 286 showed poor agreement of field measured and modelled results over short distances from 100 to 200 m, while the scaling factor of 154 greatly improved the performance of AERMOD for predicting OC over short distances. Besides, statistical parameters (paired differences, paired sample correlations, and fractional bias) indicated smaller paired difference and better paired sample correlations between modelled and field measured results when using the scaling factor of 154, thus is suggested to use for adjusting the modelled results. The scaling factor may also be utilized in future studies on dispersion modelling by AERMOD for commercial poultry barns under similar Canadian Prairies climate and terrain conditions, however, the measurement methods of OC and OI as well as the dispersion model configuration (e.g., treat the barns as volume sources) should be the same to minimize the bias.
3) Using the developed OC-OI relationship in Stevens' power law for the broiler barn, higher OC was generated for the same OI than previous studies because of the different scaling methods for ranking OI as well as different odour characteristics caused by various reasons. More data collecting for weak odour (e.g., OI $\leqslant$2) of similar broiler barns on the Canadian Prairies will help evaluate the OC-OI relationship acquired in this study.

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CHAPTER 9
DISPERSION MODELLING OF ODOUR, GASES, AND RESPIRABLE DUST USING AERMOD FOR POULTRY AND DAIRY BARNS ON THE CANADIAN PRAIRIES

9.1 CONTRIBUTION OF THE PH.D. CANDIDATE

The emission data collecting, dispersion modelling, data analysis, and manuscript writing were performed by the candidate. Zimu Yu and Zhu Gao provided technical support as for AERMOD model set-up. Dr. Huiqing Guo provided editorial input and suggestions on methods and data analyses.

9.2 CONTRIBUTION OF THIS PAPER TO THE OVERALL STUDY

This study presents the modelled results to study the outdoor impact of odour, gases, and respirable dust emissions from the dairy, broiler, and layer barns on the adjacent areas using an air dispersion model AERMOD. With the data input of monthly measured odour emissions in previous chapters, the impact areas of odour were plotted for all three barns. Using the recommended odour impact criteria and newly developed odour impact criteria in Chapter 2, directional setback distances were determined. Dispersion of gases and respirable dust were also modelled. The directional setback distances obtained from using odour impact criteria were compared with that using ambient gas and dust criteria.

9.3 ABSTRACT

The dispersion modelling of odour, ammonia (NH_3), hydrogen sulfide (H_2S), and respirable dust were conducted using an US EPA air dispersion model AERMOD for a dairy, a broiler, and a layer barn on the Canadian Prairies, with the measured monthly emission rates of all four air pollutants. The simulation was conducted using five years of meteorological data from 2003 to 2007. Results showed that the layer barn presented the greatest odour impact area followed by the broiler and

dairy barns. Odour traveled farthest in the north due to the prevailing south wind and shortest in the south for all three barns under the similar meteorological conditions. Under the suggested odour impact criteria by the Government of Saskatchewan (OC limit from 1 to 6 OU m^{-3} with averaging time of 1 hour and odour occurrence-free frequency of 99.5%), maximum setback distances were decreasing from 1941 to 641 m for the layer barn and from 980 to 320 m for the broiler barn along with the increasing of OC limit, all in the north direction. While for the dairy barn, setback distances were determined only under an OC limit of 1 OU m^{-3} with the same above averaging time and odour occurrence-free frequency, which were maximum 205 m in the north and minimum 171 m in the south. Using the newly developed odour impact criteria from the relationships between odour properties, maximum setback distance of 558 m in the north was determined for the layer barn under an odour impact criterion of 9 OU m^{-3}, while no odour occurrence-free frequency contours or setback distances could be generated for the dairy and broiler barns due to low source odour emissions. However, the newly developed odour impact criterion of 23 OU m^{-3} proved to be applicable to similar broiler barns with full-year operation, with maximum setback distance of 168 m determined in the north. The modelled results of NH_3, H_2S, and respirable dust showed they were all below the ambient concentration threshold limits at the minimum setback distances determined from odour dispersion modelling. Hence, the results suggest the use of odour impact criteria to determine setback distance rather than using gas threshold limits set in ambient air quality standards as the former always requires much greater setback distances than the latter.

9.4 INTRODUCTION

Air dispersion modelling is the mathematical simulation to predict the atmospheric dispersion of air pollutants within the plume (Holmes and Morawska, 2006). In the past decades, researchers have applied various industrial air dispersion models to livestock odour for assessing odour impact on the nearby communities and determining setback distances, such as AERMOD (AMS/EPA Regulatory Model), CALPUFF (A Lagrangian Puff model), ISCST (Industrial Source Complex-Short Term), etc. AERMOD is one of the most commonly used models worldwide based on Gaussian dispersion theory (Sarr et al., 2010). It is also the recommended regulatory model by both US EPA and all jurisdictions in Canada including Saskatchewan.

Although various physical, chemical, and biological technologies have been studied to reduce odour emissions (OEs) from animal facilities (Schlegelmilch et al., 2005), few of those were adopted by farmers due to their high cost or high maintenance requirements. Comparing to these methods, establishing appropriate setback distances through dispersion modelling to separate the livestock production facilities from residences or public facilities seemed to be promising and attractive (Yu and Guo, 2011; Guo et al., 2006). Sarr et al. (2010) used AERMOD to assess the efficiency of the setback distances defined by the Quebec Ministry of Environment for swine farms and installation place of swine production units without public odour nuisance in Quebec, Canada. They considered ammonia (NH_3) as the odour indicator. Karageorgos et al. (2010) estimated odour nuisance by taking both NH_3 and hydrogen sulfide (H_2S) as odour indicators at various distances from the swine facilities and used a peak-to-mean ratio to predict the maximum odour concentrations (OC). Sheridan et al. (2003) developed a new odour impact criterion from the relationship of OC and intensity for pig production units, with a lower odour threshold than the recommended threshold used by Ireland EPA, thus a greater setback distance was determined. Similarly, Hayes et al. (2006) determined setback distances for broiler, layer, and turkey units by ISCST3 model using the recommended odour impact criterion by the Ireland Environmental Protection Agency (EPA, Ireland) and a newly developed odour impact criterion. The maximum setback distances determined were decreased from 660 to 460 m for broilers, from 665 to 500 m for layers, and from 1035 to 785 m for turkeys (Hayes et al. 2006).

Effective mitigation methods and accurate setback distances can only be acquired based on accurate source emission data, good understanding about odour properties and then followed by appropriate dispersion modeling. So far, no dispersion models can give convincing setback distance results mainly due to the three reasons. First, since the seasonal and diurnal variations of odour and gas emissions for animal and poultry barns were not well characterized in previous studies, the majority of these studies only used emission data from snapshot or short-term measurements to predict dispersion for livestock odour and gases. Second, livestock odour properties and their relationships (e.g. OC vs. odour intensity, OC vs. hedonic tone) are not well understood thus the correlation of the dispersion model predictions and field measured intensity are not well established. Third, development of science-based community odour impact criteria is still a challenge. In the previous chapters, the detailed seasonal emission profiles of odour, NH_3, H_2S, and respirable dust were obtained through long-term measurements (one year) for the study dairy, layer, and broiler barns, which would be utilized as source emission input for dispersion modelling in this study. The five odour properties, including OC, odour intensity (OI), hedonic tone (HT), persistence, and character descriptor, for all three barns were also fully studied, the relationships between odour properties were acquired and new odour impact criteria were developed for the dairy, layer, and broiler barns considering both OI and HT (in Chapter 2).

With the above improved prerequisites, this study conducted dispersion modelling for odour, gases (NH_3 and H_2S), as well as respirable dust with the following objectives: 1) to generate odour occurrence-free frequency contours for dairy and poultry barns under the Canadian Prairies climate and determine directional setback distances under both the recommended odour impact criteria by the Government of Saskatchewan (2012) and the newly developed odour impact criteria; 2) to reveal if the concentrations of NH_3, H_2S, or respirable dust exceed the threshold limits of ambient clean air standards at the minimum setback distances determined from odour dispersion modelling; and 3) to compare the determined setback distances through dispersion modelling of NH_3, H_2S, and respirable dust with that of odour impact criteria.

9.5 MATERIALS AND METHODS

9.5.1 Description of the dairy, broiler and layer barns

The study barns include a dairy barn, a broiler barn and a cage-layer barn in Saskatoon, the specific details can be found in Chapter 3 for the dairy barn and Chapter 4 for the broiler and layer barns.

9.5.2 Sampling and measurement methods

To acquire seasonal emission profiles of odour, NH_3, H_2S, and respirable dust, monthly sampling and measurements were conducted for one selected day from Feb 2015 to Jan 2016 for the dairy barn, from Mar 2015 to Feb 2016 for the layer barn, and for 6 available operation flocks for the broiler barn from Apr 2015 to Jan 2016. For odour measurements, replicate room air samples were acquired in both morning (2 hours) and afternoon (2 hours), the average of which gave the daily average and represented monthly results. Air samples were collected using 10-L Tedlar® air bags and were analyzed for OC in the Olfactometry Laboratory at the University of Saskatchewan. The screening of panelists and measurements of OC were conducted in compliance with CEN (2003) standard. For NH_3 and H_2S measurements, an NH_3 sensor (C21 NH_3 transmitter, GFG Instrumentation, USA) and H_2S analyzer (JEROME 631-X, Arizona Instrument Corporation, Arizona Instrument LLC, USA) continuously monitored the gas concentrations within the same morning and afternoon periods and one data recording was made every 5 minutes by a data logger (CR10X, Campbell Scientific Corporation, Canada). More details of these gas analyzers can be found in Chapter 3. Respirable dust was sampled and measured according to NMAM 0600 (NIOSH, 1998) by Aluminum cyclones with three-piece cassette and tared 37-mm, 5-μm PVC filters (SKC, Inc., PA, USA). Replicates were made in both morning and afternoon periods.

Besides, continuous diurnal measurements of odour, NH_3, and H_2S for all three barns were conducted from 6 a.m. to 9 p.m. for two days in typical cold (Jan or Feb), warm (Jul or Aug), and mild (Apr or Oct) months. Five diurnal levels were considered for each measuring day, including 6 a.m. to 9 a.m., 9 a.m. to 12 p.m., 12 p.m. to 3 p.m., 3 p.m. to 6 p.m., and 6 p.m. to 9 p.m. Within each diurnal period, 2 replicate odour samples were collected, while NH_3 and H_2S concentrations were continuously measured with 5 min averages recorded.

9.5.3 Ventilation rate and emission rate calculation

Using a CO_2 mass balance method, which is a commonly used method to estimate ventilate rate (VR) for livestock barns (Li et al., 2004; Xin et al., 2009; Guo et al., 2006; Wu et al., 2012), the VR was calculated based on total heat production with a series of equations reported by CIGR (2002). The detailed methods are given in Chapter 3 for the dairy barn and Chapter 4 for the two poultry barns. Knowing the odour and gas concentrations and VR, the odour and gas emissions were calculated as follows:

$$E = VR \times \Delta C \qquad (9.1)$$

Where E is odour emission rate in unit of OU s^{-1}, or gas and dust emission rates in units of mg s^{-1}; VR is VR of the barn in m^3 s^{-1}; and ΔC is the difference of odour and gas concentrations between the room incoming air and exhaust air in units of OU m^{-3} or ppm. The concentrations of odour, NH_3, H_2S, and respirable dust of inlet air (ambient air) were negligible compared to the indoor concentrations and were treated as 0.

9.5.4 Configuration for AERMOD

To run the dispersion modelling system, three major data inputs need to be prepared: source odour or gas emission rate, meteorological data (temperature, relative humidity, wind speed, wind direction, cloud cover, etc.), and terrain data (elevation and hill height). There are three modules in the AERMOD modelling system to process these data inputs, including AERMET which processes meteorological data and generate meteorological data profiles, and AERMAP which processes terrain data to generate a terrain data profile for specified receptors. These two profiles, together with source odour or gas emission rates, are input into the third module, AERMOD, to generate output profiles that containing modelled hourly concentrations for all receptors within the selected period.

Source emission data. It was found that seasonal variations of odour emissions were obvious for all three barns (Table 9.1), suggesting variable odour emissions should be used rather than using constant values for all seasons. In this study, all three barns were treated as volume source type. The measured volume emission rates (OU s^{-1} or mg s^{-1}) for each month are listed in Table 9.1. It should be noted for both layer and broiler barns, monthly odour and gas emission rates were obtained only under worst-case conditions, when it was the last day before the manure would be removed from the belt for the layer barn and when it was the last week of each flock for the broiler barn. As for the study broiler barn, which is under quota restriction of the Government of Saskatchewan to balance market production, there were only 6 operation flocks available within the study year with each flock occupying around one month. For the other 6 months, odour and gas emissions were 0. In addition, to do dispersion modelling for broiler barn with continuous operation under the same Canadian Prairies climate, the average of the summer results, including June and August was used to fill the missing data for May, July and September, and the average of the winter results, including November and January was used for February, March and December. The summer and winter averages for the three barns are all given in Table 9.1. Among the three barns, the layer barn had the highest annual average OE which was about 2.5 times of both dairy and broiler barns. The annual average NH_3 emission was also highest for the layer barn, followed by the dairy barn and then the broiler barn. The annual average H_2S emission was similar for the dairy and layer barns, while was quite low for the broiler barn. The highest annual average respirable dust emission was observed from the broiler barn, which was about 2 times of that of the dairy barn with least emission.

Table 9.1 Monthly odour, gases, and respirable dust (RD) emissions of the three barns.

	Dairy				Layer (worst-case)				Broiler (worst-case)			
	Odour (OU s^{-1})	NH_3 (mg s^{-1})	H_2S (mg s^{-1})	RD (mg s^{-1})	Odour (OU s^{-1})	NH_3 (mg s^{-1})	H_2S (mg s^{-1})	RD (mg s^{-1})	Odour (OU s^{-1})	NH_3 (mg s^{-1})	H_2S (mg s^{-1})	RD (mg s^{-1})
Jan	2900	46	1.4	0.4	7182	115	0	0.9	5741	209	3.5	3.8
Feb	3635	120	1.7	1.4	8110	96	0.2	1	0	0	0	0
Mar	8719	93	2.8	1.8	11366	201	4	1.9	0	0	0	0
Apr	13280	161	13	4.3	22782	287	1.6	4.4	24291	0	1.1	3.7
May	8243	80	6.5	1.2	17170	72	8.2	1.6	0	0	0	0
Jun	13642	82	17	4.1	26553	299	8	6.2	17674	100	1.5	8
Jul	10214	70	6	1.2	51226	103	10.3	7.4	0	0	0	0
Aug	6491	122	2.2	0.2	28687	229	7.4	1.5	25855	22	2.8	3.5
Sep	5257	89	1	0.4	13963	149	3.5	3	0	0	0	0
Oct	12318	100	0.5	1.9	24773	97	0.1	2.1	11550	163	0.3	7.3
Nov	4077	63	1.4	0.5	9184	87	0.04	0.8	6831	298	0.7	10.8
Dec	3433	53	1.6	0.4	10284	67	0.1	1.4	0	0	0	0
Summer average	8769	89	6.5	1.4	27520	170	7.5	3.9	21765	61	2.2	5.8
Winter average	4553	75	1.8	0.9	9225	113	0.9	1.2	6286	254	2.1	7.3
Annual Average	7684	90	4.6	1.5	19274	150	3.6	2.7	7662	66	0.83	3.1

Meteorological data. The metrological data included surface weather data and upper air sounding data, which were to be extracted and quality assessed by AERMAT to generate two meteorological data profiles for being used in AERMOD. To make modelling consistent and reproducible across the province, the Government of Saskatchewan (2012) has prepared a series of meteorological data sets referred to as "Regional Meteorological Data Sets" generated by using hourly meteorological data for a period of 5 years from 2003 to 2007. In this study, all three barns located in the air dispersion modelling zone of Central Saskatchewan, thus the "Regional Meteorological Data Sets" for Central Zone were downloaded with "Urban" surface class selected for the dairy barn and "Agricultural" surface class selected for both poultry barns.

Terrain data. The Canadian Digital Elevation Data (CDED) input in AERMAP consists of an ordered array of ground elevations at regulatory spaced intervals. Ground elevations are recorded in meters relative to mean sea level based on the North American Datum 1983. The study used

1:50,000 CDED data as suggested by the Government of Saskatchewan (2012), which was downloaded from Geobase Canada (2017). AERMAP was used to prepare the terrain information based on the input CDED data, source locations, and receptor locations.

Receptor. The modelling employed Cartesian grid receptors with 100-m receptor spacing. The study area was 4 km by 4 km centering around each barn (distances of 2 km from the source). Thus, a total of 1680 receptors (excluding the source) were acquired for each barn. The height of each receptor was 1.5 m.

9.5.5 Concentration contours and odour occurrence-free frequency contours

The output files from AERMOD, which included hourly concentration predictions, were extracted and were input in Surfer 10 (Golden Software, USA) to generate concentration contours with the animal barn being the center point (odour and gas emission source) in the figures. Since hourly OC at all receptors were modelled for a period of 5 years, the total hours when an odour threshold (such as 1 OU m^{-3}) was violated could be counted with the help of Excel. Thus, the odour occurrence-free frequency could be calculated, which is the ratio of the total hours when an odour threshold was not violated (odour occurrence-free) to the total hours of the period (5 years in this study). The results were generated into odour occurrence-free frequency contours by Surfer 10.

9.6 RESULTS AND DISCUSSION

9.6.1 Modelled annual, daily, and hourly average OC

9.6.1.1 Annual average OC contours

The annual average OC contours are shown in Fig. 9.2. Each contour consisted of all the receptors under a same OC. Thus, from the contours different odour travel distances could be determined at different directions where odour is dispersed to a certain level (such as 0.01 OU m^{-3}). In the following discussions, only the four major directions were considered, including North, South, East, and West. To discuss the impact of wind direction on OC contours, a wind distribution chart by WINDFINDER (2018) for Saskatoon Airport is given in Fig. 9.1.

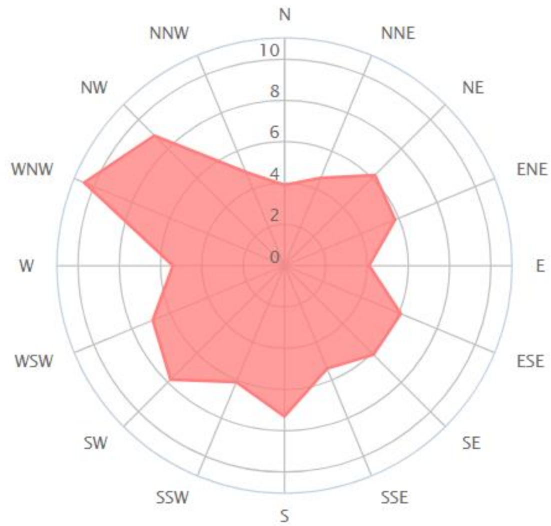

Figure 9.1 Wind direction distribution (%) in year for Saskatoon Airport based on data between October 2008 and March 2018 (WINDFINDER, 2018).

It should be pointed out that there is no regulation or guidelines on ambient air quality to regulate the average annual odour concentrations. The purpose of presenting the annual average OC results is to quantify the annual impact and compare annual average OC contours with odour occurrence-free frequency contours in the following section. As for annual average OC contours, very low odour concentration limits (as low as 0.01 OU m^{-3}) were selected to plot odour travel distances, which is because annual average OCs above 1 OU^{-3} presented very short travel distances already (<100 m) and even an OC of 0.1 OU m^{-3} only had a maximum distance of 728 m. However, the determined odour travel distances under a regulated odour occurrence-free frequency of 99.5% (Government of Saskatchewan, 2012) for an odour unit of 1 OU m^{-3} were much greater (e.g., >1000 m for the layer barn in all four directions), the details of which can be found in section 9.6.2.

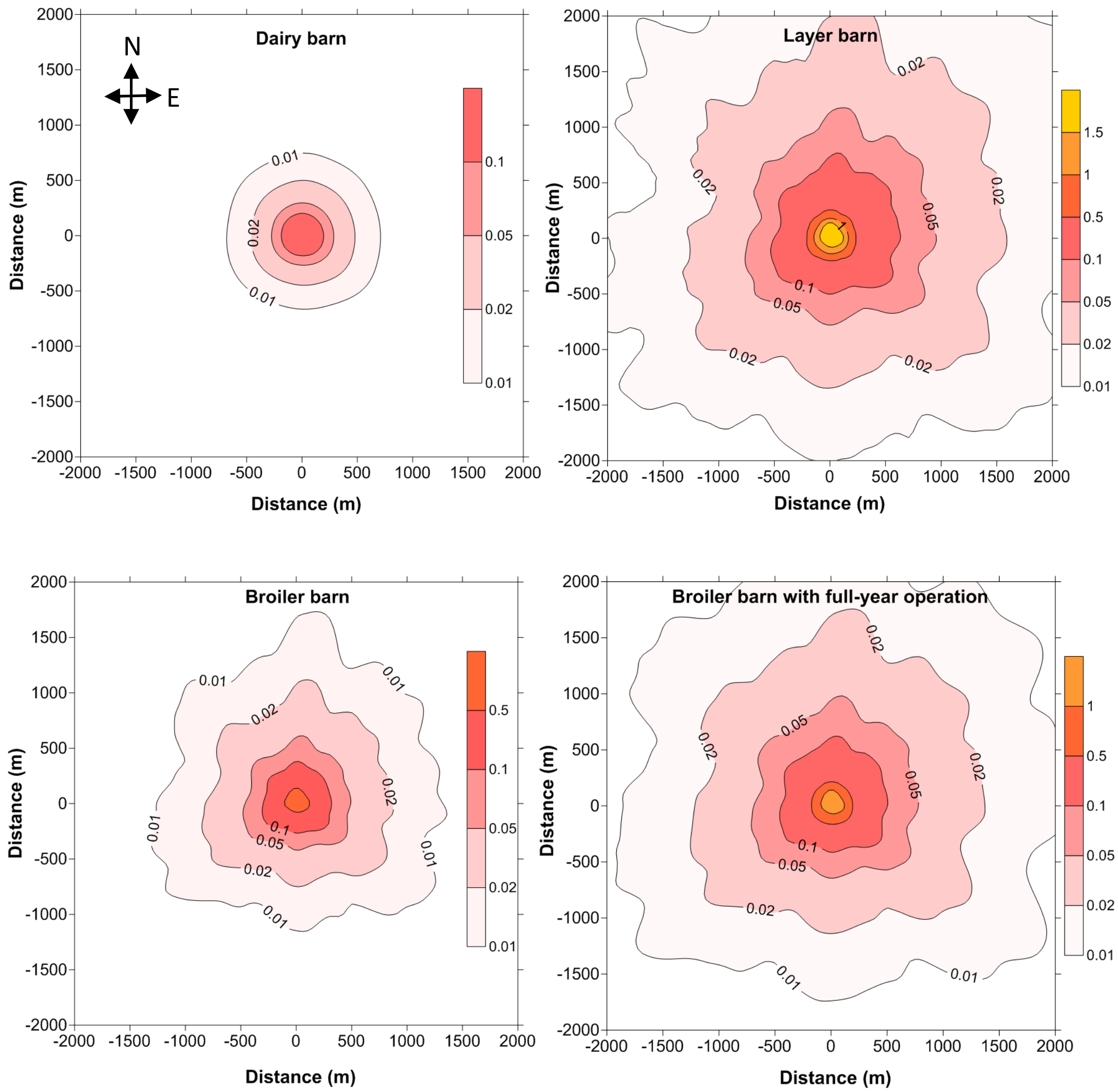

Figure 9.2 Annual average OC (OU m^{-3}) contours for the dairy barn, layer barn, broiler barn, and broiler barn with full-year operation.

It was found that the farthest odour travel distance all occurred in the north and shortest in the south. This may be explained by that among only the four major directions wind blows most from the south and least from the north from wind statistics for Saskatoon Airport (Fig. 9.1). Comparing the three barns, the impact areas are obviously different, with the greatest odour impact area predicted for the layer barn, followed by the broiler, and then the dairy barn which were mainly due to the differences of the emission rates. Taking an OC of 0.01 OU m^{-3} for example, the maximum odour travel distance is up to 3023 m for the layer barn compared to 1676 m for the broiler barn and only 746 m for the dairy barn. More comparisons of directional odour travel distances could be found in Table 9.2. Since various factors affect odour dispersion in the ambient, it is difficult to attribute the reasons for such great difference of the three barns to one single factor; however, A much higher OE for the layer barn than the other two barns should be the major reason to explain its much greater impact area. Though the annual average OE for the broiler barn is comparable to that of the dairy barn, the much higher OE during the operation flocks still caused a greater impact area than the dairy barn (the average OE for all six flocks of the broiler barn was 15324 OU m^{-3} comparing to the annual average OE of 7684 OU m^{-3} of the dairy barn).

Table 9.2 Directional odour travel distances for the dairy barn, layer barn, broiler barn, and broiler barn with full-year operation.

OC (OU m^{-3})	Directional odour travel distance (m)							
	Maximum (North)				Minimum (South)			
	Dairy	Layer	Broiler	Broiler*	Dairy	Layer	Broiler	Broiler*
0.01	746	3023	1676	2597	665	2009	1147	1740
0.02	500	1987	1076	1689	448	1344	749	1138
0.1	202	728	378	601	181	498	265	410
0.5	/	247	138	219	/	189	76	162
1	/	149	/	104	/	135	/	57

Notes: Broiler* indicates broiler barn with full-year operation

9.6.1.2 Daily and hourly OC contours

To show how odour would be dispersed outdoor in different seasons, daily average OC at various receptors was modelled based on the OE measured from diurnal measurements (Chapter 3 for the dairy barn and Chapter 4 for the broiler and layer barns). This study only shows the modelled daily OC for the dairy barn in the cold and mild seasons with the minimum and maximum daily OE, respectively.

Table 9.3 Odour emission input in AERMOD for the dairy barn in February and October.

	Date	Hour of Day						
		24:00-06:00	06:00-09:00	09:00-12:00	12:00-15:00	15:00-18:00	18:00-21:00	21:00-24:00
OE (OU s^{-1})	Feb 9-12	2539	2539	4657	3670	5729	4827	4827
	Oct 13-15	11924	11924	11569	28705	46409	12429	12429

Since 3-hourly average OE was measured on Feb 9th and 12th in the winter of 2015, and on Oct 13th and 15th in the fall of 2015 for the dairy barn (Table 9.3), daily average OC was modelled for Feb 9-12 and Oct 13-15 using the 5 years of hourly meteorological data. The modelled daily average OC contours are shown in Fig. 9.3. It is obvious that with a much higher OE in the mild season, the odour from the dairy barn traveled much farther in all directions compared to that in the cold season, which suggests more possible odour annoyance in the mild season than the cold season. To show the worst scenarios that could happen, the modelled hourly OCs for the 15th hour (14:00-15:00) and 18th hour (17:00-18:00) on Oct 15th, 2004 (when modelled OCs were high) are given in Fig. 9.4, which used the 3-hour average emission rate during the period of 12:00-15:00 and the 3-hour average emission rate during the period of 15:00-18:00 in Table 9.3, respectively. Compared to the annual average OC contours for the dairy barn in Fig. 9.2, the hourly concentration contour shows much higher odour impact for a certain direction, which is basically the leeward of the wind direction during the hour. Besides, although the average annual concentration was quite low, the possibility of occasional odour sensation (peak OC) could be much higher, e.g., in the afternoons and early evenings of October when source OE is high or other environmental parameters (e.g., wind direction, wind speed) are favorable to ambient odour travel. It also needs to point out that the modelled hourly averages could not represent the strongest odour occurred during the hour as odour episodes usually last from seconds to a few minutes, therefore peak to mean ratio is commonly used to translate the modelled hourly averages to peak values which has been mentioned earlier in the introduction. Xing et al. (2007) conducted sensitivity analyses for four different dispersion models, including ISCST3, AUSPLUME, CALPUFF, and INPUFF2 to study how environmental parameters affect predicted OCs and odour travel distances. They found that odour transport was favored by stable atmospheric conditions, low wind speed, and high ambient temperature. Faulkner et al. (2008) reported that the predictions of ISCST3 were sensitive to changes in wind speed, temperature, solar radiation (which affects stability class), and mixing heights below 160 m, while AERMOD was sensitive to changes in albedo, surface roughness, wind speed, temperature, and cloud cover. Small changes in these parameters may cause the difference of several hundred meters in particulate matter travel distances for AERMOD (Faulkner et al., 2008).

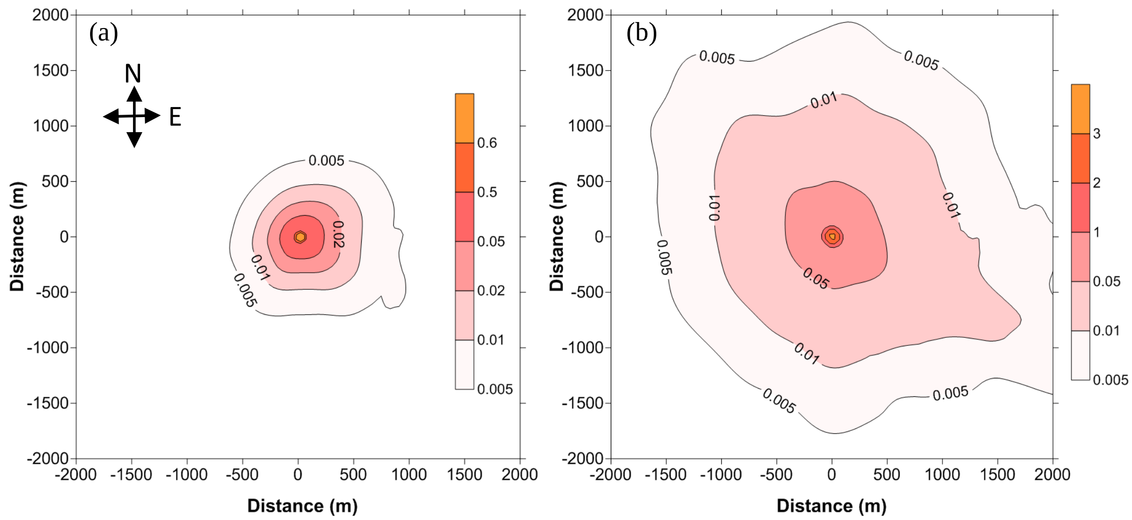

Figure 9.3 Daily average OC (OU m^{-3}) contours for the dairy barn in the cold and mild seasons; (a) is for Feb 9-12 and (b) is for Oct 13-15.

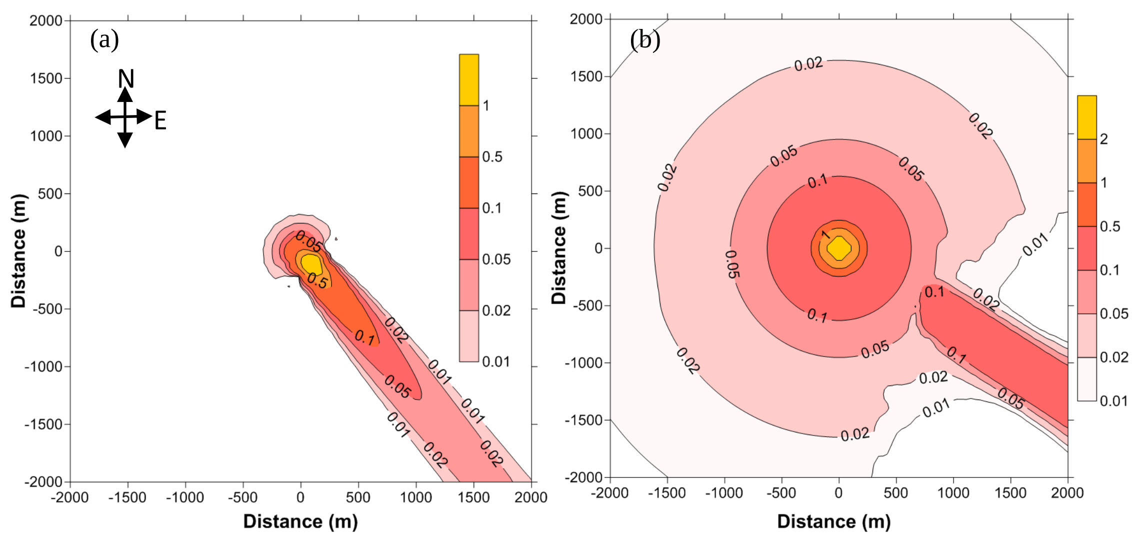

Figure 9.4 Hourly OC (OU m^{-3}) contours for the dairy barn for the 15th hour (14:00-15:00) (a) and 18th hour (17:00-18:00) (b) on Oct 15, 2004 (two of the worst scenarios).

9.6.2 Odour occurrence-free frequency contours

9.6.2.1 Odour impact criteria

Odour impact criteria are usually set using an OC threshold (such as 1 OU m^{-3}) over an averaging time (such as 1 hour) and with an odour occurrence-free frequency (such as 99.5%). This is further utilized to determine travel distances by dispersion modelling to ensure the odour impact criterion is not violated in all directions, which are also called setback distances. In Canada, odours are regulated differently in different provinces and territories or local authorities (Brancher et al., 2017). According to the Government of Saskatchewan (2012), odour impact criteria of 1, 2, 4, and 6 OU m^{-3} with averaging time of 1 hour and odour occurrence-free frequency of 99.5% are recommended to use for different land use purposes (Table 9.4). However, the above odour impact criteria were proposed without fully understanding odour properties (OC, OI, HT, etc.) from different OE sources. For example, odour properties for different animal barns are expected to be different, therefore, acceptable odour thresholds for different odour sources should take odour properties into consideration when being developed.

Table 9.4 Recommended ambient odour criteria in Saskatchewan (Government of Saskatchewan, 2012).

Odour threshold	Averaging time	Annual frequency	Land use
1 OU m^{-3}	1 hour	99.5%	Urban residential zones
2 OU m^{-3}			Urban commercial zones or mixed residential and commercial zones
4 OU m^{-3}			Industrial or restricted business zones and rural zones with mixed utilisation
6 OU m^{-3}			Industrial or agricultural zones with predominantly agricultural utilisation

To establish an odour impact criterion considering not only how strong the odour is (OI) but also the degree of odour annoyance (HT), the previous study (Chapter 2) investigated the relationships among OC, OI, and HT for the three different animal barns. Besides the data points acquired from seasonal measurements and diurnal measurements, extra full-strength air samples were collected in winter when OC was high and were diluted by 2, 4, 8, 16, 32, 64 and 128 times to obtain 4 identical diluted samples of each dilution ratio. As a result, there was a total of 62 data points of OC, OI, and HT for both the layer and dairy barns and a total of 50 data points for the broiler barn. Each data point was the average of two replicates. The detailed methods can be found in Chapter 2. Significant correlations between OC and OI existed for all three odours ($P<0.01$). The relationships between OI and OC and between HT and OC were investigated using Weber-Fechner law and are given in Table 2.2. Therefore, with an OI limit of 0, which indicates no smell of odour, and an HT limit of 0, which means people neither dislike nor like the odour, an odour threshold of 9, 23, and 17 OU m^{-3} were determined, respectively, for the layer, broiler, and dairy barns. To be consistent with the Government of Saskatchewan (2012), an averaging time of 1 hour and odour occurrence-free frequency of 99.5% were also applied to establish odour impact criteria.

9.6.2.2 Odour occurrence-free frequency contours and setback distances

According to Saskatchewan Air Quality Modelling Guideline (2012), the maximum modelled concentrations can be due to rare and unusual meteorological condition, thus the top 8 highest hourly concentrations are considered to be outliers and are eliminated when generating odour occurrence-free frequency contours. As odour impact criteria of 1, 2, 4, and 6 OU m^{-3} with averaging time of 1 hour and odour occurrence-free frequency of 99.5% were suggested to use for different land use purposes by the Government of Saskatchewan (2012) (Table 9.4), frequency contours were generated under all four odour impact criteria for the three barns but only the odour occurrence-free frequency contours for the layer barn with the biggest impact areas are displayed in Fig. 9.5. Sommer-Quabach et al. (2014) compared two different odour impact criteria, one with a low OC threshold and a high exceedance probability, and the second with a high OC threshold and a low exceedance probability. Because the former one is more sensitive to the site specific meteorological data, they concluded that a low OC and higher exceedance probability is more appropriate to use for odour impact criteria. Thus, contours for variable odour occurrence-free frequencies from minimum 80% to 99.5% were also generated for further comparison.

It was found that under the four odour impact criteria, the maximum setback distances for the layer barn were all in the north leeward of the prevailing south wind and minimum in the south, with the difference up to 900 m for the odour threshold of 1 OU m^{-3} and odour occurrence-free frequency of 99.5%. With the odour threshold increasing from 1 to 6 OU m^{-3}, the setback distance was gradually decreasing from 1941 to 641 m in the north, and from 1023 to 365 m in the south. The setback distances determined in other directions are listed in Table 9.5.

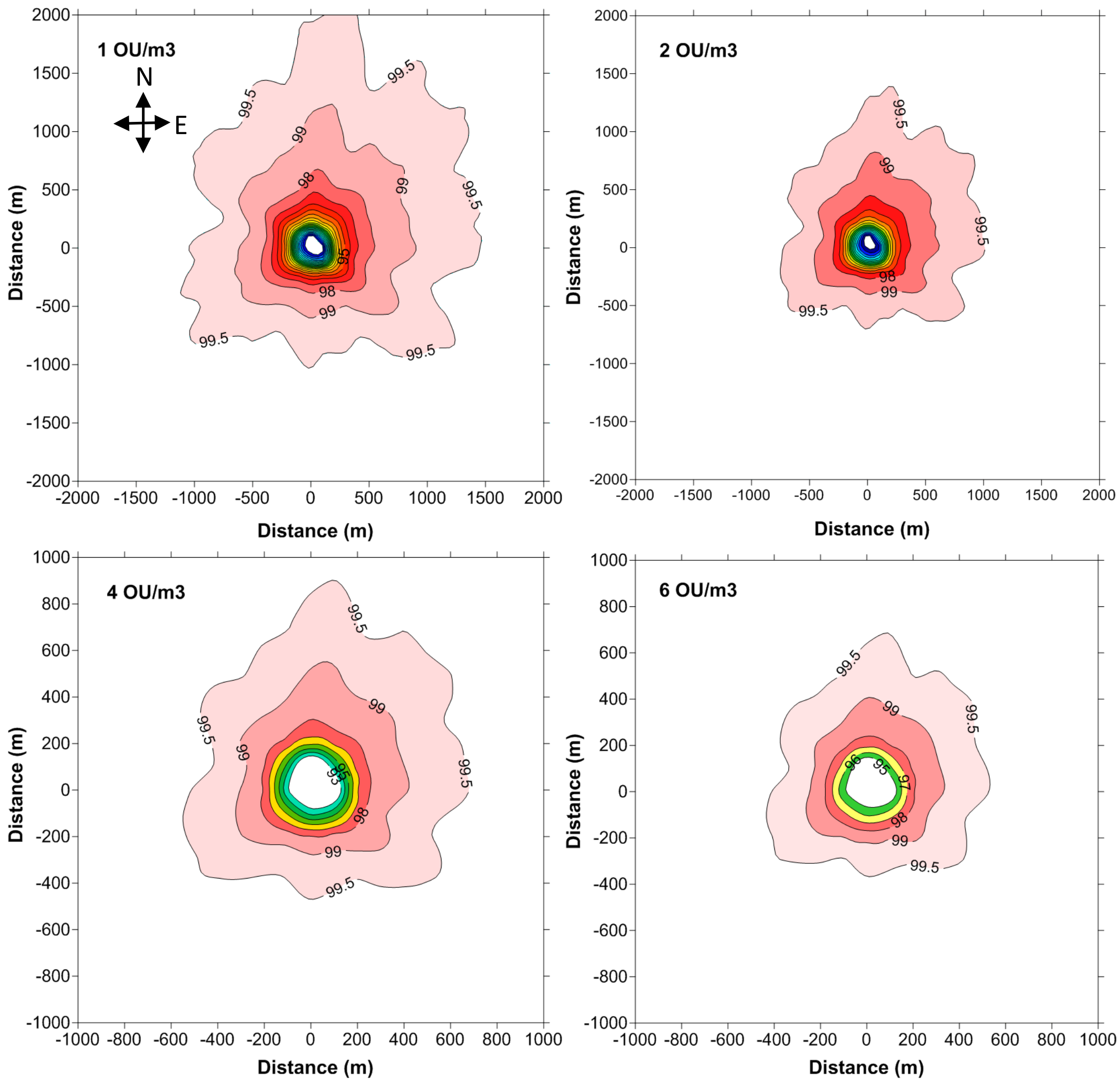

Figure 9.5 Odour occurrence-free frequency contours for the layer barn using the recommended odour impact criteria by Government of Saskatchewan (2012).

Besides, from an odour occurrence-free frequency of 99.5% to 80%, odour impact area under a certain odour threshold was also decreasing. Similarly, under the same weather condition, setback distances for the broiler barn and broiler barn with full-year operation were also highest in the north and lowest in the south under all recommended odour impact criteria. Along with the increasing of odour threshold from 1 to 6 OU m^{-3}, the setback distance gradually decreased from 980 to 320 m in the north and from 519 to 192 m in the south for this study broiler barn, and decreased from 1691 to 472 m in the north and from 914 to 306 m in the south for broiler barn with full-year operation. Because the modelled OCs for the dairy barn were below 2 OU m^{-3} when distances were greater than 100 m, only odour occurrence-free frequency contour for the odour threshold of 1 OU m^{-3} could be generated. For the odour occurrence-free frequency of 99.5%, the maximum setback distance of 205 m in the north and minimum 171 m in the south were obtained, which are apparently much shorter than the setback distances for the layer and broiler barns.

Table 9.5 Directional setback distances with averaging time of 1 hour and odour occurrence-free frequency of 99.5%.

		Directional setback distance (m)				
		Using recommended odour criteria[a]				Using newly developed odour criteria
		1 OU m^{-3}	**2 OU m^{-3}**	**4 OU m^{-3}**	**6 OU m^{-3}**	**17 OU m^{-3}**
Dairy	North	205	/	/	/	/
	South	171	/	/	/	/
	East	184	/	/	/	/
	West	181	/	/	/	/
		1 OU m^{-3}	**2 OU m^{-3}**	**4 OU m^{-3}**	**6 OU m^{-3}**	**9 OU m^{-3}**
Layer	North	1941	1286	845	641	558
	South	1023	697	469	365	287
	East	1452	1010	678	527	526
	West	1046	724	513	411	324
		1 OU m^{-3}	**2 OU m^{-3}**	**4 OU m^{-3}**	**6 OU m^{-3}**	**23 OU m^{-3}**
Broiler	North	980	655	427	320	/
	South	519	337	223	192	/
	East	713	485	326	249	/
	West	577	394	264	212	/
		1 OU m^{-3}	**2 OU m^{-3}**	**4 OU m^{-3}**	**6 OU m^{-3}**	**23 OU m^{-3}**
Broiler*	North	1691	1056	640	472	168
	South	914	615	408	306	105
	East	1305	852	537	392	139
	West	1034	687	446	341	129

Notes: [a] indicates recommended odour impact criteria from Saskatchewan Air Quality Modelling Guideline (2012); Broiler* indicates broiler barn with full-year operation.

The odour occurrence-free frequency contours under the developed odour impact criteria for the layer barn and broiler barn with full-year operation are shown in Fig. 9.6. The odour emissions were low for the study dairy barn and the broiler barn; thus, no odour occurrence-free frequency contours or setback distances were generated using the new odour impact criteria. The comparisons of setback distances under the odour threshold of 9 OU m^{-3} for the layer barn and 23 OU m^{-3} for the broiler barn, as well as under the four odour thresholds suggested by the Government of Saskatchewan are given in Table 9.5. The setback distance was also found to be maximum in the north and minimum in the south under the new odour impact criteria, and much shorter compared to that using the four recommended odour impact criteria by the Government of Saskatchewan (2012), e.g., the setback distances under the odour threshold of 9 OU m^{-3} for the layer barn varies from 287-558 m comparing to 1023-1941 m under the odour threshold of 1 OU m^{-3}.

Although the newly developed odour impact criteria limiting both OI and HT are not applicable to the study dairy and broiler barn due to their relatively low OE or odour occurrence frequency, the newly developed odour impact criteria may still be applied to other broiler barns with continuous operation or dairy barns with possible higher emission rates. This is confirmed by the dispersion modelling results for broiler barn with full-year operation, with which much greater odour travel distances are found compared to this study broiler barn with 6 flocks in a year, and a maximum setback distance of 168 m is obtained in the north direction under the newly developed odour impact criterion (23 OU m^{-3}). Therefore, different odour impact criteria may be selected for difference odour sources and land use purposes. Taking layer barns and broiler barns with full year operation for example, strict odour impact criteria thus greater setback distances for sensitive areas may still be used (e.g., 1 OU m^{-3}). While for less sensitive areas, an odour threshold of up to 9 OU m^{-3} and 23 OU m^{-3} may be allowed, respectively, for the layer and broiler barns, thus shorter setback distances are needed. In the future, more studies need to be carried out to verify the newly established odour impact criteria for the three types of animal barns and efforts need to be taken to improve the regulations for practical application.

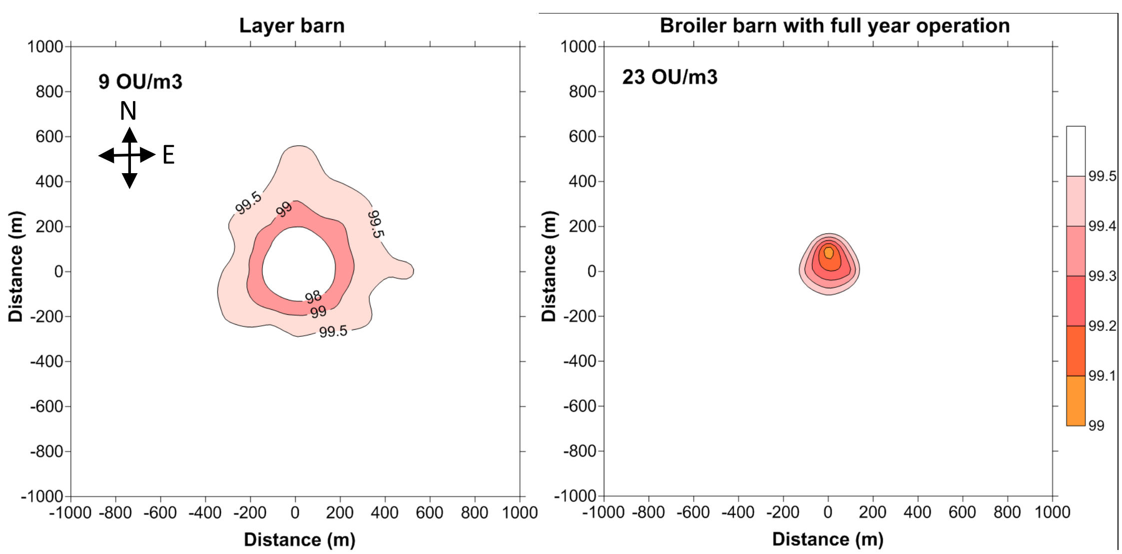

Figure 9.6 Odour occurrence-free frequency contours for the layer barn and broiler barn with full-year operation using the newly developed odour impact criteria.

9.6.3 Dispersion modelling for NH_3, H_2S, and respirable dust

The dispersion of NH_3, H_2S, and respirable dust, which are three pollutants usually concerned in ambient air quality standards, were also conducted to verify if their concentrations at these setback distances determined from odour impact criteria violated the regulations or not. The methods were the same as for odour dispersion modelling by conducting 5-year simulation and using monthly gas and respirable dust emission rates. From different ambient clean air standards for regulating NH_3, H_2S, and respirable dust for the Canadian provinces of Saskatchewan, Alberta, and Manitoba, an hourly threshold limit of 1.4 mg m^{-3} for hourly NH_3, 14 μg m^{-3} for hourly H_2S, and 50 μg m^{-3} for 24-hourly respirable dust was set, respectively (Table 9.6).

In compliance with Saskatchewan Air Quality Modelling Guideline (2012), the 9th highest gas concentrations in a year for 1-hour average and 2nd highest respirable dust concentrations for 24-hour average were taken as maximum concentrations to be compared to ambient air quality standards. This process was repeated for five times (once for each year of meteorological data). Only the highest gas and respirable dust concentrations among the 5 years, which were picked from the 9th highest gas concentrations for 1-hour average and 2nd highest respirable dust concentrations for 24-hour average from a distance of 100 m to 300 m in the four major directions, are listed in Table 9.6. The corresponding ambient concentration threshold limits for gases and respirable dust cited from different standards are also given in Table 9.6. At the minimum setback distances for all directions using the lowest odour impact criteria (9 OU m^{-3} for the layer barn, 23 OU m^{-3} for the broiler barn, and 1 OU m^{-3} for the dairy barn), none of the three pollutants exceeded the thresholds set in ambient air quality standards. The NH_3, H_2S, and respirable dust concentrations are all below the threshold limits set in the clean air standards beyond a distance of 100 m, with the only exception that the modelled H_2S concentration is above ambient concentration limit within a distance of 300 m for the layer barn. Therefore, using the ambient concentration threshold limits for NH_3, H_2S, and respirable dust, no setback distance is determined for the dairy and broiler barns, while a setback distance of 287 m in the north, 256 m in the south, 295 m in the east, and 273 m in the west is determined for the layer barn from the H_2S concentration contours in Fig. 9.7.

Table 9.6 The 9th highest hourly NH_3 and H_2S concentrations and 2nd highest 24-hourly respirable dust concentrations at receptors over 5 years.

	Maximum concentration at receptor (X, Y)	NH_3 (mg m^{-3}), 1-hour				H_2S (µg m^{-3}), 1-hour				Respirable dust (µg m^{-3}), 24-hour			
		Dairy	Layer	Broiler	Broiler*	Dairy	Layer	Broiler	Broiler*	Dairy	Layer	Broiler	Broiler*
A distance of 100 m	North (0,100)	0.038	1.27	0.84	0.94	0.46	38	11	11	0.35	3.92	6.80	7.42
	South (0,-100)	0.034	1.29	0.76	0.88	0.46	37	10	10	0.35	2.87	4	5.70
	East (100,0)	0.034	1.02	0.77	0.91	0.42	37	10	10	0.32	3.10	5.02	6.69
	West (-100, 0)	0.033	1.30	0.77	0.88	0.49	36	10	10	0.34	3.02	4.84	5.69
A distance of 200 m	North (0,200)	0.014	0.75	0.53	0.70	0.13	21	8	8	0.12	1.83	2.85	3.40
	South (0,-200)	0.012	0.68	0.44	0.63	0.13	19	6	6	0.11	1.18	1.79	3.00
	East (200,0)	0.012	0.57	0.51	0.66	0.12	22	8	8	0.10	1.46	1.96	2.78
	West (-200, 0)	0.012	0.74	0.50	0.60	0.14	19	7	7	0.11	1.16	1.87	3.05
A distance of 300 m	North (0,300)	0.008	0.52	0.39	0.53	0.06	13	7	7	0.06	1.02	1.62	2.53
	South (0,-300)	0.006	0.38	0.29	0.51	0.06	12	4	5	0.06	0.70	1.11	1.73
	East (300,0)	0.007	0.41	0.36	0.52	0.06	13.8	6	6	0.05	0.88	1.11	1.69
	West (-300, 0)	0.007	0.52	0.33	0.47	0.07	13	5	5	0.05	0.73	1.10	2.17
Concentration threshold in the ambient air		1.4 mg m^{-3} for hourly NH_3				14 µg m^{-3} for hourly H_2S				50 µg m^{-3} for 24-hourly respirable dust			

Notes: X and Y are horizontal and vertical distances (m) from the barn (0, 0); Broiler* means broiler barns with full-year operation; the concentration threshold is cited from Saskatchewan Ambient Air Quality Standards (2015) for NH_3, from Alberta Ambient Air Quality Objectives and Guidelines Summary (2013) for H_2S, and from Manitoba Ambient Criteria (2005) for respirable dust.

From odour occurrence-free frequency contours for the layer barn in Figs. 9.5 and 9.6, none of the odour impact criteria was violated at the above determined setback distances for the layer barn. Comparing the setback distances determined from gas criteria and odour criteria for the dairy and poultry barns, greater setback distances were always determined for the latter. Thus, to protect the air quality of the neighbouring communities from being affected by the polluted gases (NH_3 and H_2S) and respirable dust from livestock buildings, and also to reduce odour nuisance, odour impact criteria rather than gas and respirable dust impact criteria were suggested to be used to ensure sufficient and effective setbacks from the dairy and poultry barns. As the impact distances found in this study were likely within the property lines of the farms, the impact of the air emissions on the nearby land uses may not be a concern, however, in jurisdictions that the neighbors are located close by, the impact of odour and gas/dust emissions on air quality should not be negligible and the odour criteria and setbacks presented in this study may be applied to ensure acceptable air quality.

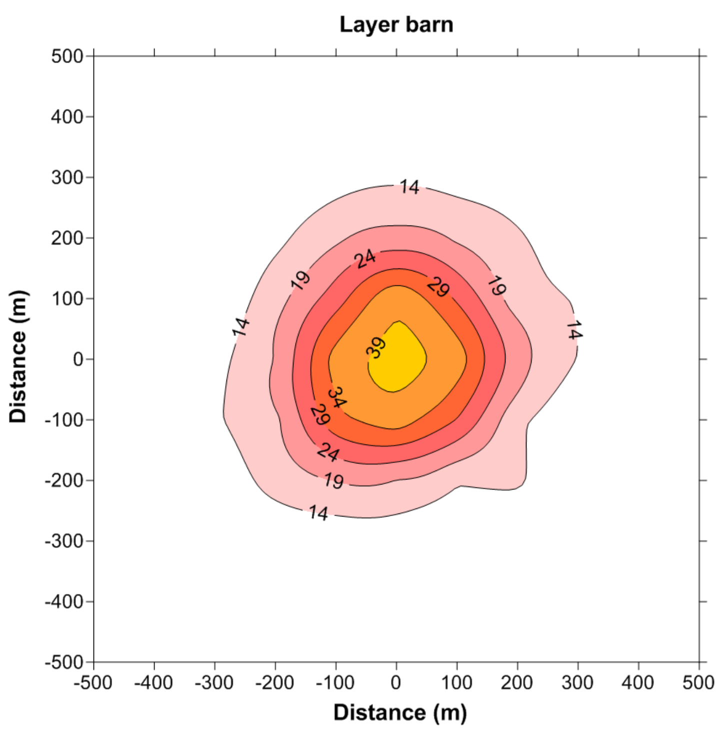

Figure 9.7 Hourly H_2S concentration (μg m^{-3}) contours using the 9th highest 1-hour concentrations for the layer barn.

9.7 CONCLUSIONS

Previous studies on determining setback distances through dispersion modelling for livestock sources could not give convincing results mainly due to that the seasonality of odour and gas emissions was ignored to give accurate source emission input, odour properties were not well understood, and odour impact criteria was not properly established. With the input of diurnal and seasonal odour, gas, and respirable dust emission rates measured over long-term (one year) for a dairy barn, a layer barn, and a broiler barn, the established relationships between odour properties as well as the newly developed odour impact criteria, this study conducted dispersion modelling of odour, gases, and respirable dust over a 5-year period using AERMOD for these three barns under the Canadian Prairies climate condition. The summary of the results are as follows:

1) With overall higher OE than the broiler and dairy barns, the layer barn presented the greatest impact area followed by the broiler and dairy barns. Considering only the four major directions (North, South, East, and West), odour traveled farthest in the north and shortest in the south for all three barns as the prevailing wind is from the south;
2) The annual average OCs were very low (close to 0 for most hours of a year) even at very close distances from all three barns, thus under a same OC limit much shorter odour travel distances were determined than that with odour occurring above the threshold should be no more than 99.5% of the time being regulated, which proves it is not suitable to regulate only annual average OC and odour occurrence frequency should be considered in odour impact criteria;
3) Using the four suggested odour impact criteria regarding different land uses by the Government of Saskatchewan (2012), as well as the newly developed odour impact criteria, directional setback distances were obtained for all three barns. From 6 OU m^{-3} to 1 OU m^{-3} (with averaging time of 1 hour and odour occurrence-free frequency of 99.5%), maximum setback distances were in the north, decreasing from 1941 to 641 m for the layer barn and from 980 to 320 m for the broiler barn. Setback distances for the dairy barn were much shorter and only applicable under an odour impact criterion of 1 OU m^{-3} (maximum 181 m in the north). Using the newly developed odour impact criteria, no odour occurrence-free frequency contours or setback distances were generated for the dairy and broiler barns, while maximum setback distance of 558 m in the north was

determined for the layer barn under an odour impact criterion of 9 OU m^{-3}. This is shorter than the setback distance from using the above four odour impact criteria due to the more permissive OC limit. In addition, the newly developed odour impact criterion of 23 OU m^{-3} was proved to be applicable to similar broiler barns with full-year operation in determining stricter setback distances for sensitive land uses;

4) Dispersion modelling of NH_3, H_2S, and respirable dust were also conducted. No setback distances were determined for the dairy and broiler barns as NH_3, H_2S, and respirable dust concentrations are all already below the thresholds limits at/beyond a distance of 100 m. A setback distance of 287 m in the north, 256 m in the south, 295 m in the east, and 273 m in the west is determined for the layer barn from the H_2S concentration contours;
5) None of the NH_3, H_2S, and respirable dust concentrations exceeded the ambient air quality standard at the distances determined from odour dispersion modelling. Hence, in determining setback distances by dispersion modelling using AERMOD, it is suggested to use odour impact criteria rather than gas and respirable dust as the former always requires much greater setback distances than the latter.

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CHAPTER 10
SUMMARY, CONCLUSIONS, CONTRIBUTIONS AND FUTURE WORK

10.1 INTRODUCTION

In the last several decades, intensive confined animal housing and feeding practice around the world has been largely developed and has raised more and more public concerns about their environmental and health impact. Intensive animal production is associated with various air emissions, including odour, ammonia (NH_3), hydrogen sulfide (H_2S), greenhouse gases (GHGs), dust, volatile organic compounds, etc., which present negative impacts on quality of human life and health, and global climate change, etc.

So far, odour emission factors and relationships between odour properties (e.g., odour concentration [OC] vs. odour intensity [OI], odour concentration vs. hedonic tone [HT]) for dairy and poultry operations were still not clear. Simultaneously, long-term monitoring of gases, including NH_3, H_2S, and GHG were rarely performed and how these odorous gases correlate with odour was not well understood for dairy and poultry barns in Canada. Although it is a well-known fact that the air in animal barns contains over several hundreds of compounds, no indoor air quality index has been established based on the combined effect of these pollutants on human health from the occupational health point of view. Besides the indoor air quality concerns, acquiring accurate source emission data is also the first step for air dispersion modelling, establishing odour and gas impact criteria and determining setback distances for the neighboring communities. Various factors have been reported to affect livestock odour emissions (OE), including climate, animal species, feed, manure management, and housing systems, etc. Thus, directly applying the data acquired from the other regions such as USA and Europe to Canada probably will not be scientific, especially for those regions such as Canadian Prairies where the weather changes drastically.

Moreover, it has been reported that odour and gas concentrations and emissions from livestock production varied diurnally and seasonally. Snapshot measurements will not reflect accurate emissions that probably will vary in different seasons and at different time of a day, which further will affect decision making on applying emission mitigation methods and also regulations established to control the odour impact, as air emission impacts on the neighboring area is usually predicted by air dispersion modelling.

In the past decades, researchers have applied various industrial air dispersion models to livestock odour for assessing odour impact on the communities and for determining setback distances, while this kind of work has been rarely performed for poultry and dairy barns. As mentioned above, source odour or gas emission rate is one major data input for dispersion modelling. Since the seasonal and diurnal variations of odour and gas emissions for dairy and poultry barns were not well quantified in previous studies, most of these studies only used emission data from snapshot or short-term measurements for livestock odour and gas dispersion modelling. In addition, the development of odour impact criteria is complex and is still a developing science. Although various ambient odour criteria are applied in the USA, Canada, Australia, Europe, and Asia, in many cases the criteria are used for wastewater treatment plants or composting facilities or for all sources while only a few of them are specifically regulated for livestock odour sources. Besides, all developed odour impact criteria were established with only OC or OI threshold limit, while none considered HT (pleasantness or unpleasantness of an odour) to estimate odour annoyance. Accurate and effective setback distance can only be determined with reasonable and effective impact criteria. Hence, it is necessary to develop an impact criterion based on good understanding of odour properties. Moreover, all industrial dispersion models are initially designed for predicting industrial gas emissions, while significant differences exist between industrial gas and livestock odour. Thus, evaluations of these models are also very important to judge the credits of the modelled results and provide the scientific basis for selecting dispersion models for animal source air emissions.

The objective of this chapter is to give general conclusions of the whole research, to emphasize on the contributions, and to provide recommendations for future work.

10.2 GENERAL DISCUSSION

The topic of this dissertation focused on odour, gases, and respirable dust concentrations and emissions as well as odour, gases, and dust dispersion modelling for a commercial dairy barn, broiler barn, and layer barn on the Canadian Prairies, which have been rarely studied in Canada.

As previous studies have reported the seasonality of odour and gas concentrations and emissions from swine barns, the data collecting lasted for one year to characterize the seasonal variations of odour, toxic gases, greenhouse gases, and dust concentrations and emissions as well their diurnal variations (excluding respirable dust) in different seasons for the dairy, layer, and broiler barns under the Canadian Prairies climate. In consistent with previous studies, it was found that generally seasonal odour, NH_3, H_2S, and respirable dust concentrations varied with higher odour and NH_3 concentrations in the cold season (from November to March) but higher odour and NH_3 emissions in the mild and warm seasons (from April to October), except that NH_3 emission was higher in the cold season for the broiler barn. The identified seasonal variations of odour and gases were critical as they would not only generate more accurate emission factors and further serve as the input data for odour and gas dispersion modelling, but also would reveal the indoor air quality and potential outdoor impact in different seasons, which provided reference for establishing appropriate controlling strategy to reduce odour and gas concentrations and emissions and their impact on the nearby areas. Through this study, the indoor air quality was evaluated from a view of occupational health effect considering both the individual and additive health effect of NH_3, H_2S, and respirable dust. The air emission factors under the Canadian Prairies climate (a cold region) for typical dairy, layer, and broiler barns were revealed and compared to dairy and poultry barns in other regions. The impact of environmental parameters (temperature [T], relative humidity [RH], and ventilation rate [VR]) on odour and gases were also investigated and prediction models of OE were derived for all three types of barns.

Along with the measurement of OC, other four odour properties were also studied in Chapter 2, including OI, HT, persistence, and character descriptor. Thus, the relationships between odour properties (OC vs. OI, OC vs. HT, and OI vs. HT) were investigated with data collected in all seasons. The relationship between OC and OI is critical for the comparison of field measurements and modelled predictions to evaluate the performance of air dispersion models. Since odour properties were influenced by various factors, including animal species, feed, housing systems, manure management, ventilation, etc., it is necessary to derive specific relationships between odour properties for dairy and poultry barns under the climate of Canadian Prairies. Besides, previous odour impact criteria only regulated OC or OI; however, it has been proved that odour annoyance is affected also by HT. The newly developed odour impact criteria in this study adopted odour threshold criteria considering various levels of OC, OI and HT, thus they are comprehensive yet flexible to meet different land use requirements. The advantage of the method is that various OC limits determined from various odour intensities and HT could be selected in odour impact criteria with the acceptance of odour annoyance being estimated to meet the requirements of different land use purposes instead of merely using very low OC limits (e.g., 1 OU m^{-3}).

This study also measured seasonal and diurnal CO_2, CH_4, and N_2O concentrations and emissions, which were the three major GHG released from livestock operations. It was found that the majority of GHG emission were attributed to CO_2 emissions for the broiler and layer barns, while for the dairy barn comparable CO_2 emission and CH_4 emission in CO_2 equivalent was observed, which together contributed to the majority of total GHG emission. The seasonal effect seemed to be not significant for GHG emissions although similar seasonal variations to OC were observed for GHG concentrations. However, great diurnal variations existed for both CO_2 and CH_4 emissions and total GHG emissions in all seasons for the dairy barn. Diurnal CO_2 and total GHG emissions were relatively constant for the broiler barn but were varying with highly consistent diurnal patterns in all seasons for the layer barn. With the diurnal trends for the layer barn, seasonally measured CO_2 emissions over middle hours of a day were found to be over-high to represent the daily results. Thus, correction factors for modifying seasonally measured CO_2 emissions in different seasons were acquired for the layer barn. With the fact that data of GHG emissions from livestock barns still remains scarce, the GHG emission factors obtained from long-term measurements for the dairy and poultry barns in this study contributed to the emission database for the livestock sector and could be further utilized to validate and adjust the estimated GHG emission factors in the national inventory.

Then, field odour plume measurements were conducted to validate the performance of AERMOD model, which is a model initially designed for modelling industrial gas dispersion, in predicting odour dispersion in Chapter 8. The developed OC and OI relationship in this study was applied to convert the field measured odour intensities to concentrations. In agreement with previous studies, the modelled OC were all much lower than the field measured OC, thus scaling factors were needed to adjust the modelled results to the same magnitude as the measured OC and make the comparison possible. By plotting all data of modelled predictions against field measured OC, scaling factor of 286 was obtained, which greatly improved the modelled OC with an overall agreement of 76% between modelled predictions and measured results. However, when using only the geometric means of each odour plume, scaling factor of 154 was determined, which achieved a higher overall agreement of 81% and also obviously improved the predictions over short distances within 100 and 200 m as compared to the scaling factor of 286.

As very few previous studies on odour and gas dispersion modelling for setback distance determination could give convincing results due to that odour and gas emissions were usually collected through short-term measurements and also the relationships between odour properties were not well established. With the input of variable odour, NH_3, H_2S, and respirable dust emissions measured in Chapters 3, 4 and 5, dispersion modelling of the four air pollutants were conducted by using AERMOD to study their outdoor impact in Chapter 9. Using 5 years of meteorological data and terrain data for the study areas, it was found that odour traveled farthest in the north and shortest in the south for all thee barns as the prevailing wind is from the south; and the greatest impact area modelled was for the layer barn, followed by the broiler and then dairy barns as the layer barn had the highest odour emission rate. With the recommended odour impact criteria by the Government of Saskatchewan (2012) and the newly developed odour impact criteria from the OC-OI relationship and OC-HT relationship for the three animal barns by this study, setback distances were determined through odour dispersion modelling. By comparing the setback distances required by the odour criteria with that required by gas and dust threshold limits in the ambient clean air standards, it was found that using odour impact criteria would always generate greater setback distances than using the ambient threshold limits of NH_3, H_2S, and respirable dust, which suggests odour impact criteria should be stricter than that of gases or respirable dust to ensure better air quality for the nearby residents.

10.3 GENERAL SUMMARY AND CONCLUSIONS

The final goal of this research was to study both the indoor and outdoor air pollution for dairy and poultry barns on the Canadian Prairies.

For the study on indoor air quality, the concentrations of odour, toxic gases (NH_3 and H_2S) and respirable dust were measured with their seasonal variations throughout a year and diurnal variations in mild, warm, and cold seasons being characterized. The indoor air quality was evaluated using a quantified indicator based on the combined occupational health effect of respiratory irritation from NH_3, H_2S, and respirable dust. The results and discussion can be found in Chapter 3 for the dairy barn and Chapter 5 for the broiler and layer barns. The study on outdoor air pollution included two parts: 1) GHG emissions that would impact on the atmosphere and climate change, and 2) odour, toxic gases, and respirable dust that were studied mainly due to their adverse health effect on the neighborhoods. For Part 1, the study regarding GHG emission was presented in Chapter 6 for the dairy barn and Chapter 7 for the broiler and layer barns. For Part 2, first odour properties were characterized and relationships between odour properties (OC vs. OI, OC vs. HT, and OI vs. HT) were investigated in Chapter 2. Then odour and gas emission factors were quantified by long-term measurements (both seasonally and diurnally) in Chapter 3 for the dairy barn and Chapters 4 and 5 for the broiler and layer barns. The performance of AERMOD in predicting odour dispersion was validated by conducting field odour plume measurement in Chapter 8. Finally, the emission factors were input in a dispersion model AERMOD to predict odour, toxic gases, and respirable dust dispersion in the ambient air of the surrounding areas and directional setback distances were determined in Chapter 9. The following are the main conclusions of this study:

1. Comparing odour properties of the dairy, layer, and broiler barns, the highest OC, strongest OI and most unpleasantness (HT) were found for odour from the broiler barn followed by the layer barn and then the dairy barn. Significant correlations existed between OC and OI, between OC and HT, and between OI and HT for all three barns ($P<0.01$). Increased OC came along with increased OI but decreased HT; however, the rates were different. when OC increased at the same rate, HT decreased more quickly for the broiler-barn odour than the other two. The odour persistence of the layer-barn odour was -0.78 compared to -0.92 for the dairy-barn odour and -1 for the broiler-barn odour, which suggests the layer-barn odour is more persistent than the other two barn odours; the same dilution would result in the greatest decrease in OI for the broiler-barn odour followed by the dairy-barn odour and then the layer-barn odour. Using the OI-OC and HT-OC relationships derived, a reference table was generated listing OC limits under a boundary limit of OI from 0 (no odour) to 2

(faint odour) and of HT from -2 (dislike slightly) to 0 (neutral). This table gives various levels of odour impact criteria by considering OC, OI and HT, thus can be used to establish appropriate odour impact criteria for different land use purposes.

2. The highest annual average odour and NH_3 emission rates were from the layer barn (140 OU s^{-1} AU^{-1} and 1.10 mg s^{-1} AU^{-1}), followed by the broiler barn (127 OU s^{-1} AU^{-1} and 1.06 mg s^{-1} AU^{-1}) and then the dairy barn (45.9 OU s^{-1} AU^{-1} and 0.53 mg s^{-1} AU^{-1}). The annual average H_2S emissions were similar for the dairy barn (28 μg s^{-1} AU^{-1}) and layer barn (26.80 μg s^{-1} AU^{-1}), both were higher than the broiler barn (13.77 μg s^{-1} AU^{-1}). While the annual average respirable dust emissions were much higher for the broiler barn (50 μg s^{-1} AU^{-1}) than the layer barn (20 μg s^{-1} AU^{-1}) and dairy barn (9 μg s^{-1} AU^{-1}). Seasonal variations of odour, NH_3, H_2S, and respirable dust emissions were observed for all three barns. It was found that OEs were higher in the mild and warm seasons (from April to October) than the cold season (from November to March) for all three barns. Similar findings were found for NH_3 emissions for the dairy and layer barns, while for the broiler barn NH_3 emission was higher in the cold season. Besides, respirable dust was significantly higher in winter than in the mild and warm seasons for the broiler barn, however, only slightly higher respirable dust in winter was observed for the other two barns. Diurnal trends of odour and gas emissions were more obvious in the mild season when diurnal ambient T and VR would change greatly; overall, odour and NH_3 emissions were likely to be higher in the afternoon when VR was high for the dairy barn and the layer barn. Similar observation was found for OEs but not for NH_3 emissions of the broiler barn in the mild season, when NH_3 emissions were very low and only detectable in the early morning (06:00-09:00 a.m.).

3. A quantified indicator was used to describe the indoor air quality of the three animal barns based on the similar occupational health effect (respiratory irritation) of NH_3, H_2S, and respirable dust. It was found that considering the additive health effect of the air pollutants made a big difference for evaluating the indoor air quality than only considering individual air pollutants. The results indicated that the indoor air quality was acceptable in the warm and mild seasons. Comparing the indoor air quality of the three animal barns in the cold season when worst scenarios occurred, the indoor air quality was the poorest for the broiler barn followed by the dairy barn and then the layer barn. In the winter, the 8-hourly exposure

limit of NH_3 was exceeded for both broiler and dairy barns, and even the 15-minute exposure limit of NH_3 was exceeded for the broiler barn. In the future, validation of the accumulation method for combing health effect caused by the three air pollutants need to be conducted.

4. For the layer barn, manure removal from the belt greatly reduced odour and NH_3 concentrations and emissions in both mild and cold seasons. In the mild season, the reduction efficiency was 30% for OC and 26% for OE; and was 89% for NH_3 concentration and up to 90% for NH_3 emission. In the cold season, the reduction efficiency was 31% for OC and 32% for OE; and was 61% for NH_3 concentration and 62% for NH_3 emission.

5. It was found that increased NH_3 concentration was associated with increased OC for both dairy and layer barns ($P<0.01$), while no statistical relationship between NH_3 and OC was found for the broiler barn. On the contrary, OC was not related to H_2S concentration ($P>0.05$) for any of the three barns. Besides, VR was the most influential factor to odour for all three barns, with negative impact on OC but positive influence on OE ($P<0.01$). Finally, the regression models of OE were derived for all three animal barns with VR as the only common factor remained in the models, making OE very easy to predict.

6. Regarding GHG emissions, the layer and broiler barns presented much higher CO_2 emissions but lower CH_4 emissions than the dairy barn. The annual average CO_2 and CH_4 emissions were 116 and 3.1 mg s^{-1} AU^{-1} for the dairy barn, 437 and 0.06 mg s^{-1} AU^{-1} for the broiler barn, and 435 and 0.21 mg s^{-1} AU^{-1} for the layer barn. The highest annual average N_2O emission was observed for the layer barn (8.79 µg s^{-1} AU^{-1}), followed by the dairy barn (5 µg s^{-1} AU^{-1}) and then broiler barn (4.74 µg s^{-1} AU^{-1}). Seasonal variations were not obvious for CO_2 and CH_4 emissions but were great for N_2O emission of the dairy and broiler barns. For the layer barn, seasonal effect was considerable for both CH_4 and N_2O emissions, with higher emissions in the mild and warm seasons, but was not observed for CO_2 emission. The vast majority of total GHG emissions were contributed by CO_2 (59.8%) and CH_4 emissions (39.5%) for the dairy barn and by only CO_2 emissions (>98%) for the broiler and layer barns. For the dairy barn, great diurnal variations existed for both CO_2 and CH_4 emissions in all seasons, which were low in the morning and high in the afternoon and evening, thus total GHG emissions presented no significant seasonal variations, but

obvious diurnal variations similar to that of CO_2 and CH_4 emissions in all seasons. Diurnal CO_2 and total GHG emissions were relatively constant for the broiler barn, but were varying with highly consistent diurnal patterns in all seasons for the layer barn, with peak periods within 9:00 a.m. to 3:00 p.m.

7. Field measured OI was converted to OC through the developed OC and OI relationship in this study to validate the modelled OC. The modelled OCs were all much lower than the field measured results. Thus, to adjust the modelled results, scaling factors were generated by finding the slopes of field measured OCs against modelled OCs. Using all data points of the 14 odour plumes and using the geometric mean of each odour plume, scaling factors of 286 and 154 were developed, respectively. Both of them achieved good agreement between the field measurements and model predictions; however, the scaling factor of 154 was suggested to use due to its better performance in improving modelled predictions over short distances from 100 to 200 m and also in improving statistical evaluations.

8. Dispersion modelling of odour, NH_3, H_2S, and respirable dust were performed for all three animal barns using AERMOD with the input of variable emissions measured through the long-term measurement. The layer barn was found to have the greatest impact area. Odour traveled farthest in the north and shortest in the south for all three barns. Directional setback distances were determined for the three barns using the recommended odour impact criteria by the Government of Saskatchewan as well as the newly developed odour impact criteria in Chapter 2. Under the former criteria, maximum setback distances were determined in the north, which were in the range of 641 to 1941 m for the layer barn, and in the range of 320 to 980 m for the broiler barn, while only maximum 181 m in the north was determined under the strictest odour impact criterion (1 OU m^{-3}) for the dairy barn. The newly developed odour impact criteria determined maximum setback distance of 558 m in the north for the layer barn, while were not applicable to the dairy and broiler barns with relatively low OE or odour occurrence frequency. Dispersion modelling of NH_3, H_2S, and respirable dust showed none of them exceeded the ambient air quality standard at the determined setback distances from odour dispersion modelling and odour impact criteria. Besides, odour impact criteria were suggested to use rather than gases and respirable dust as the former always required greater setback distances than the latter.

10.4 CONTRIBUTIONS OF THE RESEARCH WORK

The objectives of this study have been successfully achieved with the following original contributions to the scientific knowledge:

1. Odour properties, including OC, intensity, HT, persistence, and character descriptor, were well studied for a commercial dairy, layer, and broiler barn under the Canadian Prairies climate condition. The relationships between OC and OI, between OC and HT, and between OI and HT were derived for all three animal barns, which could have various applications, such as help establish odour control strategies and odour impact criteria, evaluate the performance of dispersion models for predicting odour dispersion, and determine setback distances. New odour impact criteria were developed by considering OC, OI, and HT and may be applied in land management with OC limits determined under both OI and HT boundaries.

2. With the measurements over a year, the indoor air quality of the three animal barns were investigated in different seasons and were quantified by air quality indicators considering not only the health effect of individual air pollutants but also their additive health impact. The information could be utilized to ensure the indoor air quality for dairy and poultry barns concerning the occupational health of workers.

3. The emission factors of odour, odorous gases (NH_3 and H_2S), GHG (CO_2, CH_4, and N_2O) as well as respirable dust were acquired for the three animal barns with both their diurnal variations (excluding respirable dust) and seasonal variations being characterized. This improves the emission database for dairy and poultry barns from very limited related studies in Canada and provides solid reference in understanding the contribution of air emissions of each animal species to the whole animal sector and help establish appropriate mitigation methods for those air pollutants. Based on the data collected, prediction models for OE were developed with the environmental parameters as the variables, which are useful in estimating OE for other similar dairy and poultry barns.

4. AERMOD model was validated for predicting odour dispersion of the broiler barn on the Canadian Prairies by conducting field odour plume measurements and scaling factors were generated to adjust the modelled results by AERMOD for other similar studies. Impact

areas of OE from all three animal barns were studied by dispersion modelling using AERMOD. Using the regulated odour impact criteria by the Government of Saskatchewan and the newly developed odour impact criteria in this study, directional setback distances were determined for the three barns, which will provide reference in land management and planning.

10.5 RECOMMENDATIONS FOR FUTURE WORK

The following work were suggested for future research based on the work of this thesis.

10.5.1 Data collecting from more types of barns

- In this thesis, the data collecting was performed only for one selected barn for each animal species. It is recommended to collect more OE data from other dairy and poultry barns on the Canadian Prairies with different animal density, housing systems, building design, etc., and investigate how these factors would affect OE, so that the prediction models of OE could be improved and will be applicable to various types of dairy and poultry barns.

10.5.2 Different methods for estimating VR

- It is suggested to use other methods, e.g., tracer gas or fan method, for the broiler and layer barns (mechanically ventilated) to estimate VR. Thus, the odour and gas emission factors from this study could be calibrated, and the uncertainty of the results could be reduced.

10.5.3 Study on spatial odour and gas distribution in the barns

- Study the spatial odour and gas distribution inside the dairy and poultry barns and may investigate the relationship between spatial odour and gas concentration distribution and temperature and moisture distribution. This could be used to modify the concentrations and emissions that were measured from one single sampling point in this study, as well as to acquire peak odour and gas emissions as for studying their outdoor impact.

10.5.4 Identify and quantify the key components of odour

- Characterize and quantify the volatile organic components in the mixed odorous air from the dairy and poultry barns, and study their contribution to the total OC, intensity and HT. Thus, the key odorous components could be determined. This will provide information to develop appropriate mitigation methods for odour.

10.5.5 Study on the roles of odour occurrence frequency and duration in establishing odour impact criteria

- Study how odour occurrence frequency and odour episode duration will affect the perception of odour. For example, compare the annoyance level of one odour with high odour occurrence frequency but short odour episode duration to the annoyance level of the same odour with low odour occurrence frequency but long odour episode duration.

10.5.6 Conduct more field odour plume measurements

- Conduct more field odour plume measurements in the warm season under different meteorological conditions (cloud cover, wind speed, etc.) as well as in the mild season to do validation for AERMOD. Thus, the performance of AERMOD in simulating OC could be better evaluated and scaling factors may be improved.

APPENDIX A
RESPIRABLE DUST CONCENTRATIONS AND EMISSIONS OF THE DAIRY BARN

Due to that Chapter 3 (Diurnal and seasonal variations of odour and gas emissions from a naturally ventilated free-stall dairy barn on the Canadian Prairies) did not include the respirable dust concentrations and emissions but that chapter has alreay been published in a journal, the respirable dust concentrations and emissions of the dairy barn are given in Table A.1. The whole barn respirble dust emission rate (in unit of mg s^{-1}) can be found in Table 9.1. The sampling periods are the same as that for monthly NH_3 and H_2S measurements for the dairy barn in Chapter 3. The sampling and measuring methods are the same as that for the broiler and layer barns in Chapter 5.

Table A.1 Respirable dust concentrations and emissions of the dairy barn.

	Respirable dust concentration (mg m^{-3})	Respirable dust emission (μg s^{-1} AU^{-1})	Respirable dust emission (μg s^{-1} cow^{-1})	Respirable dust emission (μg s^{-1} m^{-2})
09-Feb-2015	0.26	8	12	0.43
17-Mar-2015	0.10	10	15	0.55
20-Apr-2015	0.07	24	37	1.32
21-May-2015	0.05	7	10	0.36
23-Jun-2015	0.06	26	39	1.28
21-Jul-2015	0.04	8	12	0.37
27-Aug-2015	0.01	1	2	0.06
24-Sep-2015	0.02	2	3	0.12
13-Oct-2015	0.07	11	17	0.60
19-Nov-2015	0.06	3	4	0.14
17-Dec-2015	0.07	3	4	0.14
19-Jan-2016	0.08	2	4	0.13
Average of cold season	0.11	8	5	0.28
Average of warm season	0.04	13	9	0.44
Average of mild season	0.07	27	18	0.96
Annual average	0.08	13	9	0.46

Notes: Cold season includes February, March, November, December, and January; warm season includes May to September; and mild season includes April and October.

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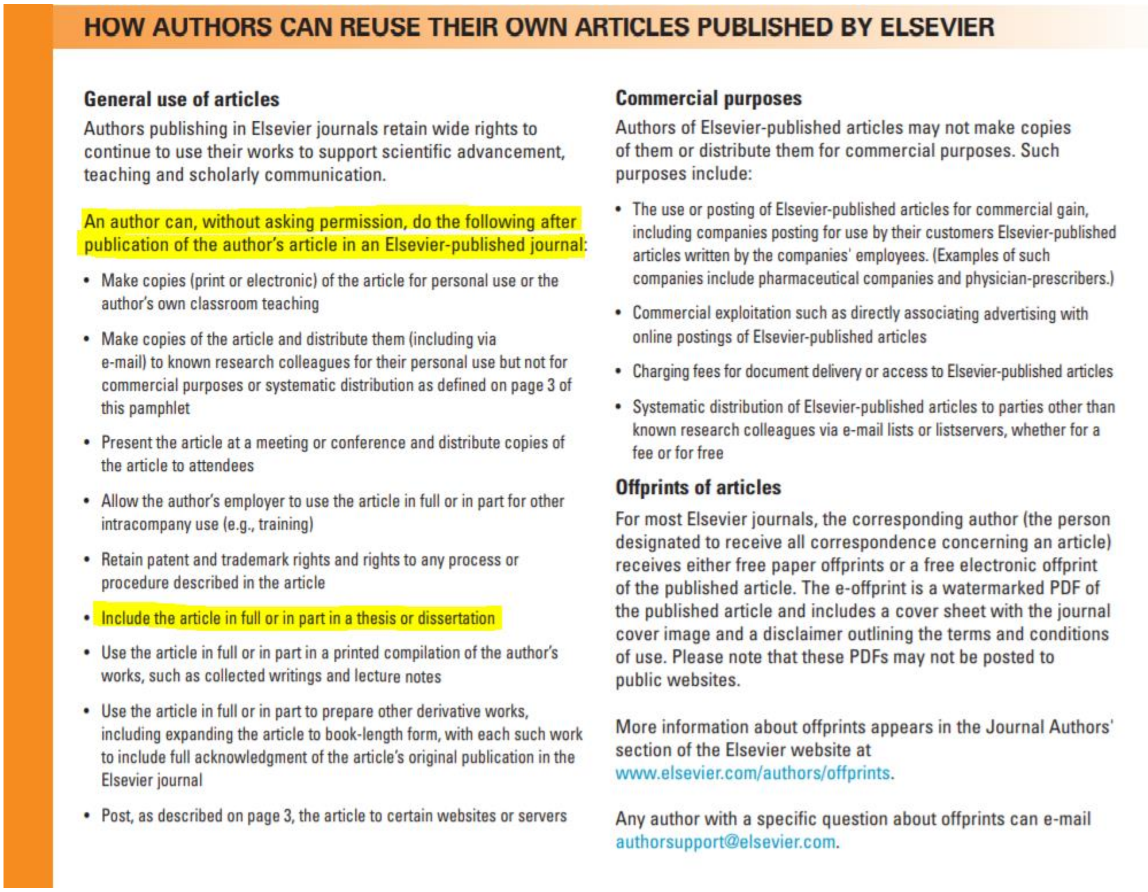
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