Implications of a Cage-free Layer System on Ammonia and Particulate Matter Generation

by

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ABSTRACT

IMPLICATIONS OF A CAGE-FREE LAYER SYSTEM ON AMMONIA AND PARTICULATE MATTER GENERATION

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Pollutants resulting from poultry housing facilities are of great concern to the environment, public health and hen welfare. A shift in consumer attitudes towards hen welfare has influenced food distributors to publicly commit to transitioning exclusively to the use of eggs from cage-free housing systems. In order to meet the needs of consumers, the egg production industry is transitioning to cage-free, enriched-cage or free-run systems. To assess the environmental sustainability of cage-free housing, a one-year measurement campaign was conducted to determine the emission factors of ammonia (NH$_3$) and size fractioned particulate matter (PM$_{2.5}$ & PM$_{10}$) from a commercial cage-free facility in Perth County Ontario. The emission factors, of this facility, determined experimentally, were compared to the emission levels reported in literature for conventional battery cages. The average emission factors of NH$_3$, PM$_{2.5}$ and PM$_{10}$ were $81.41 \pm 42.92$, $24.93 \pm 5.47$ and $51.78 \pm 13.19$ g day$^{-1}$ AU$^{-1}$ (AU – Animal Unit equivalent to 500 kg live mass), respectively. The emission rates for NH$_3$, PM$_{2.5}$ and PM$_{10}$ found in this study were 4.2, 22.7 and 20.3 times higher than those for a conventional battery cage layer facility located in Wellington Country Ontario.
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1 Introduction

The poultry sector has seen trends of intensification due to an increase in demand caused by population and consumption growth. High-density operations are economically justified as they are highly efficient for production, however they introduce significant environmental and animal welfare concerns. Today’s consumers care more about where their food comes from and the conditions under which it is produced. Social media, via the internet, has highlighted poor animal welfare conditions which has caused consumers to not only re-evaluate their choices about food, but also demand improved animal welfare. This shift in consumer attitudes is placing immense pressures on the egg industry in Canada. Numerous restaurants and food distributors are publicly committing to transitioning exclusively to the use of eggs from cage-free housing systems. This list is rapidly increasing with names such as McDonalds, Tim Hortons, Starbucks, Burger King, Walmart, and Cara Foods. The egg production industry, which has operated primarily by means of hens living in the confines of battery cage facilities, is having to rapidly transition to enriched cage, cage-free or free-run systems. While extensive research has focused largely on aspects of hen welfare, there is a research gap concerning the environmental implications of cage-free systems.

Significant aerial pollutants resulting from intensive poultry operations are ammonia (NH₃) and size fractioned particulate matter (aerodynamic diameter of 10 µm (PM₁₀) and 2.5 µm (PM₂.₅)). In 2015, agriculture operations alone contributed to more than 90% of the total national NH₃ emissions in Canada (Environment and Climate Change Canada, 2017). Gaseous ammonia is formed through microbial degradation of uric acid, which is rich in nitrogen, resulting from high protein diets (Schefferle, 1965; Maliselo et al., 2015). Ammonia is proven to have adverse effects on the environment while also increasing risk to public health, agriculture workers and birds. Atmospheric ammonia largely contributes to acidification and nitrification of the environment (Groot Koerkamp, 1994; Behera et al., 2013). In addition, ammonia can rapidly undergo chemical reactions to form ammonium salts and secondary aerosols (Krupa, 2003) typically in the PM₂.₅ size fraction, which contribute to the formation of smog (Renard et al., 2004). Ammonia can be detected by birds at 5 ppm and is considered harmful within a range of 20 – 25 ppm (National Farm Animal Care Council, 2017). High concentrations of ammonia can
cause lower production rates, increased risk of disease (Ritz et al., 2004), and irritation and damage to the respiratory tract (Green et al., 2007). Particulate matter in animal housing is a mixture of airborne particles of feed, feces, dander, feathers, and hair (Donham et al., 2002). Due to the small size of particulate matter, particles can be inhaled and can penetrate in the deeper respiratory airways causing infection, reactions, and asthma-like symptoms (Cambra-Lopez et al., 2010). Ammonia and dust production are affected by the barn air temperature and humidity, size and activity of the bird, the ventilation rate and number of air exchanges within the barn, as well as the litter or manure quality (Green et al., 2007).

The evaluation of aerial pollutants resulting from poultry production is complex and can be difficult to obtain as it varies based on climatic conditions, geographic location, type and number of poultry, management practices employed, lighting and feeding regimes, ventilation type, and manure storage and removal (Morgan et al., 2014). Studying emission behaviours from a variety of poultry production operations is important as it will create greater accuracy when characterizing atmospheric releases.

1.1 Research Objectives

The objective of this study is to quantify and evaluate aerial pollutant emissions from a commercial cage-free laying facility located in Perth County, Ontario, Canada. To acquire data, a monitoring system was implemented at the facility to continuously monitor ventilation rates, ammonia and size fractioned particulate matter concentrations, and environmental parameters. The monitoring campaign will span over three seasons to ascertain the effects of seasonal variations on emission factors. Emission factors will be developed from the results as they reflect a universal unit that can be applied and compared to a variety of types of facilities. The emission factors from the cage-free facility will be compared with emissions reported in literature for conventional battery cages to characterize trends and improve understanding of the differences in emissions from the two types of facilities.
1.2 Thesis Outline

The format of the thesis is a literature review presented in Chapter 2 detailing two types of commercial layer facilities and their aerial pollutants of concern. The literature review provides insight on the excreta management systems, floor styles, packing densities, operation and typical layout of conventional battery facilities and cage-free facilities. The literature review investigates the aerial pollutants emitted from commercial layer facilities and their concern to the environment and human health. A review of similar studies demonstrates the information available on emissions from commercial layer facilities. A background of the instrumentation used in this study is given detailing the functionality and effectiveness of the equipment for its intended use.

The layer facility used for this study is described in Chapter 3. The layout, size, bird information, ventilation, management systems and general operation are described. The experimental layout is described in the Methodology given in Chapter 4. This section also describes how ventilation rates were characterized and emission factors were developed. This section highlights the data collection process, difficulties encountered, quality control and data processing.

The results from the monitoring campaign are provided in Chapter 5. The results are presented and discussed in the following order: house parameters, seasonal pollutants, and overall emission summary. Chapter 6 provides a detailed comparison of the results from this study, with a study on conventional battery cage facilities presented by Morgan et al., (2014). The comparison shows the similarities and differences in emissions from the two types of facilities. The conclusions drawn from this study are highlighted in Chapter 7. Chapter 8 provides recommendations that may benefit future research projects of a similar focus.

2 Literature Review

In recent years, there has been a greater focus on understanding the emissions from commercial poultry facilities around North America and Europe. An increased number of facilities have been built to meet the consumer demands for poultry products. High density livestock operations have greater space requirements, produce significantly more waste, and are typically more difficult to
keep clean resulting in greater environmental impacts. Studies have been performed to develop baseline emission data for conventional battery cage facilities (Groot Koerkamp et al., 1998; Nicholson et al., 2004; Liang et al., 2005; Lin et al., 2012; Fournel et al., 2012; Morgan et al., 2014), however, a greater emphasis is needed on the environmental impacts of alternative housing facilities as the industry shifts towards facilities with conditions for improved hen welfare. The following sections provide information regarding the types of commercial layer facilities, typical aerial pollutants from poultry operations, a background on the development of emission factors, a review of similar studies, and a technology background of the typical measurement techniques used in field studies.

2.1 Commercial Layer Facilities

In 2018, Statistics Canada (2018) reported that egg production in Canada had increased by 3.1% since November 2016. This production increase is reflective of the increasing demand for egg products by consumers. As of March 2018, there were an estimated 32,213,000 layer hens in Canada (Statistics Canada, 2018). Currently, approximately 90% of egg production in Canada uses conventional battery cage facilities, whereas the other 10% uses alternative housing facilities such as enriched cage, free-run, aviary, and free-range (Egg Farmers of Canada, 2016). According to Egg Farmers of Canada (2018), over the next 8 years an estimated 50% of facilities will be reconstructed or repurposed as alternative housing. The goal set out by Egg farmers of Canada is to attain all production in enriched housing, free-run, aviary or free-range by 2036 (Egg Farmers of Canada, 2016). Due to the rapidness of the transition to alternative housing facilities in the egg industry, there are fewer studies that quantify the aerial emissions from cage-free housing alternatives in comparison to conventional housing. Aerial emissions of NH$_3$, PM$_{2.5}$ and PM$_{10}$ are influenced by the facility management systems, bird activity and facility layout. This study is focused on quantifying emissions from cage-free housing to provide a baseline for cage-free housing systems in Canada. The following sections describe conventional battery cage facilities and aviary cage-free facilities.
2.1.1 Conventional Battery Cage Facilities

Battery cage facilities are the most commonly operated style of laying hen facility due to their production efficiency and high stocking densities (Groot Koerkamp, 1994). Cages are lined in rows and stacked vertically for higher stocking densities. Birds are confined in small social groups with 4-6 birds in each cage, limiting social stresses which results in lower aggression and cannibalism (Pohle et al., 2009). The layers do not have free access to the litter floor, perching wires, or nesting areas but have access to automatic feed and water systems. Eggs are commonly collected automatically via conveyor belts.

The two most common styles of battery cage facilities, defined based on their manure management practice, are high-rise (HR) and manure belt (MB). In HR facilities, manure is stored beneath the lower level of the building and is often stored for the duration of 1 year before it is removed (Liang et al., 2005). MB facilities operate multiple manure belts located beneath the cage wire to allow manure droppings or excreta to fall onto the belt. The belts are operated frequently, typically between two and seven times a week (Liang et al., 2005). Manure is conveyed to one end of the house where it is transferred to an on-farm or off-farm storage location. HR cage layer systems represent 70% of the total cage layer houses in the United States, whereas MB represent the remaining 30% (Xin et al., 2011). A schematic of high-rise and manure belt facilities is shown in Figure 1 and Figure 2, respectively.

![Figure 1: Schematic representation of a high-rise layer house (Groot Koerkamp, 1994)](image-url)
Manure belts can be naturally dried with ambient air or mechanically dried with forced air (Fournel et al., 2012). The process of drying is done to lower the moisture content of the manure to attain lower ammonia emissions. Generally, the manure removed has a moisture content between 30-60% depending on the drying process, and seasonal climate (Xin et al., 2011). Typically, naturally dried manure has a moisture content of 60%, whereas mechanically dried manure has a moisture content as low as 30% (Fournel et al., 2012).

Many studies have shown that HR housing systems emit much greater quantities of NH$_3$ than MB housing systems (Liang et al., 2005; Groot Koerkamp et al., 1998a; Xin et al., 2011). The interval of manure removal can also have a significant effect on NH$_3$ emissions. Liang et al., (2005) found that manure belt houses removed semi-weekly emitted 74% more NH$_3$ than those with daily removal of manure. However, the overall emissions from MB facilities do not include the emissions from the manure storage facility, whereas HR systems encompass the emissions from the bird system and manure storage.

With the hens confined in cages, facility staff have the ability to periodically sweep surfaces between the rows of cages throughout the production cycle. This can reduce the accumulation of dust and other particulates between the rows of cages, keeping the facility cleaner. The effectiveness of this practice in reducing dust emissions is highly dependent on the staff schedule and varies between facilities.
2.1.2 Cage-Free Facilities

A common cage-free system is known as an aviary housing facility. They are a relatively progressive housing alternative that encourages hens to exercise natural behaviors. These facilities are increasingly popular as they improve hen-welfare while maintaining high production rates. Cage-free systems provide increased space for the hens, the freedom to move, designated nesting areas, a litter floor for dust bathing and perching areas. A typical aviary style facility is shown in Figure 3 where there are multiple rows of multi-tiered structures spaced between open litter floors. Most aviary systems operate manure belts which remove excreta from the facility on a scheduled basis. The manure belts are most commonly located beneath the wired tiers so that the manure can fall through onto the belt.

![Figure 3: Cross-Sectional view of an aviary hen house (Hayes et al., 2013)](image)

Cage free-facilities can be ventilated in a variety of ways but are most commonly mechanically ventilated with fans on either side of the facility or are tunnel ventilated with fans at either ends or a combination of both. Cage-free systems tend to have lower minimum ventilation requirements to maintain comfortable temperatures in the colder months. Due to the lower packing density (fewer number of birds in similar space as conventional facilities) there is less body heat warming the air inside the barn. This often requires supplemental heaters and lower ventilation rates (Green et al., 2007).
The greatest deviation from conventional facilities is the open litter floor. The hens have unlimited access to the open litter floor that runs the area of the facility underneath each tier. The litter floor is often replenished with fresh bedding such as wood shavings, saw dust, cedar chips etc., and is not cleared out until the end of the production cycle. Initially the litter floor consists primarily of the bedding material, however over the duration of the production cycle, the litter becomes predominantly dried excreta resembling a granular sand-like mixture (Groot Koerkamp et al., 1998b). Additional and frequent replenishment of fresh bedding on the litter floor can reduce the litter moisture content (Xin et al., 2011). Management of the litter floor has significant effects on ammonia and particulate matter generation. The high level of bird activity can kick up particulate matter which result in dustier environments.

Based on a study in the Midwestern United States by Xin et al. (2012), production costs were estimated to be 60% higher for cage-free systems over those of conventional housing systems. This cost is caused by the increased space requirement per bird as well as higher equipment costs for operation (Xin et al., 2012). Furthermore, due to this added cost, it is crucial to quantify the emissions for cage-free systems to develop mitigation strategies and best management practices so that facilities can operate with lower environmental footprints while maintaining production efficiencies.

2.2 Aerial Pollutants from Commercial Poultry Facilities

There are several factors that influence the aerial emissions of animal feeding operations. Examples include feed, manure characteristics and handling practices, temperature and humidity, bedding material/litter, animal and other facility accessories (heating devices, lighting schedules, and manure storage conditions) (Xin et al., 2011). Animal feeding operations can result in emissions of a variety of gases and particulates. Specifically, to poultry facilities, ammonia and size fractioned particulate matter (PM$_{2.5}$ and PM$_{10}$) are of environmental and health concerns. There is increasing concern for ammonia emissions from poultry facilities contributing to the known detrimental effects on the environmental, human and animal health. Emissions of ammonia and particulate matter are different for high-rise, manure-belt, and cage-free layer facilities (Green et al., 2007). It is important to study the emissions from various animal feeding
operations to understand the relationship of climate, location, management strategies on emissions, and to further develop mitigation strategies to reduce the environmental impact of animal feeding operations.

2.2.1 Ammonia

Gaseous ammonia (NH$_3$) is a colourless gas with a pungent odour that is primarily generated and emitted from livestock operations resulting from waste management and fertilizer production (Environment and Climate Change Canada, 2013). The odour of ammonia is pungent and noticeable at concentrations above 50 ppm (Phillips, 1995). NH$_3$ is formed through the degradation of uric acid and undigested proteins. High protein diets exceed the storage mechanisms for amino acids in chickens, causing excess amino acids to be deaminated deriving nitrogen (Maliselo et al., 2015) which is excreted primarily as uric acid and undigested proteins (70 and 30% respectively) (Groot Koerkamp et al., 1998b). Enzymes uricase and urease, which are formed through microbial degradation in poultry excreta, readily convert uric acid to ammonia through a series of chain reactions (Maliselo et al., 2015). The first step in the production of NH$_3$ is the hydrolysis of uric acid by microbial uricase (Kim et al., 2003).

\[
2C_5H_4N_4O_3 + 2H_2O + O_2 \xrightarrow{uricase} 2C_4N_2H_2O_4 + 2CH_4N_2O
\]

The products of this first reaction are alloxan/mesoxalyl urea (C$_4$N$_2$H$_2$O$_4$) and urea (CH$_4$N$_2$O). The next step in ammonia gas formation is further microbial degradation into NH$_3$ and carbon dioxide (CO$_2$) by urease and other uricolytic enzymes.

\[
CH_4N_2O + H_2O \xrightarrow{urease} 2NH_3 + CO_2
\]

Gaseous ammonia can also be produced through volatilization when ammonium (NH$_4^+$) is present in manure or litter. NH$_4^+$ is converted to dissolved ammonia gas through the following chemical process (Meisinger et al., 2000):

\[
NH_4^+(aq) \leftrightarrow NH_3(aq) + H^+
\]
This chemical process is highly pH and temperature dependent. Higher pH levels will shift the equilibrium equation towards the right hand side of the above equation resulting in greater NH₃ formation, while lower pH levels will shift the equilibrium left. The effect of pH and temperatures on this chemical process is illustrated in Figure 4 below:

![Figure 4: Effect of pH and temperature on the NH₃(aq) and NH₄⁺(aq) equilibrium reaction (Behera et al., 2013)](image)

The temperature has a quickening effect on the formation of NH₃ in relation to pH. At lower temperatures (15°C) the equilibrium is shifted to the right at higher pH values (pH greater than 9), whereas at higher temperatures (25-35 °C) the equilibrium is shifted right at lower pH values (pH greater than 8). This infers that at higher temperatures, greater quantities of NH₃ will form at the same pH. Figure 4 also depicts how a small change in pH can result in much greater quantities of aqueous NH₃. A change from a pH of 8 to 9 will cause significant production of NH₃, whereas a pH below 7 will result in almost all ammonia bound as NH₄⁺ (Groot Koerkamp, 1994).

Gaseous ammonia is dependent on the partial pressure of gaseous ammonia and is directly proportional to the concentration of ammonia in the liquid phase (Groot Koerkamp, 1994). Henry’s law governs the equilibrium reaction for the volatilization of ammonia from the liquid phase:

\[ \text{NH}_3(aq) \leftrightarrow \text{NH}_3(g) \]
Factors that influence the formation of gaseous ammonia from poultry manure and litter include: high concentrations of ammonium (NH$_4^+$), elevated temperatures and humidity in the air, and elevated moisture content and pH in the manure/litter (Meisinger et al., 2000). As seen in the equations above, water is a reactant required in both step processes for NH$_3$ formation, thus higher moisture contents in the manure results in greater NH$_3$ formation. If manure can achieve 60% dry matter content within the first 50 hours, ammonia emissions can be minimized (Groot Koerkamp et al., 1998a). Favorable conditions for microbial activity are temperatures ranging between 20 – 30 °C (Groot Koerkamp et al., 1998a) and pH levels ranging from 8-13 (Maliselo et al., 2015).

NH$_3$ gas is well known for its negative impacts on the environment, human health, and bird health. NH$_3$ is classified as a toxic substance under the Canadian Environmental Protection Act 1999, in the form of gas and as ammonia dissolved in water (CEPA, 2018). The short-term exposure limit for gaseous NH$_3$ is 35 ppm for 15 minutes of exposure and the permissible average exposure limit over an 8-hour work day is 25 ppm as defined by the Ontario Ministry of Labor (Ministry of Labour, 2018). Elevated concentrations of ammonia have been found to reduce feed efficiency, growth rate and egg production (Charles et al., 1966; Reece et al., 1983), damage the respiratory tract (Ritz et al., 2004) and impair immune response (Maliselo et al., 2015). NH$_3$ is poisonous if inhaled in copious amounts and is an irritant to the eyes, nose and throat in smaller quantities (Phillips, 1995). Birds can detect gaseous ammonia as low as 5 ppm and is considered harmful when exceeding 20-25 ppm (mass per volume) (National Farm Animal Care Council, 2017).

NH$_3$ emissions are a growing environmental concern. Gaseous ammonia is quickly transformed after atmospheric releases due to its reactive nature. It can readily undergo chemical reactions to form secondary aerosols and ammonium salts such as ammonium sulfate and ammonium nitrate (Krupa, 2003). It is then transported by winds and returns to the surface through wet and dry deposition (Behera et al., 2013), which can cause eutrophication and nutrient loading (Greber et al., 2007). In addition, a great concern of atmospheric ammonia emissions is that it is a primary precursor for PM$_{2.5}$ which is a respiratory irritant (US EPA, 2001).
Methods used to reduce ammonia emissions from AFO’s can be of high expense, can impair bird growth, or add other forms of pollution. These methods include: dietary manipulation, chemical amendment to the litter, and improvement to ventilation system such as scrubbers (Singh et al., 2009). Further research will improve the accuracy of characterizing sources which will contribute to effectively assessing mitigation strategies for ammonia emissions (Faulkner and Shaw, 2008).

### 2.2.2 Particulate Matter

Particulate matter is composed of a mixture of solid and liquid droplets suspended in air. It is emitted directly to air from cars, homes, fires, agricultural practices, waste burning, smoking and industrial practices (Environment and Climate Change Canada, 2017). Fine particulate matter is one of the major contributors of smog. It can cause adverse health effects in humans and animals, as well as cause damage to vegetation, contribute to haze and reduced visibility (Environment and Climate Change Canada, 2017). In 2014, the average ambient concentration of PM$_{2.5}$ in Southern Ontario was measured at 8.3 μg/m$^3$ (Environment and Climate Change Canada, 2017).

Particulate matter can be found as various compositions such as acids, metals, soot, smoke, organic chemicals and dust particles. The size of PM determines the extent of environmental and health risk associated with exposure. There are three size categories of PM denoted by Environment Canada based on their associated risk (Environment Canada, 2013): Total Particulate Matter (TPM) refers to airborne particulate matter with an upper size limit of 100 μm in aerodynamic diameter. Particulate Matter < 10 microns (PM$_{10}$) refers to airborne particulate matter with an aerodynamic diameter less than 10 μm. Particulate Matter < 2.5 microns (PM$_{2.5}$) refers to airborne particulate matter with an aerodynamic diameter less than 2.5 μm. Working in areas with high concentrations of airborne particulates can cause adverse health effects. The primary and most significant exposure pathway of particulates is through inhalation.

Particulate matter present in poultry housing facilities is primarily organic or biological in nature. The concentration of PM suspended in air is dependent on a variety of factors including temperature, relatively humidity, species, number of birds, age of birds, type of housing, manure
cycle, type of feed, and number of air exchanges within the barn (Green et al., 2007). Particulate matter in animal housing is a mixture of airborne particles of feed, feces, dander, feathers, and hair (Donham et al., 2002). The concentration of PM is usually higher in colder seasons when ventilation of the facility is minimized. PM is often suspended in air through agitation of the litter and manure caused by animal, human, ventilation or mechanical activity (Wood et al., 2015). Trends of lower concentrations of PM are generally found at nighttime due to the lower activity level of the birds (Wood et al., 2015). High air temperatures and lower relative humidity is known to increase concentrations of microorganisms in the air (Jerez et al., 2014).

Particulate matter can harm the respiratory tract of poultry and also act as a pathway for the transmission of infectious agents (National Farm Animal Care Council, 2017). Odours, acids and other contaminants can attach to airborne particulates (Ministry of Agriculture and Food, 1999), which can cause added health effects when inhaled.

Short term and long term exposure to particulate matter can cause adverse health effects including: asthma, chronic bronchitis, irritation to the airway, decreased respiratory function, higher chance of lung cancer, and premature death to individuals with history of lung or heart disease (Viegas, et al., 2013). In Ontario, an occupational exposure limit has been set under Regulation 833 control of exposure to biological or chemical agents for particulates. Two standards have been identified, one for the inhalable fraction of particulates at 10 mg/m$^3$, and the other for the respirable fraction of particulates at 3 mg/m$^3$ (Ontario Ministry of Labour, 2015). The inhalable fraction refers to PM$_{10}$ and the respirable fraction refers to PM$_{2.5}$. The standards are based on a time-weighted average over an 8 hour work day. The standards are only relevant for indoor human exposure.

2.3 Emission Factors

An emission factor relates the quantity of a pollutant released to the atmosphere with an activity associated with that release. Emission factors are generally related to a unit weight, volume, distance, or duration (US EPA, 1995).
Animal feeding operations can emit a variety of pollutants. In the United States, the Environmental Protection Agency (EPA) regulates a permit program for discharge of pollutants to water through the Clean Water Act’s National Pollutant Discharge Elimination System permit program. However, there still lack any AFO-specific standards under the Clean Air Act (CAA). In the late 1990’s, the Environmental Protection Agency recognized insufficient air emissions data that would allow for reliable emission estimating methodologies (US EPA, 2017). In 2001, the EPA and United States Department of Agriculture (USDA) released a draft for estimating emissions from AFO’s. In 2003, the NAS (National Academy of Sciences) reported that accurate AFO emissions were required to determine impacts, and control strategies. This initiated a volunteer based emissions monitoring study in 2005 by the EPA and USDA. AFO’s could apply to estimate their emissions over the duration of a 2-year study to determine the applicability of CAA permitting under the National Air Emissions Monitoring Study (NAEMS) program (US EPA, 2017). The goal of the study was to allow AFO’s to collect emissions from a variety of AFO’s to develop emission estimating methodologies (EEM). Participating AFO’s were requested to collect other measurements such as meteorological data, the type of facility and manure management practices.

The quantity and type of emission is highly dependent on the type of facility, feeding regiment, type of manure management system, and the method of land application (US EPA, 2001). Emission factors were developed by regulatory agencies to estimate pollutant emissions from specific sources (Faulkner & Shaw, 2008) while accounting for differences in animal production methods (US EPA, 2001).

Livestock emission factors are based on average emissions, in terms of mass of pollutant emitted per time per unit of live mass (animal unit (AU), equivalent to 500 kg of live mass) regardless of the type of housing facility (Faulkner and Shaw, 2008). For NH$_3$ from poultry operations, the emission factors ($EF_{NH3}$; g day$^{-1}$ AU$^{-1}$) were calculated as:

$$EF_{NH3} = \left[ Q \left( \frac{PM_w}{R(273 + T)} \right) (C_i - C_o) \right] \times \frac{500kg}{AU}$$
where $Q$ is the total exhaust ventilation rate of the facility ($m^3 \ day^{-1}$), $P$ is the barometric pressure (Pa), $M_w$ is the molecular weight of NH$_3$ (g/mol), $R$ is the universal gas constant (Pa $m^3$ mol$^{-1}$ K$^{-1}$), $T$ is the indoor temperature (°C), $M$ is the combined total mass of the birds in the house (kg), $C_i$ is the indoor concentration of ammonia (ppm) and $C_o$ is the ambient concentration of ammonia (ppm) (Wood et al., 2015).

For PM$_{2.5}$ and PM$_{10}$ from poultry operations, the emission factors ($EF_{PM}$; g day$^{-1}$ AU$^{-1}$ were) calculated as:

$$EF_{PM} = Q(C_i - C_o) \times \frac{500kg}{AU}$$

Where, $Q$ is the total exhaust ventilation rate of the facility ($m^3 \ day^{-1}$), $C_i$ is the indoor concentration of Particulate matter (PM$_{2.5}$ or PM$_{10}$) (g/m$^3$) and $C_o$ is the ambient concentration of particulate matter (g/m$^3$).

To acquire the average emission factor for the facility, emission factors were developed with a 5 minute resolution and averaged as shown below:

$$EF = \frac{\sum \left( Q \left( \frac{PM_w}{R(273 + T)} \right) (C_i - C_o) \right)}{n} \times \frac{500kg}{AU}$$

Where, the flow rate, concentration, temperature, pressure and bird mass taken every 5 minutes were transformed into an emission factor, summed and divided by $n$, which is equivalent to the number of data points.

### 2.3.1 Review of cases

Many studies have focused on developing emission factors for NH$_3$, PM$_{2.5}$ and PM$_{10}$ for poultry operations in Europe and North America. Table 1 below summarizes NH$_3$ emission factors found in literature for conventional battery cage and cage-free layer facilities. Table 2 below summarizes the size fractioned particulate matter emission factors (PM$_{2.5}$, PM$_{10}$ and Total suspended particles (TSP)) found in literature for conventional battery cage and cage-free layer facilities.
facilities. Table 2 reflects the same references illustrated in Table 1. Study duration, ventilation measurement method and test data ratings in Table 1 are applicable to the studies examined in Table 2.
Table 1: NH₃ emission factors for laying hens reported in literature (adapted from Wood et al., 2015)

<table>
<thead>
<tr>
<th>Source</th>
<th>Location</th>
<th>Housing type/manure management</th>
<th>Duration</th>
<th>NH₃ measurement method</th>
<th>Ventilation measurement method</th>
<th>Emission Factor (g day⁻¹ AU⁻¹, AU = 500 kg)</th>
<th>Test data rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laying hen facilities – conventional battery cage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heber et al., 2005</td>
<td>United States (IN)</td>
<td>High rise/Deep pit</td>
<td>15 month sampling campaign</td>
<td>Chemiluminescent Analyzer</td>
<td>Static pressure sensors, impellor anemometers and FANS Numeration System (FANS)</td>
<td>278 ± 34</td>
<td>A</td>
</tr>
<tr>
<td>Heber et al., 2005</td>
<td>United States (IN)</td>
<td>High rise/Deep pit</td>
<td>15 month sampling period (Dec 8, 2002 – March 8, 2004)</td>
<td>Chemiluminescent Analyzer</td>
<td>Static pressure sensors, impellor anemometers and FANS Numeration System (FANS)</td>
<td>298 ± 44</td>
<td>A</td>
</tr>
<tr>
<td>Lin et al., 2012</td>
<td>United States (CA)</td>
<td>High rise (Manure was scraped off dropping boards under the cages into the first floor, where it was stored for six months prior to removal)</td>
<td>October 2007 – October 2009</td>
<td>Photoacoustic (INNOVA model 1412)</td>
<td>Static pressure sensor, fan rotational speed sensor (magnetic proximity sensor) and FANS</td>
<td>287 ± 20</td>
<td>B</td>
</tr>
<tr>
<td>Liang et al., 2005</td>
<td>United States (IA and PA)</td>
<td>High rise/Deep pit (encompasses data from 6 different facilities)</td>
<td>48 h of continuous measurements performed weekly (IA) of every three weeks (PA) for a year</td>
<td>PMU – Electrochemical sensor</td>
<td>CO₂ balance</td>
<td>298 ± 34</td>
<td>D</td>
</tr>
<tr>
<td>Wang-Li et al., 2013</td>
<td>United States (NC) house 3</td>
<td>High rise/deep pit</td>
<td>Continuous monitoring across two production cycles from Sept 24, 2007 – Dec 31 2009</td>
<td>Photoacoustic (INNOVA model 1412)</td>
<td>Static pressure sensor, fan speed sensor, and FANS</td>
<td>197 ± 66</td>
<td>B</td>
</tr>
<tr>
<td>Wang-Li et al., 2013</td>
<td>United States (NC) house 4</td>
<td>High rise/deep pit</td>
<td>Continuous monitoring across two production cycles from Sept 24, 2007 – Dec 31 2009</td>
<td>Photoacoustic (INNOVA model 1412)</td>
<td>Static pressure sensor, fan speed sensor, and FANS</td>
<td>197 ± 82</td>
<td>B</td>
</tr>
<tr>
<td>Liang et al., 2005</td>
<td>United States (IA)</td>
<td>Manure belt (Daily Cleaning)</td>
<td>48 h or longer of continuous measurements performed bi-weekly or weekly for a year</td>
<td>PMU – Electrochemical sensor</td>
<td>CO₂ balance</td>
<td>17.6 ± 1.5</td>
<td>D</td>
</tr>
<tr>
<td>Liang et al., 2005</td>
<td>United States (PA)</td>
<td>Manure belt (Twice a week)</td>
<td>48 h or longer of continuous measurements performed every three weeks for a year</td>
<td>PMU – Electrochemical sensor</td>
<td>CO₂ balance</td>
<td>30.8 ± 5.9</td>
<td>D</td>
</tr>
<tr>
<td>Morgan et al., 2014</td>
<td>Canada (ON)</td>
<td>Manure belt (Twice a week)</td>
<td>Continuous monitoring Nov 26, 2010 – Sept 12, 2011</td>
<td>Chemiluminescent Analyzer</td>
<td>Static pressure sensor, fan stage monitor and FANS</td>
<td>19.5 ± 20</td>
<td>A</td>
</tr>
<tr>
<td>Laying hen facilities – alternative housing</td>
<td></td>
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</tr>
<tr>
<td>Hayes et al., 2013</td>
<td>United States (IA)</td>
<td>Aviary/Manure belt (Twice weekly)</td>
<td>June 2010 – December 2011</td>
<td>Photoacoustic (INNOVA, Model 1412)</td>
<td>Static pressure sensor, fan stage monitor and FANS</td>
<td>41 ± 23</td>
<td>B</td>
</tr>
<tr>
<td>Lin et al., 2017</td>
<td>United States (CA)</td>
<td>Cage-free/Manure belt (Twice weekly)</td>
<td>January 3, 2012 – January 4, 2013</td>
<td>Photoacoustic (INNOVA, Model 1412)</td>
<td>Static pressure sensor, fan current sensor and FANS</td>
<td>83.3 ± 67</td>
<td>B</td>
</tr>
</tbody>
</table>

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a The uncertainty provided in the listed EFs is one standard deviation as described in each individual study.

b The EF reported is the overall average from all six facilities included in the study.

c The studies were added to a table adapted from Wood et al. (2015).
<table>
<thead>
<tr>
<th>Reference</th>
<th>Location</th>
<th>Housing type/manure management type</th>
<th>PM measurement method</th>
<th>Emission Factor (g day⁻¹ AU⁻¹ AU = 500 kg)¹</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Laying hen facilities – conventional batter cage</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Heber et al., 2005</td>
<td>United States (IN)</td>
<td>High rise/deep pit</td>
<td>Tapered Element Oscillating Microbalance (TEOM) ambient PM₁₀ monitors (Model 1400a Rupprecht &amp; Patashnick, Albany, NY)</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2878 ± 334</td>
</tr>
<tr>
<td>Heber et al., 2005</td>
<td>United States (IN)</td>
<td>High rise/deep pit</td>
<td>Tapered Element Oscillating Microbalance (TEOM) ambient PM₁₀ monitors (Model 1400a Rupprecht &amp; Patashnick, Albany, NY)</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3489 ± 501</td>
</tr>
<tr>
<td>Lin et al., 2012</td>
<td>United States (CA)</td>
<td>High rise (Manure was scraped off dropping boards under the cages into the first floor, where it was stored for six months prior to removal)</td>
<td>Tapered Element Oscillating Microbalance (TEOM Model 1400a, Thermo Environmental Instruments, Franklin, MA)</td>
<td>2.1 ± 4.5</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>10.5 ± 9.1</td>
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<td></td>
<td></td>
<td></td>
<td>23.8 ± 14.2</td>
</tr>
<tr>
<td>Liang et al., 2005</td>
<td>United States (IA and PA)</td>
<td>High rise/Deep pit (encompasses data from 6 different facilities)</td>
<td>N/A</td>
<td>N/A</td>
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<td></td>
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<td></td>
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<td>N/A</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>Li et al., 2013b</td>
<td>United States (NC) house 3</td>
<td>High rise/deep pit</td>
<td>Beta attenuation PM monitor (model FH62C-14 beta gauge, Thermo Fisher Scientific, Franklin, MA.) &amp; Tapered Element Oscillating Microbalance (TEOM Model 1400a, Thermo Environmental Instruments, Franklin, MA)</td>
<td>0.09 ± 0.27</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.4 ± 2.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>13 ± 5.6</td>
</tr>
<tr>
<td>Li et al., 2013b</td>
<td>United States (NC) house 4</td>
<td>High rise/deep pit</td>
<td>Beta attenuation PM monitor (model FH62C-14 beta gauge, Thermo Fisher Scientific, Franklin, MA.) &amp; Tapered Element Oscillating Microbalance (TEOM Model 1400a, Thermo Environmental Instruments, Franklin, MA)</td>
<td>0.14 ± 0.25</td>
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<td></td>
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<td></td>
<td></td>
<td>6.67 ± 2.81</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15.4 ± 4.68</td>
</tr>
<tr>
<td>Morgan et al., 2014</td>
<td>Canada (ON)</td>
<td>Manure belt (Twice a week)</td>
<td>DustTrak aerosol analyzer (Model 8520, TSI Incorporated, Shoreview, MN, USA)</td>
<td>1.10 ± 1.52</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.55 ± 2.10</td>
</tr>
<tr>
<td><strong>Laying hen facilities – alternative housing</strong></td>
<td></td>
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</tr>
<tr>
<td>Hayes et al., 2013</td>
<td>United States (IA)</td>
<td>Aviary/Manure belt (Twice weekly)</td>
<td>Tapered element oscillating microbalances (TEOM) (model 1400a, Thermo Fisher Scientific, Walham, MA.)</td>
<td>2.1 ± 1.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>29.5 ± 11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>Lin et al., 2017</td>
<td>United States (CA)</td>
<td>Cage-free/Manure belt (Twice weekly)</td>
<td>Beta Gage monitor (Model FH62 C-14, Thermo Environmental Instruments, Franklin, MA)</td>
<td>5.5 ± 3.8</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>47.2 ± 17.9</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
</tbody>
</table>

a The uncertainty provided in the listed EFs is one standard deviation as described in each individual study
b Li et al., 2013 study was Part II of National Air Emissions Monitoring Study’s Southeast Layer Site, which accompanies the Wang-Li et al., 2013 study in Table 1.
Table 1 above illustrates that HR with deep pit manure storage had much higher NH$_3$ emission factors than those with MB removal. Furthermore, the cage-free systems had higher emissions of NH$_3$ than the conventional battery cage facilities with manure belt management, but lower emissions than the HR facilities. This is a result of the emission reported from the HR facilities to encompass both the emissions from the birds, and the storage of manure. In manure belt facilities, the overall emissions do not take into account the emissions from a manure belt house.

Particulate matter emissions reported in literature, shown in Table 2, demonstrate that HR with deep pit manure storage had greater emissions of PM$_{10}$ than those using MB removal. This is attributed to the dry manure that is stored beneath the pen floors. MB removal however, had greater emissions of PM$_{2.5}$ than the HR houses from the study by Li et al. (2013a, 2013b), but lower than the HR house from the study by Lin et al. (2012). The alternative housing layer facilities had greater emissions of PM$_{2.5}$ and PM$_{10}$, than both the MB and HR battery cage facilities.

### 2.4 Monitoring Equipment

#### 2.4.1 Instrumentation

There are a variety of monitoring methods used to quantify aerial pollutants and facility ventilation rates. Data collection from animal feeding operations is a complex process as it involves many factors. Type of facility, management system, type of animal, climatic conditions and location can influence the type of equipment necessary for accurate monitoring. Certain conditions require different measurement techniques. It is important to develop emission factors from various AFO’s using varying equipment to truly develop representative emissions from these sources. The following section outlines a few of the most common monitoring equipment used in research and details the equipment used in this study and in studies of a similar nature.
2.4.1.1 Ammonia Analysis

Common ammonia measurement techniques used in animal feeding operations and their associated relative accuracies are shown in Table 3. The table produced by Wood et al. (2015) highlights 15 monitoring techniques used world-wide to quantify NH$_3$ emissions from AFO’s.
Table 3: Measurement techniques for ammonia gas in animal feeding operations (Wood, et al., 2015)

<table>
<thead>
<tr>
<th>Measurement technology</th>
<th>Relative Accuracy (%)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermo Electron Corp. 17C – Chemiluminescent Analyzer</td>
<td>3.7-13</td>
<td>Mennen et al., 1996</td>
</tr>
<tr>
<td>Portable monitoring unit (PMU)</td>
<td>1.7 (As compared to Chemiluminescent analyzer)</td>
<td>Xin et al., 2002 |</td>
</tr>
<tr>
<td>Continuous Flow Denuder</td>
<td>1.2-4</td>
<td>Mennen et al., 1996</td>
</tr>
<tr>
<td>Thermodenuder (V₂O₅ or WO₃)</td>
<td>2-28</td>
<td>Mennen et al., 1996</td>
</tr>
<tr>
<td>Citric acid coated diffusion Denuder</td>
<td>4-103 (As compared to Chemiluminescent analyzer)</td>
<td>Mennen et al., 1996</td>
</tr>
<tr>
<td>Photoacoustic analyzer (KEMA)</td>
<td>81</td>
<td>Mennen et al., 1996</td>
</tr>
<tr>
<td>Aerodyne research Inc. QC-TILDAS – infrared laser spectrometer</td>
<td>4.7-10</td>
<td>US EPA, 2004a</td>
</tr>
<tr>
<td>Bruker Daltonics OPAG 22 open-path gas analyzer – Fourier transform infrared spectrometer</td>
<td>26</td>
<td>US EPA, 2004b</td>
</tr>
<tr>
<td>Molecular analytics IonPro-IMSAmmonia analyzer – ion mobility spectrometer</td>
<td>18.3</td>
<td>US EPA, 2004d</td>
</tr>
<tr>
<td>Omnisens SA TGA310 ammonia analyzer photoacoustic spectrometer</td>
<td>2.2</td>
<td>US EPA, 2004e</td>
</tr>
<tr>
<td>Pranalytica, Inc. NitroluxTM 1000 ambient ammonia analyzer e Resonant photoacoustic spectrometer</td>
<td>10-44</td>
<td>US EPA, 2004f</td>
</tr>
<tr>
<td>Mechatronics instruments BV AIRRmonia ammonia analyzer e membrane diffusion sampler</td>
<td>2.4-34</td>
<td>US EPA, 2004c</td>
</tr>
<tr>
<td>Electrochemical sensors (Dräger/environmental Sensors Inc.)</td>
<td>3-10</td>
<td>Hale et al., 2010</td>
</tr>
<tr>
<td>Colorimetric pull tube (Gastec/RAE Systems)</td>
<td>25</td>
<td>Hale et al., 2010</td>
</tr>
<tr>
<td>Passive flux sampler</td>
<td>20-25</td>
<td>Mosquera et al., 2005</td>
</tr>
</tbody>
</table>

<sup>a</sup> The relative accuracy is the percent deviation from the reference method used in each study, the reference methods were not the same in all studies.
Determining NH₃ emissions from AFO’s require continuous or semi-continuous monitoring of ambient concentrations with good sensitivity and wide dynamic measurable ranges (Li et al., 2015). Budget often puts limitations on accessibility of equipment and the ability to monitor multiple sample points (Wood et al., 2015). NH₃ can vary within a facility due to non-uniform air exchanges, and sources such as manure storage or litter accumulation therefore, it is crucial to choose the most representative location for measurement especially if only one sampling location is used (Gates et al., 2005).

The following section describes the three NH₃ measurement technologies used in the studies presented in Table 1. The three technologies that were repeatedly used were the Photoacoustic (INNOVA Model 1412) sensor, the Portable Measurement Unit (PMU) Electrochemical (EC) sensor (PAC III H, Dräger Safety) and the Thermo Electron Corporation 17C – Chemiluminescent Analyzer. The Thermo Electron Corporation 17C – Chemiluminescent Analyzer was the monitoring technique used in this study, and therefore more emphasis will be placed on the details of this technology.

Photoacoustic gas monitors are a fast-response high precision analyzer. The system measures gas concentration by measuring the effects of light absorption and converting light absorbance to acoustic signals (Li et al., 2015). These systems are able to measure any gas that absorbs infrared light. The INNOVA 1412 can measure up to five gases, water vapour and temperature. The system can compensate for temperature and pressure fluctuations, and interference from water vapour and other known gases to be present (LumaSense Technologies, 2007).

An infrared light source is reflected off of a mirror and then passed through a mechanical chopper wheel which modulates the light source. It is then passed through the optical filter in the filter wheel which removes all wavelengths other than the characteristic wavelength of the target gas. In the analysis cell, the target gas absorbs the light transmitted through the optical filter which energizes the molecules and, as a result, dissipates heat to increase the temperature. The chopper wheel, which pulsates the light, causes the temperature to increase and decrease periodically. This creates an equivalent increase and decrease in the gas pressure in the analysis cell (acoustic signal). Two microphones mounted within the analysis cell wall measure the
acoustic signal then convert it to an electrical signal which is directly proportional to the concentration of the target gas. The filter wheel can turn to allow passage of light through the next optical filter associated to a new target gas. This process is repeated as necessary depending on number of different gases. The photoacoustic Field Gas-Monitor has a NH$_3$ detection limit of 0.2 ppm at 20°C and 1 atm (LumaSense Technologies, 2011).

Portable Measurement Units (PMU) Electrochemical (EC) sensor are commonly used due to their long life span, low cost and reasonable measurement of NH$_3$ (Gates, et al., 2005). Generally they are used if data is collected from multiple poultry houses at one time, as they are portable and relatively inexpensive. The EC sensors are designed to monitor background NH$_3$ concentrations, where little to no NH$_3$ is present, and thus have a tendency to saturate when exposed to elevated levels of NH$_3$ (Xin, et al., 2002). The EC sensors require a zero gas to be used to rejuvenate the sensor, this is referred to as purging (Dräger Safety, 2009). Nitrogen (N$_2$) is used as a zero gas but ambient outdoor air is common during a field study. The ratio of monitoring NH$_3$ and purging depends on the type of gas used for purging and the range of NH$_3$ concentrations being monitored. Commonly these sensors can only be used on the extent of minutes and then purging must occur for a greater duration. The PAC III H PMU’s used in the case-studies shown in Table 1, (Dräger Safety, Inc., Pittsburgh, Pa.) have a measuring range of 0-200 ppm with a resolution of ± 1 ppm and an accuracy of ± 3 ppm (Dräger Safety, 2009). Gas enters the sensor and undergoes a chemical reaction causing a change in electrical output. The sensor is filled with an electrolyte gel specific to the target gas causing a reaction. The electrical output is proportional to the concentration of the target gas. PMU’s can be used with a variety of EC sensors encompassing over 30 gases. The life of an EC sensor is dependent on the exposure time and concentration to the gas. Once the sensor has reached the end of its operational life, a new sensor can easily be replaced in the PMU.

The Thermo Electron Corporation 17C – Chemiluminescence Analyzer is a high accuracy advanced system used to monitor gases in air. The 17C – Chemiluminescence Analyzer is capable of outputting concentrations of nitric oxide (NO), nitrogen dioxide (NO$_2$), nitrogen oxides (NO$_x$), total nitrogen (N$_t$) and ammonia (NH$_3$). The analyzer uses a reaction of nitric oxide (NO) with ozone (O$_3$) to produce light intensity.
\[ \text{NO} + \text{O}_3 \rightarrow \text{NO}_2 + \text{O}_2 + h\nu \]

An external pump draws sample air to the analyzer. The sample air mixes with O\textsubscript{3}, generated by the internal ozonator, in the reaction chamber. The reaction chamber is maintained at 50 °C to ensure instrument stability. The ozone is produced in excess in the internal component to ensure it is not the limiting reagent. Outside air is drawn to the ozonator through a drying column filled with desiccant drierite. This ensures the air supply is dry. This reaction produces a characteristic luminescence \((h\nu)\) with intensity proportional to the concentration of NO. Light emissions are detected photometrically from the decay of energized NO\textsubscript{2} molecules to lower energy states. The photomultiplier tube generates an electrical signal which is processed into a NO concentration read by the microcomputer. The sample air must be entirely transformed into NO for this reaction to be effective. To do this, the sample air initially enters a converter module prior to reaching the analyzer module where the reaction chamber is situated. A flow schematic of the 17C – Chemiluminescence Analyzer is shown in Figure 5 below.

**Figure 5: 17C – Chemiluminescence Analyzer flow schematic (Thermo Electron Corporation, 2004)**

Sample flow is directed through a converter module which reduces both NH\textsubscript{3} and NO\textsubscript{2} into NO. The converter module is divided into three pathways towards the analyzer module. The three pathways consist of the NO, NO\textsubscript{x} (NO + NO\textsubscript{2}) and N\textsubscript{t} (NO + NO\textsubscript{2} + NH\textsubscript{3}). The NO in the sample
air passes through a capillary which maintains a constant flow, to an NH\textsubscript{3} scrubber which removes any residual NH\textsubscript{3}, then reaches the reaction chamber where it reacts with O\textsubscript{3}. The resulting signal represents the NO in the sample air. The NO\textsubscript{x} in the sample air passes through a capillary, through an NH\textsubscript{3} scrubber, to a molybdenum converter maintained at 325 °C. The NO\textsubscript{2} reacts with the molybdenum and is converted into NO. The original NO and the converted molecules pass into the reaction chamber where it reacts with O\textsubscript{3}. The resulting signal generated by the photomultiplier represents the NO\textsubscript{x} in the sample intake. The N\textsubscript{i} in the sample intake passes through a capillary, to a stainless-steel converter heated to 750°C. Within this converter NO\textsubscript{2} and NH\textsubscript{3} are converted into NO molecules. Lastly, the sample air passes through the NH\textsubscript{3} scrubber to ensure any remaining NH\textsubscript{3} residuals are removed. The original NO and the converted molecules pass into the reaction chamber where it reacts with O\textsubscript{3}. The resulting signal represents the N\textsubscript{i} in the sample intake. The capillary is used to maintain a constant flow through all three pathways.

The information stored from the 17C – Chemiluminescence Analyzer produces three analog outputs, NO, NO\textsubscript{x} and N\textsubscript{i}. Two equations can be used to manipulate the data output into NO\textsubscript{2} and NH\textsubscript{3} concentrations. The two calculations are shown in the equations below.

\[
\textit{NO}_x - \textit{NO} = \textit{NO}_2
\]

\[
\textit{N}_t + \textit{NO}_x = \textit{NH}_3
\]

The 17C – Chemiluminescence Analyzer must be operated in a climate-controlled setting. The analyzer is sensitive to temperature and must be operated in an ambient environment within 15° – 35°C. The analyzer has a lower detection limit of 0.001 ppm, and can handle extended ranges up to 0 – 100 ppm (Thermo Electron Corporation, 2004). The ability to monitor ranges of this size while maintaining high accuracy is advantageous, as it can be applied to a variety of conditions.
2.4.1.2 Particulate Matter Analysis

Monitoring particulate matter concentrations can be a challenging task due to the range in size of particles. Techniques are often selected based on the aerodynamic diameter of the particulate desired to quantify. The following section describes the three PM measurement technologies used in the studies presented in Table 2. The three technologies that were used recurrently were the Tapered Element Oscillating Microbalance (TEOM Model 1400a, Thermo Environmental Instruments, Franklin, MA), the Beta attenuation PM monitor (model FH62C-14 beta gauge, Thermo Fisher Scientific, Franklin, MA) and the DustTrak aerosol analyzer (Model 8520, TSI Incorporated, Shoreview, MN, USA). The DustTrak DRX aerosol analyzer (Model 8534, TSI Incorporated, Shoreview, MN, USA) was the monitoring technique used in this study, and therefore more emphasis will focus on the details of this technology. The DustTrak DRX (Model 8534) is a newer handheld version of the DustTrak (Model 8520) used in the study performed by Morgan et al. (2014) and therefore the DustTrak DRX (Model 8534) will be described.

Tapered Element Oscillating Microbalance referred to as a TEOM system is a real-time mass monitoring system. It measures mass collected on a sample filter directly, whereas optical particulate counters (OPC) and Beta attenuation monitors make inferred measurements of particulate mass. Since the TEOM measures mass directly, readings can be affected by factors such as chemical composition, size of particulate and relative humidity (Ruppercht et al., 1992). The filter-based monitor uses an inertial mass transducer patented by Rupprecht & Papashnick Co., Inc.

The sample air is drawn through the PM$_{10}$ inlet at 16.67 L/min (Thermo Fisher Scientific Inc., 2007). The collection filter is attached to an inertial mass transducer and TEOM sensor. The filter is weighed continuously as matter is accumulated on the filter. The tapered element oscillates at a frequency based on the physical properties of the tapered tube and the mass of the free end. The vibrations will decrease as more particulate accumulates on the filter. A frequency counter measures the oscillation frequency through positive feedback and provides its output to the microprocessor. The oscillation is monitored and automatically maintained at a constant amplitude despite the change in mass. The air passing through the TEOM, and the filter is
maintained at 50°C to reduce condensation and moisture build up, thus standardizing weighing conditions despite ambient conditions (Patashnick et al., 1991).

A beta attenuation PM monitor (model FH62C-14 beta gauge, Thermo Fisher Scientific, Franklin, MA) is real-time monitoring system with a measuring range of 0 – 5000 µg/m³ (Thermo Electron Corporation, 2002). Particulate matter is accumulated on a moveable filter tape and beta particles are passed through using a Carbon-14 (C₁⁴) source. C₁⁴ is commonly used as it has a high enough energy level to allow for the beta particles to pass through the air, filter and particulate as well as the facts that C₁⁴ is safe, abundant and has a half-life of 5,568 years (Thermo Fisher Scientific, 2018). A baseline beta count through an empty filter is measured prior to collection. Thus, as the beta particles are absorbed by the particulate matter, the difference between the beta count and the beta baseline is determined. This difference is directly proportional to the mass of PM in the sample. The chamber for particulate collection and measurement lies between the source and the filter.

Optical particulate counters (OPC) use light scattering techniques to illuminate a sample of particulate to capture the overall number of particles and convert the number of particles to mass of particulate in the sample. An example of an OPC is the DustTrak II DRX Aerosol Monitor, which uses a 90° light scattering sensor to determine mass concentrations of particulate. The DustTrak II DRX Aerosol Monitor (Model 8532) is a single channel photometric instrument used to determine the mass concentration of aerosols in air. The handheld unit is capable of real-time monitoring of particulates, reading concentrations up to 150 mg/m³ with a resolution of ±0.1% of reading or 0.001 mg/m³ (TSI Incorporated, 2012). The DustTrak DRX systems can detect, measure and output mass concentrations in mg/m³ of PM₁, PM₂.₅, PM₄, PM₁₀ and total suspended particulates (TSP). The system is capable of real-time monitoring. Figure 6 below depicts the flow schematic for the handheld DustTrak.
Sample air is drawn into the DustTrak through the aerosol inlet using a diaphragm pump capable of drawing 3 L/min (TSI Incorporated, 2007). The stream of air is split in two where some of the air passes through a HEPA filter before it is injected back into the stream as sheath flow. The remaining flow passes into the optics chamber. A laser diode forms a thin sheet of light by passing a laser through a collimating lens and a cylindrical lens. The sheet of light illuminates the sample air and a gold coated spherical mirror, situated perpendicular to the laser and the sample air stream, captures the light scattered by the particles. The mirror focuses the scattered light onto the photo detector. The voltage drop across the photo detector is proportional to the mass concentration of the particulate in air. The light scattering response is influenced by the size distribution, refractive index, shape factor and the density. The DustTrak is advantageous as it has high concentration measurement capabilities, it is portable, and has large internal digital storage.
2.4.1.3 Ventilation Analysis

Ventilation quantification in AFO’s can be a complex process but is vital for accurate emission rate and emission factor estimations. Poultry facilities typically have numerous fans, inlets and outlets. The majority of mechanical fans are installed with shutters to prevent backflow of air and discharge cones. Studies have shown that shutters can reduce air flow efficiency by 10-25%, whereas discharge cones will increase air flow (Casey et al., 2008). To determine an accurate estimation for the overall air exchange within a facility a number of factors must be accounted for including: frequency of equipment maintenance, equipment cleanliness, environmental factors (i.e. temperature, wind, and pressure), time, and construction methods (Gates et al., 2004). Any number of these factors can affect the field performance of a fan and thus must be considered when estimating the overall ventilation rate.

The most common ventilation measurement techniques used to quantify ventilation in naturally ventilated AFO’s are tracer gases and CO2 balance. The most common technique used for mechanically ventilated AFO’s are a Fan Assessment Numeration System (FANS) as they are easy to operate and have a high relative accuracy of 1-3% (Wood et al., 2015). The most common ventilation measurement techniques for naturally and mechanically ventilated animal feeding operations and their associated relative accuracies is given in Table 28 in Appendix B. The table, modified from the one given by Wood et al., (2015), describes 10 monitoring techniques used world-wide to quantify ventilation rates from AFO’s.

The majority of studies found in Table 1 (8 out of 12) applied a FANS unit for ventilation monitoring. The remaining 3 studies used a CO2 balance which is used for naturally ventilated housing systems. The following section focuses on FANS technology as it is most commonly used for quantifying ventilation in mechanically ventilated housing. The facility used for the monitoring campaign for this study was mechanically ventilated and, consequently, this section emphasizes only technologies reflective of that.

Fan Assessment Numeration System (FANS) was initially developed by the USDA Poultry Laboratory. The purpose of this device is to quantify in-situ volumetric flow rate from poultry
and livestock buildings exhaust fans. Six propeller anemometers are aligned horizontally and used to vertically traverse the exhaust fan’s extent to generate an in-situ velocity profile of a ventilation fan. The anemometers produce a DC voltage which is linearly proportional to the air velocity. The velocity profile is multiplied by the cross-sectional area to determine the in-situ volumetric flow rate. The unit is designed for fans sizing up to 1.37 m (54 in) in diameter. Typically, fans are tested at various static pressure readings. Once the volumetric flow-rates are determined, real-time monitoring by monitoring the static pressure and fan activity will provide the necessary information to determine real-time volumetric flow rates. A 3-dimensional drawing of FANS is shown below in Figure 7.
The unit is constructed of lightweight aluminum, with stainless-steel bolts and rods. The anemometers are fastened to the anemometer bar that remains parallel to the ground. The anemometer bar is attached to a guide rail ensuring the bar remains parallel and moves as a unit. The bar is attached to leadscrew rails on either side of the unit which controls the vertical ascend and descend of the unit. A gear motor is connected to a chain that drives the movement of the leadscrews. Data cables run the length of the anemometer bar, attaching to each individual anemometer and returning to the control box. The FANS unit can be connected to a computer through Bluetooth or RS-232 cable connection. The FANS unit is controlled with the use of a
FANS interface software downloaded onto the computer. One full traverse of the anemometer bar takes approximately 185 s and collects approximately 1775 readings (Gates et al., 2004).

The development of FANS has created a practical and accurate method for quantifying in-situ volumetric flow rates from ventilation fans in poultry buildings. In a study by Gates et al., (2004) the FANS unit was found to have predicted the airflow rate within 1%. The FANS unit has proven to be an accurate device in quantifying ventilation, which is crucial to determine accurate emission rates and factors from poultry facilities. Furthermore, with the knowledge of the degree of accuracy of this device, other methods of in-situ air flow monitoring can be evaluated.
3 Commercial Cage-Free Facility

3.1 Facility description

The cage-free layer facility used in this study was located in Perth County, Ontario Canada. The facility consisted of six barns. Five of the six barns are used as conventional battery cage facilities whereas the sixth barn is used as an aviary style cage-free facility. The sixth barn was used exclusively for the monitoring campaign in this study.

Figure 8: Aerial view of layer facility used in the monitoring campaign (GRCA, 2018)
The aerial view shown above in Figure 8 illustrates the large facility including barn six which is outlined in black. The facility has approximately 1388 m² of pen space holding between 20,000-23,000 birds. The barn utilized an aviary system consisting of five rows of multi-tier systems divided into three pens along the length of the building. Each multi-tier system was approximately 2.15 m wide and 2 m tall. Each row had three tiers. The bottom tier was an elevated open litter floor at 12.5 cm, the middle tier was either a nesting or perching tier and the top tier was a perching area. Two of the rows did not contain laying nests and instead had two perching areas. Between each row there was 1.05 m of open litter floor. The pens were approximately 462 m² in area and held approximately 6,950 birds each, resulting in a packing density of 665 cm² bird⁻¹. A typical production cycle at this facility lasts approximately 52 weeks. The birds arrived when they were 19 weeks of age and were depopulated at 71 weeks of age. The facility typically depopulates in the first week of January. The measurement campaign thus spanned over two production cycles. Table 4 indicates the dates, number of birds, and average weekly mortality rate of each of the production cycles monitored.

<table>
<thead>
<tr>
<th>Dates</th>
<th>Initial bird flock size (birds)</th>
<th>Average weekly mortality rate (birds/week)</th>
<th>Bird Genetic Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>January 2017</td>
<td>20 779</td>
<td>20</td>
<td>Hy-line &amp; Dekalb White</td>
</tr>
<tr>
<td>January 2018</td>
<td>20 898</td>
<td>23</td>
<td>Dekalb White</td>
</tr>
</tbody>
</table>

The facility utilized 10 manure belts, placed underneath the nesting and perching tiers, to remove excreta twice weekly on Tuesdays and Fridays. The lower and upper manure belts were approximately 95 cm and 150 cm from the ground respectively. The manure cleanout times varied between 10:00 – 14:00 depending on worker availability. The excreta was removed from the facility and transferred to a storage building on site where it remained until it was land applied. The manure storage is located adjacent to Layer Barn 6 to the south-west. The excreta on the manure belts dried naturally, as there were no dedicated fans over the belts to enhance the drying process.

Circulation of air in the aviary was achieved using a total of 18 recirculation fans located on the ceiling of the pen. They were evenly spaced down Rows 2 and 5, each row having a total of 9
fans. The recirculation fans were constantly running to ensure constant movement and mixture of pen air.

The lighting regimen in the facility began with 11 hours of illumination (lights on) when a new production cycle began. Over the first few weeks, the illumination time increased by one hour every week for three weeks. At three weeks, the lights were on for 14 hours. After the initial three weeks, another 0.5 hour of light was added every two weeks until reaching a maximum of 15 hours. Once the maximum lighting duration was reached, it was maintained for the remainder of the production cycle. At this point the lights were turned on at 05:30 each day and turned off for complete darkness at 20:30 for a total of 15 hours of light and nine hours of darkness. When the facility goes dark, the hens are trained to return to their nesting boxes for the duration of the night.

There were three egg conveyor belts that lie between the nesting boxes that carry the eggs from the layer facility to the packing area. The nesting boxes were slightly slanted towards the middle to allow the eggs roll from the nesting box onto the conveyor belt.

The facility was operated using a Genius - 430LS control system (Varifan Inc., Quebec ON). This controller monitors the indoor and outdoor temperatures of the facility and regulates the majority of other operations including lighting, feed and water, ventilation, inlets and set-point temperatures. This system was not capable of recording and storing information. This limited the ability of downloading facility reports on usage, ventilation, temperatures etc.

### 3.2 Ventilation

The facility was mechanically ventilated using a total of 22 exhaust fans. Six were variable speed fans 0.46 m (18 in), four were 0.61 m (24 in) variable speed fans and twelve were 0.91 m (36 in) on/off fans. The fans were located on either side of the facility along the length of the building (11 each side). Each fan was installed with a shutter on the inside wall of the facility and a discharge cone orientated away from the building. A layout of the facility with the location of the fans and fan staging is shown in Figure 9.
Figure 9: Barn 6 Layout with fan groups
The fan operation was dependent on the ambient barn temperature. The ventilation rate was dependent on the temperature differential from the set-point temperature assigned by the facility operators. A set-point temperature is chosen to ensure that the temperature is comfortable for the birds. When the temperature inside the barn exceeded the set point temperature, the ventilation rate would increase causing a slight negative pressure in the barn which then pulled more fresh air through the 0.5 m baffles along the top of the lengths of both sides. The set-point temperature at the facility was typically between 22 – 23.5 °C depending on the season. The set point temperature was monitored with the use of 6 evenly spaced temperature probes.

The set-point temperature could be adjusted at any time at the discretion of the facility operators. A few examples of reasons for a set point temperature adjustment are:

- Seasonal temperatures will affect the set-point temperature. In the summer months when the outdoor temperature is high, the set point temperature is often increased so that it is attainable. In the winter months, when the outdoor temperatures are cold, a lower set-point is generally chosen to maintain a comfortable indoor temperature while continuing to ventilate the facility.
- Static pressure inside the facility may affect the set-point temperature.
- The set-point temperature is usually higher when the flock is young.
- If the birds are over-eating, the set-point temperature is often adjusted to lower food consumption. Birds typically over-eat when they are feeling cold.
- If there is an illness in the flock, the set-point temperature is often increased.

The set point temperature varied over the duration of the study. The Table 5 lists the set-point temperatures for each season with any changes that were made.
Table 5: Set-point temperatures in the barn over the sampling campaign

<table>
<thead>
<tr>
<th>Season</th>
<th>Set-point temperature °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>23°</td>
</tr>
<tr>
<td>Fall</td>
<td></td>
</tr>
<tr>
<td>September 22nd – October 31st 2017</td>
<td>23°</td>
</tr>
<tr>
<td>October 31st – December 21st 2017</td>
<td>23.5°</td>
</tr>
<tr>
<td>Winter</td>
<td></td>
</tr>
<tr>
<td>January 19 – March 6th 2018</td>
<td>22°</td>
</tr>
<tr>
<td>March 6th – March 31st 2018</td>
<td>22.5°</td>
</tr>
</tbody>
</table>

The facility used an eight stage ventilation system. Stage 1 consisted of six 0.46 m diameter (18 in) variable speed fans. The fans began operating at a minimum power of 35% when the inside barn temperature was at the set-point temperature (i.e. \( \Delta T = T_{\text{barn}} - T_{\text{set point}} = 0.0 ^\circ \text{C} \)). With each \( \Delta T \) increment of 0.1 °C, the variable stage increased linearly until it reached its maximum power of 100% at a \( \Delta T \) of 0.6 °C. Stage 1 was the minimum ventilation stage, therefore it was always running unless the temperature dropped 0.5 °C below the set-point temperature, in which case Stage 1 was deactivated. Stage 2 commenced when \( \Delta T \) is 0.7 °C and Stage 1 was running at maximum power. Stage 2 consisted of four 0.61 m (24 in) variable speed fans. Stage 2 fans ran at their minimum power of 35% and increased linearly with every increment of 0.1 °C until they reaches their maximum power at a \( \Delta T \) of 1.5 °C. Stage 2 stayed on until \( \Delta T \) dropped to 0.2 °C, at which point it was deactivated.

Stages 3 through 8 consisted of single stage 0.91 m (36 in) fans. Each stage operated two fans. Details of the summary of the ventilation stages, based on the temperature differential from the set-point temperature, are given in Table 6. A summary of the variable speed stages based on the temperature differential is given in Table 7.
Table 6: Summary of Ventilation stages based on temperature differential

<table>
<thead>
<tr>
<th>Type</th>
<th>Phase</th>
<th>Size</th>
<th># of Fans</th>
<th>ΔT - On (°C)</th>
<th>ΔT - Off (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable</td>
<td>1</td>
<td>0.46 m (18&quot;)</td>
<td>6</td>
<td>0</td>
<td>-0.5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.61 m (24&quot;)</td>
<td>4</td>
<td>0.7</td>
<td>0.2</td>
</tr>
<tr>
<td>Single</td>
<td>3</td>
<td>0.91 m (36&quot;)</td>
<td>2</td>
<td>1.6</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.91 m (36&quot;)</td>
<td>2</td>
<td>2.1</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.91 m (36&quot;)</td>
<td>2</td>
<td>2.6</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.91 m (36&quot;)</td>
<td>2</td>
<td>3.1</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.91 m (36&quot;)</td>
<td>2</td>
<td>3.6</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.91 m (36&quot;)</td>
<td>2</td>
<td>4</td>
<td>3.5</td>
</tr>
</tbody>
</table>

The table above was provided by the facility operators, and describes at what temperature each of the fan phases is turned on. It also illustrates at what temperature the fan is turned off again. The number of fans for each phase is also listed.

Table 7: Variable speed fans staging with activation temperature differentials

<table>
<thead>
<tr>
<th>Variable Stage</th>
<th>Fan Size</th>
<th>Power (%)</th>
<th>Activation Temperature Differential (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.46 m (18&quot;)</td>
<td>35</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>45</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>56</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>67</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>78</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>89</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>0.6</td>
</tr>
<tr>
<td>2</td>
<td>0.61 m (24&quot;)</td>
<td>35</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>43</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>51</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
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<td>59</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>67</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>75</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>83</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>91</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>1.5</td>
</tr>
</tbody>
</table>
The facility ventilation rate is shown in Figure 10, and is based on whether the temperature differential was increasing or decreasing. The ventilation rate pattern varied based on whether the temperature differential was increasing or decreasing as the activation and deactivation temperatures are different for each phase. The main difference, in Figure 10, is that the ventilation rate is shifted by -0.5 °C due to the fact that the deactivation for each stage is 0.5 °C less than its respective activation temperature. The maximum ventilation rate of the facility was approximated as 243,734 m³/hr, which was calculated by summing up the maximum ventilation rate of the 22 exhaust fans.
4 Methodology

The sampling campaign consisted of continuous air monitoring, ventilation evaluation, monitoring of environmental and barn parameters, set-up of the trailer which housed the experimental and auxiliary equipment, data collection, processing and quality control. The following section details the methodology of the experiment. See Appendix C for photos of the experimental set-up.

4.1 Continuous air monitoring

Continuous air monitoring occurred to collect readings of NH$_3$, PM$_{10}$, and PM$_{2.5}$. See Section 2.4 for details on the operation and technology background of the continuous air monitoring equipment.

4.1.1 Ammonia

The analyzer and support gases were housed in a climate-controlled research trailer located adjacent to the facility. The analyzer was zeroed and calibrated bi-weekly using gases at concentrations that were similar to those in the facility air. The gases and respective concentrations used in calibration are shown in Table 8. The logging interval was set at 5-minutes with a 10 second time constant. The analyzer was connected to the computer in the trailer via R-232 cable. Through iport software, the computer could remotely access the analyzer to adjust variables and to pull data.

Concentrations of NH$_3$ in the facility were continuously monitored using a chemiluminescence NH$_3$ analyzer (Model 17C, Thermo Electron Corporation, Franklin, MA). Sample air was drawn to the analyzer from the facility via a heated sample line, maintained at constant temperature of 123 °C (255 °F), to prevent condensation (Model 0723-100, Clean Air Engineering Inc.). The sampling port was equipped with a 0.1 µm filter (FALP04700, EMD Millipore Corporation, MA) to minimize passage of dust into the line and analyzer. Two additional filters were placed at
the end of the heated sample line and at the back of the analyzer. The filter at the sample port in the facility was changed bi-weekly in the summer when the dust levels were lower, and weekly in the winter as the filter clogged more frequently. The filters in the trailer were changed monthly as little build up occurred.

Table 8: Calibration gases and information for the 17C ammonia analyzer

<table>
<thead>
<tr>
<th>Gas</th>
<th>Certified Concentration</th>
<th>Purpose</th>
<th>Calibration frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen (N$_2$) High Purity</td>
<td>99.999 % pure</td>
<td>17C Zero-Calibration</td>
<td>Bi-weekly</td>
</tr>
<tr>
<td>Nitrogen Oxide (NO)</td>
<td>2.58 ppm</td>
<td>17C Calibration</td>
<td>Bi-weekly</td>
</tr>
<tr>
<td>Nitrogen Dioxide (NO$_2$)</td>
<td>2.06 ppm</td>
<td>17C Calibration</td>
<td>Annually</td>
</tr>
<tr>
<td>Ammonia (NH$_3$)</td>
<td>25.1 ppm</td>
<td>17C Calibration</td>
<td>Bi-weekly</td>
</tr>
</tbody>
</table>

The heated sample line entered through the long (north-east) side of the building just beneath the baffles. The line was suspended along the ceiling by c-straips that were secured with screws. The line traversed the ceiling until it reached the third row of tiers, at an approximate location of 38 m from the front (east) end of the barn and 7 m from the (north-east) side. The third row of tiers was chosen as it was close to the center of the facility, it was not adjacent to any of the recirculation fans and it was not over a manure belt. Furthermore, the position was chosen to minimize interference with the facility operators and the hens. The sample line inlet was placed 2.5 m above the ground, which is approximately 2/3 of the height of the pen.

4.1.2 Particulate Matter

Particulate matter concentrations were continuously monitored using two DustTrak Aerosol Monitors (Model 8534, TSI Incorporated, Shoreview, MN, USA) located on opposite sides of the barn and approximately halfway along the length of the facility. The DustTrak units were mounted on the wall approximately 1.5 m from the ground and were housed in plastic toolboxes to protect the equipment from dust build-up. A short sampling tube was attached to the inlet of the DustTrak and was placed approximately 0.9 m from the unit and 1 m away from the closest 0.46 m exhaust fan. The sampling tube was cleaned regularly to ensure limited accumulation of particulate in the tubing. The sampling port location was chosen to minimize interference with facility staff duties while still being close to exhausts points that operated year-round. This
ensured that the measurements would be reflective of the PM concentrations emitted from the facility.

The DustTrak unit has an internal memory where readings are stored. A USB-port is located on the side of the unit, and data is downloaded directly from the DustTrak onto the USB as an excel CSV file. The DustTrak is programmed directly on the handheld monitor. A 5-minute logging interval was used with a 5 second time constant. Tests were set to run for 50 days. Figure 11 below illustrates the monitor display when a test is in progress. A certain PM size can be chosen to display larger than the others as see in the top left. The top right of the display shows the remaining size fractioned mass concentrations. The bottom left provides the information of the test, including the name, run mode, the time elapsed and total length of test. The bottom right shows the status of the pump, laser and filters. The green circle indicates that they are working properly. If the circle turns red it indicates that the component has failed. This frequently occurred for the filters.

![Figure 11: DustTrak Aerosol Monitor (Model 8532, TSI Incorporated, Shoreview, MN) Start screen monitor display (TSI Incorporated, 2012)](image)

Filters were replaced weekly. During this time, the data was pulled using a USB key and the instrument was zero-calibrated. To calibrate, a zero filter was placed onto the inlet and the zero test was performed. Figure 12 below illustrates the handheld unit with a zero-filter attached to the inlet.
4.2 Ventilation rate

A fan assessment numeration system (FANS) (Model G4-5403, University of Kentucky, Lexington, KY, USA) was used to measure the in-situ volumetric flow rate from the exhaust fans. The 4th generation unit used six 27106T Gill propeller anemometers to quantify in-situ volumetric flow from an exhaust fan. The propellers move vertically traversing the cross-sectional area of the fan. The resulting DC voltage generated from the anemometers is linearly proportional to the air velocity. The velocity obtained from the anemometer was multiplied by the cross-sectional area to calculate the volumetric flow rate.

The FANS unit was centered and sealed to an exhaust fan by connecting the discharge cone to the frame of the FANS unit with plastic sheeting and securing it with duct tape. This created a direct tunnel between the unit and the fan. The unit worked well for the 0.91 m (36 in) fans. For the smaller 0.46 m (18 in) and 0.61 m (24 in) fans, foam pieces were fixed inside the unit to make a smaller cross-sectional area. Three of the anemometers were removed and the unit was operated manually by adjusting the leadscrew rails while running the test. The FANS unit testing apparatus for a 0.91 m (36 in) and 0.46 m (18 in) fan are shown in Figure 13 and Figure 14, respectively.
Figure 13: FANS unit sealed to a 0.91 m (36 in) fan prior to testing
As seen above in Figure 13, all six anemometers were used to determine the volumetric flow rate from the fan. The fan was large enough that, with the FANS unit centered, all six anemometers would traverse the ventilation fan cross-sectional area and contribute to flow estimation. When testing the smaller fans (0.46 m and 0.61 m), the FANS unit extended past the fan, resulting in anemometers reading no flow or negative flow. To produce an accurate representation of the volumetric flow from the smaller fans, a smaller frame was installed within the unit as shown in Figure 14. By creating a smaller cross-sectional area, and removing 3 of the anemometers, the
anemometers used for the test were centered and within the cross-sectional area of the fan. To test within the smaller range, the bar was manually adjusted to the bottom of the foam frame. Once the test had begun, the bar was manually stopped as the bar reached the top of the foam frame. This ensured that the operational anemometers could traverse the entire cross-sectional area of the fan.

To activate a test, the FANS unit was connected to a computer through a Bluetooth connection. The FANS unit was controlled with the use of a FANS interface software, produced by the University of Kentucky, and downloaded onto the computer. The FANS user interface allows the user to raise and lower the anemometer bar, start and stop tests, and view airflow and pressure data in real-time. To begin a test, the anemometer bar needed to be at the very bottom of the unit, and the Start Test button is selected.

The data from the user interface software is exported as an Excel csv file. The data output file returns the average airflow from the test, and the velocity as measured by each of the anemometers in rotations per minute (RPM). An example of the raw data output is shown in the Appendix in Figure 57.

The raw data from the FANS tests provides the velocity of each anemometer. To manipulate the propeller velocity in rpm to velocity in m/s, the following equation was used (Young, 2011) for propeller anemometers (Model 27106T):

\[
\text{Air Velocity} \left( \frac{m}{s} \right) = 0.005 \times \text{anemometer velocity (rpm)}
\]

The average volumetric flow rate for a fan was obtained by multiplying the cross-sectional area with the air velocity and averaging all six anemometers. For the smaller fans, only the three anemometers inside the foam frame were used to calculate the average flow rate.

FANS testing took place on two separate occasions. The first FANS testing occurred on Monday August 21st 2017. The second FANS testing occurred on Friday November 17th 2018. Table 9 below illustrates the number of tests performed on each fan. See Figure 9 in section 3.2 which illustrates the location of the fan based on associated number.
### Table 9: Dates and tests performed with FANS

<table>
<thead>
<tr>
<th>Date of test</th>
<th>Fan tested</th>
<th>Fan size</th>
<th>Fan type</th>
<th>Total Number of tests</th>
<th>Fan stage tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>August 21&lt;sup&gt;st&lt;/sup&gt; 2017</td>
<td>1</td>
<td>0.91 (36in)</td>
<td>On/Off</td>
<td>2</td>
<td>Max</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.46 (18in)</td>
<td>Variable</td>
<td>4</td>
<td>35%, 100%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.91 (36in)</td>
<td>On/Off</td>
<td>3</td>
<td>Max</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.61 m (24in)</td>
<td>Variable</td>
<td>5</td>
<td>35%, 100%</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.46 (18in)</td>
<td>Variable</td>
<td>6</td>
<td>35%, 100%</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.61 m (24in)</td>
<td>Variable</td>
<td>5</td>
<td>35%, 100%</td>
</tr>
<tr>
<td>November 17&lt;sup&gt;th&lt;/sup&gt; 2018</td>
<td>2</td>
<td>0.46 (18in)</td>
<td>Variable</td>
<td>10</td>
<td>45%, 56%, 67%, 78%, 89%</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.61 m (24in)</td>
<td>Variable</td>
<td>14</td>
<td>45%, 56%, 67%, 78%, 89%</td>
</tr>
</tbody>
</table>

In the first test performed on August 21<sup>st</sup> 2017, the on/off fans were tested. These fans only have one stage and therefore were tested at their maximum power. The variable speed fans were tested at their maximum and minimum powers. In the summer, the variable speed fans were almost always running at their maximum power, along with the on/off fans and therefore this was tested at that time.

In the fall and winter, the on/off fans were covered and turned off for the remainder of the season. The variable speed fans were solely used at their various stages. See section 3.2 for variable speed fans stages. At this point in the fall, FANS testing re-occurred to test the performance of the variable speed fans at their various stages. Since the fans performance at the minimum and maximum stages were established in the summer, they were not tested again.

To perform a test, the fan stage of the fan being tested was manually adjusted through the control panel in the barn. The control panel allows a user to manually adjust the variable speed fans from 0% to 100%. The fan was set to 0% when the FANS unit was attached to a fan to ensure a sealed tunnel was created. The fan was then adjusted to the desired stage, and through walkie-talkie communication the team outside at the fan could initiate the test using the FANS interface software.

Analog current sensors (Hawkeye 922, Veris Industries, OR, USA) were attached to the fan power supply wires to monitor the current to each fan under various fan staging conditions.
Sensor wire transmitted the current output of the fans to a CR-1000 datalogger (Campbell Scientific, CR-1000 Measurement and Control Datalogger, Edmonton, AB). Eight pieces of sensor wire attached to eight current sensors inside the control panel. The sensor wire then exited the bottom of the control board, and was run the length of the ceiling to the opposite wall, where it relayed to the datalogger. The datalogger was kept in a plastic toolbox to reduce exposure to dust. Two current sensors monitored the variable speed fans (Fan Groups 1 & 2), one sensor connected to a 0.46 m fan and the other to a 0.61 m fan. The remaining six current sensors monitored one 0.91 m fan from each of the six stages in Fan Group 3. See Figure 9 in Section 3.2 for a list of the fan groups, stages and an aerial view of the location of each fan. The datalogger recorded average measurements every 5 minutes with a 5 second time constant. The current output of each fan correlated to the fan stage, temperature gradient and respective volumetric flow rate determined using the FANS system. Consequently, volumetric flow for any current output and temperature gradient could then be estimated for each fan.

### 4.3 Additional Measurements

Throughout the sampling campaign, additional measurements were taken to evaluate both environmental and barn parameters. It was important to monitor environmental parameters as temperature and relative humidity will impact ventilation rates, ammonia and PM releases. Barn parameters were monitored to gather information that was relevant to this study, these are shown in Table 10.
Table 10: Additional measurements taken at the facility for the duration of the measurement campaign

<table>
<thead>
<tr>
<th>Barn parameters</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manure samples</td>
<td>Twice weekly</td>
</tr>
<tr>
<td>Litter samples</td>
<td>Twice weekly</td>
</tr>
<tr>
<td>Litter depth</td>
<td>Every two weeks</td>
</tr>
<tr>
<td>Bird weight</td>
<td>Every two weeks</td>
</tr>
<tr>
<td>Bird info (Bird numbers, egg production, mortality rates)</td>
<td>Monthly reports</td>
</tr>
<tr>
<td>Set-point temperature</td>
<td>Seasonally dependent</td>
</tr>
<tr>
<td>Fan Amperage</td>
<td>5 minute logging interval</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Environmental parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Barn ambient Temperature</td>
<td>5 minute logging interval</td>
</tr>
<tr>
<td>Barn Relative humidity</td>
<td>5 minute logging interval</td>
</tr>
<tr>
<td>Outdoor ambient temperature</td>
<td>5 minute logging interval</td>
</tr>
<tr>
<td>Outdoor relative humidity</td>
<td>5 minute logging interval</td>
</tr>
</tbody>
</table>

The temperature and relative humidity in the barn were continuously monitored using three Tiny Tag sensors (TinyTag Plus 2 TGP-4500, Gemini Data Loggers Ltd., Chichester, UK). The sensors were attached to three of the six barn temperature probes, evenly spaced in the facility, in order to corroborate the facility measurements. A 5-minute logging interval was used with a 5 second time constant. A fourth Tiny Tag sensor was placed outside, shaded from the sun, to determine ambient temperature and relative humidity readings.

Manure and litter samples were collected twice weekly. The collected samples were taken to the University of Guelph Agriculture and Food Laboratory Services for testing. The manure and litter sample were tested for dry matter content, potassium, Total Kjeldahl Nitrogen (TKN), ammonium-N, phosphorus and pH. Lab results for the duration of the study are contained in Appendix F.

The mortality rate, total bird numbers, bird weight, and egg production were recorded daily by the facility operators. A monthly report with this information was acquired.

4.4 Trailer set-up

A 1.82 m by 3.66 m, climate controlled trailer housed the analyzers, pumps, computers, calibration gases and various tools. The trailer was parked adjacent to the building on the north
side. A power outlet, compatible with the trailer’s requirements, was installed outside the facility’s generator house, in order to supply power to the trailer. The trailer temperature was controlled with an AC unit in the summer and a space heater in the fall and winter. The temperature was maintained between 15°-25°C.

Barn air was pulled to the trailer via a heated sample line using a Single Heated Head Diaphragm Teflon lined stainless-steel Sampling Pump (Model 9769T1, Clean Air Engineering, Palatine, IL), located inside the trailer. The pump has a maximum capability of pumping 26 L/min. Due to the length of the sample line the flowrate ranged between 5-10 L/min. This was checked twice weekly using a flow meter, attached between the pump and the analyzer. As the ammonia analyzer required a minimum sample flow rate of 0.6 L/min, pulling sample air from the barn at a rate of 5-10 L/min was more than adequate. Unused barn air was exhausted via an atmospheric dump. The remaining sub-sampled air was pumped to the analyzer where it passed through a last filter house located at the back of the analyzer. After the air was analyzed, it exhausted through a discharge port through the bottom of the trailer.

4.5 Emission Factors

As described in Section 2.3 the characterization of emissions is a complex process and is influenced by type of facility, feeding regiment, type of manure management system, and the method of land application (US EPA, 2001). To account for the difference between facilities, a representative emission characterization system is used. Livestock emission factors directly relate mass of pollutants to units of live mass. This allows for results to be comparable between facilities.

The first step in developing an emission factor is determining the pollutant concentration in mg/m³. Generally, PM concentrations are monitored in mg/m³, whereas NH₃ concentrations are typically recorded in parts per million (ppm). Using the equations described in Section 2.3, concentrations of NH₃ and PM can be converted into emission factors in units of g day⁻¹ AU⁻¹ along with the calculated ventilation rates and the total bird mass (BMtotal) present in the barn. The total bird mass is estimated as:
\[ BM_{\text{total}} = \text{total \# \textit{birds}} \times \text{average \textit{bird mass}} \]

Sample calculations are shown in Appendix A.

**4.6 Quality control**

The monitoring equipment used in this study was cleaned, calibrated and fixed regularly to ensure high standards of data collection. The NH\(_3\) analyzer was stored in a climate controlled trailer to reduce environmental interference. The dust and ventilation stage monitors were stored in toolboxes to reduce dust build-up and interaction with hens. NH\(_3\), PM and current sensor data was acquired weekly. The temperature and relative humidity data was acquired every 2 months. The equipment was frequently maintained, calibrated, and data collected to ensure a high quality of data collection. It was ensured that the equipment was working properly to provide accurate monitoring results.

The measurement campaign spanned three seasons in order to ascertain the effects of seasonal variations on the emission factors. The summer and fall campaign were measured using the first flock of birds and ran from July 7\(^{\text{th}}\) through to September 21\(^{\text{st}}\), 2017, and from September 22\(^{\text{nd}}\) through to December 21\(^{\text{st}}\), 2017, respectively. The winter campaign was measured on the second flock and ran from January 19\(^{\text{th}}\) through to March 31\(^{\text{st}}\), 2018. The total number of data points collected and processed within a season are recorded in Table 11 along with the percentage of completion of the entire campaign. The difference in data points collected and data points processed is a result of filtering the data for equipment errors, other equipment failures and calibration. The summer had the lowest percentage of completion due to an extended break taken as a result of the AC unit breaking. Figure 15 illustrates the data collection distribution over the duration of the sampling period. Concentrations of NH\(_3\), PM\(_{10}\) and PM\(_{2.5}\) are shown in orange, purple and blue, respectively. The breaks in the data can be seen clearly in this figure. The first break was in late August when the AC unit needed to be replaced in the trailer. The second break occurred between December 22\(^{\text{nd}}\), 2017 and January 19\(^{\text{th}}\), 2018 due to the depopulation that occurred at the facility. A new flock was introduced in mid-January and the sampling campaign recommenced.
Figure 15: Measured data collection over entire sampling period
Table 11: Total number of data points collected and total number of data points processed for results

<table>
<thead>
<tr>
<th>Season</th>
<th>Sampling period</th>
<th>NH₃</th>
<th>PM₁₀ &amp; PM₁₀</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Total data points collected</td>
<td>% collected of total campaign</td>
</tr>
<tr>
<td>Summer</td>
<td>July 18th – September 21st, 2017</td>
<td>16,360</td>
<td>87.4</td>
</tr>
<tr>
<td>Fall</td>
<td>September 22nd – December 20th, 2017</td>
<td>25,817</td>
<td>99.6</td>
</tr>
<tr>
<td>Winter</td>
<td>January 19th – March 31st, 2018</td>
<td>20,345</td>
<td>99.5</td>
</tr>
</tbody>
</table>
4.7 Data collection concerns

Any study will encounter problems that impact data collection. This section will describe issues that were encountered over the duration of the study and their impacts on data collection.

The first issue that was faced were the high temperatures in the summer 2017. The trailer air conditioning unit could not maintain the trailer temperature given the high ambient temperatures. As a result, the temperature inside the trailer exceeded the appropriate range, causing a temperature alarm on the 17C-chemiluminescence analyzer. The NH$_3$ analyzer is temperature sensitive and cannot run effectively at high temperatures. To fix this issue a new air conditioning unit was installed in the trailer in late August. This resulted in a two-week loss of data collection at the end of August.

The next issue that was faced was the harsh winter conditions. Cold ambient temperatures resulted in lower temperatures in the trailer despite the constant use of a space heater. The lower trailer temperature caused buildup of condensation in the sample line. The sample air was drawn from the barn to the trailer in a heated sample line at 123°C. Once inside the trailer the sample air leaves the heated sample line and is drawn to the analyzer by the pump through Teflon tubing. There was approximately 2 m of sample line between the heated line and the analyzer that was not insulated. The drastic change in temperature of the sample air leaving the heated line and entering the colder trailer temperatures, approximately 17°C in the winter, formed condensation in the line. Moisture build-up occurred at the back of the analyzer in the filter house, which was removed as necessary. This is an issue due to the highly soluble nature of ammonia. Ammonia readily dissolves in water which would affect an accurate ammonia reading in air. Colder ambient conditions also affected the temperature loggers. The Tiny Tag sensor (TinyTag Plus 2 TGP-4500, Gemini Data Loggers Ltd., Chichester, UK) is capable of reading temperatures between -25°C to +85°C. Occasionally the winter temperatures fell below -25°C causing the sensor to fail. This resulted in missing data for a period of a month. Unfortunately, there was no sign that the sensor failed so it was not discovered and reset until a month had passed. The cold weather also impacted FANS testing that was performed in the fall. To effectively test a fan performance with the FANS unit, a seal must be made between the unit and the exhaust fan. The
duct tape that was used to create this seal between the fan and the unit lost its adhesive characteristic. This resulted in an imperfect seal. To compensate for this, staples, screws and push pins were used to maintain the tunnel between the fan and the unit.

Another difficulty that was faced in this study was the monitoring of the ventilation rate. In the summer when the majority of the fans were operational, monitoring fan activity was simple. As the temperatures grew colder in the late fall and winter, fewer fans were operational and the ones that were, were variable speed fans. The fans for this facility were controlled from a central control panel. The current sensors that were installed to monitor the fan activity did not portray a linear relationship between current and fan stage. This was due to the fact that as a fan stage increased there were also other controllers and operations that drew power at the same time, resulting in a non-conclusive relationship which is shown and discussed in Section 5.1.3. To compensate for the non-linearity of the amperage, the set-point temperature was referenced to ensure ventilation activity was monitored successfully.

### 4.8 Data processing

The data collected during the sampling campaign underwent data processing to determine emission values that are representative of the laying facility. Data was processed in Matlab (MathWorks Inc., 2015) and Microsoft excel. Data was processed on a seasonal basis to distinguish seasonal trends. Within each season, an hourly average was used to evaluate diurnal trends. In doing so, results from this study could be effectively compared to other studies with a similar focus.
5 Results and Discussion

The following sub-sections describe the results that were obtained from the cage-free facility over the duration of this study. This section also provides the details of the data analysis and discusses the relevancy and significance of the data. The first section covers the house parameters including: information concerning the flock size and mass, the lab results from litter and excreta samples taken throughout the study, and the ventilation rate of the facility. The second section details the analysis of aerial pollutants monitored in the house and emitted from the facility. The final section summarizes the emissions determined from the cage-free layer facility.

5.1 House parameters

The measurement campaign covered the last half of the production cycle for the first flock of layers (July to December, 2017) and the first three months of a second production cycle with the depopulation of the first flock and introduction of the second flock occurring in January 2018.

5.1.1 Bird mass and flock size

Flock size and bird mass were observed in monthly reports provided by the facility. The first production cycle (Flock 1) began in January 2017, with a mix of Hy-Line and Dekalb white hens totaling 20,779 birds. The average mortality rate during the production cycle was 20 birds/week. At the time the monitoring campaign commenced, there were 20,260 birds at an approximate age of 43 weeks. The monitoring campaign was paused when Flock 1 was depopulated in early January. The campaign resumed in late January 2018 when a new flock was introduced (Flock 2). Flock 2 started with 20,898 Dekalb white hens at an approximate age of 19 weeks. The average mortality rate was 24 birds/week.

The sampling campaign was initiated halfway through the production cycle of flock 1. The hens were already well accustomed to their environment, contributing to a constant mortality rate.
Flock 2 had an increased number of bird mortality in the first 5 weeks of the production cycle. The average mortality rate in the first 5 weeks of the production cycle for Flock 2 was 39 ± 8 birds/week, compared to 12 ± 4 birds/week in the weeks that followed. At the beginning of the production cycle the birds would not be familiarized with their environment and were under greater stress, resulting in higher mortality. As the hens settled, the mortality rate decreased and the relationship between number of birds and age regained linearity.

Typically, in conventional battery caged facilities, the facility staff can weigh the same group of birds. In cage-free systems this is not the case as the birds have free run of their pen. The process of finding the same birds to weigh is both time consuming and laborious. Therefore, a different group of birds is used for each weighing period. To account for differences in bird groups and individual birds, a large sample of birds was weighed. At this facility, 72 birds were weighed every two weeks. The uniformity of the sample group is noted by the staff on the report. The uniformity generally ranged between 80 – 100 %. The following graphs have an x-axis starting at 15 weeks, as the birds are introduced into the facility at 19 weeks of age and depopulated at 72 weeks of age. The average bird mass over age for Flock 1 (given in red) and Flock 2 (given in black) are illustrated in Figure 16 below:
The mass of birds in Flock 2 follows an increasing trend. At the start of the production cycle the birds are still young and small at 19 weeks. In the early weeks of placement, the hens still increased in mass until they reached a relatively steady mass. As Flock 1 was the latter half of the production cycle, the bird mass was relatively constant, and even starting to taper off as shown in Figure 16. The average mass for Flock 1 was 1.67 ± 0.021 kg. The standard deviation from the average mass was 0.1 %, indicating that the mass was relatively uniform. Comparatively, the average mass for Flock 2 was 1.50 ± 0.92 kg. The standard deviation was 6.1 % signifying a greater variation due to the birds growing into their mature body mass.

To quantify the total mass of birds in the facility at a given time, the average bird mass was multiplied by the total number of birds. This information is imperative for emission factor calculations as the amount of live mass in the facility is required to effectively relate the quantity of emissions to animal activity. The total facility bird mass for Flock 1 and Flock 2 are shown in Figure 17 below and follows much the same trends as the average bird mass given in Figure 16.
Eggs were collected via conveyor belts every morning. Floor eggs were transferred to conveyor belts manually by staff on their daily walking rounds through the pens. The total number of eggs produced by the hens were reported daily and are given in Figure 18 and Figure 19 for Flocks 1 and 2, respectively.

Figure 17: Total facility bird mass vs bird age over the measurement campaign
Figure 18: Egg Production for Flock 1

Figure 19: Egg Production for Flock 2
The eggs produced over the production cycle for Flock 1 follows a near linear trend with a slightly negative slope. The negative slope is a result of decline in egg production by 75 eggs per week. The R² value for the linear regression is 0.8301 illustrating that there is a reasonably strong linear relationship between egg production and hen age. The average number of eggs produced during the period of the production cycle monitored for Flock 1 was 18860 ± 590 eggs. There is limited variation from the mean, with a standard deviation of 3.1 %. At the beginning of the Flock 2 production cycle, the hens were just reaching their sexual maturing which resulted in a low numbers of eggs. As the hens aged and matured, the number of eggs produced drastically increased until reaching a steady state. The data for Flock 2 was fit to a linear trend-line after week 24, depicted in Figure 19. The resulting R² value was very low due to the fluctuation of egg production as the hens reached sexual maturity. As it was still early in the production cycle some hens may have reached maturity earlier than others, causing the low linear trend. The average number of eggs produced by Flock 2 was 17980 ± 3232 eggs. There is a greater variation from the mean, subsequently the standard deviation was calculated as 18.0 %. If data points were collected over the remainder of the production cycle it is expected that this variation in the data would be drastically reduced Furthermore, the data would continue to converge towards steady state until reaching a linear relationship as seen for Flock 1.

It is important to account for the change in bird population over the production cycle to encompass the overall production efficiency of the hens. To do so, the number of eggs produced per bird was calculated and is illustrated in Figure 20 below.
For Flock 1, the production efficiency decreases by 0.003 eggs/bird/week which is equal to approximately 60 eggs/week. Comparatively, Flock 2 is at the start of the production cycle, thus the production efficiency of the hens is rapidly increasing. It is expected that the efficiency would continue to increase until reaching a steady state. Once at steady state, the production efficiency would begin to decrease nearing the end of the production cycle similar to Flock 1.

### 5.1.2 Litter and Excreta Analysis

Litter and excreta samples were collected twice every week and sent to the University of Guelph Laboratory Services for analysis. The samples were analyzed for pH, dry matter content (%) Potassium, Total Kjedahl Nitrogen (TKN) (%) wet, Ammonium – N (mg/kg wet) (NH₄-N) and Phosphorus. A total of 43 tests on 86 samples (1 each of litter and manure for each test) were performed and the reports produced from Lab Services are included in Appendix F for future reference.
The composition of litter and excreta can greatly influence emissions of NH$_3$ and PM matter in a facility. High pH levels, temperature, moisture content, and NH$_4$-N can significantly increase ammonia concentrations and subsequently fine particulate formation. Low moisture content in the litter, on the other hand, can increase the PM concentrations and create dustier environments. Further investigation on the effects of manure and litter composition on the concentration of ammonia and PM will be discussed in section 5.2.1 and 5.2.2 respectively.

Reported pH levels from litter and manure samples over the sampling campaign are illustrated in Figure 21 and Figure 22 respectively. The summer and fall measurements on the litter and manure from Flock 1 are marked in red and green respectively. The winter measurements on the litter and manure from Flock 2 are marked in dark blue.

Figure 21: pH results from litter samples for Flock 1 and Flock 2
The results from the litter pH tests depict an increasing trend at the end of the fall and the beginning of the winter. The summer had a relatively consistent and low pH level with an average of 6.93 ± 0.19, resulting in a variation of 2.74%. There was no evident trend for the summer litter pH. The fall had a greater average litter pH level with an overall increasing trend as the season progressed. The average was 7.57 ± 0.49, resulting in a variation of 6.47%. The fall litter pH followed an increasing linear trend with a $R^2$ value of 0.6724, indicating a reasonably strong linear relationship. The winter, which corresponded to the placement of Flock 2, had the greatest litter pH averaging 8.01 ± 0.33. The overall winter trend linearly decreased as the season progressed resulting in an $R^2$ value of 0.6447. The season started with an abnormally high pH level for the first 2 weeks of Flock 2, in part due to the wet litter conditions that existed at the time. The pH slowly declined until reaching a steady state in the last few weeks of the sampling campaign. The pH levels significantly affect the equilibrium reaction of $\text{NH}_4^+$ and $\text{NH}_3$, favoring the formation of $\text{NH}_3$ at higher pH levels. This equilibrium relationship can be referenced in Figure 4 located in Section 2.2.1. The formation of $\text{NH}_3$ is significantly favored with small incremental increases in pH over 8. Thus, based on this relationship as the pH level
increases above 8 the formation of NH₃ should also increase. The litter pH results illustrated in Figure 21 show that elevated concentrations of NH₃ should be expected at the end of the fall, and beginning of the winter. Based on the pH levels in litter for the fall, the concentrations of NH₃ should theoretically increase reaching a maximum at the end of the season. Comparatively, the winter should theoretically have higher concentrations of NH₃ at the beginning of the season, and reduce over the remainder of the season. The results from the manure pH tests did not portray any significant trends. The manure pH was generally less than the litter pH. The summer had the lowest manure pH average of 6.09 ± 0.36. The fall and winter had consistent manure pH averages of 6.74 ± 0.64 and, 6.73 ± 0.41 respectively.

Ammonium-N content (mg/kg wet) in litter and manure are illustrated in Figure 23 and Figure 24, respectively.

![Figure 23: Ammonium-N (mg/kg wet) content from litter samples for Flock 1 and Flock 2](image)

The litter NH₄-N content was relatively consistent through the summer and the fall with an average of 1084.1 ± 165.4 and 1026.2 ± 262.7, respectively. The fall campaign had greater variation with a standard deviation of 25.6% compared to 15.25% in the summer. The percent
difference between the NH$_4$-N content in the litter between the summer and fall was a mere 5.63%. The winter had the largest spread of data, with a general decreasing trend over the season. The first two weeks of the production cycle for Flock 2 produced litter with very high NH$_4$-N content in comparison to the other seasons. The first few weeks into the production cycle, the average NH$_4$-N content was 2368.6 ± 935.4, which is twice as high as the fall and summer average. Over the next few weeks, the NH$_4$-N content decreased until reaching a steady state. During the transitional behavior, the average was 1677.4 ± 537.1, which was 1.5 times higher than the summer and fall. The NH$_4$-N reached a steady state at the end of the monitoring campaign resulting in an average NH$_4$-N content of 853 ± 103.9 which was approximately 0.75 of the summer and fall average. Overall, the winter season had the greatest quantity of NH$_4$-N in the litter averaging 1633 ± 880.5, which is 1.5 times greater than flock 1. Furthermore, Flock 2 had a standard deviation of 53.9% which illustrates how drastic the change in NH$_4$-N content was over the duration of the season. Elevated quantities of NH$_4$-N in the litter can contribute to greater NH$_3$ formation. The combination of greater pH levels as illustrated in Figure 21, and higher quantities of NH$_4$-N in the litter shown in Figure 23, can be expected to release greater concentrations of NH$_3$ as the equilibrium reaction shifts towards the right at higher pH levels.
Figure 24: Ammonium-N (mg/kg wet) content from manure samples for Flock 1 and Flock 2

The NH₄-N content in the manure did not follow a noticeable trend. Generally, each season had a range where many of the data points fell, along with a couple of more extreme values. This is especially evident in the fall data. The fall season had an average of 1709.4 ± 1036.1, resulting in a standard deviation of 60.6%. This may be attributed to the timing of the data collection. Most manure samples were collected on Tuesdays and Fridays with some variation. In most cases the manure samples were collected prior to manure belt removal, however, on occasion the belt was run earlier than normal which resulted in a fresher manure sample. The summer and winter averages were 2092 ±450.7 and 2279.3 ± 833.3, respectively. Overall, Flock 2 had the greatest NH₄-N content followed by Flock 1 in the summer and fall, respectively.

Total Kjedhal Nitrogen (TKN) was another important parameter monitored in the litter and manure. TKN is the sum of total organic nitrogen and total ammonia nitrogen. As the NH₄-N content was particularly high for Flock 2 in the winter, the ratio of NH₄-N/TKN was calculated as a percent to evaluate the composition of TKN. As NH₄-N is the component in TKN which contributes to the formation of NH₃, it was imperative to determine if there was a shift in the
ratio of NH$_4$/TKN. A sample calculation for the unit conversion from TKN (% wet) to TKN (mg/kg wet) is shown in Appendix B. Once the units for TKN were adjusted to the same units as NH$_4$-N content, it was possible to calculate the percent composition of NH$_4$-N in TKN. This was performed on the litter as the NH$_4$-N content had a noticeable trend for Flock 2 for litter but did not show any significant trends in the manure. Figure 25 below demonstrates the results from this calculation.

![Figure 25: Composition of Ammonium-N (mg/kg wet) of Total Kjedhal Nitrogen (mg/kg wet) in Litter](image)

Figure 25 illustrates the percent composition of NH4-N in TKN which is relatively consistent for Flock 1 apart from a slight increase at the end of the fall season. The overall composition of TKN did not shift significantly. The composition of TKN for Flock 2, however, shifted greatly in favor of NH$_4$-N content. At the beginning of Flock 2, there were elevated levels of NH$_4$-N in TKN at approximately three times higher than that for the average for Flock 1. This was reduced over the season and returned to a consistent value in the last month of the campaign. The mean and % standard deviation for the % composition of NH$_4$-N in TKN for each season is shown in Table 12. Winter is divided into three periods to best illustrate the changes over the season. The
three periods each include five samples taken over a 3-week period. The first period represents the start of the production cycle, the second period represents a transition period, and the third period represents Flock 2 at a stabilized steady state level. Due to this behavior, the winter season is divided into these periods for further analysis in future sections.

Table 12: % Composition of NH4-N of Total Kjedhal Nitrogen from litter samples for each season

<table>
<thead>
<tr>
<th>Season</th>
<th>% Composition of NH$_4$-N of TKN</th>
<th>% Standard Deviation of the Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer – Flock 1</td>
<td>3.78 ± 0.72</td>
<td>18.95</td>
</tr>
<tr>
<td>Fall – Flock 1</td>
<td>3.29 ± 1.28</td>
<td>38.98</td>
</tr>
<tr>
<td>Winter – Flock 2</td>
<td>a) Start 11.07 ± 5.04</td>
<td>45.57</td>
</tr>
<tr>
<td></td>
<td>b) Transition 6.59 ± 2.71</td>
<td>41.20</td>
</tr>
<tr>
<td></td>
<td>c) Steady state 2.59 ± 0.31</td>
<td>11.98</td>
</tr>
<tr>
<td>Overall</td>
<td>5.92 ± 4.79</td>
<td>80.89</td>
</tr>
</tbody>
</table>

The composition of TKN as NH$_4$-N for the litter samples of Flock 1 remained relatively constant. For Flock 2, however, there is a clear upset in the composition of the TKN at the start which was related to high moisture content in the litter. The composition of TKN as NH$_4$-N is a key factor for evaluating NH$_3$ volatilization.

The moisture content or, inversely, the dry matter content of litter and manure is a key factor in ammonia and PM emissions. The seasonal average dry matter content of the litter samples is shown in Table 13 below.

Table 13: Average dry matter content from litter samples for summer, fall and winter measurement campaigns

<table>
<thead>
<tr>
<th>Season</th>
<th>Dry Matter (%)</th>
<th>% Standard Deviation of the Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer – Flock 1</td>
<td>80.34 ± 3.76</td>
<td>4.69</td>
</tr>
<tr>
<td>Fall – Flock 1</td>
<td>81.24 ± 2.27</td>
<td>2.80</td>
</tr>
<tr>
<td>Winter – Flock 2</td>
<td>a) Start 70.56 ± 2.35</td>
<td>3.34</td>
</tr>
<tr>
<td></td>
<td>b) Transition 79.10 ± 2.86</td>
<td>3.62</td>
</tr>
<tr>
<td></td>
<td>c) Steady state 83.06 ± 1.58</td>
<td>1.91</td>
</tr>
<tr>
<td>Overall</td>
<td>77.57 ± 5.71</td>
<td>7.36</td>
</tr>
</tbody>
</table>
Overall, the average dry matter content between the summer and fall seasons did not change drastically. Flock 2 had the lowest dry matter content or wettest conditions, especially at the start of the bird cycle. During this period, the litter had an abnormally high moisture content and caused accumulation of litter on the floor in wet mounds. The facility staff cleaned out areas of accumulated wet litter for approximately 3 weeks into the production cycle and replaced the litter with wood chips, which reduced the moisture content in the later winter periods as seen in Table 13. The seasonal dry matter content of the manure samples is shown in Table 14.

Table 14: Average dry matter content from manure samples for summer, fall and winter measurement campaigns

<table>
<thead>
<tr>
<th>Season</th>
<th>Dry Matter (%)</th>
<th>% Standard Deviation of the Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer – Flock 1</td>
<td>31.53 ± 2.68</td>
<td>8.49</td>
</tr>
<tr>
<td>Fall – Flock 1</td>
<td>29.66 ± 3.39</td>
<td>11.43</td>
</tr>
<tr>
<td>Winter – Flock 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Start</td>
<td>27.44 ± 2.62</td>
<td>9.54</td>
</tr>
<tr>
<td>b) Transition</td>
<td>31.30 ± 3.09</td>
<td>9.86</td>
</tr>
<tr>
<td>c) Steady state</td>
<td>29.16 ± 4.78</td>
<td>16.40</td>
</tr>
<tr>
<td>Overall</td>
<td>29.30 ± 3.95</td>
<td>13.47</td>
</tr>
</tbody>
</table>

The start of the winter season had the lowest dry matter content or wettest conditions. During the transition period a relatively large increase in dry matter content is seen. The dry matter content increased due to a dietary manipulation executed at the discretion of the facility staff in attempt to reduce the moisture content of the bird excreta. Elevated moisture content in excreta increases the likelihood of NH$_3$ formation via favorable conditions for microbial degradation as discussed in Section 2.2.1. The summer had the highest manure dry matter or driest conditions, attributed to elevated temperatures and high air exchanges. Thus, the summer had the least favorable conditions for NH$_3$ formation with regards to moisture content of the manure.

Overall, the winter had the highest pH, NH$_4$-N, % composition of NH$_4$-N in TKN and moisture content of litter. Further discussions on the implications of the litter and manure analysis results on ammonia and PM concentrations can be found in Section 5.2.1 and 5.2.2, respectively.
The litter depth was recorded weekly using a caliper. On average, 10 depth measurements were taken along the third row of the first pen in the barn for each day. The same locations were used for measurements to ensure that the measurements were relative to each other. The litter measurements are illustrated in Figure 26. The error bars indicated one standard deviation from the mean, based on the 10 measurements for each day.

![Figure 26: Recorded litter depth over measurement campaign with one standard deviation from the mean](image)

The standard deviation ranged from 10-23% indicating a large variation in the measurements. The overall trend for both Flock 1 and Flock 2 was an increasing litter depth. This is to be expected as the litter is accumulated over the duration of the production cycle. A combination of dried excreta, feathers, dander and bedding contribute to the accumulation of litter on the floor.

As the production cycle progresses, greater quantities of excreta accumulate on the litter floor resulting in primarily sand-like litter.

### 5.1.3 Ventilation rate

The facility operated a total of 22 mechanical ventilation fans (refer to Section 3.2 for a description of fan operation and configuration). A FANS unit was used to test the in-situ volumetric flow-rate from the ventilation fans. Two 0.46 m diameter, 0.61 m diameter and 0.91
m diameter fans were tested in order to validate the estimated flow rate by comparing the results from multiple fans. The test results from the FANS testing for each size fan and fan stage for the variable speed fans is given in Table 15.

<table>
<thead>
<tr>
<th>Fan Size</th>
<th>Fan Stage</th>
<th>Average airflow measurement (m³/hour)</th>
<th># of Tests</th>
<th>Standard Deviation (m³/hour)</th>
<th>% Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.46 m (18 in)</td>
<td>35</td>
<td>2771</td>
<td>7</td>
<td>918</td>
<td>33.1</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>3823</td>
<td>2</td>
<td>14</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>56</td>
<td>4707</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>4812</td>
<td>2</td>
<td>51</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>78</td>
<td>5067</td>
<td>2</td>
<td>272</td>
<td>5.4</td>
</tr>
<tr>
<td></td>
<td>89</td>
<td>5109</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>7962</td>
<td>5</td>
<td>706</td>
<td>8.9</td>
</tr>
<tr>
<td>0.61 m (24 in)</td>
<td>35</td>
<td>4338</td>
<td>5</td>
<td>225</td>
<td>5.2</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>4161</td>
<td>2</td>
<td>932</td>
<td>22.4</td>
</tr>
<tr>
<td></td>
<td>56</td>
<td>5401</td>
<td>2</td>
<td>18</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>4913</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>78</td>
<td>5698</td>
<td>2</td>
<td>119</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>89</td>
<td>6308</td>
<td>2</td>
<td>0.57</td>
<td>0.009</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>9822</td>
<td>5</td>
<td>377</td>
<td>3.8</td>
</tr>
<tr>
<td>0.91 m (36 in)</td>
<td>ON</td>
<td>14175</td>
<td>4</td>
<td>441</td>
<td>3.1</td>
</tr>
</tbody>
</table>

The mean airflow rate, in units of m³/hour, was derived from the results of each test. The standard deviation and % standard deviation is also presented to illustrate the uniformity of the tests. For some stages, only one test was completed, in which case there is no standard deviation. The number of tests varied between the sizes of fans, due to time constraints. The average airflow rates for the variable speed fans were plotted against the fan stage to derive a fan performance curve. The resulting plots for the 0.46 m and 0.61 m diameter fan tests are shown in Figure 27 and Figure 28 respectively. The fan performance curves were best fit to a linear regression to model the average airflow at each stage. The linear regression equation and associated R²-values are given in the figures.
Figure 27: 0.46 m (18 in) Fan Performance Curve from FANS testing

Figure 28: 0.61 m (24 in) Fan Performance Curve from FANS testing
The linear regression for the 0.46 m fan yielded a higher $R^2$–value than the 0.61 m fan and thus displayed a greater linearity between the fan stage and the airflow rate.

The airflow of each fan was calculated using the linear regression equations. Overall, the linear relationships characterized the data well, estimating a flow rate within 20% of the measured flow. The % difference between the calculated flow from the linear regression equations and the measured flow obtained through in-situ testing with the FANS unit is presented in Table 16. During the testing period for the variable speed fans (both 0.46 m and 0.61 m diameter), cold ambient temperatures introduced difficulties in keeping the tunnel from fan deflector to the FANS unit completely sealed. The anemometers tore some of the plastic of the tunnel which may have caused a resulting underestimation of the airflow. This may have caused a greater deviation from the linear trend (refer to Section 4.7 for more details on the data collection concerns).

<table>
<thead>
<tr>
<th>Fan Size</th>
<th>Fan Stage</th>
<th>% Difference of measured flow and calculated flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.46 m (18 in)</td>
<td>35</td>
<td>5.91</td>
</tr>
<tr>
<td></td>
<td>46</td>
<td>7.11</td>
</tr>
<tr>
<td></td>
<td>56</td>
<td>10.39</td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>1.47</td>
</tr>
<tr>
<td></td>
<td>78</td>
<td>8.72</td>
</tr>
<tr>
<td></td>
<td>89</td>
<td>17.83</td>
</tr>
<tr>
<td>0.61 m (24 in)</td>
<td>35</td>
<td>17.45</td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>15.23</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>17.72</td>
</tr>
</tbody>
</table>

The calculated airflows used in the development of the ventilation profile for the facility are contained within Appendix A.

At the same time the FANS tests were performed, the current output was recorded at each phase. The current sensors attached to the fans power supply relayed information to a datalogger. The datalogger was attached to a computer and real-time current output was displayed in LoggerNet.
A range of current readings at each operation point were recorded. The current output was plotted in relation to the operation point to characterize the current requirements and evaluate the trends for the fans. By doing so, the ventilation rate could be associated to any current output reading from the fans. This allowed for real-time monitoring of the ventilation of the facility. The current output plots are shown for the 0.61 m and 0.46 m fans in Figure 29 and Figure 30 respectively.

![Graph showing current output vs fan stage for 0.61 m fans.](image)

**Figure 29: 0.61 m (24 in) variable speed fan current measurements at each fan stage**

The current output for the 0.61 m fans decreased with increasing operation stage (% of maximum). This indicates that the 0.61 m fans increase in efficiency as they increase in power, and have lower efficiency at lower operation points. The current output followed a decreasing linear trend with an $R^2$-value of 0.9923 indicating that a linear relationship accurately represented the data. The linear trend simplified the process of characterizing the current output and associating it with the correct ventilation stage.
The 0.46 m fan current output was more complex. The current output decreased initially until reaching 60 - 70% of the maximum. At that point as the operation point increased the current requirements also increased creating a scoop-like trend. The current output decreased by 60% when 4 or less fans were operational, however, maintaining the same scoop-like trend. In order to characterize the current output and assign it to an associated ventilation stage, the set-point temperature was used to split the curve in two. Based on the set-point temperature, if the barn temperature is within 0.3 °C of the set point temperature, it was assumed that the lower stages were operational (35%, 45%, 56%, 67%). If the barn temperature was greater of equal to 0.4 °C of the set point temperature, it was assumed that the higher stages were operational (78%, 89%, 100%). A series of if-statements were used to evaluate the current output, barn temperature, and number of operational fans to ensure the appropriate fan stage and ventilation rate was assigned. The code that included the if-statements is included in Appendix D. The current range values used to identify the fan stages are shown in Table 30 in Appendix B.

Temperature is the driving force for the ventilation of the barn. The set-point temperature and deviation from the set point temperature in the barn dictate the ventilation requirements. As the barn temperature increases from the set-point temperature, ventilation is increased to reduce the barn temperature back to the set-point. The outdoor temperature will also influence the
ventilation requirements, as the temperature of the incoming air is the only means of returning the barn temperature back to the set point temperature. If the temperature is cooler outside, ventilation will be decreased to reduce the amount of outdoor air entering through the inlets, maintaining a comfortable indoor temperature. As the outdoor temperature increases, greater air exchanges occur to cool the indoor temperature. The set point temperature changed seasonally at the discretion of the staff. The details of the set-point temperature and the fans operation with respect to temperature is detailed in Section 3.2. The indoor and outdoor temperatures along with the resulting ventilation rates are depicted in Figure 31 for the summer, fall and winter seasons. Note that the breaks in data occur when there is missing data, resulting from equipment malfunctions.

Figure 31: Ventilation temperature profile for each season with outdoor and barn temperatures (top panel) and ventilation rates (bottom panel)

The ambient temperatures drastically fluctuated over the three seasons, whereas the barn temperature remained relatively constant, with drastic exceedances only occurring when the outdoor temperature exceeded the set point. The bandwidth, in which the barn and ambient
temperature fluctuated, along with the mean ± one standard deviation (SD) for barn temperature, outdoor temperature, relative humidity and ventilation for each season is given in Table 17.

Table 17: Seasonal mean barn temperatures, relative humidity, outdoor temperatures and ventilation rates

<table>
<thead>
<tr>
<th>Season</th>
<th>Barn Temperature</th>
<th>Barn Relative Humidity</th>
<th>Outdoor Temperature</th>
<th>Ventilation rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Bandwidth</td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
</tr>
<tr>
<td>Summer</td>
<td>25.1 ± 1.1</td>
<td>6.1</td>
<td>61.5 ± 7.3</td>
<td>18.8 ± 4.9</td>
</tr>
<tr>
<td>Fall</td>
<td>24.3 ± 0.93</td>
<td>8.3</td>
<td>60.3 ± 5.6</td>
<td>5.7 ± 8.9</td>
</tr>
<tr>
<td>Winter</td>
<td>22.3 ± 0.49</td>
<td>3.7</td>
<td>65.6 ± 4.4</td>
<td>-4.1 ± 5.7</td>
</tr>
</tbody>
</table>

In the summer, the outdoor temperature fluctuated within a bandwidth of 25 – 50 °C compared to the barn temperature which fluctuated between a bandwidth of 3.5 – 8 °C. In the summer, the outdoor temperature averaged 18.8 °C although the data from the first part of the summer campaign is absent due to a data logger failure. The fall and winter seasons had lower outdoor temperatures averaging 5.7 and -4.1 °C, respectively. As evidenced in Figure 31, the ventilation rates fluctuate both seasonal and diurnally. The summer ventilation rates were significantly higher than those of the fall and winter as all of the fans were operational to maintain a comfortable indoor temperature. The fall and winter ventilation rates approximated 45% and 18% of that of the summer rate. This is attributed to the colder outdoor temperatures, and the number of operational fans. Typically, the ventilation rate peaked in the mid-afternoon when temperatures were at their highest, and would fall overnight.

Individual season ventilation temperature profiles are shown for the summer, fall and winter in Figure 32, Figure 33, and Figure 34, respectively. Ventilation rates are illustrated in black, outdoor temperatures are in blue, and indoor temperatures are in red. These enlarged plots are graphed on a y-axis that is best suited for the ventilation of that season, in order to demonstrate the effects of temperature on ventilation rate. Thus, the magnitude of the ventilation plots should not be compared without consulting the y-axis.

A seasonal statistical analysis was performed to identify and validate the significance of temperature on ventilation. For each season, a series of linear regressions were performed to
determine the $R^2$-value and $p$-value of the relationships. If the $p$-value was less than 0.0001, it was reported as 0.

Figure 32: Summer ventilation rate with ambient and barn temperatures

The summer had the highest ventilation requirements. As evidenced in Figure 32 above, as the outdoor temperature peaks, the indoor temperature also peaks and as a result the ventilation rate operates at a maximum capacity. The troughs in the ventilation are associated with lower outdoor temperatures, typically occurring during the night. It can be seen that within each trough of ventilation, the outdoor temperature also reached a low point at the same time. The ventilation rates fluctuated very drastically in the summer with varying temperatures, because the 0.91 m on/off fans were operational. There are six stages for the On/Off fans, each operating two of the 0.91 fans. The ambient temperatures were generally warm enough in the summer that the minimum ventilation fans (0.46 m and 0.61 m) were running at full capacity day and night. The ventilation rate, with only the minimum ventilation fans operating, was 73 630 m$^3$/hour. When the set point temperature was exceeded by 1.6 °C, each additional increase of 0.5°C resulted in
an additional ventilation rate of 28,350 m³/hour which was a significant increase. Over the course of the summer there were only four instances when the 0.91 m fans were not required, and they are shown in Figure 32 as the four lowest troughs when the outdoor temperature was the lowest of the season. For the remainder of the season, the majority of the fans were operating. The 27 peaks in ventilation shown in Figure 32 indicate that the facility ventilation was running at the maximum rate of 243,734 m³/hr.

To validate the significance of temperature on the summer ventilation rates four linear regression models were produced, the results are shown in Table 18 below.

<table>
<thead>
<tr>
<th>Linear Regression Model</th>
<th>R² value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilation rate ~ Barn Temperature</td>
<td>0.725</td>
<td>0</td>
</tr>
<tr>
<td>Ventilation rate ~ Outdoor Temperature</td>
<td>0.835</td>
<td>0</td>
</tr>
<tr>
<td>Ventilation rate ~ Barn Temperature + Outdoor Temperature</td>
<td>0.892</td>
<td>0, 0</td>
</tr>
<tr>
<td>Barn Temperature ~ Outdoor Temperature</td>
<td>0.582</td>
<td>0</td>
</tr>
</tbody>
</table>

The linear regression model relating ventilation rate to both barn temperature and outdoor temperature yielded the highest R²-value of 0.892. This suggests that both the indoor temperature and outdoor temperature had a very significant role on the ventilation rate. The p-value was found to be less than 0.0001 (p<0.0001), which validated this assumption. The ventilation rate had a greater correlation with outdoor temperature than indoor temperature with R²-values of 0.835 and 0.725 respectively. Both factors had p-values of 0, thus adding significance to the model, however the R²-value dictates that outdoor temperature explained more of the variability in the data than indoor temperature. Lastly, the barn temperature was modelled with outdoor temperature, yielding an R²-value of 0.582, and a p-value of 0. Nevertheless, this demonstrated a strong relationship, proving that barn temperature is influenced by outdoor temperature.
The fall had the greatest change in ventilation, and temperature. The fall ventilation can be divided into three periods; i) high, summer-like ambient temperatures and ventilation rates (September 22nd – October 31st, 2017), ii) cooler temperatures and mid-range ventilation rates (November 1st – December 2nd, 2017) and iii) cold, winter-like ambient temperatures and low ventilation rates (December 3rd – December 21st, 2017). This is evident in Figure 33. The ventilation temperature profile mimics the summer trend, with high maximum peaks in the first 10 days. Both the indoor and ambient temperatures peaked around 30°C, which initiated maximum ventilation rates. There were five peaks in the fall period that reached the maximum ventilation rate, representing a series of five days with elevated daytime temperatures. The outdoor temperatures began to fall resulting in falling ventilation rates, where only a few 0.91 m on/off fans were running. Throughout October, as the outdoor temperature warmed, additional 0.91 m fans would turn on, however only reaching a maximum another two times. As the temperature started to drop, the 0.91 m fans would turn off leaving only one or two phases running along with the variable speed fans. On October 31st, 2017 the ventilation profile
drastically changed, as all of the 0.91 m on/off fans were turned off and covered for the season. This was done as the lower outdoor temperatures ensured they were not required. This is shown in Figure 33, as the peaks in ventilation now capped at approximately 75 000 m$^3$/hour which reflected full operation of the 0.61 m and 0.46 m fans. As the temperature outside decreased, smaller quantities of outdoor air were brought into the facility through the baffles, in attempt to maintain a comfortable indoor temperature. It is also evident that, as the temperature dropped below 0 °C, only the 0.46 m fans were operational. They are the smallest troughs shown on the graph. The last winter-like period, occurred in the beginning of December. The 0.61 m fans were turned off and covered with the exception of one of the four. The last week of ventilation in the fall saw only six of the 0.46 m fans and one of the 0.61 m fans operating, resulting in the lowest ventilation rate in the season. The fluctuation of the fall season resulted in a standard deviation from the seasonal mean of 73 %. In Figure 33, a step like function can almost be identified when looking from right to left. The smallest step represents the operation of the 0.46 m variable speed fans, the second step adds the 0.61 m variable speed fans and the third step and up represent the six phases of 0.91 m on/off fans.

To validate the significance of temperature on the summer ventilation rates four linear regression models were produced, the results are shown in Table 19 below.

<table>
<thead>
<tr>
<th>Linear Regression Model</th>
<th>R$^2$ value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilation rate ~ Barn Temperature</td>
<td>0.646</td>
<td>0</td>
</tr>
<tr>
<td>Ventilation rate ~ Outdoor Temperature</td>
<td>0.737</td>
<td>0</td>
</tr>
<tr>
<td>Ventilation rate ~ Barn Temperature + Outdoor Temperature</td>
<td>0.787</td>
<td>0, 0</td>
</tr>
<tr>
<td>Barn Temperature ~ Outdoor Temperature</td>
<td>0.591</td>
<td>0</td>
</tr>
</tbody>
</table>

The linear regression model relating ventilation rate to both barn temperature and outdoor temperature yielded the highest fit to the data, similar to the summer season although the fall season has a lower R$^2$-value. The p-value was 0 for both variables, proving that they add significance to the model. The barn temperature and outdoor temperature had a significant relationship with an R$^2$-value of 0.591 and p-value of 0. This value was slightly greater than the summer relationship, signifying that the temperatures had a greater correlation in the fall than the summer.
The winter had the lowest ventilation requirements of all the other seasons. The average winter ventilation was 18% of that of the summer and 40% of the fall. The y-axis shown on Figure 34 is only 20% of the y-axis for the summer and fall plots shown in Figure 32 and Figure 33, respectively. The large break in the outdoor temperature data was caused by logger failure. The outdoor temperature plummeted below -25 °C which caused the logger to fail. Over the winter season the number of operational fans varied. A breakdown of the number of operational fans over the season is given in Table 31 in Appendix B.

Table 20: Linear regression analysis for winter ventilation

<table>
<thead>
<tr>
<th>Linear Regression Model</th>
<th>$R^2$ value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilation rate ~ Barn Temperature</td>
<td>0.318</td>
<td>0</td>
</tr>
<tr>
<td>Ventilation rate ~ Outdoor Temperature</td>
<td>0.229</td>
<td>0</td>
</tr>
<tr>
<td>Ventilation rate ~ Barn Temperature + Outdoor Temperature</td>
<td>0.442</td>
<td>0, 0</td>
</tr>
<tr>
<td>Barn Temperature ~ Outdoor Temperature</td>
<td>0.059</td>
<td>0</td>
</tr>
</tbody>
</table>
The temperature had the least significant effect on ventilation rate in the winter associated with the varying number of operational fans. The number of fans operating at a given point changed thirteen times over the winter season. This influenced the relationship between temperature and ventilation as the ventilation would drastically change at the same temperature solely based on the number of operational fans. This was especially true for the winter season as the barn temperature bandwidth was the smallest of the seasons, at 3.7 °C. This caused a significantly lower relationship between ventilation and outdoor temperature, and barn and outdoor temperature. The $R^2$-value for the barn and outdoor temperature linear regression was 0.059. Although the correlation was much smaller, the $p$-value shows evidence that the relationship still has some significance. The outdoor temperature bandwidth was 29.9 °C, meaning, that even with large outdoor temperature fluctuations, there were minimal fluctuations in the barn temperature. This resulted in the lowest $R^2$-values for all of the linear regression models. The outdoor temperature had the lowest impact on the model in the winter compared to the other seasons. The model showed that ventilation had the greatest correlation when barn temperature and outdoor temperature were included in the model.

Hourly average ventilation rates were calculated to evaluate diurnal and seasonal patterns. The hourly average ventilation rates for summer, fall and winter seasons are shown in Figure 35, Figure 36, and Figure 37, respectively. The hourly mean is illustrated with error bars signifying one standard deviation from the mean. The same y-axis is used to depict the change in magnitude caused by seasonal variations.
Figure 35: Summer hourly average ventilation rates with one standard deviation

Figure 36: Fall hourly average ventilation rates with one standard deviation

Figure 37: Winter hourly average ventilation rates with one standard deviation
A clear diurnal pattern was present for the fall and summer ventilation as illustrated in Figure 35 and Figure 36. The ventilation rate increased during the day and decreased overnight. In the summer, the ventilation began to rise as early as 07:00, which is related to when the sun rises. The peak occurred at 14:00, which is generally the warmest time of day, and began decreasing after 17:00 as the evening sets in. The fall followed a similar trend as the summer, however at a much lower ventilation rate and with more variability in the data due to changing temperature regimes. The ventilation rate began to rise later in the day than in the summer, as the sun was not as strong. The rise began around 09:00 and peaked at 15:00, when it began to decrease over night. The overnight ventilation rate in the fall was lower than that of the summer as the summer experienced higher temperatures overnight in comparison to the fall. The winter did not follow the same diurnal pattern as the summer and fall seasons as the outdoor temperature had a lower impact on the ventilation rates.

### 5.2 Seasonal pollutant emissions

Ammonia and particulate matter concentrations were monitored in the facility every five minutes over the duration of the study. Measurement of the pollutant concentrations along with estimating the facility ventilation rate resulted in quantification of emission factors. The impacts of the daily activities in the barn, the management and composition of litter and excreta form a foundation for the evaluation of pollutants. The results from the real-time monitoring campaign for ammonia and particulate matter concentrations in the barn are discussed in the following section. A summary of the emissions and concentrations of ammonia and particulate matter are found in Section 5.3.

#### 5.2.1 Ammonia

Ammonia concentrations were monitored in the facility every 5 minutes using a 17C – chemiluminescence ammonia analyzer, for three consecutive seasons. Real time monitoring of ammonia over three seasons portrayed seasonal differences and allowed for evaluation of the impacts of litter and excreta on ammonia concentrations. The concentrations of ammonia that
were monitored over time for the summer, fall and winter season are shown in Figure 38, Figure 39, and Figure 40, respectively. The y-axis scale is constant for all three time series plots to illustrate the drastic change over the seasons.

NH₃ concentrations over the summer season were the lowest of the three seasons, with a maximum concentration of only 3.1 ppm. According to the National Farm Animal Care Council (2017), birds are able to detect ammonia at 5 ppm. The summer concentrations remained well below this threshold denoting that the birds likely could not detect NH₃ in the air. The average concentration was 0.81 ± 0.50. The lower concentrations of NH₃ are attributed to the high facility ventilation rates over the summer period. High exchanges of air diluted the concentrations by mixing fresh incoming air with barn air more frequently. As the ventilation of the facility was increased there was a greater negative pressure in the barn, which pulled fresh air in through the baffles and as a result increased the mixing of air. Consequently, there were greater emissions of barn air into the environment, however, at a much lower concentration of NH₃, as compared to the fall and winter seasons. In the summer there were no significant changes in the litter and
excreta parameters. The pH, NH$_4$-N, dry matter content and the percent composition of TKN as NH$_4$-N remained relatively constant over the 3 month period (refer to Section 5.1.2 for the detailed litter and excreta analysis). This is directly reflected in the ammonia concentrations in the facility over the summer, which portray few significant changes. Nonetheless, the data illustrates fluctuations, which were attributed to the manure cleanout schedule and litter accumulation which will be discussed in detail further in this section.

Figure 39: Fall ammonia concentration time series

The fall season had a much greater overall concentration of NH$_3$ of 9.37 ± 10.74 ppm. Figure 39 above illustrates the drastic fluctuation in NH$_3$ concentrations in the facility. The first month of the fall had low summer-like concentrations, the next month and half had greater concentrations of ammonia, and the last three weeks had very high concentrations of ammonia. The maximum concentration was 59.08 ppm, and the minimum concentration was 0.06 ppm. This exemplifies the significance of the change in concentration. The first factor that contributed to this change was the facility ventilation. As discussed in Section 5.1.3, the fall ventilation was divided into three periods; i) high, summer-like ambient temperatures and ventilation rates (September 22$^{nd}$ –
October 31st, 2017), ii) cooler temperatures and mid-range ventilation rates (November 1st – December 2nd, 2017) and iii) cold, winter-like ambient temperatures and low ventilation rates (December 3rd – December 21st, 2017). The first period of summer-like ventilation rates resulted in higher air exchanges diluting the concentration of ammonia, resulting in lower overall concentrations. The average concentration in the first period of the fall was 1.72 ± 1.41 ppm. On October 31st, the ventilation changed due to cooler temperatures and the boarding up of the 0.91 m fans. With only the 0.61 m and 0.46 m fans operating, the air exchange in the facility was decreased, with lower quantities of outside air being pulled through the baffles. Lower mixing of air caused the accumulation of ammonia in the facility, resulting in higher concentrations, as illustrated in Figure 39. The concentration of ammonia began to increase as of October 31st 2017. Over this period, the concentration fluctuated with higher peaks and low troughs. However, the concentration remained below 20 ppm, averaging 9.95 ± 3.69. The last period, with winter-like ventilation rates, began in early December and was as a result of three out of four 0.61 m fans being turned off and covered. Low ventilation rates decreased the quantities of incoming air by even more resulting in additional accumulation of ammonia. Figure 39 depicts the concentration of ammonia increasing drastically starting in early December. The average concentration in the last period was 27.84 ± 12.64 ppm, which is three times higher than the overall seasonal average. The next factor that contributed to the change of concentration of ammonia over the fall was the litter and excreta parameters. The main factor that changed the most over the fall was the pH levels in the litter. The pH gradually increased from 6.8 to 8.4 over the season. The pH level has a significant effect on the formation of NH₃ from NH₄-N. This is explained in Section 2.2.1 and illustrated in Figure 4. Approximating from Figure 4, a pH of 6.8 will have limited effects shifting the equilibrium in favor of NH₃ formation, however a pH of 8.4 can increase NH₃ formation by 30 – 40%. Furthermore, the NH₄-N content increased slightly in the litter nearing the end of the season. The combination of lower ventilation rates, a greater NH₄-N content and higher pH, explain the drastic increase in ammonia concentrations in December.
Figure 40: Winter ammonia concentration time series

The winter ammonia concentrations were measured on a new flock of birds that arrived in early January, 2018. The winter ammonia concentrations fluctuated drastically over the duration of the winter season. The winter can be divided into three periods as introduced in Section 5.1.2. The first period represents the start of the production cycle when Flock 2 was first introduced into the facility, the second period represents a transition zone as the hen, litter and manure conditions began to stabilize, and the third period represents Flock 2 at a stabilized, steady state. The first period had the highest ammonia concentrations averaging 40.68 ± 16.40 ppm, with a maximum measurement of 84.76 ppm. According to National Farm Animal Care Council (2017), the exposure beyond the range of 20 – 25 ppm is dangerous for hens and farm workers. This range was well exceeded during this period. The first factor that contributed to this magnitude of concentration were the low ventilation rates. The month of January had the lowest ventilation requirements attributed to low outdoor temperatures. This is illustrated in Figure 34 in Section 5.1.3. There were three to six of the 0.46 m fans operating and only one of the 0.61 m fans operating sporadically. For a breakdown of the number of fans operating in the winter refer
to Table 31 in Appendix B. This resulted in minimal air exchanges between the outdoor air and barn air and an accumulation of ammonia concentrations in the barn. The next factor that contributed to high concentrations of ammonia were the litter and excreta parameters. Firstly, the pH levels in first 5 weeks of winter were very high as illustrated in Figure 21 in Section 5.1.2. The average pH in the first 5 weeks was 8.4, which gradually decreased over the remainder of the season to 7.8. The next parameter was NH$_4$-N content which was very high in the litter in the first 5 weeks. The average in the first 5 weeks was 2368 ± 935 (mg/kg wet), which gradually reduced to an average of 853 ± 104 (mg/kg wet) in the last 5 weeks. The combination of increased NH$_4$-N content and high pH levels significantly favor the formation of NH$_3$, which explains the increased concentration in the first month. Lastly, the moisture content in the litter in the first 5 weeks was 10% higher than that at steady state. As described in Section 2.2.1 the abundance of water will favor microbial degradation of bacteria causing increased releases of NH$_3$. It also caused accumulations of wet piles of litter on the floor. The transition zone began in early February and was triggered by two management activities in attempt to reduce the concentration of ammonia. The first was a dietary manipulation to reduce the moisture content in the excreta. The second was manually cleaning out the accumulated piles of litter on the floor and replenishing the litter floor with bedding (wood chips/shavings). These two activities were successful and resulted in a decrease in the concentration of ammonia, pH, NH$_4$-N content, and the moisture content. As illustrated in Figure 40, there are significant peaks and troughs. This is especially evident in the transition zone from February to March, 2017. While the ammonia concentrations fluctuated, there is a general trend of the peaks reaching the highest values on Tuesdays with slightly lower peaks of Fridays. These peaks and troughs are correlated to the manure-cleanout periods performed on Tuesdays and Fridays. Manure accumulated on one of the 10 manure belts, which gradually increased the concentration of ammonia, due to volatilization from the excreta surface, and drastically decreased the concentration as the excreta was removed from the facility. Further discussion on manure cleanouts will follow later in this section. Overall, the winter had an average concentration of 21.27 ± 14.94 ppm. The results from the winter campaign show the importance of hen, litter and manure management on the ammonia concentrations in the facility.
A statistical analysis was performed to identify the significance of litter and excreta parameters on ammonia concentrations in the facility. A series of 14 linear regressions were performed to identify the $R^2$-value and the associated p-value. It should be noted that a p-value of 0 identifies a value less than 0.0001 ($p<0.0001$). The results are shown in Table 21 below. A p-value marked in green demonstrates a significant relationship whereas a p-value marked in red demonstrates that the variable did not add significance to the model.

Table 21: Linear regression analysis of litter and manure samples with ammonia concentrations

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Linear Regression Model</th>
<th>$R^2$ value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$NH_3 \sim$ Litter pH</td>
<td>0.626</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>$NH_3 \sim$ Litter $NH_4$-N content</td>
<td>0.712</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>$NH_3 \sim$ Litter dry matter content</td>
<td>0.348</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>$NH_3 \sim$ % composition of $NH_4$-N of TKN in litter</td>
<td>0.728</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>$NH_3 \sim$ Litter pH + litter $NH_4$-N + Litter dry matter</td>
<td>0.883</td>
<td>0, 0.433</td>
</tr>
<tr>
<td>6</td>
<td>$NH_3 \sim$ Manure pH</td>
<td>0.110</td>
<td>0.033</td>
</tr>
<tr>
<td>7</td>
<td>$NH_3 \sim$ Manure $NH_4$-N content</td>
<td>0.095</td>
<td>0.051</td>
</tr>
<tr>
<td>8</td>
<td>$NH_3 \sim$ Manure dry matter content</td>
<td>0.077</td>
<td>0.080</td>
</tr>
<tr>
<td>9</td>
<td>$NH_3 \sim$ % composition of $NH_4$-N of TKN in Manure</td>
<td>0.041</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>$NH_3 \sim$ Manure pH + Manure $NH_4$-N + Manure dry matter</td>
<td>0.305</td>
<td>0.051, 0.006, 0.067</td>
</tr>
<tr>
<td>11</td>
<td>$NH_3 \sim$ Litter pH + litter $NH_4$-N + Litter dry matter + Manure pH + Manure $NH_4$-N + Manure dry matter</td>
<td>0.889</td>
<td>0, 0.393, 0.838, 0.392, 0.206</td>
</tr>
<tr>
<td>12</td>
<td>$NH_3 \sim$ Barn Temperature</td>
<td>0.474</td>
<td>0</td>
</tr>
<tr>
<td>13</td>
<td>$NH_3 \sim$ Barn Relative Humidity</td>
<td>0.353</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>$NH_3 \sim$ Barn Temperature + Barn Relative Humidity</td>
<td>0.559</td>
<td>0, 0.010</td>
</tr>
</tbody>
</table>

The first 5 tests were performed on characteristics of the litter. The linear regression of $NH_3$ with pH had a high $R^2$-value denoting a high correlation between $NH_3$ concentration and litter pH. The associated p-value was 0, proving that pH is significant to the model. The 2$^{nd}$ and 4$^{th}$ linear regression ($NH_3$ with $NH_4$ –N and $NH_3$ with % composition of $NH_4$-N of TKN) have the highest $R^2$-values for single variable regressions, which show that they are both highly correlated with ammonia concentrations. Both parameters are significant to the model as expressed by the p-value. The dry matter content of the litter had the lowest $R^2$ value meaning it had a lower relationship with ammonia concentrations as compared to the three prior characteristics. However, the p-value still identified dry matter content as a significant factor. The 5$^{th}$ test performed included pH, $NH_4$-N content and dry matter content. This test had the highest $R^2$-value of 0.883. Based on the p-value, the litter pH and $NH_4$-N content added significance to the
model, however the dry matter content had a p-value > 0.05 indicating that it was not a significant factor.

Another 5 tests were performed on the characteristics of the manure. The results from the linear regressions for manure were less significant as it was difficult to encompass the effects of manure-cleanout, which lowered the accuracy of the tests. Based on the results, manure pH and the composition of TKN as NH₄-N were significant variables as their p-values were less than 0.05. Dry matter content and NH₄-N content were not significant as their associated p-values were greater than 0.05. The R²-values were very small for all of the single variable regressions showing low correlation between the manure characteristics and NH₃ concentrations. Test 10 included manure pH, NH₄-N content and manure dry matter content. Based on the results from this test, pH and dry matter content were not significant, however NH₄-N was significant. The 11th test included the litter and manure parameters, which generated the best model, with an R²-value of 0.889. However, based on the p-values, the only two parameters that added significance to the model were litter pH and NH₄-N content.

The last 3 tests were performed to identify the relationship of barn temperature and relative humidity on NH₃ concentrations. Barn temperature had a greater R²-value than relative humidity, indicating a stronger relationship with temperature than humidity. This is shown again in test 14, where both barn temperature and relative humidity were added into the model. The resulting R²-value was the highest of the 3 tests, and both variables were deemed significant based on the p-value.

The concentration of ammonia was averaged on a weekday, and hourly basis to evaluate the effects of manure cleanout. The summer concentrations were plotted on a different y-axis than the fall and winter plots, in order to visualize the weekly trend. The weekly averages for summer, fall and winter seasons are shown in Figure 41, Figure 42, and, Figure 43 respectively.
The manure cleanout periods occurred twice weekly, on Tuesdays and Fridays. The timing fluctuated based on staff availability, however, was generally between the hours of 10:00 and 14:00. The weekly average analysis above illustrates that the concentration of ammonia increases and peaks on Tuesdays, and then is reduced. Another peak occurs on Friday, however it was not as significant as the Tuesday peak. This is because there was one extra day associated with the Tuesday cleanout for the manure to accumulate compared to the Friday cleanout. The trend is
best illustrated in the winter season shown in Figure 43. The peak on Tuesday is a point-like peak which illustrates the spike in concentration as the manure belts are being operated. The manure that has been accumulating on the manure belt for 4 days, forms a crystal-like exterior. The operation of the belt and removal of the manure aggravates the manure breaking up the exterior. When this crystal barrier is fragmented, there are rapid releases of ammonia, causing a spike in the overall concentration. Once the removal is completed and the manure belts are bare, the concentrations are decreased. A similar spike can be seen on Friday, however at a lower concentration, as only 3 days of accumulated manure are removed.

The lower ammonia concentration at the end of Tuesday and Friday, and early into Wednesday and Saturday, are associated to the ammonia released from litter. This low point in ammonia concentration was considered the baseline concentration from the litter accumulation. The litter was always present in the facility, and contributed to the ammonia concentrations. The weekly average graph depicts the contribution from manure accumulation and litter baseline. Litter baseline concentrations were calculated by taking an average of Tuesday/Wednesday and Friday/Saturday, from 18:00 – 03:00. The litter baseline concentrations for the summer, fall and winter were 0.55 ± 0.11, 7.86 ± 0.45 and 15.73 ± 2.43 ppm, respectively. The weekly average analysis graphs also depict a diurnal trend in the ammonia concentrations as the ammonia levels increase during the day and reduce at night. This is especially evident in the summer and winter plot (Figure 41 and Figure 43, respectively).

To investigate the diurnal patterns further, hourly averages were calculated for ammonia concentrations as well as ammonia emission factors for each season and are illustrated in Figure 44 below:
A diurnal pattern is evident in the hourly means for ammonia concentration in winter and emission factors in summer, fall and winter. This pattern is seen repeatedly in the time series data but, due to changing magnitudes, the standard deviations become quite large. The emission factors have a diurnal pattern due to increased ventilation rates throughout the day, and reduced rates overnight. Emission factors are a factor of ventilation, concentration and activity factor, and thus the diurnal pattern from ventilation is highlighted in the emission factors. The ammonia
concentration shows evidence of having a diurnal pattern as seen in the winter hourly and the weekly averages shown in Figure 41, Figure 42, and Figure 43, respectively. This is attributed to the movement of the birds, and spike in fresh manure during hours of illumination. The birds remain in their nesting areas for the duration of the night, and are free to move around in the day. As the birds emerge from their nesting boxes, they typically expel excreta during the day, which could contribute to higher daytime emissions. Warmer daytime temperatures may also contribute to higher daytime ammonia releases as higher temperatures favor ammonia formation.

A three-week period was selected from each season to illustrate the concentration, ventilation rate and resulting emission factor and is shown in Figure 45. The winter season was divided into two columns, reflective of barn specific events. The summer is shown in the first column (a), the fall in the second (b) the beginning of flock 2 in the winter is shown in the third column (c-1) and the fourth column depicts the winter as flock 2 conditions when stabilized (c-2). Manure belt cleanout periods are shown with dashed vertical lines. The shaded red line shows the ammonia concentration threshold (20 – 25 ppm) that is considered harmful according to the National Farm Animal Care Council (2017).
Figure 45: Concentration, ventilation rate and resulting emission factor of ammonia for summer (a), fall (b) and two winter periods (c-1) corresponding to the beginning of Flock 2 and (c-2) corresponding to when conditions had stabilized for Flock 2.
Ammonia concentrations in the summer were much smaller than the fall and winter concentrations and thus can barely be seen in the graph. The summer ventilation rate was significantly greater than the other seasons. The very low concentrations and very high ventilation rates resulted in emission factors that are visible on the graph, but still the lowest of the three seasons. The fall and winter ammonia concentrations follow a similar trend, and increase up to a dashed vertical line (signifying a manure cleanout), and decreasing following the cleanout. The dashed vertical lines are aligned with the majority of the greatest peaks in concentration showing that, prior to manure cleanouts, the concentration was at the highest, caused by an accumulation of manure on the belt. Following a manure cleanout, the concentration dropped and slowly climbed until the next cleanout event. The fall and winter ventilation rates are much lower than the summer. This resulted in the ammonia concentration being the main driving force of the emission factor. This is evident in the winter (c-1), as the ventilation rate was very small, but the ammonia concentration was very high. The overall emission factor was high as a result of high in house ammonia concentrations. The winter (c-2) had a slightly higher ventilation rate than winter (c-1) but the lower ammonia concentrations, still resulted in lower overall emission factors. The emission factors for the summer, fall and winter seasons are illustrated in Figure 46.

The summer had the lowest ammonia emission factors which were relatively consistent with minor fluctuations. The fluctuations were primarily a factor of diurnal ventilation patterns and manure belt cleanouts. The fall emission factors changed drastically over the season. The first
The month of the season had low ammonia concentrations and high ventilation rates, resulting in lower emission factors. The middle of the season had higher ammonia concentrations and lower ventilation rates which resulted in slightly higher emission factors than the first part of the season. The last month had very high ammonia concentrations, and lower ventilation rates, resulting in ammonia being the driving force behind the high emission factors. The winter had significant emission factors at the start of the season attributed to the high ammonia concentrations caused by higher pH, NH$_4$-N and moisture content of the litter. Although the winter initially had lower ventilation requirements, caused by lower outdoor temperatures, the high ammonia concentrations resulted in higher emission factors. The transition period for the winter ammonia concentrations gradually reduced the emission factor, however with some fluctuations. These fluctuations were associated with the ventilation rate and the change in number of operational fans. The period of steady state in the winter showed a reduced emission factor, and then increased at the end of the winter period. A drop in the ventilation rate caused this small dip in the winter as seen in Figure 34. Overall, the summer, fall, and winter emission factors averaged 22.94 ± 9.72, 96.50 ± 106.11 and 124.78 ± 76.88 g day$^{-1}$ AU$^{-1}$, respectively. The large standard deviations are attributed to the diurnal ventilation patterns. The overall emission factor of the cage-free facility was 81.41 ± 42.92 g day$^{-1}$ AU$^{-1}$.

### 5.2.2 Particulate matter

Particulate matter (PM$_{2.5}$ and PM$_{10}$) concentrations were monitored every 5 minutes using two DustTrak aerosol monitors for three consecutive seasons. An average was taken from the two sampling ports to represent the facility concentration. Only one monitor at one sampling location was used if a logger failed or was under maintenance. The entire winter season used only one monitor located at the north side of the facility. Results from the real-time monitoring campaign for the summer, fall and winter seasons, for PM$_{2.5}$ and PM$_{10}$ are illustrated in Figure 47, Figure 48, and Figure 49, respectively. The y-axis is constant for all three seasons to easily illustrate the seasonal differences.
The summer had the lowest particulate matter concentrations of all three seasons. The seasonal averages for PM$_{2.5}$ and PM$_{10}$ were 0.405 ± 0.426 and 0.861 ± 0.994 respectively. During the summer, the ventilation rates were very high resulting in lower retention times. Particulate could settle more easily or be mixed with incoming air diluting the concentration. The summer campaign was divided by a break from August 21$^{\text{st}}$ – September 9$^{\text{th}}$, 2017. Figure 47 illustrates that the concentration of both PM$_{2.5}$ and PM$_{10}$ increased after the break in sampling. The average temperature and relative humidity in the barn remained relatively constant averaging 25.20 ± 1.10 °C and 61.47 ± 7.21 % before the break, respectively, and, 24.71 ± 0.89 °C and 61.23 7.69 % after the break, respectively. This could not explain the change in concentration between the
two breaks. The dry matter content averaged 81.5 ± 3.04 % before the break and 77.63 ± 3.89 % after the break indicating that the moisture content of the litter increased after the break which should have theoretically resulted in lower particulate emissions. An accumulation of litter material may explain the increased emissions after the two-week break. As more excreta is left on the litter floor it accumulates along with feathers, skin and dander. This added material can easily be entrained in the air due to the scratching and dust bathing of the birds, consequently increasing the overall concentration of PM.
The fall is segregated into three parts divided by breaks in the real-time monitoring campaign. This was caused by logger failure and maintenance. The concentration of particulate matter (PM$_{10}$ and PM$_{2.5}$) was the highest in the first part of the season, up to approximately October 20$^{th}$, 2017. During this one-month period in the fall, the average dry matter content was higher than the average for the season, averaging 83.5 $\pm$ 2.21 %. The increased dry matter content caused particulate in litter to be more easily disrupted into small dry particles and become suspended in air. The first period also had the highest average temperature and lowest relative humidity which is known to increase particulate concentrations. The average temperature and relative humidity were 24.74 $\pm$ 1.51 °C and 58.98 $\pm$ 7.27 %, respectively. The next two periods
in the fall, had similar concentrations of particulate, with the exception of the last two weeks. The average dry matter content during this period was 80.5 ± 1.47 %. The lower dry matter led to lower concentrations of PM$_{2.5}$ and PM$_{10}$. The temperature and relative humidity were lower than the first period averaging 24.06 ± 0.35 °C and 60.06 ± 3.74 %, respectively, which could have contributed to the lower formation of PM. The last two weeks of the fall season had the lowest dry matter content (or wettest litter) resulting in a very low concentration of PM$_{2.5}$ and PM$_{10}$, as illustrated in Figure 48 after December 11$^{th}$, 2017. The average dry matter content in the last two weeks of the fall was 78.6 ± 0.45 %. The last two weeks also had the lowest temperature and highest relative humidity, averaging 23.96 ± 0.23 °C and 65.41 ± 3.06 % respectively, resulting in lower generation of PM.

The peaks in particulate concentration occur during the daytime while the troughs occur during the nighttime. Each individual peak/trough cycle represents one day. This is caused by the activity of the birds in the daytime and the lack of activity at nighttime, when the birds have returned to their nesting boxes. The overall PM$_{2.5}$ and PM$_{10}$ concentrations in the fall were 0.694 ± 0.958 and 1.24 ± 1.82 respectively. The standard deviation for the fall average was very significant demonstrating the large variation in the data. The data showed diurnal patterns but also changed significantly throughout the season.
The winter had the greatest concentrations of both PM$_{10}$ and PM$_{2.5}$. The winter data is split into two parts divided by a break for monitor maintenance. The first period reflects the beginning of Flock 2 during the high ammonia event. The dry matter content hit the lowest of all of the seasons, reaching 70.56 ± 2.35 %. The moisture in the litter was so high that accumulated piles of wet litter began forming resulting in very low formation of PM$_{10}$ and PM$_{2.5}$. During this period, the average temperature was lower and the relative humidity was higher averaging 21.85 ± 0.39 °C and 68.67 ± 4.21 %, respectively. After the break, the concentration of particulate matter increased drastically. The average dry matter content for the remainder of the winter was 82.29 ± 1.75 % which is 12% higher than the first period. This increase had a drastic effect on
particulate emissions, allowing for small dryer particles to be easily entrained in air. The daytime peaks of PM$_{10}$ were much more significant attributed to reduced air exchanges in the winter months which would allow particulate matter to accumulate in the barn air without much settling. The overall winter PM$_{2.5}$ and PM$_{10}$ concentrations were $2.94 \pm 2.84$ and $6.17 \pm 6.24$, respectively.

A linear regression analysis was performed on the particulate matter concentrations to validate the implications of temperature, relative humidity and dry matter content. A series of 8 tests were performed, and the associated $R^2$-value and p-values are shown in Table 22 below. The p-values marked in red reflect non-significant variables, whereas the p-values marked in green represent variables that add significance to the model.

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Linear Regression Analysis</th>
<th>$R^2$-value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PM$_{10}$ ~ litter dry content</td>
<td>0.003</td>
<td>0.742</td>
</tr>
<tr>
<td>2</td>
<td>PM$_{10}$ ~ barn temperature</td>
<td>0.005</td>
<td>0.670</td>
</tr>
<tr>
<td>3</td>
<td>PM$_{10}$ ~ barn relative humidity</td>
<td>0.002</td>
<td>0.714</td>
</tr>
<tr>
<td>4</td>
<td>PM$_{10}$ ~ barn temperature + relative humidity</td>
<td>0.006</td>
<td>0.742, 0.898</td>
</tr>
<tr>
<td>5</td>
<td>PM$_{2.5}$ ~ litter dry content</td>
<td>0.0004</td>
<td>0.904</td>
</tr>
<tr>
<td>6</td>
<td>PM$_{2.5}$ ~ barn temperature</td>
<td>0.466</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>PM$_{2.5}$ ~ barn relative humidity</td>
<td>0.041</td>
<td>0.245</td>
</tr>
<tr>
<td>8</td>
<td>PM$_{2.5}$ ~ barn temperature + relative humidity</td>
<td>0.474</td>
<td>0, 0.488</td>
</tr>
</tbody>
</table>

The results from the statistical analysis did not result in any models that adequately predicted the variation in the PM concentrations as all of the tests had very small $R^2$-values, with the exception of test 6 and 8. The two significant tests performed were PM$_{2.5}$ concentrations with barn temperature and PM$_{2.5}$ concentrations with barn temperature and relative humidity. The $R^2$-values were 0.466 and 0.474 respectively, demonstrating a weak albeit significant correlation. The associated p-values for barn temperature obtained were 0, indicating barn temperature is a significant variable for PM$_{2.5}$ concentration. One explanation for this is the generation of secondary inorganic aerosols, typically in the PM$_{2.5}$ fraction, form faster at higher temperatures. Overall, the strong diurnal pattern in the particulate matter concentrations could not be modelled using a simple linear regression. The concentrations fluctuated drastically from day to night which influenced the overall daily mean concentration, making it more difficult to run an accurate statistical analysis.
To further investigate the diurnal pattern of particulate matter, hourly averages were obtained for the three seasons. The hourly average concentration and emission factors for PM$_{2.5}$ and PM$_{10}$ are illustrated in Figure 50 below. The summer is shown in the first column, followed by the fall in the second and the winter in the third. The same y-axis is used to better illustrate seasonal trends as well as diurnal trends. The first two rows illustrate the PM$_{2.5}$ concentration and emission factors, respectively, and the last two rows illustrate the PM$_{10}$ concentration and emission factors, respectively.
Figure 50: PM$_{2.5}$ and PM$_{10}$ hourly concentration and emission factors for each season

The diurnal pattern viewed above is caused by the activity of the birds during hours of illumination. Particulate matter concentration is directly related to the bird’s movement. During the hours of illumination, birds are free to exercise their natural behaviors such as foraging, dust
bathing, perching, scratching, and wondering around. All of these activities agitate the litter floor causing particles to be entrained and suspended into the air thus increasing the daytime concentrations. The combination of high daytime concentrations of particulate caused by bird activity and high daytime ventilation rates caused by warmer ambient temperatures, resulted in higher daytime emission factors as seen above.

To further demonstrate the effects of the lighting regime on particulate matter generation, a one-week snap shot during the summer, fall and winter is given in Figure 51 with the concentrations in the top panels, ventilation rates in the middle panels and emission factors on the bottom panels for PM$_{2.5}$ and PM$_{10}$. The shaded vertical bars represent the hours of darkness during a 24-hour period. The PM$_{2.5}$ and PM$_{10}$ concentrations were plotted against the same vertical axis to demonstrate the difference in magnitude.
Figure 51: Concentration (top panel), ventilation rate (middle panel) and emission factor (bottom panels) during a one-week period in each season for PM$_{2.5}$ (left panels for each season) and PM$_{10}$ (right panel for each season)
Figure 51 illustrates the diurnal trends of particulate concentrations and ventilation rates. The non-shaded vertical bars indicating illumination hours, which contain the peaks for both concentrations and ventilation rates. The drops in ventilation and concentrations occur within the shaded vertical lines indicating hours of darkness. This solidifies the assumption that particulate matter is primarily effected by animal activity.

The overall seasonal emission factors for PM$_{2.5}$ and PM$_{10}$ are shown in Figure 52 and Figure 53, respectively.

![Figure 52: Seasonal emission factors for PM$_{2.5}$](image)

![Figure 53: Seasonal emission factors for PM$_{10}$](image)

The overall summer, fall and winter average emission factors (g day$^{-1}$AU$^{-1}$) for PM$_{2.5}$ and PM$_{10}$ are given in Table 23.
Table 23: Seasonal average Emission Factors for PM$_{2.5}$ and PM$_{10}$

<table>
<thead>
<tr>
<th>Season</th>
<th>Emission Factor g day$^{-1}$ AU$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PM$_{2.5}$</td>
</tr>
<tr>
<td>Summer</td>
<td>21.24 ± 26.52</td>
</tr>
<tr>
<td>Fall</td>
<td>20.89 ± 39.98</td>
</tr>
<tr>
<td>Winter</td>
<td>32.64 ± 40.19</td>
</tr>
</tbody>
</table>

The summer emission factor is greater after the break in the x-axis as illustrated in Figure 52 and Figure 53. This is a result of higher particulate concentrations for both PM$_{2.5}$ and PM$_{10}$ as illustrated in Figure 47. Though the second portion is higher, it is not a drastic change. The significant standard deviation for the summer average is attributed to the diurnal fluctuations.

The fall begins with a very high emission factor, which is gradually reduced over the remainder of the season. This is attributed to two factors. The first is the elevated concentrations of particulate as a result of increased barn temperatures, lower relative humidity and high dry matter content. This is illustrated in Figure 48. The second factor that contributed to elevated emission factors is the high ventilation rates in the first part of the fall season as seen in Figure 33. The latter half of the fall season demonstrates significantly lower emission factors. This is a result of lower ventilation rates, caused by decreasing outdoor temperatures, and low particulate matter concentrations caused by lower temperatures, high relative humidity and low dry matter content. The fall emission factor was found to be less than the summer emission factor. The drastic change in ventilation and concentration in the latter portion of the fall season drastically reduced the overall emission factor. Although it is expected that the fall would produce a greater emission factor than the summer, the combination of environmental, litter and manure characteristics and manual adjustments of the fans reduced the overall fall factor. The fall had a significant deviation from the mean which is a result of the drastic change over the season, and the diurnal fluctuations. The winter had a lower emission factor for the first portion of the season as a result of higher moisture content in the litter and lower ventilation rates as seen in Figure 34. The latter portion of the winter season emission factors closely resembled the concentration profiles shown in Figure 49. This is because the ventilation rate was very low throughout the winter, causing the concentration to be the driving force in the overall emission factors for the winter season.
The daily average PM$_{2.5}$ to PM$_{10}$ ratio for each season is illustrated in Figure 54 as a bar chart and Figure 55 as a plot with standard deviations. In Figure 54, hourly concentrations of PM$_{2.5}$ are overlaid on hourly concentrations of PM$_{10}$ to demonstrate the how much of the PM$_{10}$ is composed of PM$_{2.5}$. The summer, fall and winter are plotted adjacent for each hour in pink, green and blue, respectively.

In Figure 55, average PM ratios for each hour throughout each season is given by a symbol along with error bars demonstrating one standard deviation from the mean. This further illustrates the diurnal pattern of particulate matter generation.
Figure 54: PM$_{10}$ & PM$_{2.5}$ Hourly concentration fraction
Figure 54 depicts the significance of seasonal changes on the concentration of \( PM_{2.5} \) and \( PM_{10} \), and the association \( PM_{2.5}/PM_{10} \) ratio. The summer and fall had very similar concentrations of \( PM_{2.5} \) and \( PM_{10} \) between the hours of 06:00 and 11:00. The fall had greater concentrations than the summer in the middle of the day, which is likely attributed to the reduced ventilation than in the summer. Comparatively, the winter which had the lowest ventilation rates, and the highest \( PM_{2.5} \) and \( PM_{10} \) concentrations throughout the whole 24-hour period. The concentration of \( PM_{10} \) in the winter is significantly greater than the summer and fall illustrated by the towering blue bars. It is also noticeable that the concentration of \( PM_{10} \) significantly increases and decreases between 06:00 – 19:00, whereas the \( PM_{2.5} \) remains relatively constant with some change. This trend is shown for all three seasons. This is primarily attributed to the bird activity during the day. Particles will be suspended in air as the birds move around, bathe in dust, and scratch. As the hens return to their nesting areas in the evening, the coarser particles will settle out faster than the smaller particles and thus change the \( PM_{2.5}/PM_{10} \) ratio.

Each season demonstrated a similar trend increasing overnight and decreasing during the day. This was caused by the bird activity in the facility during the daytime hours. The average ratios for \( PM_{2.5}/PM_{10} \) for summer, fall and winter were \( 0.55 \pm 0.18 \), \( 0.66 \pm 0.18 \) and \( 0.56 \pm 0.19 \), respectively. The overall mean for each season was statistically significant from one another \( (p < 0.05) \). The fall had the highest PM ratio compared to the summer and winter. The summer and winter seasons had very similar PM ratios, with winter having a slightly higher ratio overnight.
than the summer. This may be attributed to the formation of secondary aerosols causing an increase source of PM$_{2.5}$ in the fall. Typically, secondary inorganic aerosols (SIA) form faster at higher ambient temperatures, under low ventilation conditions (i.e. longer retention times in the barn), and when acid compounds are more abundant in the barn air.

The fall had a lower average barn temperature than the summer, but higher than the winter. The temperatures in the barn in the first few weeks of the fall were significantly higher than the remainder of the season, which could have caused an increase formation of SIA. The fall had large fluctuations over the season so it is difficult to identify the source causing the higher PM ratio. However, the higher ratio may be caused by the abundance of other acidic compounds, which may have contributed to the formation of SIA. Though this is not proven, other tests would need to identify the presence of other compounds. Although the summer had the highest ambient temperatures, ideal for the formation of SIA, the high ventilation rate likely significantly reduced the formation of SIA, resulting in lower overall PM$_{2.5}$ concentrations. The summer and winter seasons had very similar PM ratios, with winter having a slightly higher ratio overnight than the summer. The winter had the lowest ambient temperatures and ventilation rates. Despite having high retention times, the low ambient temperatures make it unlikely for SIA formation, which could explain the similar PM ratios in the summer and winter seasons.

5.3 Emission Summary

The overall seasonal pollutant results from the present study are recorded in Table 24. The concentration and emission factor for NH$_3$ and size fractioned particulate matter PM$_{2.5}$ and PM$_{10}$ for each season is shown in various units. One standard deviation from the mean is also recorded, to illustrate the variance of the data. The overall average of the entire sampling campaign is shown in the last row of the table.
Table 24: Overall Emission Summary

<table>
<thead>
<tr>
<th>Season</th>
<th>NH$_3$ Concentration [mg/m$^3$ [ppm]]</th>
<th>Emission Factor [g day$^{-1}$ AU$^{-1}$]</th>
<th>PM$_{2.5}$ Concentration [mg/m$^3$]</th>
<th>Emission Factor [g day$^{-1}$ AU$^{-1}$]</th>
<th>PM$_{10}$ Concentration [mg/m$^3$]</th>
<th>Emission Factor [g day$^{-1}$ AU$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>0.56 ± 0.34 [0.81 ± 0.50]</td>
<td>22.94 ± 9.72 [0.08 ± 0.03]</td>
<td>0.41 ± 0.43</td>
<td>21.24 ± 26.52 [0.07 ± 0.09]</td>
<td>0.86 ± 0.99</td>
<td>45.79 ± 60.47 [0.55 ± 0.18]</td>
</tr>
<tr>
<td>Fall</td>
<td>6.54 ± 7.50 [9.37 ± 10.74]</td>
<td>96.50 ± 106.11 [0.32 ± 0.35]</td>
<td>0.69 ± 0.96</td>
<td>20.89 ± 39.98 [0.15 ± 1.28]</td>
<td>1.24 ± 1.82</td>
<td>39.47 ± 74.99 [0.13 ± 0.25]</td>
</tr>
<tr>
<td>Winter</td>
<td>14.95 ± 10.53 [21.27 ± 14.96]</td>
<td>124.78 ± 76.88 [0.38 ± 0.23]</td>
<td>2.94 ± 2.84</td>
<td>32.64 ± 40.19 [0.10 ± 0.12]</td>
<td>6.17 ± 6.24</td>
<td>70.08 ± 86.94 [0.21 ± 0.27]</td>
</tr>
<tr>
<td>Overall</td>
<td>7.35 ± 5.90 [10.48 ± 8.39]</td>
<td>81.41 ± 42.92 [0.26 ± 0.13]</td>
<td>1.34 ± 1.13</td>
<td>24.93 ± 5.47 [0.11 ± 0.03]</td>
<td>2.76 ± 2.42</td>
<td>51.78 ± 13.19 [0.17 ± 0.04]</td>
</tr>
</tbody>
</table>
As illustrated in Table 24 the uncertainty is rather high for the majority of seasonal emission factors. This is attributed to the significant variation in ventilation rates throughout the season. Specifically the fall had the highest values of uncertainty, which is a result of the drastic ventilation changes from the start of the season to the end. As the data was collected for months at a time, there is a large variation in the ventilation requirements of the facility, which contributes to the level of uncertainty.

The results from this study were compared to similar studies on cage-free layer facilities to evaluate the similarities and differences. Two United States studies were considered and their associated results are given in Table 25. Both studies are reviewed in detail in Section 2.3.1.

Table 25: Comparison of emission factors for NH3 and particulate matter between two other cage-free layer facilities studied in the United States

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>California</td>
<td>Iowa</td>
<td>Ontario</td>
</tr>
<tr>
<td>NH3 (g day(^{-1}) AU(^{-1}))</td>
<td>83.3 ± 67</td>
<td>41 ± 23</td>
<td>81.41 ± 42.92</td>
</tr>
<tr>
<td>PM(_{2.5}) (g day(^{-1}) AU(^{-1}))</td>
<td>5.5 ± 3.8</td>
<td>2.1 ± 1.7</td>
<td>24.93 ± 5.467</td>
</tr>
<tr>
<td>PM(_{10}) (g day(^{-1}) AU(^{-1}))</td>
<td>47.2 ± 17.9</td>
<td>29.5 ± 11</td>
<td>51.78 ± 13.19</td>
</tr>
</tbody>
</table>

The results from this study closely resembled the results from the study in California on a cage-free layer facility with manure belt removal twice weekly, performed by Lin et al., (2017). The main difference between the results was the PM\(_{2.5}\) emission factor in this study, which was 4.5 times higher than that reported by Lin et al., (2017). The NH3 emission factor from the Lin et al., (2017) study was 1.02 times higher than that from this study. The PM\(_{10}\) emission factor from this study was 1.09 times higher than the Lin et al., (2017) study. This is less than 10% variation between the studies, with respect to NH3 and PM\(_{10}\). A similar study on an aviary system in Iowa, performed by Hayes et al (2013) reported slightly lower emission factors. The current study had almost 2 times greater NH3 emissions, 11 times greater PM\(_{2.5}\) emissions and 1.75 times greater PM\(_{10}\) emissions. Overall, the California study had the most similar results to this study.
6 Comparison to Conventional Battery Cage Facilities

A study conducted by Morgan et al. (2014) developed emission factors resulting from a Canadian commercial laying hen facility using conventional battery cages with manure belts operated twice a week. The battery cage facility was located approximately 70 km from the location of the current cage-free facility. Due to the geographical proximity of the facilities, similar climate conditions (albeit different years) and similar manure belt operations, they are ideal for comparison. Seasonal and overall emission factors for NH₃, PM₂.₅ and PM₁₀, for the present study and Morgan et al. (2014) are reported in Table 26. The ratio of emission factors for cage-free to batter cage systems was calculated to demonstrate the difference in magnitude.

Table 26: Comparison of emission factors for NH₃ and particulate matter between a conventional battery cage facility (Morgan, et al., 2014) and a cage-free facility (present study), both located in Ontario, Canada

<table>
<thead>
<tr>
<th>Emission Factor</th>
<th>Morgan et al. (2014)</th>
<th>Present study</th>
<th>Ratio of EFs for cage-free to battery cage systems</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conventional battery cage facility</td>
<td>Cage-free facility</td>
<td></td>
</tr>
<tr>
<td>NH₃ (g day⁻¹ AU⁻¹)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>8.13</td>
<td>22.94</td>
<td>2.82</td>
</tr>
<tr>
<td>Fall</td>
<td>12.97</td>
<td>96.50</td>
<td>7.44</td>
</tr>
<tr>
<td>Winter</td>
<td>28.89</td>
<td>124.78</td>
<td>4.31</td>
</tr>
<tr>
<td>Overall</td>
<td>19.53</td>
<td>81.40</td>
<td>4.17</td>
</tr>
<tr>
<td>PM₂.₅ (g day⁻¹ AU⁻¹)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>2.46</td>
<td>21.24</td>
<td>8.63</td>
</tr>
<tr>
<td>Fall</td>
<td>0.23</td>
<td>20.89</td>
<td>90.83</td>
</tr>
<tr>
<td>Winter</td>
<td>0.3</td>
<td>32.64</td>
<td>108.9</td>
</tr>
<tr>
<td>Overall</td>
<td>1.1</td>
<td>24.93</td>
<td>22.66</td>
</tr>
<tr>
<td>PM₁₀ (g day⁻¹ AU⁻¹)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>2.51</td>
<td>45.79</td>
<td>18.24</td>
</tr>
<tr>
<td>Fall</td>
<td>2.73</td>
<td>39.47</td>
<td>14.45</td>
</tr>
<tr>
<td>Winter</td>
<td>2.82</td>
<td>70.08</td>
<td>24.85</td>
</tr>
<tr>
<td>Overall</td>
<td>2.55</td>
<td>51.78</td>
<td>20.31</td>
</tr>
</tbody>
</table>

For NH₃ and both size fractions of particulate matter, the cage-free facility had a greater emission factor in comparison to the battery cage system. While the emission factor for NH₃ was only 4.2 times larger than that for the conventional battery cage system, emission factors for PM₂.₅ and PM₁₀ were on the order of 20 times greater. The increase in ammonia levels can be explained by the fact that the majority of excreta is removed by the manure belts twice a week in the cage-free system. However, due to the hen’s ability to move around and the litter placed on
the pen floor, hens will deposit excreta on the litter substrate, which does not get removed until
the flock is depopulated. Thus, unlike in a conventional battery cage system where nearly all the
excreta is removed on the belts (also twice weekly), the cage-free system allows for an
accumulation of some excreta as a source for bacteria to convert the nitrogen into NH₃. This
creates a source for baseline concentrations of ammonia, which is illustrated and discussed in
Section 5.2.1. The accumulation of litter on the floor also impacts dust formation. The large
increases in PM emission factors support what operators have said anecdotally stated that cage-
free facilities are dustier than conventional battery cage facilities. Allowing the hen the freedom
to express natural behaviors in a cage-free system, such as scratching and dust bathing, does
entrain more particulate matter into the barn air.
7 Conclusion

The average overall emission factor for ammonia was $81.41 \pm 42.92$ g day$^{-1}$ AU$^{-1}$ and was largely influenced by litter composition, ventilation and excreta removal. The winter produced the greatest emission factors due to the lower ventilation rate and greater ammonia build up. The first month of the winter measurement campaign produced drastically higher ammonia concentrations caused by higher levels of pH, moisture content and NH$_4$-N in the litter in the facility. The summer had the lowest NH$_3$ emission factors attributed to the greater exchanges of air caused by increased ventilation rates which dried out the excreta.

The average overall emission factors for PM$_{2.5}$ and PM$_{10}$ were $24.93 \pm 5.467$ and $51.78 \pm 13.19$ g day$^{-1}$ AU$^{-1}$ respectively. The overall fall particulate matter emission factor was found to be less than the summer, as there was a period of high concentration and high ventilation in the first few weeks of the fall season, followed by a period of drastically lower ventilation and concentrations. The lower concentrations were attributed to higher moisture content in the litter, higher relative humidity and lower barn temperatures. This lowered the overall fall emission factor reading. The winter had the highest emission factor attributed to lower ventilation requirements. The concentration of PM$_{10}$ was heavily influenced by bird activity driven by periods of illumination. The average ratios for PM$_{2.5}$/PM$_{10}$ for summer, fall and winter were $0.55 \pm 0.18$, $0.66 \pm 0.18$ and $0.56 \pm 0.19$, respectively.

The results from this study closely resembled a study performed by Lin et al., (2017) in California on a cage-free layer facility with manure-belt removal twice weekly. The NH$_3$ and PM$_{10}$ emission factors varied less than 10% from one another. The PM$_{2.5}$ emission factor on the other hand had a large variation between studies. A study performed by Hayes et al., (2013) in Iowa had lower emissions than the present study, and the study by Lin et al., (2017) however the results were still significant in comparison to conventional battery cage facilities.

The emission factors found in this study were much higher than those determined by Morgan et al. (2014) from a conventional battery cage facility. The emission factors of NH$_3$, PM$_{2.5}$ and PM$_{10}$ were 4.2, 22.7 and 20.3 times higher than the results produced by Morgan et al. (2014).
This is attributed to the freedom of the birds to access the litter floor, dust bathe, scratch and kick up dust and the accumulation of litter on the floor over the 52-week production cycle.

The results from this study show that litter and manure management is crucial to minimize emissions of NH$_3$ and size fractioned particulate matter. In cage-free systems, the accumulated litter on the floor creates a baseline emission of NH$_3$ that is not affected by manure removal. Small changes in manure and litter characteristics can have significant implications on emissions, as seen at the end of the fall and the beginning of the winter campaign. Dietary manipulation is sometimes required to reduce the moisture content of excreta to maintain an acceptable NH$_3$ concentration in the facility.

The outdoor temperature drove the ventilation rate of the facility. Through a statistical analysis the linear regression of ventilation with barn temperature and outdoor temperature yielded the strongest correlation. It was concluded that the fall and winter seasons had lower relationships between temperature and ventilation attributed to a change in the number of operational fans. This negatively impacted the significance of the temperature, ventilation linear regression.
8 Recommendations

The following recommendations are meant to help other students or researchers in future projects of a similar nature. These recommendations stem from difficulties encountered in this project, and are meant to act as guidance for those who will face similar tasks. They highlight tips that may be useful if similar equipment will be used. The recommendations also aim to identify next steps to further develop research in this area of focus.

- To ensure there is minimal moisture build-up in the sampling line it is recommended to insulate the sample line between the analyzer and the end of the heated sample line. The climate-controlled trailer stayed relatively warm in the coldest winter months, however the drastic change in temperature of the air leaving the heated sample line (124°C), running the length of the trailer (15-25°C) to the analyzer caused condensation in the line, which accumulated in the filter house. Insulating that part of the sample line could reduce the amount of condensation occurring.

- If using current sensors to monitor the fans operation, it is recommended to have a secondary monitoring technique for the variable speed fans. The ON/OFF fans worked well with current sensors, as it was easy to identify when the fans were powered OF vs OFF. However, the variable speed fans did not follow any specific trends in regards to current supply. Thus, having a secondary monitoring technique such as monitoring set-point temperature, static pressure, or fan activity directly with the barn control unit is imperative.

- To monitor fan activity, especially in the fall and winter seasons when minimum ventilation fans are running, it is recommended to use a smaller averaging period, (i.e. 1 minute, instead of 5) as the ventilation changes frequently. A larger averaging period may not capture the change of fan staging by either over estimating the current or underestimating depending on when the stage changed within that period. A shorter sampling interval will increase the accuracy of fan stage monitoring.
• It is recommended to test current sensors during minimum ventilation periods if the number of fans within a given stage is changed. (i.e. usually runs with 6 but, in minimum ventilation period, runs only 4 out of 6 fans).

• When monitoring dust (PM$_{10}$ & PM$_{2.5}$) it is recommended that the monitoring campaign run for a maximum of 24-48 hours at a given time. The equipment reaches its capacity of dust and backlogs causing inaccurate readings if running in dusty environments for longer than 48 hours. Running multiple 1-2 day sampling periods will yield more accurate results.

• It is recommended that barometric pressure be monitored to use in the unit conversion from ppm to mg/m$^3$ of NH$_3$, instead of atmospheric pressure for increased accuracy. Monitoring static pressure in the facility may also prove to be useful when identifying fan activity and the magnitude of air entering the facility.

• It is recommended that FANS testing be performed in warmer weather. Cold temperatures affect the adhesiveness of duct tape, which may impact the connection between the FANS unit and the exhaust cone. The use of stronger adhesive tape that is not affected by the cold or other connection materials to effectively create a tunnel between the fan and the FANS unit is strongly recommended.

• Further error propagation analysis should be conducted to evaluate the uncertainty of the FANS unit and ventilation monitoring in determining the flow rate of the facility.

• Depending on typical ambient temperatures, it is recommended to evaluate the performance of temperature and humidity sensors, to ensure the loggers will not fail at extreme temperatures.

• Further research should investigate emissions from cage-free facilities in Western Canada, to evaluate the impacts of geographic location and climate.
REFERENCES


decay method with Kr, compared to CO2 mass balance and discharge coefficient methods. *Biosystems Engineering*, 286-296.


Muller, H. J., & Muller, S. (1994). The determination of emission streams from livestock buildings with different tracer gasses. Fourth International Conference on Air Distribution in Rooms (pp. 529-542). ROOVENT '94.


APPENDIX A: SAMPLE CALCULATION

Emission factor calculation performed on raw data from winter campaign, January 19, 2018 at 14:00, where,

Table 27: Raw data from winter campaign pulled from January 19th 2018 at 14:00

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH₃ concentration (ppm)</td>
<td>12.93</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>21.89</td>
</tr>
<tr>
<td>Molecular weight of NH₃ (g/mol)</td>
<td>17.03</td>
</tr>
<tr>
<td>Barometric Pressure (Pa)</td>
<td>101325</td>
</tr>
<tr>
<td>Universal Gas Constant (Pa m⁴ mol⁻¹ K⁻¹)</td>
<td>8.314</td>
</tr>
<tr>
<td>Ventilation rate (m³/hour)</td>
<td>14204</td>
</tr>
<tr>
<td>Number of Birds</td>
<td>20863</td>
</tr>
<tr>
<td>Average mass of bird (g)</td>
<td>1382</td>
</tr>
</tbody>
</table>

Applying the following equation to get an NH₃ concentration in mg/m³:

\[
\left[ NH₃ \left( \frac{g}{m^3} \right) \right] = \frac{[NH₃ (ppm)] \times PM_w}{R(T + 273)}
\]

\[
\left[ NH₃ \left( \frac{g}{m^3} \right) \right] = \frac{[12.93 \times 10^{-5}] \times (101345) \times 17.03}{8.314 \times (21.89 + 273)} = 9.1 \times 10^{-3}
\]

The next step is developing an emission rate (ER) by multiplying the concentration with the ventilation rate. The emission rate is given by:

\[
ER \left( \frac{g}{day} \right) = [9.1 \times 10^{-3}] \times 14204 \frac{m^3}{hour} \times \frac{24 \; hour}{day} = 3102.3 \; g/day
\]

\[
AF = \frac{BM_{total}}{500 \; kg} = \frac{1.382 \times 20863}{500 \; kg} = 57.5 \; AU
\]

The resulting Emission factor relates the emission rate (ER) with the activity factor (AF) which is shown in the following equation:

\[
EF = \frac{3102.3}{57.6} = 53.9 \; g \; day^{-1} \; AU^{-1}
\]
The litter and manure analysis results reported NH₄-N (mg/kg wet) and Total Kjedhal Nitrogen (TKN) (% wet). A unit conversion was used to transform TKN (% wet) to TKN (mg/kg wet) to determine the percent composition of TKN as NH₄-N. The following unit conversion reported in a Nutrient Management Factsheet (Poon, 2010) was used:

\[
\text{TKN (mg/kg wet)} = \text{TKN (% wet)} \times 10000
\]

Calculation performed on raw data from a lab report from January 26th, 2018, where the litter TKN and NH₄-N content were reported as 1.84 (% wet) and 2830 mg/kg wet respectively:

\[
\text{TKN (mg/kg wet)} = 1.84 \times 10000 = 18400
\]

To get the % composition of NH₄-N of the TKN the following equation was applied:

\[
\% \text{ Composition of NH}_4 - N \text{ of the TKN} = \frac{\text{NH}_4 - N \left(\frac{\text{mg \ wet}}{\text{kg}}\right)}{\text{TKN (mg/kg wet)}} \times 100
\]

\[
\% \text{ Composition of NH}_4 - N \text{ of the TKN} = \frac{2830}{18400} \times 100 = 15.4 \%
\]
# APPENDIX B: VENTILATION

Table 28: Measurement techniques for ventilation in animal feeding operations (Wood, Cowherd, & Van Heyst, 2015)

<table>
<thead>
<tr>
<th>Measurement method</th>
<th>Relative accuracy</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naturally ventilated housing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tracer gasses</td>
<td>12-100</td>
<td>Jung and Zeller, 1994</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Muller and Muller, 1994</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Baptista et al., 1999</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Phillips et al., 2000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Demmers, 2001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Snell et al., 2003</td>
</tr>
<tr>
<td></td>
<td></td>
<td>De Souza and Pedersen, 2004</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Demmers, 2007</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mosquera et al., 2008</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Xin et al., 2009</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mosquera et al., 2010</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Samer et al., 2011a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Kiwan et al., 2013</td>
</tr>
<tr>
<td>Hot wire/ultrasonic anemometer</td>
<td>6.3-25</td>
<td>Krause and Janssen, 1990</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Scholtens and Van’t Ooster, 1994</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Calvet et al., 2010</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Van Overberke et al., 2014</td>
</tr>
<tr>
<td>CO₂ balance</td>
<td>15-55</td>
<td>Scholtens and Van’t Ooster, 1994</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Van’t Klooster and Heitlager, 1994</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Groot Koerkamp et al., 1998a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pederson et al., 1998</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Blanes and Pedersen, 2005</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Xin et al., 2001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pedersen et al., 2008</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Zhang et al., 2010</td>
</tr>
<tr>
<td>Moisture balance</td>
<td>5-40</td>
<td>Pedersen et al., 1998</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Blanes and Pedersen, 2005</td>
</tr>
<tr>
<td>CFD calculations</td>
<td>15-65</td>
<td>Campen and Bot, 2003</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fattamasi et al., 2006</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Blanes-Vidal et al., 2008</td>
</tr>
<tr>
<td>Heat balance</td>
<td>26-101</td>
<td>Van’t Ooster, 1994</td>
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<tr>
<td></td>
<td></td>
<td>Groot Koerkamp et al., 1998a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pederson et al., 1998</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fattamasi et al., 2004</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Blanes and Pedersen, 2005</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Katsoulas et al., 2006</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Samer et al., 2011b</td>
</tr>
<tr>
<td>Pressure difference</td>
<td>50</td>
<td>Demmers, 2001</td>
</tr>
<tr>
<td>Free impelling turbine</td>
<td>5-25</td>
<td>Berkmans and Goedseels, 1991</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Berkmans et al., 1983</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heinrichs and Oldenburg, 1993</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Van Ouwerkerk and Pedersen, 1994</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vranken, 1999</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Demmers et al., 1999</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vranken et al., 2005</td>
</tr>
<tr>
<td>Mechanically ventilated housing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Balometer</td>
<td>3</td>
<td>Roumeliotis and Van Heyst, 2007</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cordeau and Barrington, 2010</td>
</tr>
<tr>
<td>Fan assessment numeration system (FANS)</td>
<td>1-3</td>
<td>Pederson and Strom, 1995</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gates et al., 2004</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Casey et al., 2007</td>
</tr>
</tbody>
</table>

*The relative accuracy is the percent deviation from the reference method used in each study, the reference methods were not the same in all studies.*
The calculated airflow from the linear regression equations on Figure 27 and Figure 28 are recorded in Table 29. The calculated airflows were used to quantify the ventilation for the facility.

### Table 29: Calculated airflow (m³/hour) from linear regression equations

<table>
<thead>
<tr>
<th>Fan Size</th>
<th>Fan Stage</th>
<th>Calculated Airflow (m³/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.46 m (18in)</td>
<td>35</td>
<td>2945</td>
</tr>
<tr>
<td></td>
<td>46</td>
<td>3551</td>
</tr>
<tr>
<td></td>
<td>56</td>
<td>4218</td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>4884</td>
</tr>
<tr>
<td></td>
<td>78</td>
<td>5551</td>
</tr>
<tr>
<td></td>
<td>89</td>
<td>6218</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>6885</td>
</tr>
<tr>
<td>0.61 m (24in)</td>
<td>35</td>
<td>3581</td>
</tr>
<tr>
<td></td>
<td>43</td>
<td>4135</td>
</tr>
<tr>
<td></td>
<td>51</td>
<td>4688</td>
</tr>
<tr>
<td></td>
<td>59</td>
<td>5242</td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>5796</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>6350</td>
</tr>
<tr>
<td></td>
<td>83</td>
<td>6904</td>
</tr>
<tr>
<td></td>
<td>91</td>
<td>7457</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>8080</td>
</tr>
<tr>
<td>0.91 m (36in)</td>
<td>ON</td>
<td>14175</td>
</tr>
</tbody>
</table>

A Matlab code was used to identify the current output of a fan and relate it to its associated fan stage and airflow rate. To identify which phase the fan was operating at a series of if statements were used. A temperature was added as an additional if statement to distinguish between the 0.46 m fans operating at the top half speeds, or lower speeds. The current ranges assigned to each fan stage are shown in Table 30 below.
<table>
<thead>
<tr>
<th>Fan Size</th>
<th>Fan Stage</th>
<th>Current range full operation (5 or more fans)</th>
<th>Current range low operation (4 or less fans)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.46 m (18in)</td>
<td>35</td>
<td>≥ 4000</td>
<td>≥ 2450</td>
</tr>
<tr>
<td></td>
<td>46</td>
<td>3600 - 4000</td>
<td>2300 – 2450</td>
</tr>
<tr>
<td></td>
<td>56</td>
<td>3400 - 3600</td>
<td>2150 - 2300</td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>≤ 3400</td>
<td>&gt; 2150</td>
</tr>
<tr>
<td></td>
<td>78</td>
<td>&lt; 3400</td>
<td>&lt; 2150</td>
</tr>
<tr>
<td></td>
<td>89</td>
<td>3400 - 3700</td>
<td>2150 - 2300</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>≥ 3700</td>
<td>≥ 2300</td>
</tr>
<tr>
<td>0.61 m (24in)</td>
<td>35</td>
<td>≥ 3650</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>43</td>
<td>3520 - 3650</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>51</td>
<td>3375 - 3520</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>59</td>
<td>3230 - 3375</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>67</td>
<td>3085 - 3230</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>2940 - 3085</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>83</td>
<td>2795 - 2940</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>91</td>
<td>2650 - 2795</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>2200 - 2650</td>
<td>-</td>
</tr>
<tr>
<td>0.91 m (36in)</td>
<td>100</td>
<td>&gt; 1000</td>
<td>-</td>
</tr>
</tbody>
</table>
The facility staff recorded the number of fans that were operational upon request. The number of fans operating during a given period is reported in Table 31.

**Table 31: Number of operational ventilation fans**

<table>
<thead>
<tr>
<th>Date</th>
<th>0.46 m</th>
<th>0.61 m</th>
<th>0.91 m</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Operational fans</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>July 18\textsuperscript{th} – October 31\textsuperscript{st} 2017</td>
<td>6</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>October 31\textsuperscript{st} – December 2\textsuperscript{nd} 2017</td>
<td>6</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>January 19\textsuperscript{th}, 2018 – January 22\textsuperscript{nd} 2018</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>January 22\textsuperscript{nd}, 2018 – January 23\textsuperscript{rd}, 2018</td>
<td>6</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>January 23\textsuperscript{rd}, 2018 – January 24\textsuperscript{th}, 2018</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>January 24\textsuperscript{th}, 2018 – January 25\textsuperscript{th}, 2018</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>January 25\textsuperscript{th}, 2018 – January 26\textsuperscript{th}, 2018</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>January 26\textsuperscript{th}, 2018 – February 1\textsuperscript{st}, 2018</td>
<td>5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>February 1\textsuperscript{st}, 2018 – February 11\textsuperscript{th}, 2018</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>February 11\textsuperscript{th}, 2018 – February 13\textsuperscript{th}, 2018</td>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>February 13\textsuperscript{th}, 2018 – February 14\textsuperscript{th}, 2018</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>February 14\textsuperscript{th}, 2018 – February 16\textsuperscript{th}, 2018</td>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>February 16\textsuperscript{th}, 2018 – February 20\textsuperscript{th}, 2018</td>
<td>5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>February 20\textsuperscript{th}, 2018 – February 26\textsuperscript{th}, 2018</td>
<td>6</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>February 26\textsuperscript{th}, 2018 – March 31\textsuperscript{st}, 2018</td>
<td>6</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>
Figure 56: FANS user interface software control for operation from a computer

Figure 57: FANS raw data output for a test performed on August 21st 2017
APPENDIX C: EXPERIMENTAL SET-UP

Figure 58: Ammonia 17C- Chemiluminescence analyzer

Figure 59: Ammonia sample inlet with filter housing

Figure 60: Trailer set up with analyzer and calibration gases
Figure 61: Toolbox with current sensor wire descending from ceiling

Figure 62: Current sensors attachment in the control panel to the fans power supply

Figure 63: CR-1000 datalogger with sensor wire relaying from control panel to logger
Figure 64: Toolbox with sampling port tubing for DustTrak

Figure 65: DustTrak housed in the toolbox
Figure 66: Tiny tag attached to a facility temperature probe

Figure 67: Manure belt removal mechanism
Figure 68: Side view of FANS testing plastic tunnel connection between fan discharge cone and unit

Figure 69: Front view of FANS testing for a 0.91 m fan
Figure 70: Front view for FANS testing 0.46 m fan with foam frame
Data processing code example for winter season.

```matlab
%% Winter Ventilation

vent=xlsread('master.xlsx','wvent');
% each column represents a different stage

temp=xlsread('Master.xlsx','wtemp');
% transforming from array to table

temper=array2table(temp,'VariableNames',{'birdage','date','insidetemperature','insidehumidity','outsidehumidity'});

venter=array2table(vent,'VariableNames',{'birdage','date','v18','v24','on1','on2','on3','on4','on5','on6','num18','num24'});

C=innerjoin(temper,venter);
vent1=table2array(C);

% naming variables for if statements

birdage=vent1(:,1); % date in bird age

date=vent1(:,2); % date in number format

v18=vent1(:,7); % variable 18 inch

v24=vent1(:,8); % variable 24 inch

on1=vent1(:,9); % 36 inch phase 1

on2=vent1(:,10); % 36 inch phase 2

on3=vent1(:,11); % 36 inch phase 3

on4=vent1(:,12); % 36 inch phase 4

on5=vent1(:,13); % second 24 inch test

on6=vent1(:,14); % 36 inch phase 6

num18=vent1(:,15); % Number of 18 inch fans on

num24=vent1(:,16); % number of 18 inch fans on

% all 36 inch fans were converted and off so going to set all to zero

for i=1:20571;
    on1(i,1)=0;
    on2(i,1)=0;
    on3(i,1)=0;
    on4(i,1)=0;
    on5(i,1)=0;
    on6(i,1)=0;
end

% If statements based on inside temperature

% 18 inch (by individual fan, to get total will need to multiply by number of fans afterwards

vphase18=zeros(20571,1);

for a=1:909;
    if itemp(a,1)>22.3;
        % 78 phase
        if v18(a,1)<2150;
            vphase18(a,1)=3267;
        elseif v18(a,1)>=2150 & v18(a,1)<2300;
            vphase18(a,1)=3660;
        elseif v18(a,1)>=2300;
            vphase18(a,1)=4052;
        end
    elseif itemp(a,1)<=22.3;
        % 35 phase
        if v18(a,1)>=2450;
            vphase18(a,1)=1733;
        elseif v18(a,1)>=2300 & v18(a,1)<2450;
            vphase18(a,1)=2090;
        % 56 phase
        elseif v18(a,1)<22.3;
            % 18 inch (by individual fan, to get total will need to multiply by number of fans afterwards
    end
end
```

APPENDIX D: DATA PROCESSING CODE
vphase18(a,1)=2482;
%67 phase
    elseif v18(a,1)<2150;
    vphase18(a,1)=2875;
end
end

for b=1106:6638;
    if itemp(b,1)>22.3;
        %78% phase
            if v18(b,1)<2150;
                vphase18(b,1)=3267;
            %89 phase
                elseif v18(b,1)>=2150 & v18(b,1)<2300;
                vphase18(b,1)=3660;
            %100 phase
                elseif v18(b,1)>=2300;
                vphase18(b,1)=4052;
            end
    else itemp(b,1)<=22.3;
        %35% phase
            if v18(b,1)>=2450;
                vphase18(b,1)=1733;
            %45 phase
                elseif v18(b,1)>=2300 & v18(b,1)<2450;
                vphase18(b,1)=2090;
            %56 phase
                elseif v18(b,1)>=2150 & v18(b,1)<2300;
                vphase18(b,1)=2482;
            %67 phase
                elseif v18(b,1)<2150;
                vphase18(b,1)=2875;
            end
    end
end

for c=7236:7423;
    if itemp(c,1)>22.3;
        %78% phase
            if v18(c,1)<2150;
                vphase18(c,1)=3267;
            %89 phase
                elseif v18(c,1)>=2150 & v18(c,1)<2300;
                vphase18(c,1)=3660;
            %100 phase
                elseif v18(c,1)>=2300;
                vphase18(c,1)=4052;
            end
    else itemp(c,1)<=22.3;
        %35% phase
            if v18(c,1)>=2450;
                vphase18(c,1)=1733;
            %45 phase
                elseif v18(c,1)>=2300 & v18(c,1)<2450;
                vphase18(c,1)=2090;
            %56 phase
                elseif v18(c,1)>=2150 & v18(c,1)<2300;
                vphase18(c,1)=2482;
            %67 phase
                elseif v18(c,1)<2150;
                vphase18(c,1)=2875;
            end
    end
end

for d=910:1105;
if itemp(d,1)>22.3
    %78 phase
    if v18(d,1)<3400;
        vphase18(d,1)=3267;
    %89 phase
    elseif v18(d,1)>=3400 & v18(d,1)<3700;
        vphase18(d,1)=3660;
    %100 phase
    elseif v18(d,1)>=3700;
        vphase18(d,1)=4052;
    end
    else
        itemp(d,1)<=22.3;
        %35% phase
        if v18(d,1)>=4000;
            vphase18(d,1)=1733;
        %45 phase
        elseif v18(d,1)>=3600 & v18(d,1)<4000 ;
            vphase18(d,1)=2090;
        %56 phase
        elseif v18(d,1)>=3400 & v18(d,1)<3600;
            vphase18(d,1)=2482;
        %67 phase
        elseif v18(d,1)<3400;
            vphase18(d,1)=2875;
        end
    end
end
for e=6639:7235;
    if itemp(e,1)>22.3;
        %78 phase
        if v18(e,1)<3400;
            vphase18(e,1)=3267;
        %89 phase
        elseif v18(e,1)>=3400 & v18(e,1)<3700;
            vphase18(e,1)=3660;
        %100 phase
        elseif v18(e,1)>=3700;
            vphase18(e,1)=4052;
        end
        else
            itemp(e,1)<=22.3;
            %35% phase
            if v18(e,1)>=4000;
                vphase18(e,1)=1733;
            %45 phase
            elseif v18(e,1)>=3600 & v18(e,1)<4000 ;
                vphase18(e,1)=2090;
            %56 phase
            elseif v18(e,1)>=3400 & v18(e,1)<3600;
                vphase18(e,1)=2482;
            %67 phase
            elseif v18(e,1)<3400;
                vphase18(e,1)=2875;
            end
        end
    end
end
for f=7424:20571;
    if itemp(f,1)>22.3;
        %78 phase
        if v18(f,1)<3400;
            vphase18(f,1)=3267;
        %89 phase
        elseif v18(f,1)>=3400 & v18(f,1)<3700;
            vphase18(f,1)=3660;
        %100 phase
        elseif v18(f,1)>=3700;
            vphase18(f,1)=4052;
else itemp(f,1)<=22.3;
%35% phase
if v18(f,1)>=4000;
vphead18(f,1)=1733;
%45 phase
elseif v18(f,1)>=3600 & v18(f,1)<4000;
vphead18(f,1)=2090;
%56 phase
elseif v18(f,1)>=3400 & v18(f,1)<3600;
vphead18(f,1)=2482;
%67 phase
elseif v18(f,1)<3400;
vphead18(f,1)=2875;
end
end

vphase24=zeros(20571,1);
% 24 inch variable
for i=1:20571;
%35
if v24(i,1)>=1400 & v24(i,1)<1700 || v24(i,1)>=500 & v24(i,1)<1000;
vphead24(i,1)=2108;
%43
elseif v24(i,1)>=1200 & v24(i,1)<1400;
vphead24(i,1)=2434;
%51
elseif v24(i,1)>=1000 & v24(i,1)<1200;
vphead24(i,1)=2760;
elseif v24(i,1)<500;
vphead24(i,1)=0;
end
end

vphase18total=zeros(20571,1);
vphase24total=zeros(20571,1);
totalvent=zeros(20571,1);
for i=1:20571
vphase18total(i,1)=vphase18(i,1)*num18(i,1);
vphase24total(i,1)=vphase24(i,1)*num24(i,1);
totalvent(i,1)= (vphase18total(i,1) + vphase24total(i,1));
end

ds=dataset(birdage,date,vphase18total,vphase24total,totalvent);

%% Winter Ammonia
ammonia=xlsread('master.xlsx','wammonia');
NO = ammonia(:,3);
NOX= ammonia(:,4);
NT = ammonia(:,5);
for k=1:20345;
ammonia(k,7)= (NOX(k,1)-NO(k,1))/1000;
ammonia(k,8)= (NT(k,1)-NOX(k,1))/1000;
end
NO2 = ammonia(:,7);
NH3 = ammonia(:,8);
Manure=ammonia(:,6);

%transforming from array to table
ammon=array2table(ammonia,'VariableNames',{'birdage','date','NO','NOX','NT','Manure','NO2','NH3'});

%joining tables based on bird age
L=innerjoin(temper,ammon);
%changing ventilation dataset into table
ds1=dataset2table(ds);
%joining tables based on bird age
Overall=innerjoin(L,ds1);
% Round bird age to determine AU and number of birds at that time
birdage=Overall(:,1);
birdage1=table2array(birdage1);
agedays=zeros(20336,1);
for p=1:20336;
    agedays(p,1)=round(birdage1(p,1));
end
Overall.agedays=agedays;

%animal units
birdinfo=xlsread('Master.xlsx','wau');
au=array2table(birdinfo,'VariableNames',{'ageweeks','agedays','weight','mortality','birdnum','eggs','AU'});
Winter1=innerjoin(Overall,au,'Keys','agedays');
%unit conversion ppm to mg/m^3
Winter1.NH3mgm3=((Winter1.NH3*17.031*12.187)./(273.15+Winter1.insidetemperature));
%Emission rate g/day
Winter1.ERgday=(Winter1.NH3mgm3*0.001*24.*(Winter1.totalvent));
%Emission rate g/day/bird
Winter1.ERgdaybird=(Winter1.ERgday)./(Winter1.birdnum);
%Emission factor
Winter1.EF=(Winter1.ERgday)./(Winter1.AU));

%Change serial date number int into date and time in matlab (column 32)
DateTime1=Winter1.date;
Winter1.Time=datestr(DateTime1+datenum('30-Dec-1899'));

%% Fall PM
dust=xlsread('Master.xlsx','wdust');
PM=array2table(dust,'VariableNames',{'birdage','date','PM1','PM25','PM4','PM10','PMtotal','Lights'});
D=innerjoin(PM,ds1,'Keys','birdage');
birdage2=D(:,1);
birdage2=table2array(birdage2);
agedays2=zeros(17612,1);
for q=1:17612;
    agedays2(q,1)=round(birdage2(q,1));
end
D.agedays=agedays2;
Winter2=innerjoin(D,au,'Keys','agedays');

Winter2.PMratio=(Winter2.PM25)./(Winter2.PM10);
Winter2.ER25=(Winter2.PM25*0.001*24.*(Winter2.totalvent));
Winter2.ER25bird=(Winter2.ER25)./(Winter2.birdnum);
Winter2.ER10=(Winter2.PM10*0.001*24.*(Winter2.totalvent));
Winter2.ER10bird=(Winter2.ER10)./(Winter2.birdnum);

DateTime2=Winter2.date_PM;
Winter2.Time=datestr(DateTime2+datenum('30-Dec-1899'));
Winter2 = Winter2(:,[27 1:26]);

%% Data analysis
Winter1.Hour=str2num(datestr(DateTime1+datenum('30-Dec-1899')));
Hourly(:,1)=Winter1(:,28);

%Create new table with EF, NH3 and Hour
%Hour
Hourly(:,2)=Winter1(:,27);
% Ammonia conc
Hourly(:,3)=Winter1(:,13);

%Switch to array
Hourly=table2array(Hourly);
%% Making a 4th column where hour is equal to hour +1 can't deal with 0's
Hourly(:,4)=Hourly(:,1)+1;
%% Find Unique values and find mean and std at those values, Hour+1 so 0 is
%% +integer
A1=unique(Hourly(:,4));
A2=accumarray(Hourly(:,4),Hourly(:,3),[],@mean);
A3=accumarray(Hourly(:,4),Hourly(:,3),[],@std);
out=[A1,A2,A3];
%%Switch back so that 00 is midnight
out(:,1)=out(:,1)-1;
%%Errorbar graph
figure
errorbar(out(:,1),out(:,2),out(:,3));
xlim([0,24]);
ylabel('Ammonia concentration (ppm)');
title('Daily average');
%sxticks([0 3 6 9 12 15 18 21]);
%sxticklabels({'12AM','3AM','6AM','9AM','12PM','3PM','6PM','9PM'});
%%
A4=unique(Hourly(:,4));
A5=accumarray(Hourly(:,4),Hourly(:,2),[],@mean);
A6=accumarray(Hourly(:,4),Hourly(:,2),[],@std);
out1=[A4,A5,A6];
%%Switch back so that 00 is midnight
out1(:,1)=out1(:,1)-1;
%%Errorbar graph
figure
errorbar(out1(:,1),out1(:,2),out1(:,3));
xlim([0,24]);
xlabel('Hour of day');
ylabel('Ammonia Emission Factor');
title('Daily average');
%sxticks([0 3 6 9 12 15 18 21]);
%sxticklabels({'12AM','3AM','6AM','9AM','12PM','3PM','6PM','9PM'});

Winter2.Hour=str2num(datestr(DateTime2+datenum('30-Dec-1899'),'HH'));
%% Hour
PMHourly(:,1)=Winter2(:,28);
%% EF PM25
PMHourly(:,2)=Winter2(:,24);
%% PM25 Conc
PMHourly(:,3)=Winter2(:,5);
%% PM10 EF
PMHourly(:,4)=Winter2(:,27);
%% PM10 Conc
PMHourly(:,5)=Winter2(:,7);
%% Switch to array
PMHourly=table2array(PMHourly);
%% Making a 4th column where hour is equal to hour +1 can't deal with 0's
PMHourly(:,6)=PMHourly(:,1)+1;
%% Find Unique values and find mean and std at those values, Hour+1 so 0 is
%% +integer
PM25 conc
A7=unique(PMHourly(:,6));
A8=accumarray(PMHourly(:,6),PMHourly(:,3),[],@mean);
A9=accumarray(PMHourly(:,6),PMHourly(:,3),[],@std);
PMout=[A7,A8,A9];
%% Switch back so that 00 is midnight
PMout(:,1)=PMout(:,1)-1;
%% Errorbar graph
figure
errorbar(PMout(:,1),PMout(:,2),PMout(:,3));
xlim([0,24]);
xlabel('Hour of day');
ylabel('PM2.5 concentration (mg/m3)');
title('Daily average');
%sxticks([0 3 6 9 12 15 18 21]);
%sxticklabels({'12AM','3AM','6AM','9AM','12PM','3PM','6PM','9PM'});}
```matlab
% EF PM25
A10 = unique(PMHourly(:,6));
A11 = accumarray(PMHourly(:,6), PMHourly(:,2), [], @mean);
A12 = accumarray(PMHourly(:,6), PMHourly(:,2), [], @std);
PMout1 = [A10, A11, A12];

% Switch back so that 00 is midnight
PMout1(:,1) = PMout1(:,1) - 1;

% Errorbar graph
figure
errorbar(PMout1(:,1), PMout1(:,2), PMout1(:,3));
xlim([0, 24]);
xlabel('Hour of day');
ylabel('Emission Factor PM2.5');
title('Daily average');

date = datenum(2016, 1, 1);

% PM10 conc
A13 = unique(PMHourly(:,6));
A14 = accumarray(PMHourly(:,6), PMHourly(:,5), [], @mean);
A15 = accumarray(PMHourly(:,6), PMHourly(:,5), [], @std);
PMout2 = [A13, A14, A15];

% Switch back so that 00 is midnight
PMout2(:,1) = PMout2(:,1) - 1;

% Errorbar graph
figure
errorbar(PMout2(:,1), PMout2(:,2), PMout2(:,3));
xlim([0, 24]);
xlabel('Hour of day');
ylabel('PM10 concentration (mg/m3)');
title('Daily average');

date = datenum(2016, 1, 1);

% EF PM10
A16 = unique(PMHourly(:,6));
A17 = accumarray(PMHourly(:,6), PMHourly(:,4), [], @mean);
A18 = accumarray(PMHourly(:,6), PMHourly(:,4), [], @std);
PMout3 = [A16, A17, A18];

% Switch back so that 00 is midnight
PMout3(:,1) = PMout3(:,1) - 1;

% Errorbar graph
figure
errorbar(PMout3(:,1), PMout3(:,2), PMout3(:,3));
xlim([0, 24]);
xlabel('Hour of day');
ylabel('Emission Factor PM10');
title('Daily average');

date = datenum(2016, 1, 1);

% create dataset for all daily averages
dailyav = dataset(out, out1, PMout, PMout1, PMout2, PMout3);
dailyavg = dataset2table(dailyav);

dailyavg = dataset2table(dailyavg);

% Export
writetable(Winter1, 'FinalWinter.xlsx', 'sheet', 1);
writetable(Winter2, 'FinalWinter.xlsx', 'sheet', 2);
writetable(dailyavg, 'FinalWinter.xlsx', 'sheet', 3);
```
APPENDIX E: STATISTICAL ANALYSIS

Code:

thesis <- read.csv(file.choose())
attach(thesis)
LabMod1 <- lm(NH3 ~ lpH)
summary(LabMod1)
anova(LabMod1)
LabMod2 <- lm(NH3 ~ avgtemp)
summary(LabMod2)
anova(LabMod2)
LabMod3 <- lm(NH3 ~ lNH4)
summary(LabMod3)
anova(LabMod3)
LabMod4 <- lm(NH3 ~ lcompNH4)
summary(LabMod4)
anova(LabMod4)
LabMod5 <- lm(NH3 ~ lNH4 + ldrymatter)
summary(LabMod5)
anova(LabMod5)
LabMod6 <- lm(NH3 ~ mpH)
summary(LabMod6)
anova(LabMod6)
LabMod7 <- lm(NH3 ~ avgRH)
summary(LabMod7)
anova(LabMod7)
LabMod8 <- lm(NH3 ~ mNH4)
summary(LabMod8)
anova(LabMod8)
LabMod9 <- lm(NH3 ~ mcompNH4)
summary(LabMod9)
anova(LabMod9)
LabMod10 <- lm(NH3 ~ mdrymatter)
summary(LabMod10)
anova(LabMod10)
LabMod11 <- lm(NH3 ~ avgtemp+avgRH)
summary(LabMod11)
anova(LabMod11)
LabMod12 <- lm(NH3~lpH+lNH4+ldrymatter)
summary(LabMod12)
anova(LabMod12)
LabMod13 <- lm(NH3 ~ INH4+ lpH)
summary(LabMod13)
anova(LabMod13)
LabMod14 <- lm(NH3~mNH4+mdrymatter+mpH)
summary(LabMod14)
anova(LabMod14)
LabMod15 <- lm(NH3~lpH+lNH4+ldrymatter+mdrymatter+mpH+mNH4)
summary(LabMod15)
anova(LabMod15)
LabMod16 <- lm(NH3~lpH+lNH4+ldrymatter+mdrymatter+mpH+mNH4+avgte
mp+avgRH)
summary(LabMod16)
anova(LabMod16)

DataMod1 <- lm(svent ~ stemp)
summary(DataMod1)
anova(DataMod1)
DataMod2 <- lm(svent ~ souttemp)
summary(DataMod2)

PMMod1 <- lm(PM25 ~ ldrymatter)
summary(PMMod1)
anova(PMMod1)
PMMod2 <- lm(PM10 ~ ldrymatter)
summary(PMMod2)
anova(PMMod2)
PMMod3 <- lm(PM25 ~ avgtemp)
summary(PMMod3)
anova(PMMod3)
PMMod4 <- lm(PM25 ~ avgRH)
summary(PMMod4)
anova(PMMod4)
PMMod5 <- lm(PM25 ~ avgtemp+avgRH)
summary(PMMod5)
anova(PMMod5)
PMMod6 <- lm(PM10 ~ avgtemp)
summary(PMMod6)
anova(PMMod6)
PMMod7 <- lm(PM10 ~ avgRH)
summary(PMMod7)
anova(PMMod7)
PMMod8 <- lm(PM10 ~ avgtemp+avgRH)
summary(PMMod8)
anova(PMMod8)
Code output:

```R
> LabMod1 <- lm(NH3 ~ lpH)
> summary(LabMod1)

Call:
  lm(formula = NH3 ~ lpH)

Residuals:
   Min     1Q Median     3Q    Max
-21.430 -3.848  0.220  4.439  22.534

Coefficients:
                         Estimate Std. Error t value Pr(>|t|)
(Intercept)              -130.28     17.776  -7.329 7.60e-09 ***
lpH                       18.84       2.332   8.077 7.47e-10 ***

---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 8.235 on 39 degrees of freedom
(7394 observations deleted due to missingness)
Multiple R-squared:  0.6259, Adjusted R-squared:  0.6163
F-statistic: 65.24 on 1 and 39 DF,  p-value: 7.472e-10

> anova(LabMod1)
  Analysis of Variance Table

Response: NH3
 Df  Sum Sq Mean Sq   F value    Pr(>F)
lpH        1 4424.3  4424.3 65.2392 7.47e-10 ***
Residuals 39 2644.8   67.8
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

> LabMod2 <- lm(NH3 ~ avgtemp)
> summary(LabMod2)

Call:
  lm(formula = NH3 ~ avgtemp)

Residuals:
   Min     1Q Median     3Q    Max
-18.132 -6.642 -1.625  4.720  22.270

Coefficients:
                         Estimate Std. Error t value Pr(>|t|)
(Intercept)             191.53       30.170   6.349 1.70e-07 ***
avgtemp                  -7.58       1.278  -5.928 6.52e-07 ***

---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 9.764 on 39 degrees of freedom
(7394 observations deleted due to missingness)
Multiple R-squared:  0.4740, Adjusted R-squared:  0.4605
F-statistic: 35.14 on 1 and 39 DF,  p-value: 6.517e-07

> anova(LabMod2)
  Analysis of Variance Table

Response: NH3
 Df  Sum Sq Mean Sq   F value    Pr(>F)
avgtemp    1 3350.7  3350.7 35.1430 6.517e-07 ***
Residuals 39 3718.4   95.3
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

> LabMod3 <- lm(NH3 ~ lNH4)
> summary(LabMod3)

Call:
  lm(formula = NH3 ~ lNH4)

Residuals:
   Min     1Q Median     3Q    Max
-16.030 -5.631 -1.079  4.659  12.295

Coefficients:
                         Estimate Std. Error t value Pr(>|t|)
(Intercept)              -9.27       2.475    -3.745 0.000582 ***
lNH4                    0.0176      0.0018  10.034 2.32e-12 ***

---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 7.114 on 39 degrees of freedom
(7394 observations deleted due to missingness)
Multiple R-squared:  0.7208, Adjusted R-squared:  0.7136
F-statistic: 100.68 on 1 and 39 DF,  p-value: 2.323e-12

> anova(LabMod3)
  Analysis of Variance Table

Response: NH3
 Df  Sum Sq Mean Sq   F value    Pr(>F)
lNH4       1 5095.4  5095.4 100.687 2.323e-12 ***
Residuals 39 1973.7   50.6
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

> LabMod4 <- lm(NH3 ~ lcompNH4)
> summary(LabMod4)

Call:
  lm(formula = NH3 ~ lcompNH4)

Residuals:
   Min     1Q Median     3Q    Max
-11.990 -5.428  0.211  4.659  11.485

Coefficients:
                         Estimate Std. Error t value Pr(>|t|)
(Intercept)               2.62       1.877     1.397 0.17
lcompNH4                 3.28       0.322    10.203 3.28e-12 ***

---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 7.028 on 39 degrees of freedom
(7394 observations deleted due to missingness)
Multiple R-squared:  0.7275, Adjusted R-squared:  0.7205
F-statistic: 104.1 on 1 and 39 DF,  p-value: 1.444e-12

> anova(LabMod4)
  Analysis of Variance Table
```

XXII
Response: NH3

DF Sum Sq Mean Sq F value Pr(>F)
Term 1 1342.5 1342.5 104.1 1.446e-12 ***
Residuals 39 1926.6 49.4
---
Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

> LabMod5 <- lm(NH3 ~ ldrymatter)
> summary(LabMod5)

Call:
  lm(formula = NH3 ~ ldrymatter)
Residuals:
  Min      1Q  Median      3Q     Max
-22.3218 -6.7596   0.0988   9.6935  18.3032
Coefficients:
  Estimate Std. Error t value Pr(>|t|)
(Intercept) 152.5147    30.6763  4.972 1.37e-05 ***
ldrymatter -1.7550     0.3851 -4.558 5.00e-05 ***
---
Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Residual standard error: 10.88 on 39 degrees of freedom
(7394 observations deleted due to missingness)
DF  Sum Sq  Mean Sq  F value  Pr(>F)
NH4     1  668.3  668.29   4.0719  0.05052 .
Residuals 39 6400.8  164.12
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

> LabMod9 <- lm(NH3 ~ mcompNH4)
> summary(LabMod9)

Call:
  lm(formula = NH3 ~ mcompNH4)

Residuals:
  Min      1Q  Median      3Q     Max
-15.519  -9.575  -2.910   4.974  34.569

Coefficients:
  Estimate Std. Error t value  Pr(>|t|)
(Intercept)   7.1972     4.8974   1.470    0.150
mcompNH4      0.4454     0.3459   1.288    0.205

Residual standard error: 13.19 on 39 degrees of freedom
(7394 observations deleted due to missingness)
Multiple R-squared:  0.04079,  Adjusted R-squared:  0.01619
F-statistic: 1.658 on 1 and 39 DF,  p-value: 0.2054

> anova(LabMod9)

Analysis of Variance Table
Response: NH3
Df  Sum Sq  Mean Sq  F value  Pr(>F)
  mcompNH4  1  288.3   288.35   1.6584  0.2054
  Residuals 39 6780.8  173.87

> LabMod10 <- lm(NH3 ~ mdrymatter)
> summary(LabMod10)

Call:
  lm(formula = NH3 ~ mdrymatter)

Residuals:
  Min      1Q  Median      3Q     Max

Coefficients:
  Estimate Std. Error t value  Pr(>|t|)
(Intercept)  42.9834    16.8334   2.553   0.0147 *
mdrymatter  -1.0061     0.5592  -1.799   0.0798 .

Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 12.94 on 39 degrees of freedom
(7394 observations deleted due to missingness)
Multiple R-squared:  0.07662,  Adjusted R-squared:  0.05295
F-statistic: 3.236 on 1 and 39 DF,  p-value: 0.07976

> anova(LabMod10)

Analysis of Variance Table
Response: NH3
Df  Sum Sq  Mean Sq  F value  Pr(>F)
   mdrymatter  1  541.7   541.66   3.2363  0.07976 .
  Residuals  39 6527.4  167.37

Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

> LabMod11 <- lm(NH3 ~ avgtemp+avgRH)
> summary(LabMod11)

Call:
  lm(formula = NH3 ~ avgtemp + avgRH)

Residuals:
  Min      1Q  Median      3Q     Max
-18.284  -4.313  -1.550   3.542  20.482

Coefficients:
  Estimate Std. Error t value  Pr(>|t|)
(Intercept)  95.8483    45.1951   2.121 0.040526 *
avgtemp      5.7448     1.3674   4.201 0.000155 ***
avgRH        0.8477     0.3143   2.697 0.010377 *

Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 9.063 on 38 degrees of freedom
(7394 observations deleted due to missingness)
Multiple R-squared:  0.5585,  Adjusted R-squared:  0.5353
F-statistic: 24.03 on 2 and 38 DF,  p-value: 1.794e-07

> anova(LabMod11)

Analysis of Variance Table
Response: NH3
Df  Sum Sq  Mean Sq  F value    Pr(>F)
   avgtemp    1 3350.7   3350.7  40.796 1.678e-07 ***
   avgRH      1  597.4   597.4   7.273   0.01038 *
  Residuals 38 3121.1   82.1

Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

> LabMod12 <- lm(NH3 ~ lpH+lNH4+ldrymatter)
> summary(LabMod12)

Call:
  lm(formula = NH3 ~ lpH + lNH4 + ldrymatter)

Residuals:
  Min      1Q  Median      3Q     Max
-10.2387  -2.7431  -0.7654   3.0568  9.5632

Coefficients:
  Estimate Std. Error t value  Pr(>|t|)
(Intercept) -1.056e+02  2.465e+01  -4.285 0.000125 ***
lpH          1.154e+01  1.627e+00   7.094 1.86e-09 ***
lNH4         1.307e-02  1.631e-03   8.009 1.34e-09 ***
ldrymatter   1.803e-01  2.274e-01   0.793 0.432974

Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 4.737 on 37 degrees of freedom
(7394 observations deleted due to missingness)
Multiple R-squared:  0.8826,  Adjusted R-squared:  0.8730
F-statistic: 92.69 on 3 and 37 DF,  p-value: < 2.2e-16

> anova(LabMod12)

Analysis of Variance Table
Response: NH3
Df  Sum Sq  Mean Sq  F value   Pr(>F)
   lpH         1 4424.3  4424.3 197.915 < 2.2e-16 ***
   lNH4        1  442.3  442.3  19.791  3.79e-05 ***
   ldrymatter  1  321.1  321.1  14.211  0.000125 ***
```
NH4  1 1800.6  1800.6  80.2534  8.417e-11 ***
```

This text appears to be a statistical output from R, but it's not clear what the specific analysis is about due to the lack of context. It seems to be related to an analysis of variance (ANOVA) with some model specifications and output. The output includes coefficients, residual standard errors, and significance codes.

```
> anova(LabMod16)
Call:
  lm(formula = NH4 ~ lNH4 + lpH)
Residuals:
   Min 1Q Median 3Q Max
-9.923 -2.642 -1.083 3.271 9.748
Coefficients:...
```

```
> anova(LabMod15)
Call:
  lm(formula = NH3 ~ mNH4 + mdrymatter + mpH)
Residuals:
   Min 1Q Median 3Q Max
-16.611 -7.945 -2.462 5.929 25.473
Coefficients:...
```

```
> anova(LabMod14)
Call:
  lm(formula = NH3 ~ lNH4 + lpH)
Residuals:
   Min 1Q Median 3Q Max
-1.129 -0.3569 0.3794 8.2695
Coefficients:...
```

```
> anova(LabMod13)
Call:
  lm(formula = NH3 ~ lNH4 + lpH)
Residuals:
   Min 1Q Median 3Q Max
-7.945 -2.462 5.929 25.473
Coefficients:...
```

```
> anova(LabMod12)
Call:
  lm(formula = NH3 ~ lNH4 + lpH)
Residuals:
   Min 1Q Median 3Q Max
-1.802e+02  1.802e+02  4.221e+03  0.000171 ***
```

```
> summary(LabMod13)
```

```
> summary(LabMod14)
```

```
> summary(LabMod15)
```

```
> summary(LabMod16)
```

```
> LabMod15 <- lm(NH3 ~ TNH4 + lNH4)
> LabMod16 <- lm(NH3 ~ TNH4 + lNH4 + lDrymatter + mpH)
> LabMod17 <- lm(NH3 ~ TNH4 + lNH4 + lDrymatter + mpH + mNH4)
```

The output includes a variety of model specifications and their corresponding ANOVA tables, along with coefficients and significance levels. The models seem to be predicting NH3 based on different combinations of variables, including NH4, pH, dry matter, and possibly interaction terms involving NH4 and pH. The significance codes indicate the level of significance for each term in the model.
\begin{verbatim}
 1 pH  1 4424.3 4424.3 202.1769 2.216e-15 ***
 1 NH4+ 1 1800.6 1800.6 82.2824 2.329e-10 ***
 1 ldrymatter 1 14.1 15.1 0.6444 0.4281
 1 mdrymatter 1 0.5 0.5 0.0208 0.8861
 1 NH4 - 1 8.5 8.5 0.3869 0.5383
 1 NH4+ 1 38.3 38.3 1.7496 0.1953
 1 avgtemp 1 50.9 50.9 2.3247 0.1372
 1 avghR 1 31.8 31.8 1.4535 0.2368
 Residuals 32 700.3 23.9

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

## 1

summary(LabMod16)

Call:
  lm(formula = svent ~ stemp + souttemp)

Residuals:
   Min     1Q Median     3Q    Max
-6.455 -2.585 -1.093 3.017 8.368

Coefficients:
                               Estimate Std. Error t value Pr(>|t|)
(Intercept)              -98.280735  49.907531  -1.969 0.057633
stemp                    9.000483   2.337160   3.851 0.000531 ***
souttemp                0.013362   0.001802   7.416 1.94e-08 ***
ldrymatter               0.292540   0.245045   1.194 0.241323
mdrymatter              0.064538   0.043977   1.485 0.147315
NH4                    1.984227  1.657171   1.197 0.236962
avghR                   0.248592  0.206193   1.200 0.236801

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 31330 on 7312 degrees of freedom
Multiple R-squared: 0.9009, Adjusted R-squared: 0.8762
F-statistic: 36.38 on 8 and 7312 DF, p-value: 6.213e-14

> anova(LabMod16)

Analysis of Variance Table

Response: svent
            Df    Sum Sq Mean Sq   F value    Pr(>F)
stemp       1 246.69364 246.6936 166.50327 1.70e-44 ***
souttemp   14 56.79502  4.0561  0.238381  0.885074

---

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 31330 on 7312 degrees of freedom
Multiple R-squared: 0.9009, Adjusted R-squared: 0.8762
F-statistic: 36.38 on 8 and 7312 DF, p-value: 6.213e-14

> summary(DataMod1)

Call:
  lm(formula = svent ~ stemp)

Residuals:
   Min     1Q Median     3Q    Max
-6.455 -2.585 -1.093 3.017 8.368

Coefficients:
                               Estimate Std. Error t value Pr(>|t|)
(Intercept)              -98.280735  49.907531  -1.969 0.057633
stemp                    9.000483   2.337160   3.851 0.000531 ***

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 31330 on 7312 degrees of freedom
Multiple R-squared: 0.9009, Adjusted R-squared: 0.8762
F-statistic: 36.38 on 8 and 7312 DF, p-value: 6.213e-14

> data(DataMod1)

> summary(DataMod1)

Analysis of Variance Table

Response: svent
            Df    Sum Sq Mean Sq F value    Pr(>F)
stemp       1 246.69364 246.6936 166.50327 1.70e-44 ***
souttemp   14 56.79502  4.0561  0.238381  0.885074

---

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 31330 on 7312 degrees of freedom
Multiple R-squared: 0.9009, Adjusted R-squared: 0.8762
F-statistic: 36.38 on 8 and 7312 DF, p-value: 6.213e-14

> anova(LabMod2)

Analysis of Variance Table

Response: svent
            Df    Sum Sq Mean Sq   F value    Pr(>F)
stemp       1 246.69364 246.6936 166.50327 1.70e-44 ***
souttemp   14 56.79502  4.0561  0.238381  0.885074

---

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 31330 on 7312 degrees of freedom
Multiple R-squared: 0.9009, Adjusted R-squared: 0.8762
F-statistic: 36.38 on 8 and 7312 DF, p-value: 6.213e-14

> summary(DataMod2)

Analysis of Variance Table

Response: svent
            Df    Sum Sq Mean Sq F value    Pr(>F)
stemp       1 246.69364 246.6936 166.50327 1.70e-44 ***
souttemp   14 56.79502  4.0561  0.238381  0.885074

---

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 31330 on 7312 degrees of freedom
Multiple R-squared: 0.9009, Adjusted R-squared: 0.8762
F-statistic: 36.38 on 8 and 7312 DF, p-value: 6.213e-14

> anova(DataMod3)

Analysis of Variance Table

Response: svent
            Df    Sum Sq Mean Sq F value    Pr(>F)
stemp       1 246.69364 246.6936 166.50327 1.70e-44 ***
souttemp   14 56.79502  4.0561  0.238381  0.885074

---

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 31330 on 7312 degrees of freedom
Multiple R-squared: 0.9009, Adjusted R-squared: 0.8762
F-statistic: 36.38 on 8 and 7312 DF, p-value: 6.213e-14

> summary(DataMod3)

Analysis of Variance Table

Response: svent
            Df    Sum Sq Mean Sq F value    Pr(>F)
stemp       1 246.69364 246.6936 166.50327 1.70e-44 ***
souttemp   14 56.79502  4.0561  0.238381  0.885074

---

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 31330 on 7312 degrees of freedom
Multiple R-squared: 0.9009, Adjusted R-squared: 0.8762
F-statistic: 36.38 on 8 and 7312 DF, p-value: 6.213e-14
\end{verbatim}
```r
> anova(DataMod3)
Analysis of Variance Table
Response: sven
tDf  Sum Sq    Mean Sq   F value  Pr(>F)
  stemp        1 1.8950e+13 1.8950e+13   49116 < 2.2e-16 ***
  souttemp     1 4.3574e+12 4.3574e+12   11294 < 2.2e-16 ***
Residuals 7312 2.8211e+12 3.8582e+08
---
signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

> DataMod4 < lm(fvent ~ ftemp)
> summary(DataMod4)
Call: lm(formula = fvent ~ ftemp)
Residuals:
    Min     1Q Median     3Q    Max
-68455 -13438  3025  11222  73580
Coefficients:
     Estimate Std. Error t value Pr(>|t|)
(Intercept) -1462137.1  13197.2 -110.8   <2e-16 ***
ftemp        63593.0     546.7  116.3   <2e-16 ***
---
signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Residual standard error: 20470 on 7433 degrees of freedom
Multiple R-squared:  0.6455, Adjusted R-squared:  0.6454
F-statistic: 1.353e+04 on 1 and 7433 DF,  p-value: < 2.2e-16
> anova(DataMod4)
Analysis of Variance Table
Response: fvent
tDf Sum Sq    Mean Sq   F value  Pr(>F)
  ftemp        1 5.6679e+12 5.6679e+12   13533 < 2.2e-16 ***
Residuals 7433 3.1132e+12 4.1884e+08
---
signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

> DataMod5 < lm(fvent ~ fouttemp)
> summary(DataMod5)
Call: lm(formula = fvent ~ fouttemp)
Residuals:
    Min     1Q Median     3Q    Max
-44009 -12293  360   8515 110272
Coefficients:
    Estimate Std. Error t value Pr(>|t|)
(Intercept)  13712.98     457.91   29.95   <2e-16 ***
fouttemp     5167.21      35.81  144.30   <2e-16 ***
---
signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Residual standard error: 17630 on 7433 degrees of freedom
Multiple R-squared:  0.7369, Adjusted R-squared:  0.7369
F-statistic: 2.082e+04 on 1 and 7433 DF,  p-value: < 2.2e-16
> anova(DataMod5)
Analysis of Variance Table
Response: fvent
tDf Sum Sq    Mean Sq   F value  Pr(>F)
fouttemp     1 6.4712e+12 6.4712e+12   20824 < 2.2e-16 ***
Residuals 7433 2.3099e+12 3.1076e+08
---
signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

> DataMod6 < lm(fvent ~ ftemp + fouttemp)
> summary(DataMod6)
Call: lm(formula = fvent ~ ftemp + fouttemp)
Residuals:
    Min     1Q Median     3Q    Max
-46024 -11506  213   9816  74164
Coefficients:
     Estimate Std. Error t value Pr(>|t|)
(Intercept) -636804.87   15577.03  -40.88   <2e-16 ***
ftemp         27719.41     663.53   41.78   <2e-16 ***
fouttemp       3545.23      50.46   70.26   <2e-16 ***
---
signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Residual standard error: 15870 on 7432 degrees of freedom
Multiple R-squared:  0.7870, Adjusted R-squared:  0.7869
F-statistic: 1.373e+04 on 2 and 7432 DF,  p-value: < 2.2e-16
> anova(DataMod6)
Analysis of Variance Table
Response: fvent
tDf Sum Sq    Mean Sq   F value  Pr(>F)
  ftemp        1 5.6679e+12 5.6679e+12 22518.7 < 2.2e-16 ***
fouttemp     1 1.2426e+12 1.2426e+12   4936.8 < 2.2e-16 ***
Residuals 7432 1.8706e+12 2.5170e+08
---
signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

> DataMod7 < lm(wvent ~ wtemp)
> summary(DataMod7)
Call: lm(formula = wvent ~ wtemp)
Residuals:
    Min     1Q Median     3Q    Max
-10718.6 -3031.3 -561.3  2619.1  28900.3
Coefficients:
     Estimate Std. Error t value Pr(>|t|)
(Intercept) -161242.6  5080.9 -32.34   <2e-16 ***
wtemp       38152.1   140.8  273.03   <2e-16 ***
---
signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Residual standard error: 4347 on 7182 degrees of freedom
(251 observations deleted due to missingness)
Multiple R-squared:  0.3182, Adjusted R-squared:  0.3181
F-statistic: 3352 on 1 and 7182 DF,  p-value: < 2.2e-16
> anova(DataMod7)
Analysis of Variance Table
Response: wvent
tDf Sum Sq    Mean Sq   F value  Pr(>F)
  wtemp        1 5.6679e+12 5.6679e+12 22518.7 < 2.2e-16 ***
Residuals 7432 1.8706e+12 2.5170e+08
---
signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

> DataMod8 <- lm(wvent ~ wtemp + fouttemp)
> summary(DataMod8)
Call: lm(formula = wvent ~ wtemp + fouttemp)
Residuals:
    Min     1Q Median     3Q    Max
-46024 -11506  213   9816  74164
Coefficients:
     Estimate Std. Error t value Pr(>|t|)
(Intercept) -636804.87   15577.03  -40.88   <2e-16 ***
wtemp         27719.41     663.53   41.78   <2e-16 ***
fouttemp       3545.23      50.46   70.26   <2e-16 ***
---
signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Residual standard error: 15870 on 7432 degrees of freedom
Multiple R-squared:  0.7870, Adjusted R-squared:  0.7869
F-statistic: 1.373e+04 on 2 and 7432 DF,  p-value: < 2.2e-16
> anova(DataMod8)
Analysis of Variance Table
Response: wvent
tDf Sum Sq    Mean Sq   F value  Pr(>F)
  wtemp        1 5.6679e+12 5.6679e+12 22518.7 < 2.2e-16 ***
wtemp        1 1.2426e+12 1.2426e+12   4936.8 < 2.2e-16 ***
Residuals 7432 1.8706e+12 2.5170e+08
---
signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Residual standard error: 4347 on 7182 degrees of freedom
(251 observations deleted due to missingness)
Multiple R-squared:  0.3182, Adjusted R-squared:  0.3181
F-statistic: 3352 on 1 and 7182 DF,  p-value: < 2.2e-16
> anova(DataMod8)
Analysis of Variance Table
Response: wvent
```
DF  Sum Sq  Mean Sq  F value  Pr(>F)
wttemp  1  6.3347e+10  6.3347e+10  3352.1 < 2.2e-16 ***
Residuals 7182 1.3572e+11 1.8898e+07

---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

> DataMod8 <- lm(wvent ~ wouttemp)
> summary(DataMod8)

Call:
  lm(formula = wvent ~ wouttemp)

Residuals:
  Min     1Q   Median     3Q    Max
  -9681   -3366    -604   2176  24549

Coefficients:
  Estimate Std. Error t value  Pr(>|t|)
  (Intercept) 19682.808     78.038  252.22   <2e-16 ***
  wouttemp     427.695      9.264   46.17   <2e-16 ***

---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 4623 on 7182 degrees of freedom
(251 observations deleted due to missingness)
Multiple R-squared:  0.2288, Adjusted R-squared:  0.2287
F-statistic:  2131 on 1 and 7182 DF,  p-value: < 2.2e-16

> anova(DataMod8)

Analysis of Variance Table
Response: wvent
DF  Sum Sq  Mean Sq  F value  Pr(>F)
  wouttemp     1 4.5556e+10  4.5556e+10  2131.3 < 2.2e-16 ***
  Residuals 7182 1.5352e+11 2.1375e+07

---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

> DataMod9 <- lm(wvent ~ wtemp + wouttemp)
> summary(DataMod9)

Call:
  lm(formula = wvent ~ wtemp + wouttemp)

Residuals:
  Min     1Q   Median     3Q    Max
  -10379.7 -2608.0    -284.1  2109.3  18855.5

Coefficients:
  Estimate Std. Error  t value  Pr(>|t|)
  (Intercept)  1.313e+05  2.887e+03   45.49   <2e-16 ***
  wtemp         6.875e+03  1.314e+02   52.32   <2e-16 ***
  wouttemp     3.239e+02  8.129e+00   39.85   <2e-16 ***

---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 3934 on 7181 degrees of freedom
(251 observations deleted due to missingness)
Multiple R-squared:  0.4417, Adjusted R-squared:  0.4415
F-statistic: 2840 on 2 and 7181 DF,  p-value: < 2.2e-16

> anova(DataMod9)

Analysis of Variance Table
Response: wvent
DF  Sum Sq  Mean Sq  F value  Pr(>F)
  wtemp     1 6.3347e+10  6.3347e+10  4092.7 < 2.2e-16 ***
  wouttemp  1 2.4576e+10  2.4576e+10  1587.8 < 2.2e-16 ***
  Residuals 7181 1.1115e+11 1.5478e+07

---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

> DataMod10 <- lm(stemp~souttemp)
> summary(DataMod10)

Call:
  lm(formula = stemp ~ souttemp)

Residuals:
  Min     1Q   Median     3Q    Max
  -1.46390 -0.41310  0.07455  0.28000  2.83162

Coefficients:
  Estimate Std. Error  t value  Pr(>|t|)
  (Intercept)  22.04480  0.02973  741.57   <2e-16 ***
  souttemp    0.15439  0.00153 100.82   <2e-16 ***

---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.6433 on 7313 degrees of freedom
(120 observations deleted due to missingness)
Multiple R-squared:  0.5816, Adjusted R-squared:  0.5816
F-statistic: 1.017e+04 on 1 and 7313 DF,  p-value: < 2.2e-16

> anova(DataMod10)

Analysis of Variance Table
Response: stemp
DF  Sum Sq  Mean Sq  F value  Pr(>F)
  souttemp     1 4207.4  4207.4   10167 < 2.2e-16 ***
  Residuals 7313 3026.4  0.4

---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

> DataMod11 <- lm(ftemp~fouttemp)
> summary(DataMod11)

Call:
  lm(formula = ftemp ~ fouttemp)

Residuals:
  Min     1Q   Median     3Q    Max
  -1.00680 -0.16315  0.14422  1.83162

Coefficients:
  Estimate Std. Error  t value  Pr(>|t|)
  (Intercept)  2.347e+01  7.204e-03  3257.7 <2e-16 ***
  fouttemp     5.851e-02  5.633e-04  103.9  <2e-16 ***

---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.2773 on 7433 degrees of freedom
Multiple R-squared:  0.5921, Adjusted R-squared:  0.5921
F-statistic: 1.079e+04 on 1 and 7433 DF,  p-value: < 2.2e-16

> anova(DataMod11)

Analysis of Variance Table
Response: ftemp
XXIX

\begin{verbatim}
DF       Sum Sq  Mean Sq F value    Pr(>F)
fouttemp   1 829.84  829.84   10789 < 2.2e-16 ***
Residuals 7433 571.70    0.08

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

DataMod12 <- lm(wtemp~wouttemp)
summary(DataMod12)

Call: lm(formula = wtemp ~ wouttemp)

Residuals:
       Min       1Q   Median       3Q      Max
-0.93744 -0.24206 -0.06178  0.18381  1.71429

Coefficients:
      Estimate Std. Error t value Pr(>|t|)
(Intercept) 21.968595   0.005963 3683.90   <2e-16 ***
wouttemp     0.015094   0.000708   21.32   <2e-16 ***

Residual standard error: 0.3533 on 7182 degrees of freedom
(251 observations deleted due to missingness)
Multiple R-squared:  0.05953,  Adjusted R-squared:  0.0594
F-statistic: 454.6 on 1 and 7182 DF,  p-value: < 2.2e-16

anova(DataMod12)

Analysis of Variance Table
Response: wtemp
          Df  Sum Sq Mean Sq F value    Pr(>F)
 wouttemp  1  56.74  56.741  454.58 < 2.2e-16 ***
 Residuals 7182 896.47   0.125

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

PMMod1 <- lm(PM25 ~ ldrymatter)
summary(PMMod1)

Call: lm(formula = PM25 ~ ldrymatter)

Residuals:
       Min       1Q   Median       3Q      Max
-1.3673  -1.1564  -0.7854   0.7008   5.7131

Coefficients:
      Estimate Std. Error t value Pr(>|t|)
(Intercept)  2.059996   4.897621   0.421    0.677
ldrymatter  -0.007439   0.061433  -0.121    0.904

Residual standard error: 1.626 on 33 degrees of freedom
Multiple R-squared:  0.0004442,  Adjusted R-squared: -0.02985
F-statistic: 0.01466 on 1 and 33 DF,  p-value: 0.9043

anova(PMMod1)

Analysis of Variance Table
Response: PM25
           Df  Sum Sq Mean Sq F value    Pr(>F)
 ldrymatter  1    0.039  0.03878  0.0147 0.9043
 Residuals  33 87.268  2.64450

PMMod2 <- lm(PM10 ~ ldrymatter)
summary(PMMod2)

Call: lm(formula = PM10 ~ ldrymatter)

Residuals:
      Min     1Q    Median     3Q    Max
-273.6  -236.4  -200.1  -173.4   6407.5

Coefficients:
      Estimate Std. Error t value Pr(>|t|)
(Intercept) -938.51    3414.02  -0.275    0.785
ldrymatter     14.20     42.82   0.332    0.742

Residual standard error: 1134 on 33 degrees of freedom
Multiple R-squared: 0.003322,  Adjusted R-squared: -0.02688
F-statistic: 0.111 on 1 and 33 DF,  p-value: 0.7422

anova(PMMod2)

Analysis of Variance Table
Response: PM10
           Df  Sum Sq Mean Sq F value    Pr(>F)
 ldrymatter  1  141360  141360  0.11 0.7422
 Residuals  33 4240512 1285003

PMMod3 <- lm(PM25 ~ avgtemp)
summary(PMMod3)

Call: lm(formula = PM25 ~ avgtemp)

Residuals:
      Min     1Q    Median     3Q    Max
-2.9227  -2.6364  -2.001 -1.734  4.64075

Coefficients:
      Estimate Std. Error t value Pr(>|t|)
(Intercept) 23.0305     4.0178  5.731 2.13e-06 ***
avgtemp   -0.9114     0.1696 -5.373 6.14e-06 ***

Residual standard error: 1.188 on 33 degrees of freedom

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
\end{verbatim}
Multiple R-squared: 0.4666, Adjusted R-squared: 0.4504
F-statistic: 28.86 on 1 and 33 DF, p-value: 6.143e-06
>
>anova(PMMod3)
Analysis of Variance Table
Response: PM25
Df Sum Sq Mean Sq F value    Pr(>F)
avgtemp    1 40.735  40.735  28.864 6.143e-06 ***
Residuals 33 46.572   1.411
---
Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
>
>PMMod4<-
>lm(PM25 ~avgRH)
>summary(PMMod4)

Call:
lm(formula = PM25 ~ avgRH)

Residuals:
    Min      1Q  Median      3Q     Max
-1.6622 -0.9193 -0.7006  0.8614  5.6559

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) -2.92624    3.72458 -0.7867  0.4383
avgRH         0.07120    0.06019   1.1836  0.2451

Residual standard error: 1.593 on 33 degrees of freedom
Multiple R-squared: 0.04067, Adjusted R-squared: 0.0116
F-statistic: 1.399 on 1 and 33 DF, p-value: 0.2453
>
>anova(PMMod4)
Analysis of Variance Table
Response: PM25
Df Sum Sq Mean Sq F value    Pr(>F)
avgRH      1  3.551  3.5511  1.3991 0.2453
Residuals 33 83.756  2.5381
---
Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
>
>PMMod5<-
lm(PM25 ~avgtemp+avgRH)
>summary(PMMod5)

Call:
lm(formula = PM25 ~ avgtemp + avgRH)

Residuals:
    Min      1Q  Median      3Q     Max
-1.7475 -0.7474 -0.1512  0.6106  4.7023

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  26.46956    6.36611   4.1583 0.000224 ***
avgtemp     -0.96599    0.18789  -5.1412 1.32e-05 ***
avgRH       -0.03481    0.04971  -0.7000 0.488886

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 1.197 on 32 degrees of freedom
Multiple R-squared: 0.4746, Adjusted R-squared: 0.4418
F-statistic: 14.45 on 2 and 32 DF, p-value: 3.369e-05
>
>anova(PMMod5)
Analysis of Variance Table
Response: PM25
Df Sum Sq Mean Sq F value    Pr(>F)
avgtemp    1 40.735  40.735 28.4186 7.586e-06 ***
avgRH      1  0.703   0.703  0.4902    0.4889
Residuals 32 45.869   1.433
---
Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
>
>PMMod6<-
lm(PM10 ~avgtemp)
>summary(PMMod6)

Call:
lm(formula = PM10 ~ avgtemp)

Residuals:
    Min     1Q Median     3Q    Max
-342.2 -245.9 -215.6 -93.0 6392.1

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) -1452.1     3830.2 -0.3789  0.7076
avgtemp      69.5       161.7   0.4304  0.6700

Residual standard error: 613.7 on 33 degrees of freedom
Multiple R-squared: 0.005566, Adjusted R-squared: -0.02457
F-statistic: 0.1847 on 1 and 33 DF, p-value: 0.6701
>
>anova(PMMod6)
Analysis of Variance Table
Response: PM10
Df Sum Sq Mean Sq F value    Pr(>F)
avgtemp    1 21683.1 21683.1  0.1847 0.6701
Residuals 33 423096.3 12821.9
---
Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
>
>PMMod7<-
lm(PM10 ~avgRH)
>summary(PMMod7)

Call:
lm(formula = PM10 ~ avgRH)

Residuals:
    Min     1Q Median     3Q    Max
-342.2 -245.9 -215.6 -93.0 6392.1

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) -1452.1     3830.2 -0.3789  0.7076
avgRH        69.5       161.7   0.4304  0.6700

Residual standard error: 613.7 on 33 degrees of freedom
Multiple R-squared: 0.005566, Adjusted R-squared: -0.02457
F-statistic: 0.1847 on 1 and 33 DF, p-value: 0.6701
>
>anova(PMMod7)
Analysis of Variance Table
Response: PM10
Df Sum Sq Mean Sq F value    Pr(>F)
avgRH      1 21683.1 21683.1  0.1847 0.6701
Residuals 33 423096.3 12821.9
---
Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
>
<table>
<thead>
<tr>
<th></th>
<th>Min</th>
<th>1Q</th>
<th>Median</th>
<th>3Q</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-296.4</td>
<td>-238.4</td>
<td>-187.1</td>
<td>-134.2</td>
<td>6411.4</td>
</tr>
</tbody>
</table>

Coefficients:

| Estimate | Std. Error | t value | Pr(>|t|) |
|----------|------------|---------|----------|
| (Intercept) | 979.09     | 2651.05 | 0.369    | 0.714   |
| avgRH    | -12.75     | 42.84   | -0.298   | 0.768   |

Residual standard error: 1134 on 33 degrees of freedom
Multiple R-squared: 0.002678, Adjusted R-squared: -0.02754
$F$-statistic: 0.0886 on 1 and 33 DF, p-value: 0.7678

> `anova(PMMod7)`

Analysis of Variance Table

Response: PM10

<table>
<thead>
<tr>
<th>Df</th>
<th>Sum Sq</th>
<th>Mean Sq</th>
<th>F value</th>
<th>Pr(&gt;F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>avgRH</td>
<td>1</td>
<td>113924</td>
<td>113924</td>
<td>0.0886</td>
</tr>
<tr>
<td>Residuals</td>
<td>33</td>
<td>4242538</td>
<td>1285834</td>
<td></td>
</tr>
</tbody>
</table>

> `PMMod8 <- lm(PM10 ~ avgtemp + avgRH)`

> `summary(PMMod8)`

Call:
`lm(formula = PM10 ~ avgtemp + avgRH)`

Residuals:

<table>
<thead>
<tr>
<th>Min</th>
<th>1Q</th>
<th>Median</th>
<th>3Q</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>-357.5</td>
<td>-250.5</td>
<td>-225.0</td>
<td>-95.8</td>
<td>6388.8</td>
</tr>
</tbody>
</table>

Coefficients:

| Estimate | Std. Error | t value | Pr(>|t|) |
|----------|------------|---------|----------|
| (Intercept) | -840.343 | 6112.506 | 0.137 | 0.892 |
| avgtemp | 59.790 | 180.410 | 0.331 | 0.742 |
| avgRH | 6.191 | 47.732 | 0.130 | 0.898 |

Residual standard error: 1150 on 32 degrees of freedom
Multiple R-squared: 0.006089, Adjusted R-squared: -0.05603
$F$-statistic: 0.09802 on 2 and 32 DF, p-value: 0.9069

> `anova(PMMod8)`

Analysis of Variance Table

Response: PM10

<table>
<thead>
<tr>
<th>Df</th>
<th>Sum Sq</th>
<th>Mean Sq</th>
<th>F value</th>
<th>Pr(&gt;F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>avgtemp</td>
<td>1</td>
<td>236831</td>
<td>236831</td>
<td>0.1792</td>
</tr>
<tr>
<td>avgRH</td>
<td>1</td>
<td>22234</td>
<td>22234</td>
<td>0.0168</td>
</tr>
<tr>
<td>Residuals</td>
<td>32</td>
<td>42287397</td>
<td>1321481</td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX F: LAB RESULTS

The University of Guelph Laboratory Services completed the following lab reports. The sample ID *tray* refers to a manure sample taken from the manure belt. The sample ID *floor*, refers to a sample of the litter taken from the litter floor.
Manure Package  Method ID:CHEM-039,185,SNL-019, TOXI-024
Date Authorized: 2017-Aug-22  15:14

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Client Sample ID</th>
<th>Specimen type</th>
<th>Sampling date / time</th>
<th>Test</th>
<th>Result</th>
<th>Units</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>0001</td>
<td>MANURE TRAY</td>
<td>Manure</td>
<td>17-Aug-04</td>
<td>Dry Matter</td>
<td>26.6</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>0001</td>
<td>MANURE TRAY</td>
<td>Manure</td>
<td>17-Aug-04</td>
<td>Potassium</td>
<td>0.481</td>
<td>% wet</td>
<td></td>
</tr>
<tr>
<td>0001</td>
<td>MANURE TRAY</td>
<td>Manure</td>
<td>17-Aug-04</td>
<td>Total Kjeldahl Nitrogen</td>
<td>0.964</td>
<td>% wet</td>
<td></td>
</tr>
<tr>
<td>0001</td>
<td>MANURE TRAY</td>
<td>Manure</td>
<td>17-Aug-04</td>
<td>Ammonium-N</td>
<td>1890</td>
<td>mg/kg wet</td>
<td></td>
</tr>
<tr>
<td>0001</td>
<td>MANURE TRAY</td>
<td>Manure</td>
<td>17-Aug-04</td>
<td>Phosphorus</td>
<td>0.472</td>
<td>% wet</td>
<td></td>
</tr>
<tr>
<td>0002</td>
<td>MANURE FLOOR</td>
<td>Manure</td>
<td>17-Aug-04</td>
<td>Dry Matter</td>
<td>82.9</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>0002</td>
<td>MANURE FLOOR</td>
<td>Manure</td>
<td>17-Aug-04</td>
<td>Potassium</td>
<td>1.57</td>
<td>% wet</td>
<td></td>
</tr>
<tr>
<td>0002</td>
<td>MANURE FLOOR</td>
<td>Manure</td>
<td>17-Aug-04</td>
<td>Total Kjeldahl Nitrogen</td>
<td>3.30</td>
<td>% wet</td>
<td></td>
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<tr>
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<td>MANURE FLOOR</td>
<td>Manure</td>
<td>17-Aug-04</td>
<td>Ammonium-N</td>
<td>1460</td>
<td>mg/kg wet</td>
<td></td>
</tr>
<tr>
<td>0002</td>
<td>MANURE FLOOR</td>
<td>Manure</td>
<td>17-Aug-04</td>
<td>Phosphorus</td>
<td>1.13</td>
<td>% wet</td>
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pH  Method ID:CHEM-172
Date Authorized: 2017-Aug-22  15:14

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Client Sample ID</th>
<th>Specimen type</th>
<th>Sampling date / time</th>
<th>Test</th>
<th>Result</th>
<th>Units</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>0001</td>
<td>MANURE TRAY</td>
<td>Manure</td>
<td>17-Aug-04</td>
<td>pH</td>
<td>6.0</td>
<td></td>
<td></td>
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<tr>
<td>0002</td>
<td>MANURE FLOOR</td>
<td>Manure</td>
<td>17-Aug-04</td>
<td>pH</td>
<td>6.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
### Manure Package

**Method ID:** CHEM-039, 185, SNL-019, TOXI-024  
**Date Authorized:** 2017-Aug-22 15:16

<table>
<thead>
<tr>
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<th>Client Sample ID</th>
<th>Specimen type</th>
<th>Sampling date / time</th>
<th>Test</th>
<th>Result</th>
<th>Units</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>0001</td>
<td>TRAY</td>
<td>Manure</td>
<td>17-Aug-10</td>
<td>Dry Matter</td>
<td>35.6</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>0001</td>
<td>TRAY</td>
<td>Manure</td>
<td>17-Aug-10</td>
<td>Potassium</td>
<td>0.656</td>
<td>% wet</td>
<td></td>
</tr>
<tr>
<td>0001</td>
<td>TRAY</td>
<td>Manure</td>
<td>17-Aug-10</td>
<td>Total Kjeldahl Nitrogen</td>
<td>1.83</td>
<td>% wet</td>
<td></td>
</tr>
<tr>
<td>0001</td>
<td>TRAY</td>
<td>Manure</td>
<td>17-Aug-10</td>
<td>Ammonium-N</td>
<td>1960</td>
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<td></td>
</tr>
<tr>
<td>0001</td>
<td>TRAY</td>
<td>Manure</td>
<td>17-Aug-10</td>
<td>Phosphorus</td>
<td>0.640</td>
<td>% wet</td>
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<tr>
<td>0002</td>
<td>FLOOR</td>
<td>Manure</td>
<td>17-Aug-10</td>
<td>Dry Matter</td>
<td>80.2</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>0002</td>
<td>FLOOR</td>
<td>Manure</td>
<td>17-Aug-10</td>
<td>Potassium</td>
<td>1.48</td>
<td>% wet</td>
<td></td>
</tr>
<tr>
<td>0002</td>
<td>FLOOR</td>
<td>Manure</td>
<td>17-Aug-10</td>
<td>Total Kjeldahl Nitrogen</td>
<td>2.42</td>
<td>% wet</td>
<td></td>
</tr>
<tr>
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<td>FLOOR</td>
<td>Manure</td>
<td>17-Aug-10</td>
<td>Ammonium-N</td>
<td>1090</td>
<td>mg/kg wet</td>
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</tr>
<tr>
<td>0002</td>
<td>FLOOR</td>
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<td>17-Aug-10</td>
<td>Phosphorus</td>
<td>1.17</td>
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</table>

### pH

**Method ID:** CHEM-172  
**Date Authorized:** 2017-Aug-22 15:16

<table>
<thead>
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<th>Client Sample ID</th>
<th>Specimen type</th>
<th>Sampling date / time</th>
<th>Test</th>
<th>Result</th>
<th>Units</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>0001</td>
<td>TRAY</td>
<td>Manure</td>
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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
## Manure Package

**Method ID:** CHEM-039,185, SNL-019, TOXI-024  
**Date Authorized:** 2017-Aug-22 15:16

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## pH

**Method ID:** CHEM-172  
**Date Authorized:** 2017-Aug-22 15:16

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
Submitted By: JAIME ANDERSON
Client ID: 1773990
Owner: JAIME ANDERSON

UNIVERSITY OF GUELPH
JAIME ANDERSON
U OF G SCHOOL OF ENGINEERING
GUELPH, ON N1G 2W1

Phone: 519 824-4120
Fax: 519 836-0227
Sampling Date: 2017-Aug-16
Received Date: 2017-Aug-16

### Manure Package

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
## Manure Package

**Method ID:** CHEM-039, 185, SNL-019, TOXI-024  
**Date Authorized:** 2017-Sep-15 14:23

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## pH

**Method ID:** CHEM-172  
**Date Authorized:** 2017-Sep-15 14:23

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
Submitted By: JAIME ANDERSON
Client ID: 1773990

UNIVERSITY OF GUELPH
JAIME ANDERSON
U OF G SCHOOL OF ENGINEERING
GUELPH, ON N1G 2W1

Phone: 519 824-4120
Fax: 519 836-0227
Sampling Date: 2017-Aug-24
Received Date: 2017-Aug-24

Manure Package  Method ID: CHEM-039, 185, SNL-019, TOXI-024
Date Authorized: 2017-Sep-15 14:24

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pH  Method ID: CHEM-172
Date Authorized: 2017-Sep-15 14:24

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
## Manure Package

**Method ID:** CHEM-039, 185, SNL-019, TOXI-024

**Date Authorized:** 2017-Sep-27 15:49

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## pH

**Method ID:** CHEM-172

**Date Authorized:** 2017-Sep-27 15:49

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
# Laboratory Report

Submitted By: JAIME ANDERSON  
Client ID: 1773990  
Owner: JAIME ANDERSON

**UNIVERSITY OF GUELPH**  
JAIME ANDERSON  
U OF G SCHOOL OF ENGINEERING  
GUELPH, ON N1G 2W1

Phone: 519 824-4120  
Fax: 519 836-0227  
Sampling Date: 2017-Sep-14  
Received Date: 2017-Sep-14

---

## Manure Package Method ID: CHEM-039,185,SNL-019, TOXI-024

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## pH Method ID: CHEM-172

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca

---

Agriculture and Food Laboratory - 95 Stone Rd West, Guelph, ON N1H 8J7 - www.guelphlabservices.com
Lab: Agriculture and Food Laboratory

Submitted By: JAIME ANDERSON
Owner: JAIME ANDERSON

Phone: 519 824-4120
Sampling Date: 2017-Sep-19
Received Date: 2017-Sep-19

### Manure Package

Method ID: CHEM-039,185,SNL-019, TOXI-024

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### pH

Method ID: CHEM-172

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
# Manure Package

Method ID: CHEM-039, 185, SNL-019, TOXI-024  

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# pH

Method ID: CHEM-172  

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
Submitted By: JAMIE ANDERSON  
Client ID: 1773990  
U OF G SCHOOL OF ENGINEERING  
GUELPH, ON N1G 2W1  
Phone: 519 824-4120  
Fax: 519 836-0227  
Sampling Date: 2017-Oct-17  
Received Date: 2017-Oct-17

### Manure Package

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### pH

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
# MANURE PACKAGE

### Method ID: CHEM-039, 185, SNL-019, TOXI-024

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# pH

### Method ID: CHEM-172

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**Supervisor:** Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
Manure Package  
Method ID:CHEM-039,185,SNL-019, TOXI-024  
Date Authorized: 2017-Nov-10 09:58

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pH  
Method ID:CHEM-172  
Date Authorized: 2017-Nov-10 09:58

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca

Agriculture and Food Laboratory - 95 Stone Rd West, Guelph, ON N1H 8J7 - www.guelphlabservices.com
Submitted By: JAIME ANDERSON
Client ID: 1780481
UNIVERSITY OF GUELPH
SCHOOL OF ENGINEERING
50 STONE RD E
GUELPH, ON N1G2W1

Phone: 519 824-4120
Sampling Date: 2017-Oct-27
Received Date: 2017-Oct-27

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**Manure Package**  Method ID: CHEM-039, 185, SNL-019, TOXI-024

Date Authorized: 2017-Nov-08  16:15

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**pH**  Method ID: CHEM-172

Date Authorized: 2017-Nov-08  16:15

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
## Manure Package

**Method ID:** CHEM-039, 185, SNL-019, TOXI-024  
**Date Authorized:** 2017-Nov-10 17:02

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## pH

**Method ID:** CHEM-172  
**Date Authorized:** 2017-Nov-10 17:02

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
MANURE PACKAGE

Method ID: CHEM-039, 185, SNL-019, TOXI-024

Date Authorized: 2017-Nov-17  16:21

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PH

Method ID: CHEM-172

Date Authorized: 2017-Nov-17  16:21

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
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**pH**

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
Submitted By:  
Client ID:  **1780481**  
**UNIVERSITY OF GUELPH**  
JAIME ANDERSON  
SCHOOL OF ENGINEERING  
50 STONE RD E  
GUELPH, ON N1G2W1  
Phone: 519 824-4120  
Sampling Date: 2017-Nov-10  
Received Date: 2017-Nov-10

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### Manure Package  
Method ID: CHEM-039,185, SNL-019, TOXI-024  
Date Authorized: 2017-Nov-28 16:45

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### pH  
Method ID: CHEM-172  
Date Authorized: 2017-Nov-28 16:45

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca

---

*Printed: 2017-Nov-28*
Submitted By: 
Owner: 

Client ID: 1780481 
UNIVERSITY OF GUELPH 
JAIME ANDERSON 
SCHOOL OF ENGINEERING 
50 STONE RD E 
GUELPH, ON N1G2W1 

Phone: 519 824-4120 
Sampling Date: 2017-Nov-14 
Received Date: 2017-Nov-14 

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### Manure Package

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### pH

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca

---

Agriculture and Food Laboratory - 95 Stone Rd West, Guelph, ON N1H 8J7 - www.guelphlabservices.com

Page 1 of 2
Printed: 2017-Nov-28
### Manure Package

**Method ID:** CHEM-039,185,SNL-019, TOXI-024  
**Date Authorized:** 2017-Dec-06 15:58

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### pH

**Method ID:** CHEM-172  
**Date Authorized:** 2017-Dec-06 15:58

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
Submitted By: 
Client ID: 1773990

UNIVERSITY OF GUELPH 
JAIME ANDERSON 
U OF G SCHOOL OF ENGINEERING 
GUDELPH, ON N1G 2W1

Phone: 519 824-4120 
Fax: 519 836-0227 
Sampling Date: 2017-Nov-24 
Received Date: 2017-Nov-24

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## Manure Package

**Method ID:** CHEM-039, 185, SNL-019, TOXI-024

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## pH

**Method ID:** CHEM-172

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
## Manure Package

**Method ID:** CHEM-039, 185, SNL-019, TOXI-024  
**Date Authorized:** 2017-Dec-13 16:07

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## pH

**Method ID:** CHEM-172  
**Date Authorized:** 2017-Dec-13 16:07

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
# MANURE PACKAGE

**Method ID:** CHEM-039, 185, SNL-019, TOXI-024

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# pH

**Method ID:** CHEM-172

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
# Agriculture and Food Laboratory

Submitted By:
Client ID: **1780481**

**UNIVERSITY OF GUELPH**
JAIME ANDERSON
SCHOOL OF ENGINEERING
50 STONE RD E
GUELPH, ON N1G2W1

Phone: 519 824-4120
Sampling Date: 2017-Dec-12
Received Date: 2017-Dec-12

## Manure Package

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## pH

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
Submitted By:
Client ID: 1780481
UNIVERSITY OF GUELPH
JAIME ANDERSON
SCHOOL OF ENGINEERING
50 STONE RD E
GUELPH, ON N1G2W1

Phone: 519 824-4120
Sampling Date: 2017-Dec-15
Received Date: 2017-Dec-15

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**Manure Package**  
Method ID: CHEM-039, 185, SNL-019, TOXI-024  
Date Authorized: 2018-Jan-04 10:52

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**pH**  
Method ID: CHEM-172  
Date Authorized: 2018-Jan-04 10:52

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
Submitted By: 
Client ID: 1780481

UNIVERSITY OF GUELPH  
JAIME ANDERSON  
SCHOOL OF ENGINEERING  
50 STONE RD E  
GUELPH, ON N1G2W1

Phone: 519 824-4120  
Sampling Date: 2019-Jan-19  
Received Date: 2018-Jan-19

---

**Manure Package**  
Method ID: CHEM-039,185,SNL-019, TOXI-024

Date Authorized: 2018-Feb-13 16:43

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**pH**  
Method ID: CHEM-172

Date Authorized: 2018-Feb-13 16:43

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
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**pH**

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
Submitted By:  
Client ID:  1773990  
Owner:  JAIME ANDERSON

UNIVERSITY OF GUELPH  
JAIME ANDERSON  
U OF G SCHOOL OF ENGINEERING  
GUELPH, ON N1G 2W1

Phone: 519 824-4120  
Fax: 519 836-0227  
Sampling Date: 2018-Jan-26  
Received Date: 2018-Jan-26

### Manure Package  
Method ID:CHEM-039,185,SNL-019, TOXI-024

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### pH  
Method ID:CHEM-172

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
**Manure Package**  
Method ID: CHEM-039, 185, SNL-019, TOXI-024  
Date Authorized: 2018-Feb-15 15:52

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**pH**  
Method ID: CHEM-172  
Date Authorized: 2018-Feb-15 15:52

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Report 18-010162
Final Report
Submitted: 2018-Feb-16

LABORATORY SERVICES
Agriculture and Food Laboratory

Submitted By: JAIME ANDERSON
Owner: JAIME ANDERSON

UNIVERSITY OF GUELPH
JAIME ANDERSON
U OF G SCHOOL OF ENGINEERING
GUELPH, ON N1G 2W1

Phone: 519 824-4120
Fax: 519 836-0227
Sampling Date: 2018-Feb-06
Received Date: 2018-Feb-06

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### Manure Package
Method ID: CHEM-039, 185, SNL-019, TOXI-024

Date Authorized: 2018-Feb-16 17:04

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### pH
Method ID: CHEM-172

Date Authorized: 2018-Feb-16 17:04

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
### Manure Package

**Method ID**: CHEM-039, 185, SNL-019, TOXI-024  
**Date Authorized**: 2018-Feb-23 14:16

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### pH

**Method ID**: CHEM-172  
**Date Authorized**: 2018-Feb-23 14:16

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
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**pH**

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
Submitted By:  
Client ID:  1780481  
UNIVERSITY OF GUELPH  
JAIME ANDERSON  
SCHOOL OF ENGINEERING  
50 STONE RD E  
GUELPH, ON N1G2W1  

Phone: 519 824-4120  
Sampling Date: 2018-Feb-16  
Received Date: 2018-Feb-16

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**Manure Package**  
Method ID: CHEM-039, 185, SNL-019, TOXI-024  

Date Authorized:  2018-Mar-08  15:43

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**pH**  
Method ID: CHEM-172  

Date Authorized:  2018-Mar-08  15:43

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
### Manure Package

**Method ID:** CHEM-039,185, SNL-019, TOXI-024  
**Date Authorized:** 2018-Mar-09 16:48

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**pH**  
**Method ID:** CHEM-172  
**Date Authorized:** 2018-Mar-09 16:48

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
### Manure Package

Method ID: CHEM-039,185, SNL-019, TOXI-024

**Date Authorized:** 2018-Mar-09 16:49

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### pH

Method ID: CHEM-172

**Date Authorized:** 2018-Mar-09 16:49

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
# Manure Package

**Method ID:** CHEM-039,185,SNL-019, TOXI-024  
**Date Authorized:** 2018-Mar-12 16:40

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# pH

**Method ID:** CHEM-172  
**Date Authorized:** 2018-Mar-12 16:40

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
### Manure Package

**Method ID:** CHEM-039, 185, SNL-019, TOXI-024  
**Date Authorized:** 2018-Mar-20 16:30

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### pH

**Method ID:** CHEM-172  
**Date Authorized:** 2018-Mar-20 16:30

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Supervisor: Nicolaas Schrier MSc, Animal Health Laboratory 519 823 1268 ext. 57215 nschrier@uoguelph.ca
# Manure Package

Method ID: CHEM-039,185, SNL-019, TOXI-024

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# pH

Method ID: CHEM-172

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