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Assessment of Sprinklers on the Removal Efficiency of Ammonia and Particulate Matter in a Commercial Broiler Facility

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Abstract. Intensive poultry production can be a significant source of airborne pollutants. There are potential health risks posed to poultry and management staff that is frequently exposed to high concentrations of pollutants inside the production facility. Ammonia and particulate matter are of particular interest primarily due to their negative environmental and health effects.

A two story commercial broiler facility in Perth County, Ontario, Canada was used for this study. The effects of a sprinkler system on the emissions of ammonia (NH_3) and particulate matter (PM_{10} and $PM_{2.5}$) were investigated. The duration of the study spanned three seasons: winter, spring, and summer. During the winter, NH_3, PM_{10}, and $PM_{2.5}$ removal efficiencies were calculated to be 68%, 84%, and 60%, respectively. During the spring sampling campaign the removal efficiency of NH_3 was calculated to be 7%. Due to an unusually high concentration of PM on the treatment floor during the spring, removal efficiencies for PM could not be calculated. Removal efficiencies for the summer season for NH_3, PM_{10}, and $PM_{2.5}$ were calculated to be 22%, 89%, and 86%, respectively. In the current study water sprinkling systems have been demonstrated to be an effective control technology for reducing emissions of PM and NH_3, but are influenced by management practices and the time of year.

Keywords. *Ammonia, Particulate Matter, Sprinkler, Poultry, Pollutants*

Introduction

Numerous studies have reported that poultry production is a significant source of several aerial pollutants (Wheeler et al., 2006; Burns et al., 2007; 2008; Gates et al., 2008; Roumeliotis et al., 2010a; b; Lin et al., 2012; Morgan et al., 2014). The pollutants of particular concern are ammonia (NH_3) and particulate matter (PM) due to their adverse environmental and health effects. Many studies have documented the uncontrolled release of ammonia (see Roumeliotis and Van Heyst, 2008 for summary) that is generated by the microbial degradation of excreta and organic matter within the poultry facility. Much research, however, remains to be done in the way of determining how effectively NH_3 and PM can be controlled through the use of various technologies such as water sprinklers.

According to the National Pollution Release Inventory (NPRI) for Canada for 2011, livestock operations accounted for approximately 326 Mt of NH_3 released which represents 63% of the total ammonia being emitted into the atmosphere in Canada (Environment Canada, 2012). In addition to NH_3, livestock production also emits a large amount of PM, which has been estimated to be approximately 264 Mt for 2011 (Environment Canada, 2012). It has also been demonstrated that much of the NH_3 emitted from agriculture contributes to the fine PM (particulate matter with aerodynamic diameter of 2.5 µm or less; $PM_{2.5}$) burden (Ten Brink et al., 2001; Anderson et al., 2003). Poultry production, including meat and eggs, accounts for approximately 4% of the total number of animal production facilities within Canada (Statistics Canada, 2007). This sector, however, produces 20-40% of the total NH_3 emissions to the atmosphere based on data from the NPRI and Statistics Canada (Statistics Canada, 2012).

A wide range of management practices and technologies exist that can be used to reduce the amount of NH_3 and PM emitted from poultry housing. Management practices include reducing stress, maintaining bird health, and proper manure and litter management. Prevalent control technologies available to producers include manure and litter amendments, water/oil sprinklers, biofilters, feed additives, acid scrubbers, and water filters.

One of the more widely used methods of reducing poultry body temperature and promoting bird activity is the use of water sprinklers. The use of sprinklers has also been attributed to reducing the levels of dust and NH_3 in the barn environment. Installed sprinkler systems are typically run on a prescribed program to periodically increase the activity level of the birds and are controlled by a computer system. In the case of elevated house temperatures, the sprinklers can also be used as evaporative coolers. Using sprinklers to reduce body temperature during high heat events can reduce instances of heat stress. When sprinklers are run, birds tend to become more mobile, releasing stored heat between the underside of the bird and the litter. This also increases migration towards the feeders and drinkers. Promoting this type of behavior can lead to larger production gains and healthier birds. These benefits are further augmented by reducing airborne contaminant concentrations can also help promote healthier birds and better production.

Literature Review

Ammonia

NH_3 emission from poultry litter is the result of the microbial degradation of nitrogenous compounds present in poultry excreta. Compounds such as undigested proteins and uric acid are the two main nitrogenous components of excreta comprising 30% and 70%, respectively (Groot Koerkamp, 1994). The decomposition of uric acid in excreta is most favorable under alkaline conditions, where the pH is above 7. The enzyme responsible for catalyzing the decomposition of uric acid, uricase, has a maximum efficiency at a pH of 9 (Hong et al., 2013). The biochemical processes are complex and microbially mediated but can be simplified as follows (Groot Koerkamp, 1994):

$$\textit{(Uric acid)}\ C_5H_40_3N_4 + 1.5O_2 + 4H_2O \rightarrow 5CO_2 + 4NH_3$$

$$\text{Undigested Proteins} \rightarrow NH_3$$

NH_3 present in aqueous form in the manure/litter then becomes airborne through volatilization and dispersion. Once emitted into the atmosphere, NH_3 can be a significant contributor to negative environmental and health effects as well as be a source of odors. In addition, atmospheric NH_3 can react with acid gases (hydrochloric acid (HCl), nitric acid (HNO_3), sulfuric acid (H_2SO_4)) to generate secondary inorganic aerosols (SIA), which contribute to atmospheric levels of $PM_{2.5}$ (Baek et al., 2004). In the United States, it has been estimated that over 50% of the $PM_{2.5}$ is generated from secondary reactions involving NH_3 (Allen et al., 2011; Patterson et al., 2005).

Particulate Matter

PM in livestock facilities is typically analyzed in different size fractions because of the negative health implication associated with the specific particle size fractions. Of particular concern are PM_{10} (aerodynamic diameter of 10μm or less) and $PM_{2.5}$ due to their negative respiratory effects on both livestock and humans (Schwarze et al., 2006).

Airborne PM present in a poultry housing facility is almost entirely biological and organic in nature. Typically, it is a complex mixture of solid and aerosol materials such as feed, dander, skin, excreta, bedding material, feathers, and microorganisms. PM concentrations vary greatly in animal housing environments because levels are dependent on many factors such as: species, housing type, ventilation, feed, stocking density, time of day, season, and existing mitigation practices. PM becomes suspended in the indoor environment through mechanical agitation that can include animal activity, human activity, ventilation, and use of machinery. Consequently, PM concentrations are typically lower at night compared to the daylight hours due to the lower activity level of the poultry (Morgan et al., 2014; Roumeliotis et al., 2007; Tan et al., 2004).

Oil and Water Spraying

Oil and water spraying is a control strategy that has been used to control particulate matter concentrations in livestock housing facilities. Removal efficiencies of 23-80% for PM have been reported along with a 30% reduction in ammonia (Patterson et al., 2005). Typically, the spray is a combination of a small percentage of plant oil mixed with water that can be applied manually with a hand held sprayer or automatically using a permanently installed system (Patterson et al., 2005). Increasing the frequency of spraying can also increase the potential reduction in PM concentration (Zhang et al., 1996) but can also increase the relative humidity in the house.

PM is removed by water droplets via inertial impaction, interception, gravitational settling and diffusion. Ammonia however, is removed by the "scrubbing" action of the water droplets which absorb ammonia due to its high solubility in water. Eremin et al. (2007) have demonstrated that ammonia absorption into a water droplet increases with a decrease in the radius of the water droplet and its velocity. According to Takai and Pederson (1999), droplet size should be above 150 μm to obtain effective liquid application, although ultrasonic sprayers have been used that generated droplets ranging from 7 μm to 150 μm. While most studies on oil and water spraying look at the efficacy of the sprinklers on PM removal (see, for example, Ikeguchi et al., 2002, and Von Wachenfelt, 1999) few studies have addressed the additional benefit of the potential for ammonia reduction.

Methodology

Site Location

A two story commercial broiler facility was used for this study located in Perth County, Ontario, Canada. The dimensions of the facility were roughly 17 m wide by 96 m long. Each floor used straw as a litter material with occasional wood chips added during the winter months for moisture control. Each floor accommodated approximately 14,000 broiler chickens. The environmental parameters (i.e. temperature, ventilation, static pressure, and relative humidity) for each floor were independently controlled by Fancom F37 controllers. This production facility employed a 42 day production cycle with approximately three weeks of down time between flocks. At the end of the cycle, the final weight of a broiler chicken was approximately 2.2 kg. At growth day 42, the final stocking density was roughly 0.12 m^2/bird.

The facility was mechanically ventilated using a hybrid between cross flow and tunnel configurations to regulate the temperature inside the facility. Table 1 summarizes the number of ventilation fans that were employed on each floor. All ventilation fans, with the exception of three of the 1.21 m fans on the second floor, were located on the east side of the building. Three of the 1.21 m fans on the second floor were located on the north end of the facility and acted as tunnel fans during exceedingly warm periods. On both floors, fresh air was drawn in through inlets on the west side of the building where a baffle was used to control the size of the inlet opening. During the winter, a small inlet opening was used to achieve a higher static pressure (-18.43 Pa or -0.074 inches of water) to allow for the incoming cold air to have sufficient velocity across the ceiling to allow a circulation cell to develop for adequate fresh air mixing. During the warmer months, a lower static pressure (-12.45 Pa or -0.05 in H_2O) and a larger inlet opening was used for adequate mixing of fresh air.

Table 1: Summary of ventilation fans on Bottom and Top floors

Fan Diameter(m)	Number on Bottom Floor	Number on Top Floor
0.45	2	2
0.61	6	6
0.91	3	3
1.21	4	4

When the birds were first introduced into the house on day 1 of a production cycle, the indoor temperature was set at 33 °C and achieved by the use of natural gas radiant pipe heaters. The indoor temperature set point was then gradually reduced at regular intervals (~0.5 °C/day) until a set point temperature of 22 °C was reached on day 42.

The lighting regime changed depending on the age of the birds. When a flock first arrived, birds were exposed to only one hour of darkness. Every second day, another hour was added until five hours of darkness was reached, occurring by the eleventh growth day.

Drinking water was supplied to the birds via nipple drinkers and feed was pushed by augers down a line of feeder trays. Both feeder trays and nipple drinkers had adjustable heights such that, as the birds grew, the drinkers and feed trays could be raised to match the birds' growth.

Sprinkler System

The selected broiler facility used a computer controlled water sprinkler system to regulate bird body temperature and level of bird activity inside the facility. The sprinklers were suspended from the ceiling by a 40.6 cm (16 inches) long that was teed from a 1.27 cm diameter (0.5 in) PVC pipe that ran the length of the barn along the ceiling. This facility had two lines of sprinklers on each floor to ensure that they covered the entire floor space. Sprinkling durations lasted 20 seconds and emitted 237 ml (8 oz) of water per sprinkler over a 46.45 m^2 (500 sqft) area.

The program for the sprinkler system was activated between the 25th and 28th growth day and ran every two hours from 10:00 to 22:00. The time between sprinkler applications allowed for the birds to dry their feathers and maximize evaporative cooling.

Sampling Methodology

Due to experimental time limitations, three seasons of measurements were obtained: winter, spring, and summer. During the winter season, the top floor acted as the treatment floor and was switch with the control during the spring. For the summer sampling campaign the treatment and control floors were again alternated.

Ammonia

A mobile temperature controlled trailer was used to house the equipment that was needed to quantify the ammonia emissions from the facility. To measure concentrations of ammonia in the barn air, a model 17C Thermo Electron Corp chemiluminescent analyzer was used (Model 17C, Thermo Electron Corp, Waltham, MA, USA). A time constant of 10 seconds and a logging interval of 5 minutes were employed. Zero and calibration checks were performed every two weeks using a 27 ppm calibration gas.

Two 30.5m (100 ft) heated sample lines were used (Model 0723-100, Clean Air Engineering Inc, Chicago, IL, USA) to deliver barn air to the trailer. The sample line temperature controllers maintained a constant temperature of 124 °C (255 °F) to ensure that no condensation occurred within the sample line. The heated sample line consisted of an inner 1.27 cm diameter (0.5 inch) Teflon tube and heating coils to maintain the set temperature.

A diaphragm pump (Model ADI R-Series 9769T1, Clean Air Engineering Inc., Chicago, IL, USA) capable of pumping at 26 L/min was used to supply sample air to the analyzer located in the trailer. Once the air was delivered to the trailer it reached a three-way solenoid valve that was controlled by a CR23X Campbell Scientific data logger. The data logger alternated the valve opening between the sample line on the first floor and the sample line on the second floor every half hour.

During the first half of every hour, the solenoid valve was open to the sample line that was drawing air from the treatment floor. This was to capture sprinkling events, which occured at the beginning of every second hour.

Particulate Matter

PM was monitored continuously on the treatment and control floors using monitors housed in wall mounted cabinets. The cabinets were located such that the sampling tube could be located as close as possible to the heated sample line used for ammonia analysis. Dusttrak DRX Aerosol Monitors (Model 8533 and 8534, TSI Inc., Shoreview, MN, USA) were used on each floor to monitor levels of size fractionated PM. Monitors were setup using a 10 second time constant and a 5 minute logging interval. Zero checks were performed every two weeks.

Ventilation Rate

In order to calculate emission rates, ventilation exhaust rates are required. A Flow Assessment Numeration System (FANS) was used to determine the exhaust rate of each individual fan at specific static pressures. The FANS unit was centered against the wall in front of each exhaust fan and sealed to prevent leakage. Once in its fixed position, the FANS unit would traverse six Model 27106T Gill Propeller anemometers up and down the vertical extent of the FANS unit. The propeller anemometer rotation was then converted to a DC voltage that is linearly proportional to the air velocity. The velocity profiles were then integrated over the cross-sectional area of the FANS unit to obtain a volumetric flow rate.

The ideal fan size for the FANS unit is 0.91m and above. A methodology was adapted to allow the same unit to measure flow rates for smaller fan sizes. For smaller exhaust fan sizes, the FANS unit was centered over the exhaust fan and anemometers that were located outside the dimensions of the exhaust fan were removed. Using polystyrene boards a square frame was made that was fixed over the exhaust fan and sealed to the wall. This prevented any air infiltration and ensured that all air flow came directly through the frame inlet. Using the raw data from the FANS test and the equation:

$$\text{m/s} = \text{RPM}\times 0.005 \qquad (1)$$

the anemometer RPM was converted to a velocity. This velocity was integrated across the cross sectional area of the polystyrene square to obtain a flow rate.

Statistical Analysis

Adjustment for Serial Correlation

To analyze the means of treatment and control and to determine whether the differences observed were statistically different, a two sided *Z*-test was used. This particular test for significance was used instead of alternative such as a *t*-test due to the very large sample size. It is also important to acknowledge that the assumption of independence used for a *Z*-test was not appropriate for this analysis. This is due to the fact that data collected over time with observations taken close together are not independent but are correlated. Therefore, time series analysis was used as it presents methods to adjust for correlated observations. In time series analysis, the dependence between observations is described as serial correlation (Ramsey et al., 2002).

The method that was used is described in Ramsey et al. (2002) and is a multiplicative adjustment to the usual standard error for the difference in two means. To adjust for serial correlation the following equation was used to determine the adjusted standard error, *SE*:

$$SE(\overline{Y_T} - \bar{Y}_C) = \sqrt{\frac{1+r_1}{1-r_1}}\, s_p \sqrt{\frac{1}{n_T} + \frac{1}{n_C}} \qquad (2)$$

where $\bar{Y}$ is the mean, r_1 is the sample first serial correlation coefficient ($-1 < r_1 < +1$), s_p is the pooled standard deviation for two independent samples, *n* is the sample size, and the subscripts *T* and *C* refer to the treatment and the control, respectively. Also, the quantity $s_p\sqrt{\frac{1}{n_T}+\frac{1}{n_C}}$ is the usual standard error calculation for the difference in means. The pooled standard deviation for two independent samples, s_p, was calculated as follows:

$$s_p = \sqrt{\frac{(n_T-1)s_T^2 + (n_C-1)s_C^2}{n_T + n_C - 2}} \qquad (3)$$

where *s* is the sample standard deviation. If $r_1$in equation 2 is zero then there is no serial correlation present and the adjustment factor to the standard error is 1. The coefficient $r_1$allows for a numerical measure of the correlation between adjacent residuals. To calculate r_1, the following equations were used:

$$r_1 = \frac{c_1}{c_0}, \text{ where:} \qquad (4)$$

$$c_1 = \frac{1}{n-1}\sum_{t=2}^{n} res_t \times res_{t-1}, \text{ and} \qquad (5)$$

$$c_0 = \frac{1}{n-1}\sum_{t=1}^{n} res_t^2 \qquad (6)$$

The variables c_1 and c_0 are described as autocovariance estimates and res_t is the residual of observation *t*.

To develop a standard error for the difference in means of two time series, a pooled estimate of the first serial correlation coefficient is needed. Pooled estimates of c_1 and c_0 were first obtained and then the ratio was computed to arrive at r_1 (Ramsey et al., 2002). The equation used is:

$$Pooled\ Estimate\ of\ c_1/c_0 = \frac{(df_1 \times est_1) + (df_2 \times est_2)}{df_1 + df_2} \qquad (7)$$

where *df* is the degrees of freedom and *est* is the estimate of c_1/c_0 for each sample. Once the adjusted standard error for the difference in two means was calculated, a *Z*-statistic for testing the equality of means was developed using the following equation:

$$z = \frac{\bar{Y}_T - \bar{Y}_C}{SE(\overline{Y_T} - \bar{Y}_C)} \qquad (8)$$

For each test, the level of significance used was α=0.05 (Ramsey et al., 2002).

Data Transformation

Based on the data distribution, it was determined that the time series developed in this study would benefit from transformation to improve the accuracy of tests and conclusions. The transformation used was the natural logarithm due to the fact that it squeezes large numbers together and stretches out smaller numbers. This results in the toning down of large peaks and deepens the valleys that are present in diurnal patterns. Analysis of boxplots and histograms before and after transformation showed significant improvements in the distributions. Also, there were zero values recorded, only occurring during the first five days, therefore a small number (in this case one) was added to each value in the time series prior to transformation. The equation used to transform each time series for statistical analysis is as follows:

$$X_t = \ln(x_t + 1) \qquad (9)$$

where x_t is the observation at time *t.*

Results and Discussion

Barn parameters and emission factors are summarized, for convenience, in Table 2.

In the winter sampling campaign, ventilation rates for each floor were low but very similar. Static pressures were very similar, litter pH was similar, litter moisture was high but with little difference, and ammonium-N was higher on the control floor in the litter. Overall during the winter campaign the floors behaved in a similar manner. During the spring campaign the ventilation rates for each floor had little observed difference, although the static pressure was higher on the treatment floor. Litter pH was high but similar between floors, ammonium-N was much higher in the litter on the treatment floor, and litter moisture content was much higher on the treatment floor than the control. In the summer sampling campaign the ventilation rates were high with little difference between floors, litter moisture, litter pH, ammonium-N, and static pressure were also very similar. The behaviors of floors during the summer campaign were very similar.

Emission factors, in units of g day^{-1} AU^{-1} (AU equivalent to 500 kg of live weight), are presented in a time series format for NH_3 and PM (10 μm and 2.5 μm size fractions) collected over the winter, spring, and summer sampling campaigns in the following subsections, respectively.

Ammonia

Figure 1a illustrates the calculated ammonia emission factors for the full production cycle during the winter sampling period. The vertical dashed line on day 26 represents the beginning of the treatment period. Prior to the treatment period, both floors behaved similar with little bias evident between floors. On the right side of the dashed line, within two days of treatment activation, the emission factors began to deviate. Post treatment, the average emission factor for the control floor was 387 g day^{-1} AU^{-1} and for the treatment floor it was 195 g day^{-1} AU^{-1}, which was significantly different at a *p*-value of <0.0001. This resulted in a 50% reduction in ammonia emission factor during the treatment duration. The large magnitude of the percent reduction can be attributed to the low ventilation rates that were observed during the winter season. Typically during the winter, the facility was running at minimum ventilation rates, which allowed for a greater accumulation of NH_3 within the facility. Consequently the potential amount of NH_3 that was available for removal by the water drops was greatly increased.

Figure 1b presents the ammonia emission factors from the spring season for six days during the treatment period. Data prior to this time period was not available as a result of equipment failure. During the spring season, the treatment was activated on the 25th day of the production cycle. The average emission factor for the control floor was 275 g day^{-1} AU^{-1} and 256 g day^{-1} AU^{-1} for the treatment floor, and was determined to be significantly different at a *p*-value of 0.0292. This represents a 7% reduction in the ammonia emission factor.

The magnitude of the reduction during the spring was significantly less than during the other seasons due to the litter conditions on the treatment floor. Litter conditions were ideal for a large amount of NH_3 to be generated and released. Table 2 summarizes the observations for each of the campaigns and it is readily apparent that a high moisture content, a pH favoring NH_3 formation, and a high amount of available nitrogen on the treatment floor during the spring campaign greatly increased the NH_3 release potential from the litter compared to the control floor. Also shown in Table 2 are the average static pressures experienced inside the facility during the treatment period. The treatment floor had a much higher average static pressure which caused air infiltration from the control floor to the treatment floor (top floor to bottom floor). This resulted in the air from the control floor passing through the litter bed of the top floor thereby enhancing ammonia mass transfer into the air prior to entering the treatment floor.

Figure 1c illustrates the calculated ammonia emission factors from the summer season. The vertical dashed line on day 28 represents the beginning of the treatment period with the sprinklers active on the top floor. During the treatment period the average emission factor for the control floor was 285 g day^{-1} AU^{-1} and 221 g day^{-1} AU^{-1} for the treatment floor. These means were determined to be significantly different (*p*-value=<0.0001). Analysis of means revealed a 22% reduction in NH_3 emission factor during the treatment period. It can be noted that prior to treatment, both control and treatment floors behaved similarly. It is also evident that a short lag period existed after the treatment activation and before the emission factors begin to diverge from one another, around day 35. The two data gaps in Figure 1c between days 15 through 25 were due to equipment failure.

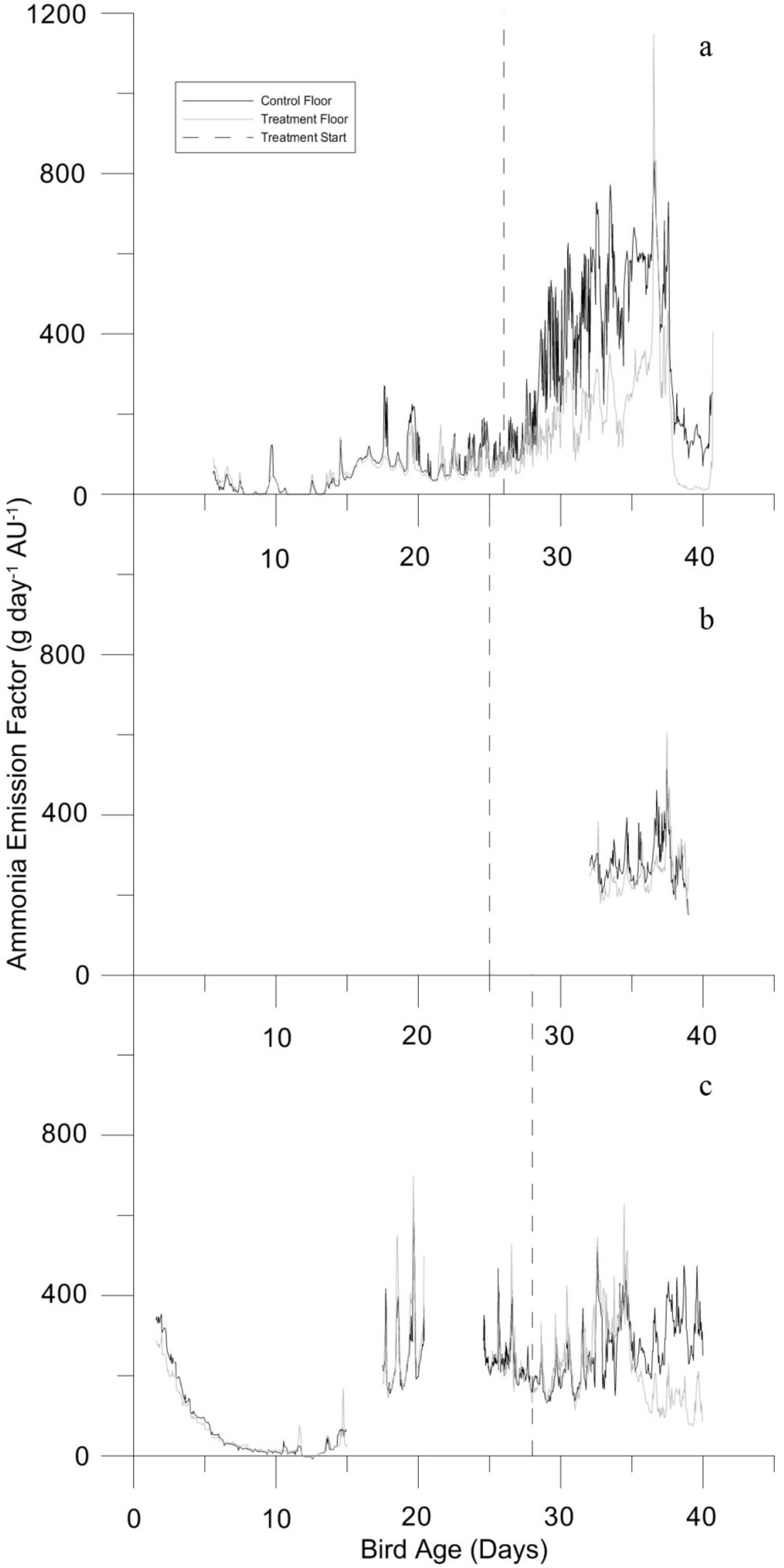

Figure 1: Ammonia emission factors developed for Winter (a), Spring (b), and Summer (c) sampling campaigns

Particulate Matter

Figures 2a & d show the emission factors calculated for PM_{10} and $PM_{2.5}$, respectively, for data collected over the winter production cycle. The vertical dashed line represents the beginning of the treatment period. The large gap in data from day 28.5 to 36.5 is where the cut off size on the aerosol monitor was switched from a 10 μm cut size to a 2.5 μm cut size. This was the only sampling campaign that did not have concurrent PM_{10} and $PM_{2.5}$ data due to the availability of equipment. This resulted in roughly a week of data for each size fraction during the treatment period. It is evident that on the treatment floor, once the treatment period began emission factor levels began to drop for both PM_{10} and $PM_{2.5}$. Average emission factors for PM_{10} during the treatment period for the control and treatment floors were 8.1 g day^{-1} AU^{-1} and 1.3 g day^{-1} AU^{-1}, respectively. The means were significantly different at a *p*-value of 0.001 and resulted in an 84% reduction in PM_{10} emissions for the period. For $PM_{2.5}$, the average emission factors during the treatment period for the treatment and control floors were 0.92 g day^{-1} AU^{-1} and 2.3 g day^{-1} AU^{-1}, respectively. The means were again significantly different at a *p*-value of <0.0001 and indicated a 60% reduction in $PM_{2.5}$ emission levels for the period.

Figures 2b & e give the emission factors for the spring season for both PM_{10} and $PM_{2.5}$, respectively. Prior to the treatment period, as indicated in Figures 2b & e, both the treatment and the control floors behaved very similar indicating that there was no bias between floors. Once the treatment period began, the emission factors on each floor started to deviate. However, it is the control floor that had a lower PM level than the treatment floor, indicating that the treatment did not have the desired effect (see Table 2 for average emission factors during the treatment period). It is important to note that during this period, the average static pressure for the treatment floor was above the control (see Table 2). As previously stated, this would cause air infiltration from the control floor passing through the litter bed and into the treatment floor. As the air from the control floor passed through the litter, it would accumulate both NH_3 and acid gases present in the poultry litter. A neutralization reaction between the basic NH_3 gas and the acid gases would result in the formation of secondary inorganic aerosol (SIA) formation (Roumeliotis et al., 2010b). This would increase the $PM_{2.5}$ concentration on the treatment floor as SIA are typically in the very fine size fraction (see discussion under $PM_{2.5}/PM_{10}$ ratio in the following section). As a result, the percent reduction in PM emission factors cannot be calculated due to the lack of independence between floors. It is important to note that this does not indicate that the treatment was not effective at reducing PM levels, but rather that a percent reduction cannot be calculated.

Figures 2c & f show the emission factors calculated for the summer sampling campaign for PM_{10} and $PM_{2.5}$, respectively. Prior to treatment, the floors behaved very similarly, however, shortly after activation the floors began to deviate from each other. After sprinkler activation on the treatment floor, the emission factors begin to drop until the end of the production cycle where levels of both PM_{10} and $PM_{2.5}$ were very low. During the treatment period, the average emission factors for PM_{10} on the control and treatment floors were 6.8 g day^{-1} AU^{-1} and 0.83 g day^{-1} AU^{-1}, respectively. This is significantly different at a *p*-value of <0.0001 and represents an 88% reduction in PM_{10} levels. Average emission factors for $PM_{2.5}$ for the same period on the control and treatment floors were 5.3 g day^{-1} AU^{-1} and 0.71 g day^{-1} AU^{-1}, respectively. At a *p*-value of <0.0001, the means were significantly different and resulted in an 86% reduction in $PM_{2.5}$ emission factors.

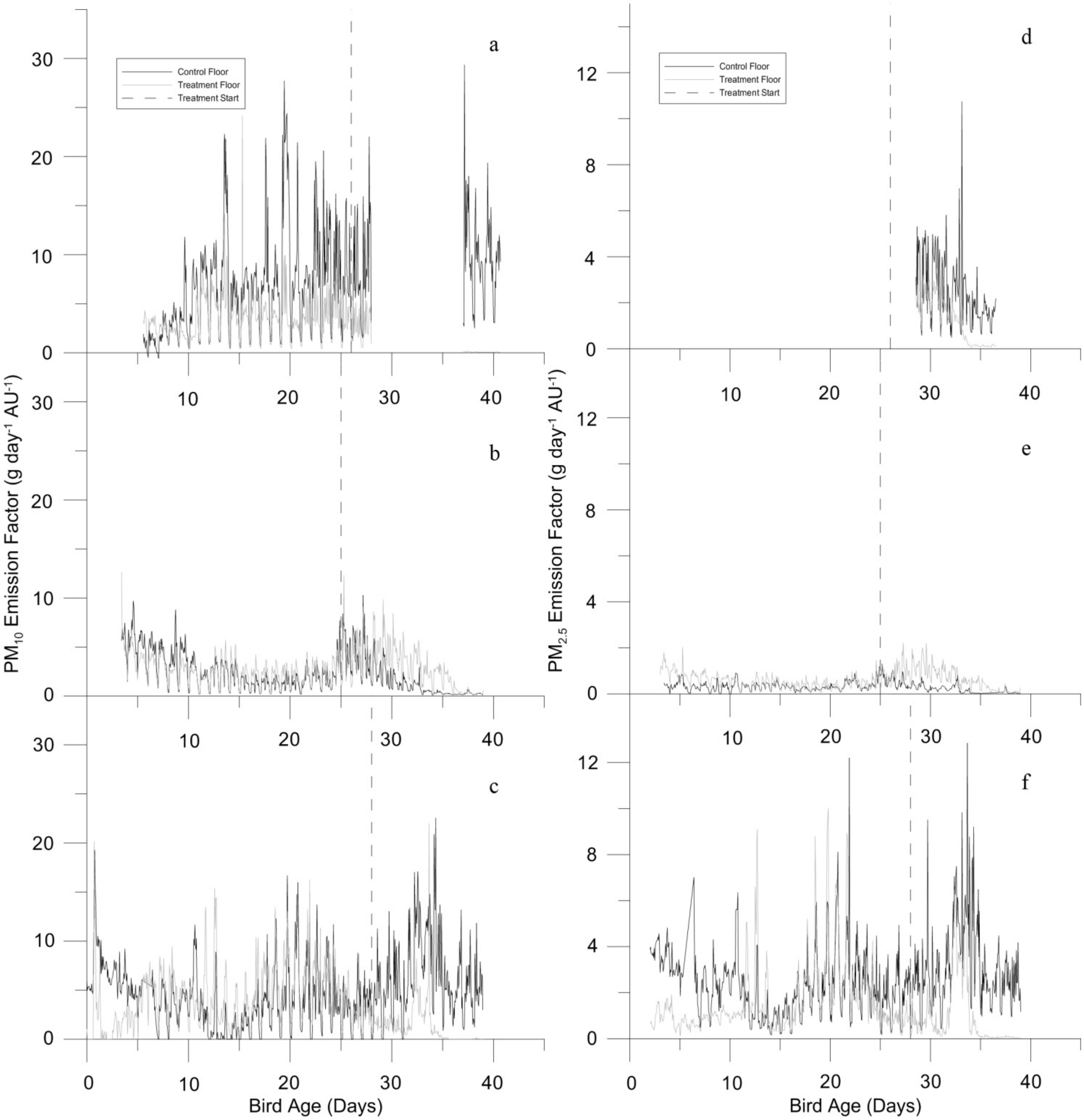

Figure 2: PM$_{10}$ emission factors for Winter (a), Spring (b), and Summer (c) and PM$_{2.5}$ emission factors for Winter (d), Spring (e), and Summer (f) sampling campaigns

PM$_{2.5}$/PM$_{10}$ Ratio

The comparison of the ratio of PM$_{2.5}$/PM$_{10}$ can be used to infer if different processes are occurring, such as SIA formation, between the treatment and control floors. Figure 3 compares the PM$_{2.5}$/PM$_{10}$ ratio between the floors for the spring and summer seasons and indicates very different behaviors for the two seasons. During the spring when the static pressures were significantly different between floors (Figure 3a), the control floor had a much lower ratio indicating that very little of the PM$_{10}$ was comprised of PM$_{2.5}$. Conversely, on the treatment floor, the PM$_{2.5}$/PM$_{10}$ is much larger indicating that a very large fraction of the PM$_{10}$ was PM$_{2.5}$. This difference in behavior is the result of the two floors not being independent from each other whereby barn air from the top control floor infiltrated the bottom treatment floor after passing through the top floor litter bed. The infiltrating air from the control floor essentially scrubbed NH_3 and acid gases from the litter bed prior to entering the treatment floor with subsequent SIA formation on the treatment floor. In contrast, during the summer (Figure 3b), where the floors were independent, the ratio for both the control and the treatment are very similar.

During the spring, the average $PM_{2.5}/PM_{10}$ ratio was 0.19 for the control floor where as the treatment floor was 0.6. During the summer, the $PM_{2.5}/PM_{10}$ ratio for the control and treatment floors were 0.45 and 0.46, respectively. Ratios for the winter season could not be calculated due to the lack of concurrent data.

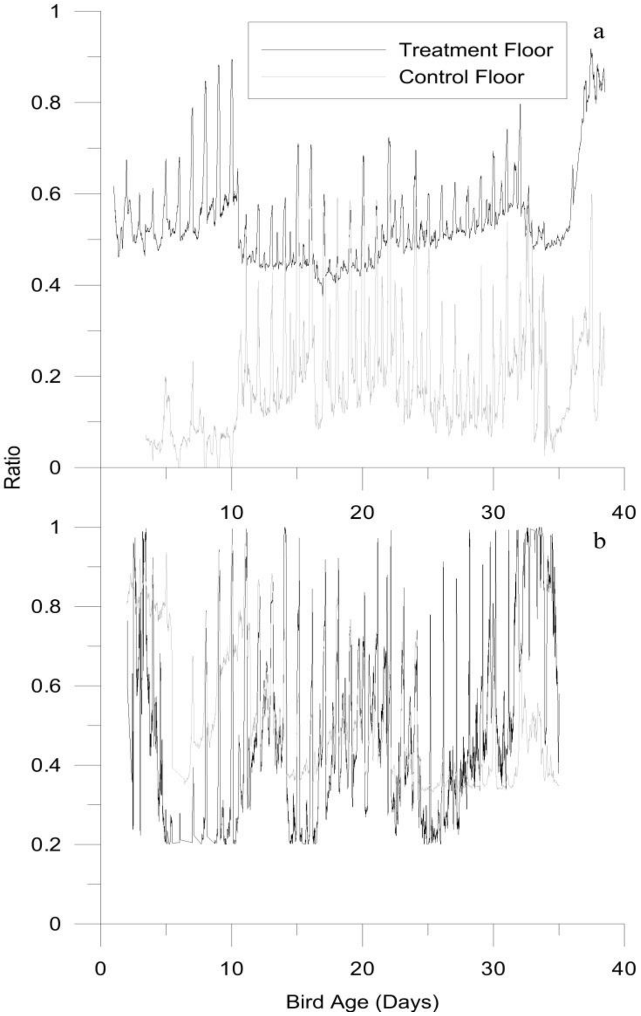

Figure 3: $PM_{2.5}/PM_{10}$ ratios for the Spring (a) and Summer (b) sampling campaigns

Summary of Results

Table 2 summarizes all the emission factors for each pollutant during each season as calculated during the treatment period. Air exchange rates, static pressures, and several parameters relating to litter conditions are also given in Table 2. A percent difference is calculated for each variable to illustrate the relative differences between seasons and also to highlight factors that may contribute to the observed differences in emission factors. This is of particular importance during the spring season where, as previously mentioned, certain litter and barn conditions led to difficulty identifying a percent reduction in PM. Percent differences were calculated by subtracting the control from the treatment over the control value. A negative percent difference would indicate a reduction on the treatment floor.

Table 2: Summary of litter conditions, ventilation, and emission factors for all three seasons

	Winter			Spring			Summer		
	Control	Treatment	% Dif	Control	Treatment	% Dif	Control	Treatment	% Dif
Litter Moisture (%)	55.5%	56.5%	1.8%	34.4%	48.2%	40.1%	39.2%	37.7%	-3.8%
Litter pH	8	7.1	-11.3%	8.2	8.4	2.4%	8.2	7.9	-3.7%
Ammonium-N (mg/kg wet)	4650	3180	-31.6%	3620	6260	72.9%	4790	4410	-7.9%

Static Pressure (Pa)	15.9	16	0.6%	14.1	16.7	18.4%	17.8	17.9	0.6%
Avg. Air Exchange Rate (Exchanges/hr)	4.1	3.8	-7.3%	11.1	11.4	2.7%	20	21.2	6.0%
PM2.5 (g/day/AU)*	2.3	0.92	-60.0%	0.2	0.59	195.0%	5.3	0.72	-86.4%
PM10 (g/day/AU)*	8.1	1.3	-84.0%	1.1	2.2	100.0%	6.8	0.83	-87.8%
NH3 (g/day/AU)*	272	86	-68.4%	275	256	-6.9%	285	221	-22.5%

***Emission factors are for the duration of the treatment period not the full production cycle**

Conclusions and Recommendations for Further Study

The current study demonstrated that a water sprinkler system is an effective control technology to help reduce the emissions of both size fractionated PM and NH_3 from commercial broiler facilities. Depending on the facility management and time of year, average reductions in emission factors for NH_3, PM_{10}, and $PM_{2.5}$ are 33% ± 19%, 86% ± 3%, 73% ± 19%, respectively, for the treatment period (typically the final 14 days of the production cycle). Use of a sprinkler system can lead to reduced emissions of NH_3 and PM thereby improving indoor and ambient air quality.

Evident throughout this study was the importance of optimal flock management practices. Maintaining the indoor environment will not only help to improve the health of birds but also add to the efficacy of any control technologies that are present to reduce indoor air pollutants. During the spring flock, wet litter, high nitrogen content, high pH, and a large static pressure difference led to a higher amount of NH_3 and fine PM on the treatment floor. This scenario illustrated that the best management practice in two story barns with a permeable dividing floor should have equal static pressures between floors to prevent infiltrating air from passing through the litter bed.

It is recommended that further studies be conducted to investigate the effects of static pressure differences in two story systems with a permeable separating floor. In addition, the efficacy of sprinkler systems in other poultry production operations, such as turkey production, should be investigated.

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