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Evaluation of a Flux Chamber for Assessing Gaseous Emissions and Treatment Effects of Poultry Manure

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Abstract. *The need to quantify air emissions from animal feeding operations (AFOs) with relative ease and reasonable certainty continues to rise. Exploration of practical means to reduce air emissions also calls for less sophisticated but reasonably dependable methods to quantify the treatment effect. Although mobile air emissions monitoring units (MAEMUs) capable of precise and real-time emission measurement is the norm for continuous, intensive monitoring of emissions from mechanically ventilated animal facilities, their relative immobility and high cost are limiting the widespread use. Several other methods, such as gas-washing, micro-meteorological, wind tunnel, flux chamber, and mass-balance methods, have been employed to accommodate different measurement needs. Flux chambers have the advantages of being portable, small size, low cost, and less labor requirement. The objectives of this study were: (1) to develop a portable emission flux chamber system (EFC) for in-situ measurement of ammonia (NH_3) and carbon dioxide (CO_2) emissions from manure; (2) to assess gaseous (NH_3 and CO_2) emissions of high-rise layer houses with the EFC vs. MAEMU; and (3) to evaluate the adequacy of using the EFC to determine the effects of dietary regimens on ammonia emissions from the layer manure. The preliminary data showed that NH_3 emission from the manure surface measured with the EFC was 8% to 16% that of the whole barn measured with the MAEMU, while CO_2 emission from the manure surface was 1% to 4% of the barn emission. The preliminary results obtained with EFC concerning the dietary efficacy of ammonia emission reduction were mixed as compared to those obtained with the MAEMU. More evaluation is continuing.*

Keywords. Ammonia emission, flux chamber, mobile air emissions monitoring unit, emission mitigation

Introduction

In modern livestock and poultry barns, proper indoor air quality is imperative in maintaining the health of workers, animal welfare and productivity. Ammonia (NH_3) and carbon dioxide (CO_2) are two of the major pollutants emitted from animal feeding operations (AFO) because of the potential health risks and impact on the environment. It has been reported that in poorly ventilated barns, high concentrations of ammonia coincided with symptoms associated with toxic or inflammatory effects on the respiratory tract of workers as well as adverse effects on animal health (Carlile, 1984; Jacobson et al., 2003). In addition, NH_3 volatilization leads to "acid rain" in the vicinity (van Breemen et al., 1982). Carbon dioxide also causes human health risks at concentrations of 1% (10000 ppm) or higher. The CO_2 toxicity and its effects increase with concentration, which may exist inside a facility when ventilation failure occurs. Furthermore, CO_2 is considered one of the major greenhouse gases that contribute to global warming.

Ammonia is mainly produced by the decomposition of nitrogenous compounds in manure through the inefficient conversion of feed nitrogen to animal products. Its characteristic strong odor makes it easily detectable at 5 to 10 ppm. Carbon dioxide, on the other hand, is odorless and produced by animal respiration and manure decomposition. The generation of both gases from poultry facilities occurs through the degradation of uric acid in the manure, although CO_2 is primarily from animal respiration (Pedersen et al., 2008). Undigested nitrogen in feces will also be mineralized to ammonia (Ad Hoc Committee, 2003; Zhao, 2007). Gas emissions are affected by environmental conditions, ventilation rate, dietary composition, animal activities, animal life stage, manure properties (e.g. moisture content, pH), and manure management practices (Liang et al., 2005).

Mobile air emissions monitoring units (MAEMUs) are capable of precise and real-time emission measurement and are typically used for continuous, intensive monitoring of emissions from mechanically ventilated animal facilities. Gas emission rate (ER) is quantified as the product of concentration difference (between exhaust and inlet air) of the pollutant and the ventilation rate (Q) through the facility (Li et al., 2008b). It involves measurement of airflow rate of the exhaust or supply fans under specific static pressure and monitoring fans run-time. Among the studies that involve use of MAEMUs is the comparison of dietary treatments of EcoCal^{TM}, DDGS and control diets. Recent laboratory studies showed a 40 – 60% reduction in ammonia emissions from laying-hen manure of an EcoCal^{TM} diet, while a study conducted in a commercial operation showed an emission reduction of up to 23.2% (Li et al., 2008a). Also, the higher supply of distillers dried grains with solubles (DDGS) in animal diets, because of the rapid increase in production of ethanol encourages comparison (Waldroup et al., 2007). Roberts et al. (2007) found a reduction of approximately 40% in NH_3 emission from manure of laying hens fed 10% dietary DDGS. In spite of the MAEMU's precision and real-time measurement capabilities, its relative immobility and high cost limits the widespread use for baseline emission and mitigation studies. Several other methods, such as gas-washing, micro-meteorological, wind tunnel, flux chamber, and mass-balance methods have been employed to accommodate different measurement needs (Liu et al., 2008; Koziel et al., 2008). Flux chambers have the advantages of being portable, small size, low cost, and less labor requirement.

The objectives of this study were: (1) to develop a portable emission flux chamber system (EFC) for in-situ measurement of NH_3 and CO_2 emissions from poultry manure or litter; (2) to assess gaseous (NH_3 and CO_2) emissions of high-rise layer houses with the EFC vs. MAEMU; and (3) to evaluate the adequacy of using the EFC to determine the effects of dietary regimens on NH_3 emissions from the layer manure. The study was conducted at a commercial farm in central Iowa, where three mechanically ventilated high-rise laying-hen houses under three different dietary regiments (EcoCal^{TM}, DDGS and Control) were monitored by a MAEMU.

Materials and Methods

Emission Flux Chamber System (EFC)

The EFC was made of a 0.32 m diameter nearly semi-spherical vessel constructed of stainless steel, with a volume of 12.3 L (fig. 1). It had an internal sample port, a fitting to check pressure and an adjustable exhaust valve located at the top of the vessel. The EFC also had four air inlet ports that split from one line, equally distributed along the perimeter of the vessel. The air inlets were positioned to form a race-track airflow pattern, thereby facilitating good air mixing inside the EFC without use of an auxiliary mixing fan. Velocity profiles inside the chamber are described in the subsequent section.

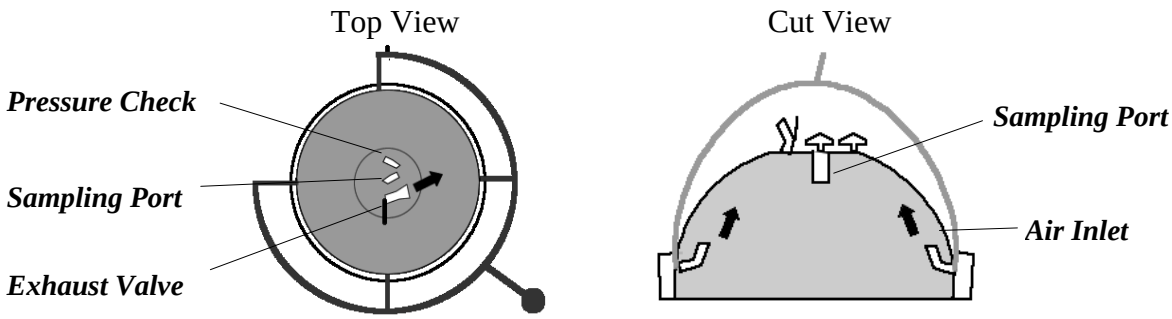

Figure 1. Schematic representation of the emission flux chamber system (EFC).

The EFC system is shown in Figure 2. The flow through the EFC was kept at approximately 8L/min (39 air changes per hour or ACH). Pressure inside the chamber was measured with a Dwyer manometer (model 25, MARK II Dwyer Instruments Michigan City, IND) and adjusted with the pressure release valve to maintain positive pressure.

The EFC has an outer replaceable ring made of 0.404 mm a galvanized metal sheet. The ring penetrates the manure pile by approximately 5cm to avoid or minimize leakage through the bottom of the EFC and force the air to pass through the designated sampling and exhaust ports at the top. An in-line air purification filter containing zeolite was used to remove most, if not all, ammonia from the incoming air to the EFC to have a relatively NH_3-free supply air from location to location. Air was obtained with a Gast DDL linear air pump (Gast Manufacturing, Benton Harbor, MI) and the flow rate controlled using a Dwyer flow meter (model RMA21SSV) with a 0 to 10 L/min range. The air was sampled using a Photoacoustic Field Gas Monitor – INNOVA 1412 (AirTech Instruments A/S, Ballerup, Denmark) that employs the photoacousitc infrared detection principle, which means the INNOVA can measure almost any gas that absorbs infrared light (LumaSense, 2007).

For the purpose of this study the INNVOA was used to sample NH_3 and CO_2 concentrations, with detection limits of 0.2 and 12.5 ppm, respectively. The INNOVA's own pump was used to extract the air from the chamber to be sampled approximately every 30 seconds. Air passed through 4 mm OD x 3 mm ID Teflon tubing from the sampling port to the INNOVA, while a more flexible, clear 9.525 mm OD x 6.35 mm ID Tygon tubing was used for all other purposes.

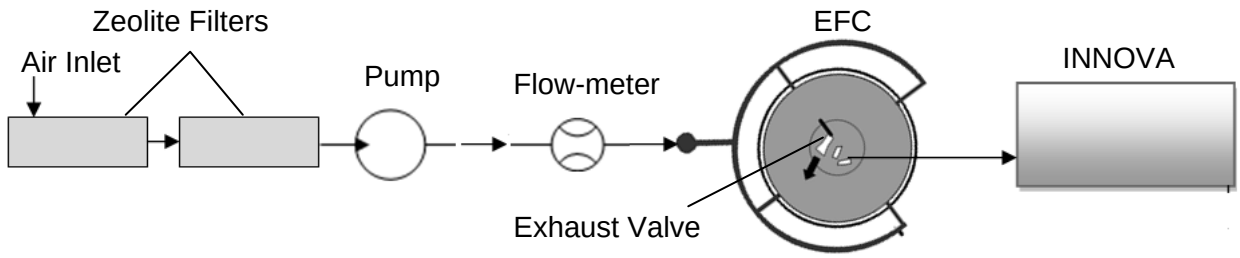

Figure 2. Schematic representation of the emission flux chamber (EFC) sampling system

Velocity Profile

An assessment of the profile velocities inside the chamber at a flow rate of 8L/min provided information on the air speed over the manure during sampling. The air inlets of the EFC were all placed at a 45 degree angle, so that air jets out in a clockwise direction and air would not flow directly on the manure. The chamber was placed on top of a circumference laid out on a clear plexi-glass plastic with the exact boundary of the chamber. The plastic had 17 holes drilled on it (fig. 3). All lines were at 45 degrees from one another and the centers of the circles in each line were separated by equal distances. All the holes were taped over and a flow rate of 8L/min was applied through the chamber. One hole was uncovered and the velocity at the hole was measured in meters per second with an omni-directional velocity transducer (model 8475-12, TSI Davis Instruments, St. Paul, MN). After the velocity was recorded the transducer was moved 2.54 cm (1 inch) further inside the EFC and the data was recorded, until the transducer could not go further. Once the first hole was completed, it was covered with tape and the next hole was uncovered and the velocity measured with the same procedure described above. This was done for all 17 holes, providing at total of 108 measurements.

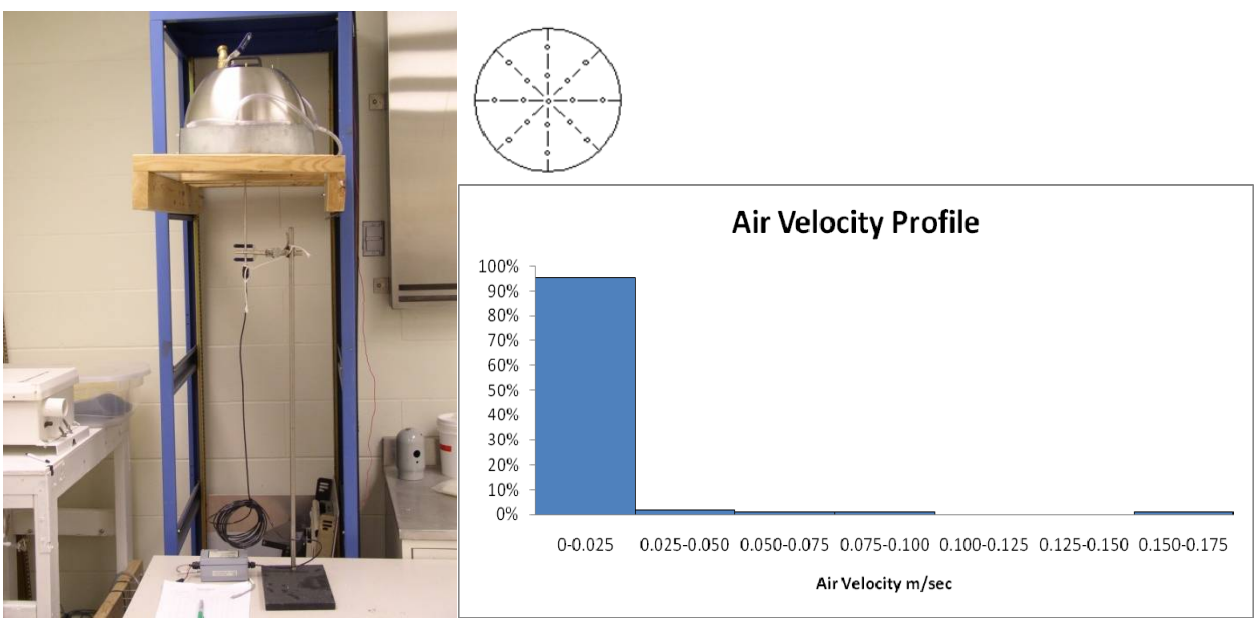

Figure 3. A picture of the setup to quantify air velocity profile showing the EFC, anemometer, and horizontal locations of the velocity measurement (upper right sketch). And a histogram showing the range of air velocities.

Air velocities inside the chamber varied from 0 m/s to 0.151 m/s. The highest velocities were near the chamber wall next to the air inlets, where air velocities ranged from 0.049 m/s to 0.151 m/s. The rest of the measurements were within 0.01 m/s (fig. 3), meaning there were very low air velocities inside the chamber.

Farm Measurements

Farm measurements at a laying-hen facility in central Iowa were conducted to determine an adequate sampling scheme considering spatial variation of emissions. Figure 4 shows the sample locations, which were chosen to determine spatial variation of NH_3 concentrations in longitudinal and latitudinal directions. Ammonia and carbon dioxide emissions measured with the EFC were also compared to those measured with the MAEMU for the three high-rise layer houses under three different dietary treatments (EcoCal™, DDGS and control). A location was chosen at approximately the middle point between mixing fans in the manure store level and a light bulb adapter was placed in one of the lights to provide power to the EFC operation. The manure store mixing fans are used to facilitate the manure drying. A position too close to one of these fans may not provide an adequate representation of manure properties throughout the house. The EFC was placed approximately mid-way between the peak and the base of the pile. A plastic bag was placed on top of the chamber to prevent any manure from falling on it. The air-supply inlet of the system was hung at a height of approximately 3 m (10 feet).

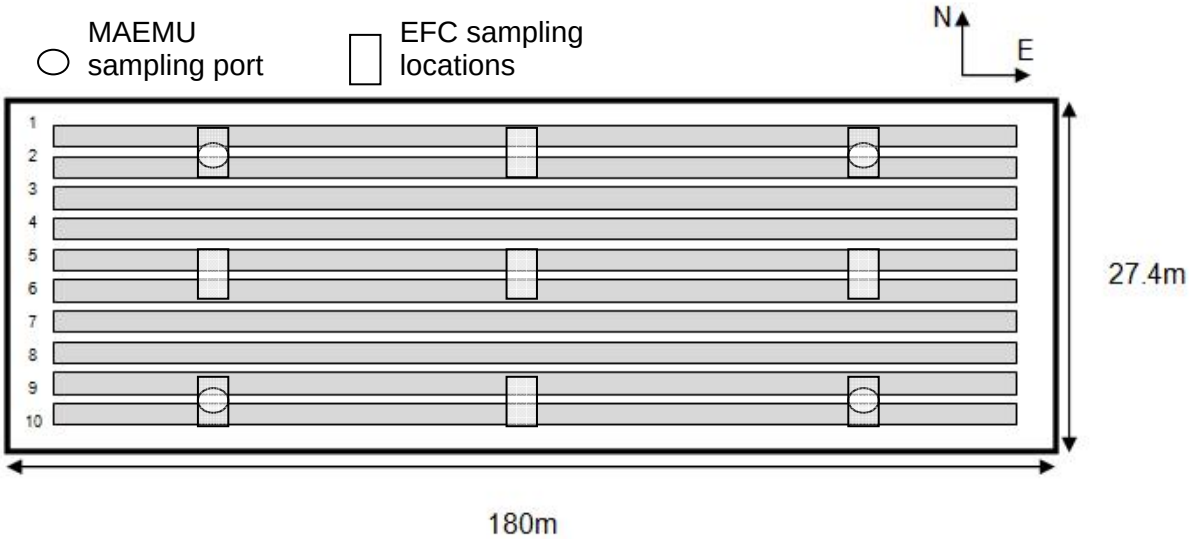

Figure 4. A sketch of the manure piles in each of the three barns sampled, showing the numbering scheme. The MAEMU's sampling ports are located between piles 1 & 2 and 9 & 10. EFC samples were taken from piles 1, 2, 5, 6, 9 and 10.

A background test was performed prior to the tests on the manure piles in each house to determine the passage rate of NH_3 through the filters and quantify the background NH_3 and CO_2 that would enter the EFC. The tubing was adjusted such that air passes directly from the Zeolite filters to the INNOVA by by-passing the EFC (fig. 5). Normally, the test lasted for 10 minutes, except when the INNOVA had not been used for a long time, in which case sampling was done for 20 minutes to allow the INNOVA to warm up. The last 5 minutes of the measurements were averaged to get the base concentration of ammonia and carbon dioxide.

To test the manure piles, the flow meter was adjusted so that air went into the EFC at 8 L/min. During sampling, the INNOVA was set to sample every 30 sec and gas concentrations were recorded every five minutes, which allowed readings to stabilize. If the difference between the first two concentrations was less than 5%, the equilibrium of gas emissions was obtained and the EFC was moved to the next location. If not, the concentrations were continuously recorded on the sheet every five minutes until the last two concentration differences were within 5%. In a research study conducted by Boriack et al (2005) there was no significant change in the concentration output due to chamber adsorption when a clean chamber was exposed, therefore it was considered negligible, as well as the adsorption due to the tubing material (Shah et al, 2006).

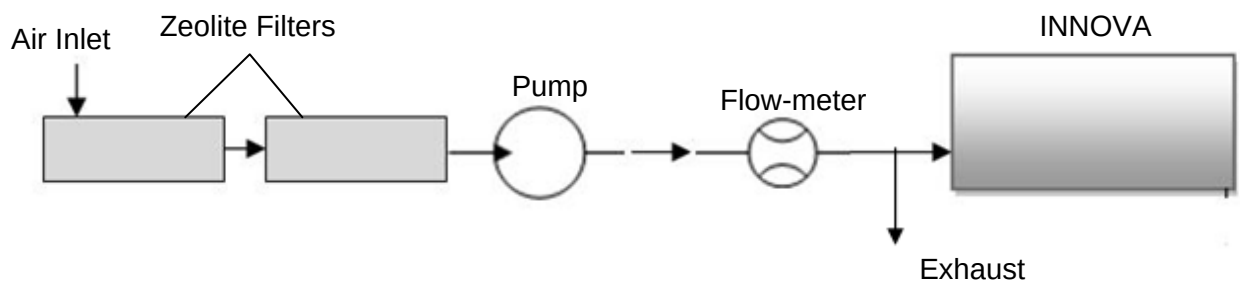

Figure 5. Sketch of the 'filter test' set up

A flux from the EFC is obtained as follows:

$$F = \frac{Q(C_e - C_o)W_m T_{std} P_a}{10^6 V_m T_a P_{std} A_{EFC}} \qquad [1]$$

where:
F = flux, g min^{-1} m^{-2}
Q = flow rate going into the chamber, L min^{-1}
C_e = gas concentration of air leaving the chamber, ppm
C_o = base concentration from 'filter test', ppm
W_m = molecular weight, g/mol
V_M = molar volume at standard temperature (0^0 C) and pressure (101.325 kPa), 22.4 L mol^{-1}
T_{std} = standard temperature, 273.15 K
P_{std} = standard pressure, 101.325 kPa
P_a = barometric pressure, 97 kPa
T_a = temperature of the sample air, 293.15 K
A_{EFC} = EFC area, 0.0804 m^2

In order to estimate the emission rate of the entire barn through the EFC, the manure surface area was estimated. The manure profile was measured by placing a measuring tape directly on the manure and over the pile, covering the entire perimeter. Three profile measurements were taken from each pile in the barn (east, middle and west). Since manure was removed from the houses multiple times during the study, samples were only taken when the pile profile was between 1.5 and 4.3 m. A weighted average of the emission rates was determined, where piles 1, 2 & 3 were considered 'north', 4, 5, 6 & 7 'middle" and 8, 9 & 10 'south' (fig. 4) resulting in the following equation:

$$ER_{manure} = \overline{F_{north}}\left(\overline{A_1} + \overline{A_2} + \overline{A_3}\right) + \overline{F_{middle}}\left(\overline{A_4} + \overline{A_5} + \overline{A_6} + \overline{A_7}\right) + \overline{F_{south}}\left(\overline{A_8} + \overline{A_9} + \overline{A_{10}}\right) \qquad [2]$$

where:

ER_{manure} = estimated emission rate of the barn through EFC, g min^{-1} $barn^{-1}$

F_i = Flux at the north, middle or south locations, g min^{-1} m^{-2}

A_i = Average area of three measurements of a pile (1 through 10), m^2, calculated from measured perimeter and length of the pile.

Statistical Analyses

Measurements were grouped by seasons. Summer included the months of June, July and August; autumn the months of September, October and November; winter the months of December, January, and February; and spring the months of March, April and May. Statistical analyses were conducted to determine an adequate sampling scheme inside the houses, considering spatial variation of gas emissions, which may broadly differ (Brewer and Castello, 1999). Several aspects taken into consideration were the east – west and north – south cross sections of the barn, as well as the emission variation between neighboring piles and along the pile profile. The Fisher F-test was conducted to determine the presence of a significant difference among the samples at the (a) east, middle and west of the barn; (b) north, middle and south of the barn; and (c) the top, middle and bottom of the pile profile. The Student t-test was performed to determine the presence of a difference between neighboring piles. In addition, a comparison between the EFC and MAEMU ER values was performed and the Student t-test was conducted to compare the control diet vs. the (i) DDGS diet and (ii) EcoCal™ diet. A P-value of < 0.05 was considered to be evidence of a significant difference in the comparisons. The significance (strong vs. weak evidence) of the obtained p-values was interpreted as indicated by Ramsey and Shafer (2002).

In the analyses, samples were paired according to location and date, because great variability in gas concentrations was observed from week to week. There were days when samples were not taken from all locations.

Results and Discussion

Spatial Variation

Manure properties and gas emissions of may vary along the length of the barn due to spatial variations in temperature, moisture content caused by water leakage and manure-drying fans and different microbial activities in the piles. The barns are east – west orientated, therefore locations were tested from the east, middle and west to determine if a difference in ammonia emissions from the piles exists. The east, middle and west denominations were matched according to pile number (fig. 4) and date. There was no statistically significant difference in ammonia concentrations between the three locations during the autumn months ($p = 0.97$) and weak evidence during the winter months with a p-value of 0.13 (fig. 6).

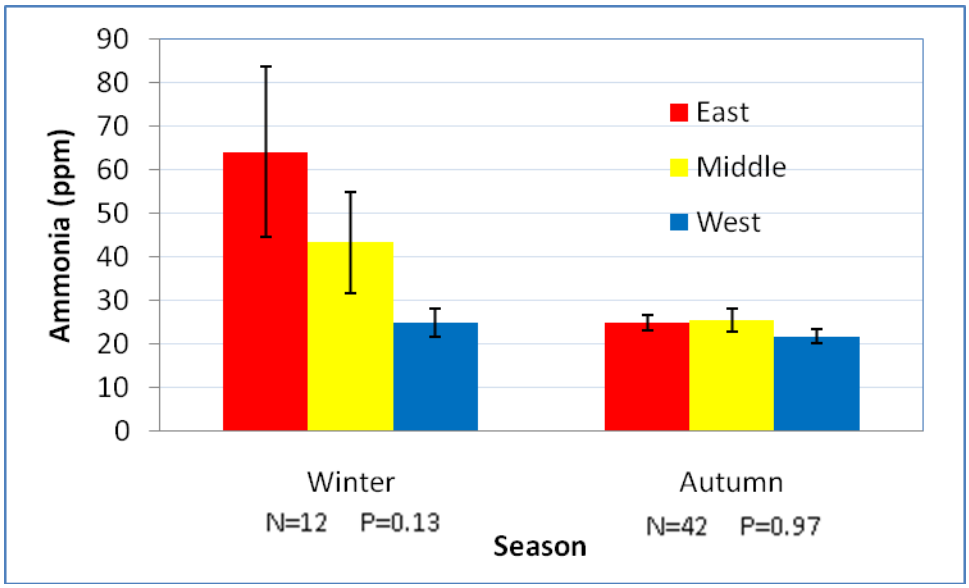

Figure 6. Longitudinal variations of NH_3 concentrations for different seasons (winter and autumn), as measured with the EFC placed on the surface of the manure piles.

Similarly, with the north-south cross-section the NH_3 emitted from the piles may vary. Samples were taken from the north, middle and south and matched according to date and pile number (fig. 4). Piles 1 & 2 represented the north, 5 & 6 represented the middle and 9 & 10 represented the south. During winter there was no difference among locations, as opposed to autumn, where the NH_3 concentration was lower in the south piles compared to the north and middle piles (P = 0.008; fig. 7). Because of this potential difference, the north, middle and south locations should be considered in the sampling scheme to determine emission rates.

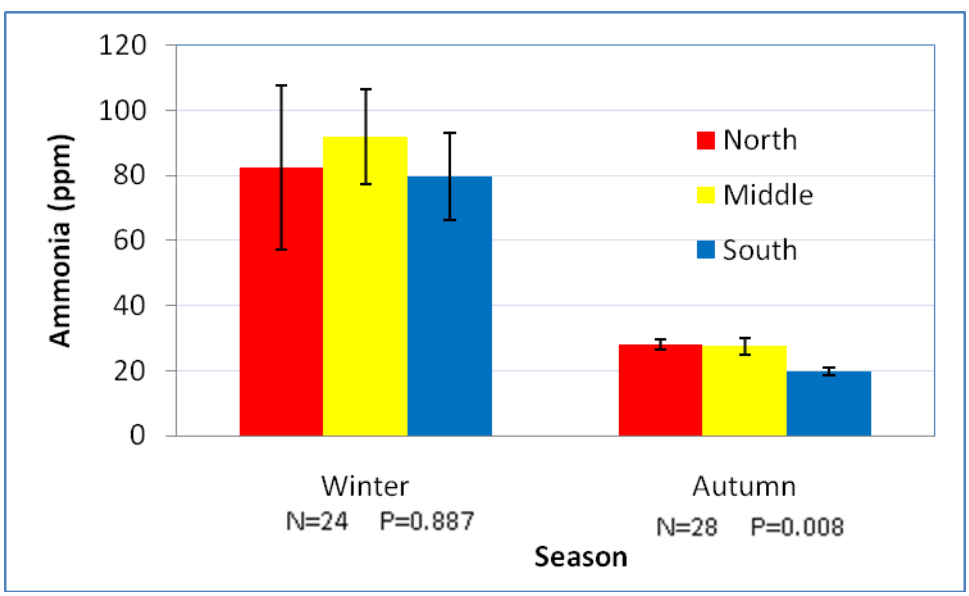

Figure 7. Variations in NH_3 concentrations across the width of the barns duirng different seasons (winter and autumn) as measued with the EFC placed on the surface of the manure piles.

A comparison between two neighboring piles (piles next to each other: 1 & 2, 5 & 6, 9 & 10) was made. Sampling areas were taken at approximately the middle of the pile and on the side that faces its neighbor. Results show that there was not a significant difference between the NH_3 concentrations of two neighboring piles. A paired-t analysis was used to compare the ammonia concentrations from any two neighboring piles; results are shown in Figure 8. The NH_3 concentration measured from neighboring manure piles was not different in the autumn or winter seasons (P = 0.725 and P = 0.984, respectively).

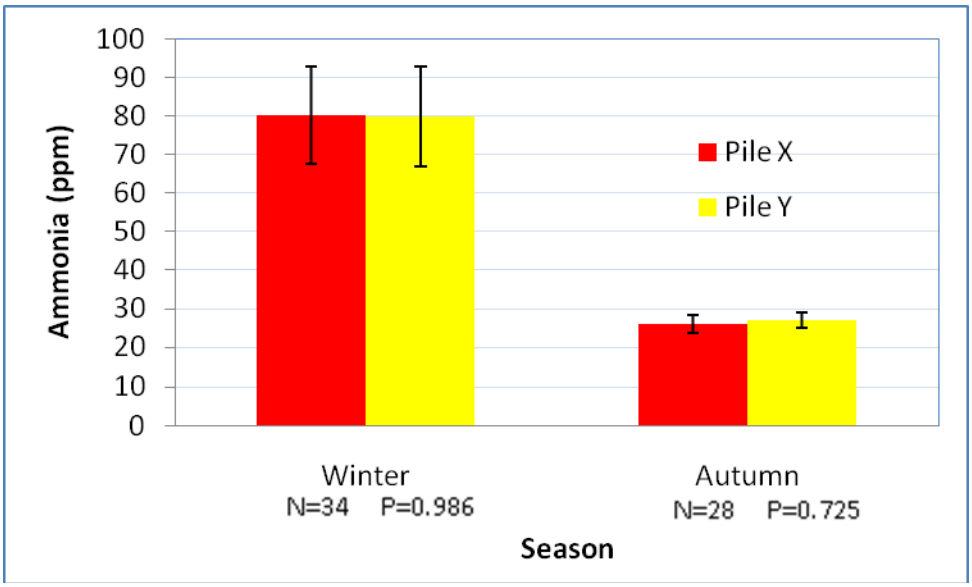

Figure 8. Example of average NH_3 concentrations from any two neighboring piles measured with the EFC on the same day.

Other positions worth considering are those along the pile profile. Manure in a pile may have different properties and therefore release different quantities of ammonia gas. As the manure accumulates and forms the pile, it is assumed that the manure at the top of the pile contains more recent deposition and hence is wetter than the lower portion of the pile. A comparison along the piles' cross section (as shown in fig. 9) was made to determine the best sampling location. Sampling areas were located along one side of the pile at the top, middle and bottom. The three were matched according to date, pile number and position in the barn.

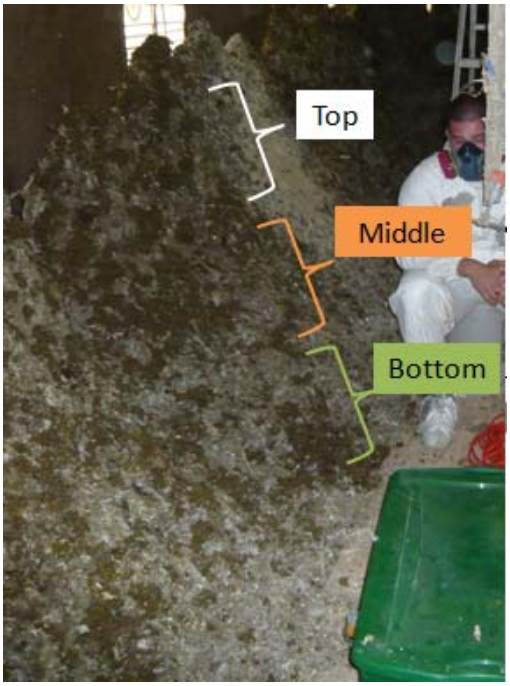

Figure 9. A picture illustrating the approximate location of EFC samples on the pile.

Measurements taken from the top of the piles proved to be the most variable with a standard deviation of 131 ppm for ammonia concentrations, whereas the middle and bottom locations with the same number of samples had standard deviations of 38 and 28 ppm, respectively. It is important to note that the average ammonia concentration for the top location was the highest among the three, and average ammonia concentration for the bottom of the pile was the lowest (fig. 10). The combined average for all three locations is similar to that of the middle location. For this reason the middle samples were considered representative of the overall pile profile.

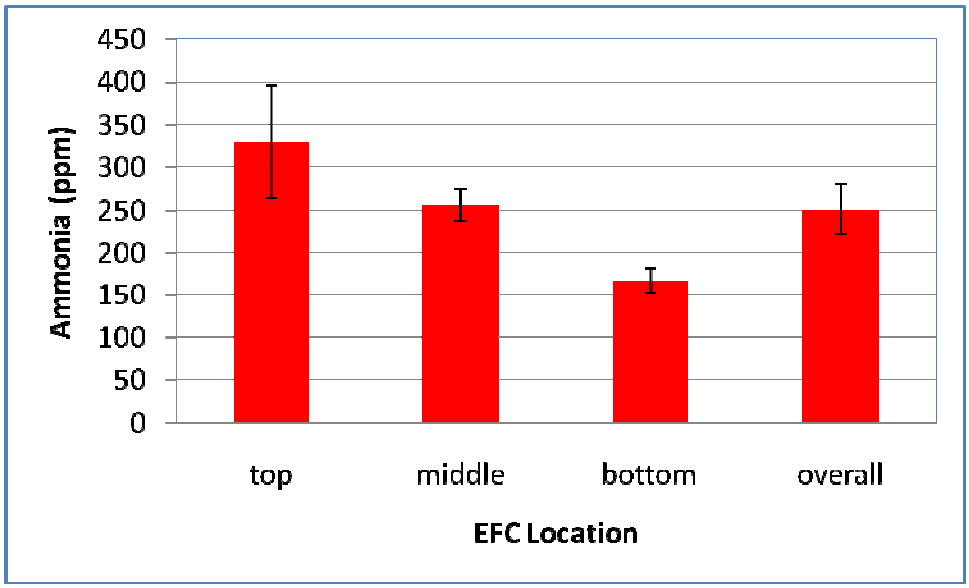

Figure 10. Average NH_3 concentrations from any pile's profile (top to bottom).

Comparison of ER Values between EFC and MAEMU

The estimation of gas ER with the EFC was compared to the MAEMU. Considering that manure scraping occurred multiple times a day and gas emissions would vary with time, samples of the same approximate locations were taken multiple times on the North-South cross-section in random order. In this way the fresh manure being scraped influenced all locations similarly. Furthermore, the variability in gas concentrations over time can be documented to obtain a more representative ER comparison between the EFC and the MAEMU.

The NH_3 ER values obtained with the EFC were 8% to 16% of those obtained with the MAEMU. This preliminary outcome suggests that the majority of NH_3 emissions of the high-rise layer barn came from somewhere other than the manure piles (fig. 11); which contradicts the MAEMU data that show drastic decrease in NH_3 concentration and thus ER once the manure is removed from the barn. Although fresh manure existed in the cage and dropping board areas, it would likely not account for the large disparity of the two measurement methods. One possible cause for the difference might have been the different air turbulence inside the EFC vs. the open manure surface influenced by the manure-drying mixing fans which could have changed the boundary layer conditions and thus NH_3 emission. In addition, the time of manure exposure to air and thus its condition also vary, which would affect the ammonia emission. Therefore, it is highly possible that the relative short-term measurement of a small manure surface area did not fully represent the conditions of the manure in the barn as monitored by the MAEMU.

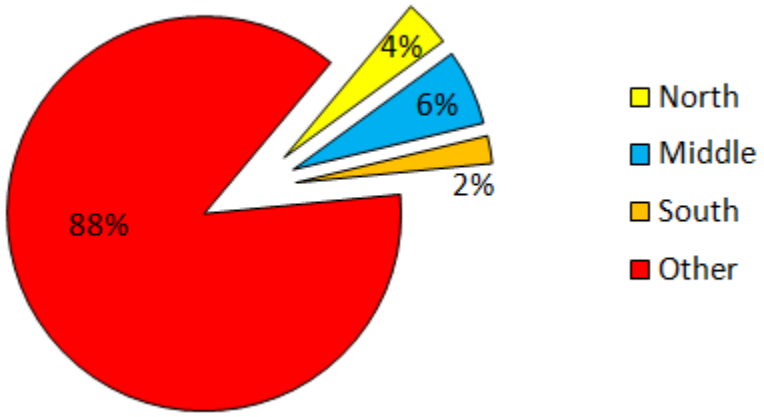

Figure 11. Percentage of NH_3 emissions from the manure piles, measured with the emission flux chamber (EFC) and surface area of the manure piles, relative to the entire-barn emission as measured by the MAEMU (N=24).

The CO_2 ER obtained with the EFC was less than 1 to 4% that of the MAEMU, suggesting that most of the CO_2 generation was not from the manure decomposition, but from the bird respiration. This outcome was in general agreement with the report by Pedersen et al. (2008), which suggested adding 10% to the CO_2 produced by respiration to account for manure CO_2 generation. Assuming the emissions determined by the MAEMU represents 100% of the CO_2 emissions and the ones determined by the EFC represent the CO_2 produced by the manure, then the manure is responsible for only 1% of emissions (fig. 12). This was considerably lower than what was described by Pedersen et al. (2008)

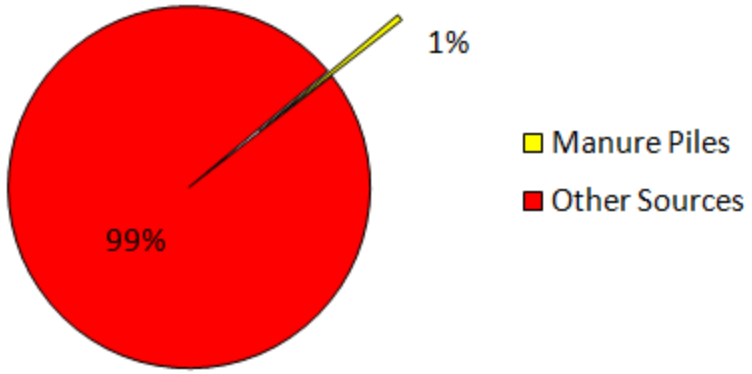

Figure 11. Percentage of CO_2 emissions from the manure piles, measured with the emission flux chamber (EFC) and surface area of the manure piles, relative to the entire-barn emission as measured by the MAEMU (N=24).

Dietary Treatment Comparison

Out of the three dietary treatments, the preliminary data shows no difference in the ER between the DDGS and control treatments (P = 0.600 for winter & P = 0.87 for summer) of NH_3. However, the ER was significantly lower from the EcoCal™ treatment compared to the control (P <0.001) for the 24 measurements during 3 days in the winter period and the 8 measurements during 3 days in the summer period (fig. 13). The percentage reduction in NH_3 emission were 61% and 60% for the summer and winter data, respectively. This is considerably higher than the 23.2% reduction measured by the MAEMU (Li, et al., 2008a). A possible reason for the discrepancy is that the MAEMU continuously monitors all the houses with the different dietary treatments, while the EFC only provides information on emissions for a small time interval. More intensive sampling may provide a more representative comparison on the dietary effects on NH_3 emissions.

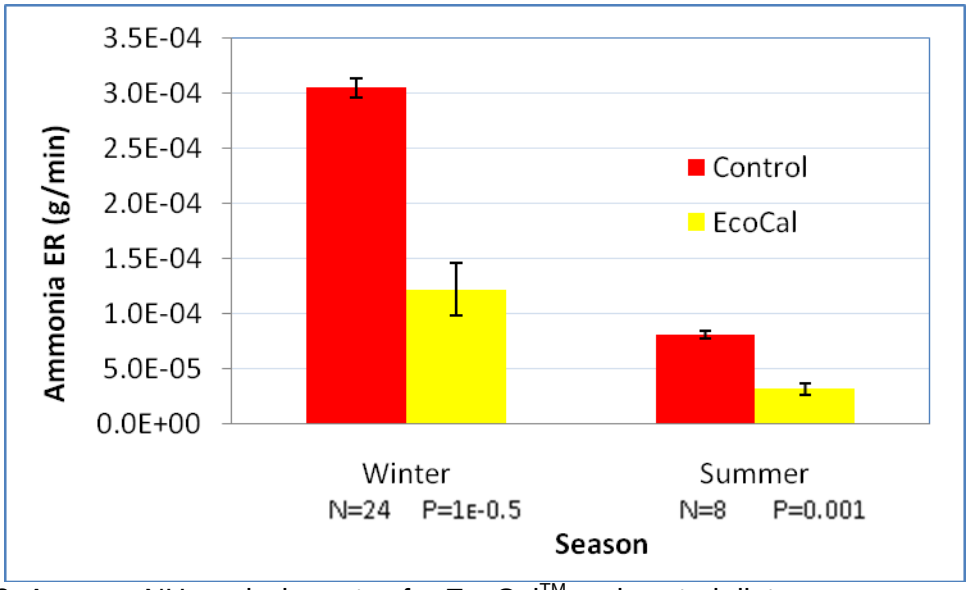

Figure 13. Average NH_3 emission rates for EcoCal™ and control diet manure measured with EFC. Concentrations were directly proportional to emission rate.

Conclusions

A portable emission flux chamber system has been developed for measuring gaseous (NH3, CO2) emissions from (poultry) manure surface. Given that the north-south cross-section was the only set of measurements that resulted in a significant difference in ammonia concentration, the sampling scheme to determine emissions had to include all three locations. Preliminary manure NH_3 emissions measured with EFC were only 8% to 16% of the barn emissions measured with MAEMU. On the other hand, the potential for correction factors exists, such as the effect of air velocity and different air exchange rates on emissions could be considered. It has been observed that seasonal ventilation rates in animal buildings seem to compensate for seasonal NH_3 concentrations and result in a fairly constant ammonia emission rate, and that ammonia emission flux increases with ventilation rate. Also, the EFC vs. MAEMU discrepancy may be determined and adjusted. Furthermore, reduction in NH_3 emissions by the treatment (EcoCal^{TM}) diet as compared to the control diet was 60% based on the intermittent EFC measurements in winter and spring, which was considerably higher than the 23.2% reduction measured with the MAEMU over more than one-year period. The difference was presumably attributed to the seasonal variation in the efficacy of NH_3 reduction by the diet.

Acknowledgements

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References

Ad Hoc Committee on Air Emissions. 2003. *Air Emissions from Animal Feeding Operations Current Knowledge, Future Needs.* National Academy of Science.

Boriack, C., R. E. Lacey, S. Mukhtar, A. Mutlu, S. C. Capereda, B. W. Shaw and C. B. Parnell. 2005 Adsorption Kinetics of Ammonia on a Dynamic Isolation Flux Chamber. ASABE paper No. 054039. St. Joseph, Mich.: ASABE.

Brewer, S. K. and T.A. Costello. 1999. In situ Measurement of Ammonia Volatilization From Broiler Litter Using an Enclosed Air Chamber. *Transactions of the ASAE.* Vol 42(5): 1415-1422.

Carlile, F. S. 1984. *Ammonia in Poultry Houses: A Literature Review.* World's Poultry Science Journal 40: 99 – 113.

Jacobson, L. D., B. P. Hetchler, V. J. Johnson, R. E. Nicolai and D. R. Schmidt. 2005. Seasonal Variations in NH_3 and PM_{10} Emissions from Pig and Poultry Buildings from a Multi-State Project. Symposium on the State of the Science of Animal Manure and Waste Management. St. Joseph, Mich.: ASABE.

Jacobson, L. D., J. R. Bicudo, D. R. Schmidt, S. Wood-Gay, R. S. Gates and S. J. Hoff. Air Emissions from Animal Production Facilities. ISAH 2003, Mexico.

Koziel, J. A., D. B. Parker, B. H. Baek, K.J. Bush, M. Rhoades and Z. Pershbacher-Buser. 2005.Ammonia and Hydrogen Sulfide Flux from Beef Cattle Pens: Implications for Air Quality Measurement Methodologies and Evaluation of Emission Controls. ASABE Paper No.701P0205. St. Joseph, Mich.: ASABE.

Liang, Y., H. Xin, E. F. Wheeler, R. S. Gates, H. Li, J. S. Zajaczkowski, P. Topper, K. D. Casey, B. R. Behrends, D. J. Burnhan and F. J. Zajaczkowski. 2005. Ammonia emissions from

U.S. laying hen houses in Iowa and Pennsylvania. Transactions of ASAE Vol 48(5): 19927-1941. St. Joseph, Mich.: ASABE.

Li, H., H. Xin, R. T. Burns, S. A. Roberts, and K. Bregendahl. 2008a. Effects of Dietary Modification on Laying Hens in High Rise Houses: Part I – Emission of Ammonia, Hydrogen Sulfide and Carbon Dioxide. ASABE paper No. 701P0408. St. Joseph, Mich.: ASABE.

Li H., H. Xin, R. T. Burns, S. J. Hoff, J. D Harmon, L. D. Harmon, L. D. Jacobson, S. Noll, J. A. Koziel. 2008b. Ammonia and PM Emissions from a Tom Turkey Barn in Iowa. ASABE paper No. 084425. St. Joseph, Mich.: ASABE.

Liu, Z., L. Wang and D. B. Beasley, E. O. Oviedo. 2007. Modeling ammonia emissions from broiler litter with a dynamic flow-through chamber system. ASABE paper No. 074090. St. Joseph, Mich.: ASABE.

Liu, Z., L. Wang and D.B. Beasley. 2008. Comparison of Three Techniques for Determining Ammonia Emission Fluxes From Broiler Litter. *Transactions of the ASAE.* Vol. 51(5): 1783-1790.

LumaSense Technologies. 2007. Photoacoustic Field Gas-Monitor – INNOVA 1412. Santa Clara, CA: LumaSense Technologies Inc.

Pedersen, S., V. Banes-Vidal, H. Joergensen, A. Chwalibog, A. Haeussermann, M. J. W. Heetkamp and A. J. A. Aarnink. 2008. Carbon Dioxide Production in Animal Houses: A literature review. Agricultural Engineering International: CIGR Ejournal. Manuscript BC 08 008, Vol. X.

Ramsey F. L. and D. W. Shafer. 2002. *The Statistical Sleuth: a course in methods of data analysis*. 2nd ed. Pacific Grove, CA: Duxbury Press.

Roberts, S. A., H. Li, H. Xin, R. T. Burns, and K. Bregendahl. 2008. Effects of Dietary Modifications on Laying hens in High Rise Houses: Part II – Hen Production Performance. ASABE paper No. 701P0408. St. Joseph, Mich.: ASABE.

Roberts, S. A., H. Xin, B. J. Kerr, J. R. Russell, K. Bregendahl. 2007. Effects of Dietary Fiber and Reduced Crude Protein on Ammonia Emission from Laying-Hen Manure. Poult Sci 86:1625-1632l.

Shah, S. B., G. L. Grabow and P. W. Westerman. 2006. Ammonia Adsorption in Five Types of Flexible Tubing Materials. *Applied Engineering in Agriculture.* Vol. 22(6): 919-923.

van Breemen, N., P.A. Burrough, E.J. Velthorst, H. F. van Dobben, T. de Wit, T. B. Ridder and H. F. R. Reijnders. 1982. Soil acidification from atmospheric ammonium sulphate in forest canopy throughfall. *Nature*. Vol. 299.

Waldroup, P. W., Z. Wang, C. Coto, S. Cerrate and F. Yan. 2007. Development of a Standardized Nutrient Matrix for Corn Distillers Dried Grains with Solubles. *International Journal of Poultry Science. Vol* 6(7): 478-483

Zhao, L. 2007. Understanding Air Emissions from Animal Feeding Operations. AEX-721-07. The Ohio State University.