Ammonia Emissions from Western Livestock Waste Lagoons

Richard H. Grant and Matthew T. Boehm

Department of Agronomy, Purdue University, 915 W. State St., West Lafayette, IN 47907, USA;
rgrant@purdue.edu

ABSTRACT

Ammonia emission inventories from livestock waste lagoons across the USA are generally based on chamber studies that do not include the influence of actual meteorological conditions on the exchange between lagoon or basin surfaces and the atmosphere. Ammonia (NH_3) emissions from waste lagoons or basins were measured periodically for two years at swine and dairy operations across the United States as part of the National Air Emissions Monitoring Study. Path-integrated NH_3 concentrations were measured using tunable diode lasers with emissions determined from on-site turbulence measurements in conjunction with inverse dispersion and integrated horizontal flux models. Emissions from livestock operations in the western USA were influenced by wind speed, animal live mass, air temperature, and probably the vapor pressure deficit. Average daily emissions from sow and finishing farm waste lagoons in OK were similar with annual average daily mean emissions of 130 g $d^{-1}AU^{-1}$ (1 animal unit, AU=500 kg) and summer average daily mean emissions of 285 g $d^{-1}AU^{-1}$. A semi-empirical model based on daily mean air temperature and daily mean wind speed accounted for 75% of the daily emission variability at these two lagoons that were filled continuously with no liquid or sludge removal. The average daily mean emissions during filling of basins at an open-lot dairy in WA were between 5 and 13 g $d^{-1}AU^{-1}$. Emissions differed at the dairy between periods of lagoon filling and periods of dry down and sludge removal. The average daily mean NH_3 emission was 7 g $d^{-1}AU^{-1}$ over the entire 280-d handling cycle of basin fill and removal.

INTRODUCTION

Ammonia emissions from western livestock operations are relatively high. Reported emissions from livestock operations are usually difficult to compare due to different measurement methods and environmental conditions as well as limited information on the animal populations. Furthermore, they are typically made for only short periods of time. Consequently annual emissions cannot be determined with any confidence.

Climates in the western USA often have low humidity, corresponding to large vapor pressure deficits and high evaporation rates from liquid waste storages (Figure 1). The high evaporation rates of water from the basin or lagoon liquid in the dry western US, in combination with low annual precipitation volumes, increase NH_3 and ammonium (NH_4^+) concentrations in open waste storage facilities and can result in crusting when the solids content of manure is high. Loss of volume in the storage facilities can even result in water being added to the facility to maintain sufficient volume for the lagoon to remain anaerobic (Cumba and Hamilton, 2002). This enhancement of NH_3 concentration would be expected to result in greater emissions for a given loading. Hence emissions from western USA manure storage facilities would be expected to be higher than similar operations in the eastern USA.

Another consequence of the elevated concentrations is crusting on the lagoon surface when the solids content of manure is high. Crusting of manure storage facilities appears to be related to the volume to surface area ratio (evaporative surface) and slurry solids content (Smith et al, 2007; Wood et al, 2012). Crusting, in turn, tends to reduce gaseous emissions from manure (Misselbrook et al, 2005; Nielsen et al, 2010), with the reduction of NH_3 emissions more associated with percentage of surface crusted than the thickness of the crust (Wood et al, 2012). The reported reductions in NH_3 emission were 40% to 60% (Smith et al, 2007; Misselbrook et al, 2005).

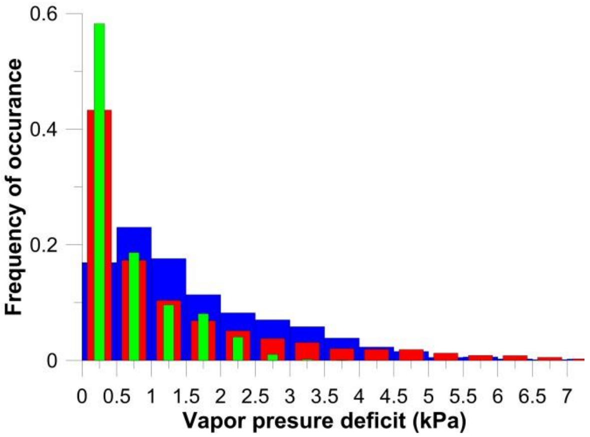

Figure 1- Vapor pressure deficits for farms in WA (Blue), OK (Red) and NC (Green)

Both dairies and hog operations in the western USA have manure storage that is exposed to the open air. Dairy operations in the western USA are typically free stall systems with open-lot exercise areas. These dairies differ in many ways from their counterparts in the eastern USA, including the effects of the dry hot air and sunny skies that result in the need for sun shelters for the cows. There are only a few studies that have evaluated the NH_3 from such dairies (Cassel et al, 2005a,b; Rumburg et al, 2008; Bjorneberg et al, 2009; Grant and Boehm, 2015). Hog operations in the western US are typically pull-pit designs that utilize the lagoon for flush water. There have been only a few studies of NH_3 emissions from lagoons at sow farms, and of these studies very few have used micrometeorological approaches. The only NH_3 emissions measurements for hog operations in the dry western US are those included here (Grant et al, 2013b). Reported emissions at sow operations vary by a factor of ten (Harper and Sharpe, 1998; Zahn *et al*, 2001; Harper *et al*, 2004; Bicudo *et al*, 2004; Szogi *et al*, 2005; Shores *et al*, 2005; Grant et al, 2013b). Of these studies, only Grant et al (2013b) reports on emissions in the western USA.

Table1- Overview of monitored open sources.

Facility type	**Location**	**Manure Handling**	**Manure source for measured storage**	**Animal capacity (head=hd)**	**LM[1], AU**
Dairy	Washington (WA)	Scraped from barns, flushed from milking parlor and holding area	milking parlor, holding area, and all barns	4400 milking 1200 dry	3461
Hog Finisher	Oklahoma (OK)	Pull plug with recharge, lagoon	All barns	3000	464
Hog Breed to wean	Oklahoma (OK)	Pull plug with recharge, lagoon	All barns	2784 sows 3898 piglets	1279

1: Piglets included in Live Mass (LM).

This study compares the annual variability of NH_3 emissions at a breed to wean hog operation (Grant et al., 2013b), a finishing hog operation (Grant et al., 2013b), and a dairy operation in the western USA (Grant and Boehm, 2015). Measurements were made as a part of the National Air Emissions Monitoring Study (Grant, 2006). Due to the wide range of temperature and wind speeds experienced during the study, the temperature and wind effects on the emissions were also assessed with the goal of developing process-based emissions estimation models.

BODY

Facility descriptions

The western (WA) free stall dairy facility consisted of six open barns (Grant and Boehm, 2010c, Table 1). Manure from the barns and milking parlor was automatically flushed four times daily with recycled water, separated from the sand bedding by gravity, and transferred to one of two settling basins. One basin was actively filling while the other was drying or having the dried solids (sludge) removed. Liquid from the filling basin was skimmed, separated, and returned as flush to the barns. After filling, each basin was allowed to air dry until the sludge could be removed by front-end loader. The removed solids were strained through screens and centrifugal/screw presses with the residual liquid transferred to large serpentine concrete basins for secondary settling and the solids stacked for drying. Dried solids were reused as cow bedding. A full cycle of filling, drying, and removal lasted approximately 280 days.

The western (OK) breed to wean hog facility consisted of three mechanically-ventilated barns (Grant and Boehm, 2010a, Table 1). Thirty-two groups of pigs were weaned at the sow farm over the course of the study. The average group took 21.5 days from farrow to wean. Manure was transferred to the lagoon weekly from the two gestation barns and every 2.5 weeks from the farrowing barn. Pits under the farrowing barn were back-filled with recycled water from the lagoon. Sludge from the lagoon had not been removed since construction. Lagoon liquid analysis was contracted by the producer every year for all nitrogen components. Water was periodically added to the lagoon during the study.

The western (OK) hog finishing facility consisted of three mechanically-ventilated all in/ all out production barns (Grant and Boehm, 2010b, Table 1). One cycle of production took approximately 120 days. Manure was transferred three times a week from the barns to the lagoon by a pull plug system with fresh water recharge. A 20% pump-out of the lagoon occurred on 1 June 2009.

Measurements

Ammonia emissions were determined using the backward Lagrangan Stochastic method (bLS; WindTrax, Thunder Beach Scientific, http://www.thunderbeachscientific.com) and the vertical radial plume mapping method (VRPM, Arcadis, Inc, Denver, CO, USA). Both emissions methods required gas concentration measurements in conjunction with some form of wind measurement. In particular, the bLS method required turbulence measurements and the VRPM method required wind profiles. Additional meteorological measurements were taken to help analyze the results (Grant, 2006).

Ammonia concentrations were measured using scanning tunable diode laser spectroscopy (TDLAS, GasFinder2®, Boreal Laser, Inc., Edmonton, Alberta, CA). Path-integrated concentrations (PICs) of NH_3 were measured by TDLAS along optical paths (OP) defined by scanning TDLAS instruments at one end and retro-reflectors at the other end. Two scanning TDLAS units were mounted on opposite corners of each lagoon or basin. Retro-reflectors were positioned 1 m abl (above berm level) approximately 1/3 and 2/3rds of the way down each side of the lagoon or basin and at 1 m, approximately 7 m, and approximately 15 m abl on a tower at opposite corners (from the scanning TDLAS) of the lagoon or basin (Grant and Boehm, 2010a,b,c). This resulted in five OP along each side of the lagoon or basin forming a y-z measurement plane for flux crossing the given side. Each scanning TDL measured ten OP (dwell time of 15 s) on the adjacent two sides of the basin. Concentrations along each OP were averaged to 30-min intervals. For the dairy basins, emissions measurements were excluded when the other basin was upwind (Grant and Boehm, 2015). For the hog operations, emissions measurements were excluded when upwind barn emissions were present (Grant et al, 2013b).

Meteorological measurements of atmospheric temperature, relative humidity, barometric pressure, solar radiation, and surface wetness were measured at an automated weather station on the lagoon or basin berm (Grant, 2006). Measurements of lagoon pH and temperature (0.3 m depth) were also made at the two hog lagoons (Grant and Boehm, 2010a,b). Information concerning farm operations and the United States Department of Agriculture National Resource Conservation Service (USDA NRCS)-required analysis of wastewater used to irrigate nearby fields were routinely collected from the producers. Estimates of manure production were derived from ASAE guidelines (ASAE, 2003, 2005) and Rotz (2004).

Three sonic anemometers (81000, RM Young, Inc, Traverse City, MI, USA) were used to determine the wind profiles for the VRPM emissions model and the turbulence characteristics for the bLS emissions model (Grant, 2006). These sonic anemometers were located at approximately 2.5 m, 4 m, and 17 m abl on a tower at a lagoon/basin corner. Turbulence statistics were calculated without rotation of the axes since the variable terrain near the sources did not assure that the flow would truly be parallel to a flat horizontal surface. Statistics over a 5 minute period were calculated when at least 90% of the possible 16-Hz measurements were recorded and the sonic temperature variance was less than 2.5 K^2.

Calibration verification checks of the TDLAS, sonic anemometers, and lagoon pH instruments were made at the beginning and end of each measurement period and semi-annual calibrations were conducted on all instruments in accordance with the Quality Assurance Project Plan (Grant, 2006). Sonic anemometers were always within 0.1 ms^{-1} of the reference sonic anemometers for each mean wind component. The TDLAS NH_3 PIC measurements were maintained to within a precision of 10% (relative standard deviation) and an accuracy of ±10% at 50 ppm-m (Grant, 2006; Grant and Boehm, 2010a,b,c). Atmospheric moisture interfered with the NH_3 measurements at the sow and finishing farms during some of the measurements (Grant et al., 2013b). Calibration adjustments to the raw measurements were made based on the multipoint calibrations conducted during the study (Grant and Boehm, 2010a,b,c). The minimum detection limit for all TDLAS systems, derived from the calibration verification checks, was less than 3 $\mu L\ L^{-1}m^{-1}$. All concentration measurements were normalized to 101.325 kPa and 20^oC (STP). Concentration measurements for a given path were considered representative of the 30-min averaging period if at least one dwell on the retro-reflector defining the path had valid measurements during the period.

The bLS emissions model was used to determine NH_3 emissions from the east basin of the dairy and both hog lagoons (Grant and Boehm, 2010a,b,c). The bLS emissions model calculates the emission from a defined source utilizing the measured turbulence statistics and the measured PIC. The model quantifies the relationship between the PIC and the average surface flux density across the source area assuming the relationship is only a function of flow characteristics (Flesch et al, 2004). Criteria for valid ½ hour NH_3 bLS emissions estimates were: absolute value of the Monin Obukov length (L) of greater than 2 m, friction velocity (u_*) greater than 0.15 m s^{-1}, standard deviation of the wind direction of less than 30^o, and touchdown fraction of greater than 0.1 (Grant et al (2013b). The bLS-derived emissions are over-determined for all basins/lagoons and consequently the background concentration (C_{bg}) was calculated by the model as a single value decomposition of linear equations (each equation representing the concentration and emission along an OP). While the bLS model estimating the NH_3 emissions from the west dairy basin is also over-determined, the measured OP are all downwind (not distributed around the sides of the basin) and thus a measured upwind background concentration was unavailable (Grant and Boehm, 2015). Consequently no bLS-determined NH_3 emissions from the west basin were possible.

The VRPM model, an integrated horizontal flux method, was used to determine NH_3 emissions from both the east and west basins of the dairy (Grant and Boehm, 2010c). The VRPM method assumed a bivariate Gaussian function to describe the distribution of mass across the vertical plane using path integrated concentration measurements made along optical paths defined by a TDLAS and a retro-reflector (Hashmonay et al, 2008). Nominally, valid VRPM estimate for a given measurement plane required the mean wind direction to be less than 60° off the perpendicular of the measurement plane, an upwind source fraction of 0.9, a minimum wind speed of 1 ms^{-1}, and various other criteria to assure detection and capture of the emission plume within the VRPM measurement plane (Grant, 2006). Complete criteria for the validation of VRPM-derived NH_3 emissions are described in Grant et al (2013c). The VRPM emissions for the east basin of the dairy were based on valid concentrations from all downwind sides of the basin as well as at least one upwind side. Emissions from the west basin of the dairy were based on a valid downwind measurement plane (the west measurement plane of the east basin) under relatively steady wind and either 1) no assumed background concentration and flux or 2) subtraction of the mean upwind flux measured at the east basin (Grant and Boehm, 2015).

A comparison between the bLS and VRPM emissions methodologies for farm lagoons on level land with minimal local wind influences indicated a mean difference between the models (VRPM and bLS) of -0.04 gs^{-1} (Grant et al, 2013a). Consequently, the two emissions models were assumed to equally represent the actual emissions at the dairy basins.

Thirty minute emission errors were determined based on the errors in the calibration gases, diluters, gas analyzers, and emissions model. Assuming a theoretical random error of 22% (Laubach and Kelliher, 2005) and a bias of -40% for TDLAS units with moisture interference, the expected error in the bLS-measurement of NH_3 emissions was ± 24%, with a bias of -40% for TDLAS NH_3 measurements subjected to moisture interference and no bias for TDLAS NH_3 measurements not subject to moisture interference. This was consistent with tracer-estimated errors of the bLS emission calculation method of between 5% and 36% (Flesch *et al*., 2004). Given a 30-min error of bLS and VRPM NH_3 emissions (24% bLS, 18% VRPM) and the many replicates for each 3-hr period during the day (Grant et al, 2013b), the error associated with the NH_3 emissions estimation based on a mean daily emission were: 8% for both bLS and VRPM emissions during filling with open surface, 2% for bLS and 3% for VRPM emissions during filling with crusted surface, 3% for bLS and 5% for VRPM emissions during drying, and 3% for VRPM during removal (Grant and Boehm, 2015).

Results

Emissions were measured at the two hog lagoons in OK and the two dairy basins in WA over the course of two years. The climatological conditions at the three locations were similar with a wide range of air temperatures and relatively low humidity characteristic of the Western USA (Figure 2). The median vapor pressure deficit was 1.25 kPa at the WA dairy and 0.64 kPa at the OK hog operations. This is much higher than the median vapor pressure deficit of 0.37 kPa over the same period of time at a Breed to wean hog operation in NC (Grant and Boehm, 2010d).

Measurements were conducted at the dairy for approximately 40 days every six months for a total of 101.9 d (Grant and Boehm, 2010c). Over the course of the measurement periods, winds were largely from the southwest and controlled by katabatic and anabatic slope flow when the synoptic flow was weak. When either basin began to be filled, the open liquid surface was exposed to the air. As the manure continued to fill the basin, a substantial crust formed on the surface. Unfortunately, exclusion of measurements due to wind direction, wind direction variability, atmospheric stability, background concentrations, and friction velocity reduced the number of emissions measurements to a point where no days had 75% or more of all possible measurements (522 and 386 ½ hour values for the east and west basins respectively)(Grant and Boehm, 2015). Consequently, the mean daily emissions for each stage of manure storage were determined by ensemble averaging the ½ h emissions into 3 h intervals through the day during the entire storage period in the basin and then averaging these 3 h intervals into a daily average assuming equal weighting of the 3-h intervals.

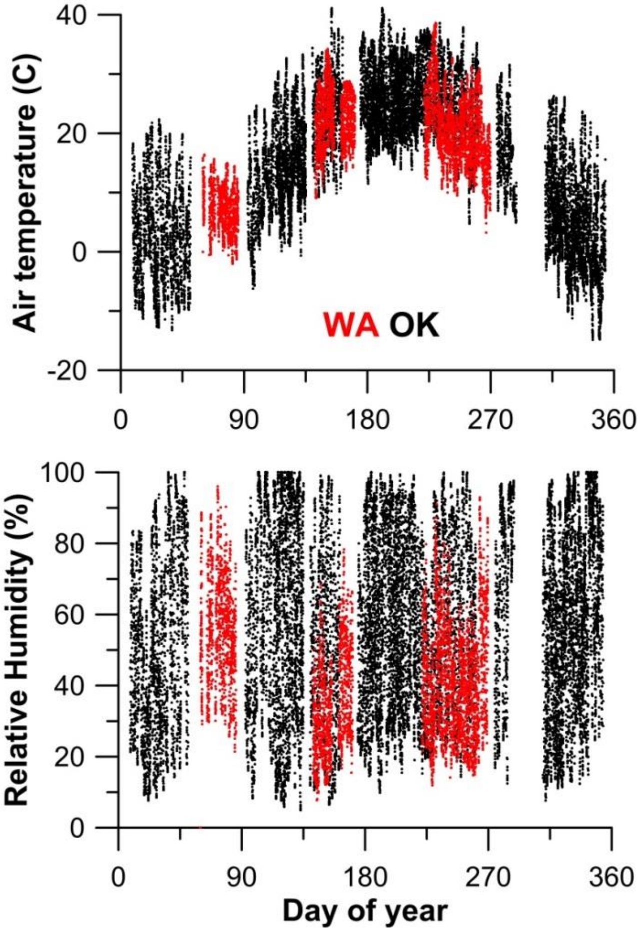

Figure 2: Climatic conditions during emissions measurements. Conditions in OK (Black) and WA (Red) are indicated.

Measurements were conducted at the lagoons of the two hog farms approximately 20 d every three months as part of a seasonal rotation with two other farms for a total of 181 d at the breed to wean farm and 155 d at the finishing farm (Grant and Boehm, 2010). Over the course of the measurements, winds were generally from the south with some periods from the north. Winds speeds were commonly greater than 5 m s^{-1}. Both lagoons generally appeared brown with little or no crusting year-round and were frozen during the winter. Exclusion of measurements due to wind direction, wind direction variability, atmospheric stability, background concentrations, and friction velocity reduced the measurements to 4526 and 4367 ½ hour measurement periods for the breed to wean and finishing farm lagoons, respectively (Grant et al, 2013b).

Table 2- Ammonia emissions from the dairy basin during manure handing stages with wind speeds less than 4 ms^{-1} (modified from Grant and Boehm, 2015)

Phase of manure handling (basin)	Mean (+/- SD)[1]	CV[2]	Mean	
	Kg d^{-1}	%	g $d^{-1}hd^{-1}$	g $d^{-1}AU^{-1}$
Liquid fill (east basin)	59.1 (23.5)	40	12.5	8.54
Liquid fill (west basin)	90.0 (27.2)	30	19.1	13.0
Liquid fill (both basins)			15.7	10.8
Crusting fill (east basin)	34.8 (29.2)	84	7.35	5.01
Crusting fill (west basin)	85.6 (49.5)	59	18.1	12.4
Crusting fill (both basins)			12.7	8.69
Drying (east basin)	34.0 (27.9)	82	7.19	4.90
Removal (west basin)	88.5 (41.5)	47	18.8	12.8

1: SD= Standard deviation
2: CV= Coefficient of variation

Emissions

The average daily mean LM- and cow-specific emission from the dairy basins were 8 g NH_3 $AU^{-1}d^{-1}$ (12 g d^{-1} hd^{-1}) during basin filling, 5 g NH_3 $AU^{-1}d^{-1}$ (7 g NH_3 $hd^{-1}d^{-1}$) during basin drying, and 13 g NH_3 $AU^{-1}d^{-1}$ (19 g NH_3 $hd^{-1}d^{-1}$) during manure removal (Table 2). These live mass basis emissions are similar to the range of monthly values reported by Bjorneberg et al (2009) for an Idaho dairy with comparable vapor pressure deficits and temperatures. Crusting of the basin surface resulted in non-significant ($p=0.05$ level) 49% and 5% NH_3 emissions reductions for the east and west basins, respectively. The east basin NH3 emissions reduction associated with crusting was similar to that reported by Smith et al (2007) and Misselbrook et al (2005), while the reduction for the west basin was significantly less. Once the east basin was crusted, the emissions did not vary from when it was still filling under the crust or no longer receiving fresh manure.

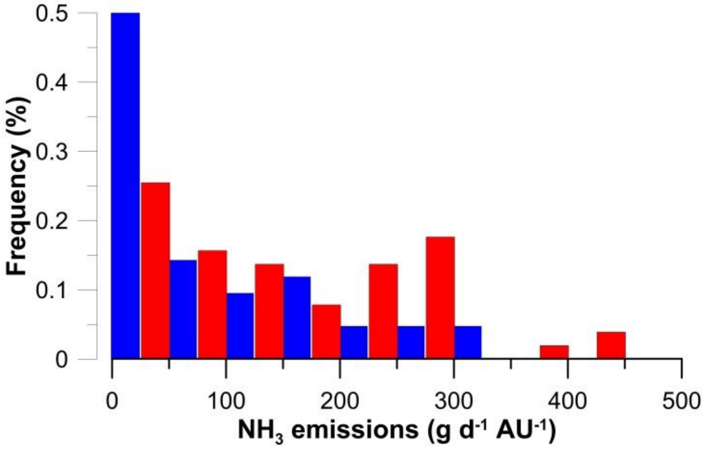

Figure 3- Distribution of daily NH3 emissions at the hog farm lagoons. The distribution of emissions at the breed to wean (red) and finisher (blue) lagoons is shown.

The emissions from the west basin are nearly identical for the liquid fill, crusting fill, and removal phases (Table 2). The emissions from the east and west basins were nearly the same during the basin filling before crust formed (Table 2). While crusting reduced the emissions from the east basin, it did not do so for the west basin (Table 2). Since the west basin emissions were based on an estimated upwind flux derived from the mean upwind fluxes measured for the east basin, errors in the east basin emissions are greater than the east basin.

The daily LM- and hog-specific emissions at the two hog farms had differing distributions, with the emission from the breed to wean farm lagoon more evenly distributed than that of the finisher farm lagoon

(Figure 3). The mean LM- and hog-specific emissions at the breed to wean farm were higher than that at the finisher farm (Table 3) and the LM- and hog-specific emissions at the breed to wean farm lagoon were more variable than at the finisher farm.

The average daily mean LM- and hog-specific emissions from the breed to wean hog lagoon (Table 3) corresponded to 53% of the estimated nitrogen (N) excretion of 233 g d^{-1} AU^{-1} based on an annual N excretion rate of 17% by animal mass for the sows and litters (Rotz, 2004). Emissions varied by a factor of ten from a summer maximum of 294 g d^{-1} AU^{-1} (135 g $d^{-1}hd^{-1}$) to a winter minimum of 23 g d^{-1} AU^{-1} (11 g $d^{-1}hd^{-1}$) (Table 3). The average daily mean LM- and hog-specific emissions from the finishing farm lagoon were 105 g d^{-1} AU^{-1} and 18 g $d^{-1}hd^{-1}$, respectively (Table 3). The mean emission corresponded to 42% of the estimated nitrogen (N) excretion of 205 g d^{-1} AU^{-1} based on an annual N excretion rate of 15% by animal mass (Rotz, 2004). The annual trend in daily NH_3 emissions showed maximum mean emissions in the summer (Table 3). This was ten times the emissions from five days of measurements in North Carolina (NC) reported by Shores *et al.* (2005). Part of this difference in emissions is likely due to the large differences in the vapor pressure deficit between OK and NC. The fall emissions (Table 3) were almost identical to that reported by Zahn *et al.* (2001). As with the breed to wean hog lagoon, the non-linear relationship between emissions and air temperature suggests that part of the difference in farm emissions is due to differences in the temperature between OK and NC during the summer. The daily emissions during the spring and summer (Table 3) were three to four times the value measured by Bicudo *et al.* (2004) using a floating wind tunnel in Minnesota. As with the sow farm emissions, the higher emissions reported here are likely due in part to the high summertime temperatures and the generally higher winds experienced at the Oklahoma farm (mean wind speed of 4.4 ms^{-1}) relative to North Central and Southeastern US farms reported in the literature.

Table 3- Measured seasonal mean emissions at the Hog farm lagoons (modified from Grant et al, 2013b).

	Breed to wean			**Finishing**		
Season	**Mean g d^{-1} hd^{-1}**	**Mean g $d^{-1}AU^{-1}$**	**CV[1] %**	**Mean g d^{-1} hd^{-1}**	**Mean g $d^{-1}AU^{-1}$**	**CV %**
Spring	55.5	120.7	50	29.9	176.4	27
Summer	135.3	294.4	24	39.2	231.9	29
Fall	64.7	140.9	56	20.6	121.8	138
Winter	10.7	23.3	33	5.3	31.3	85
Annual	69.4	151.0		17.8	105.1	

1: CV=Coefficient of variation

Factors influencing emissions

Emissions from the manure storage facilities (basin and lagoons) were influenced by the temperature of the manure surface and the wind conditions above that surface. Changes in the liquid height in the basin or lagoon and freezing or crusting of the manure storage surface prevented continuous monitoring of the liquid temperature. Consequently air temperature was used as a proxy for the liquid temperature. This proxy introduced noise in any relationship between temperature and emissions and consequently limited the ability to determine the true influence of temperature on emissions.

Emissions from the manure storage facilities (basin and lagoons) were influenced by winds over the facility. Wind conditions over the manure surface were, however, not measured directly, but assumed equivalent to that measured on the lagoon or basin berm.

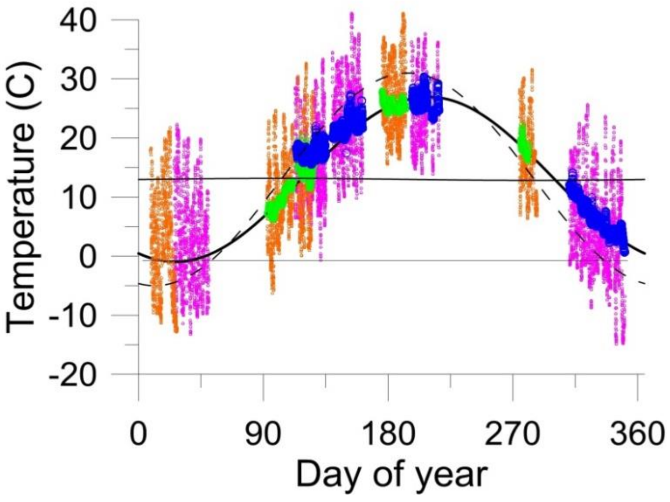

Figure 4- Comparison of lagoon liquid and air temperatures at the OK lagoons. Breed to wean lagoon (purple) and air (blue) temperatures and finisher air (orange) and lagoon (green) temperatures are indicated.

The NH_3 emissions at the dairy were positively, but weakly, correlated with air temperatures in accordance with the van't Hoff equation during all stages of the manure storage except removal. The NH_3 emissions were positively correlated with both wind speed with mean coefficients of determination (r^2) across all stages and basins of 0.73 (Grant and Boehm, 2015). The slopes of the linear regressions were highest during filling and liquid surface and during sludge removal and lower as the basin crusted and dried. Since wind speeds varied across measurement periods and manure storage and removal stages, the mean daily NH_3 emissions for each stage of manure handing were determined for conditions with similar wind speeds. Since winds strongly correlated with emissions and the range of wind speeds varied during the measurements of emissions from each manure handling stage, comparative mean emissions per handling stage were determined for periods with wind speeds less than 4 ms^{-1} in Table 2.

The NH_3 emissions at the two hog operations were correlated with air temperatures in accordance with the van't Hoff equation (r^2=0.50 and 0.55 for the breed to wean and finishing farm lagoons respectively) (Grant et al, 2013b). The ratio of measured to modeled LM-specific NH_3 emissions for both farms was linearly correlated with mean daily wind speed (r^2=0.26) according to Ro and Hunt (2006). Winter emissions from the lagoon in Oklahoma are likely a result of barn effluent entering the lagoon on top of the frozen surface.

SUMMARY AND CONCLUSIONS

The duration of each stage of manure handling at the western dairy dictates the losses of N through ammonia volatilization. Emissions during the 280 d filling of the dairy waste basin accounted for 77% of the total N lost from the manure in the basin (Grant and Boehm, 2015). Crusting of the basin surface appeared to decrease emissions in one basin (east) while not influencing the emissions in the other basin (west). Drying of the basin was estimated to last 60 d with a corresponding loss of only 10% of the total N loss. Removal of the manure from the basin after drying required approximately 30 d (Table 3) with a corresponding loss of 13% of the total N loss. The total NH_3 emissions from the manure basin were 10.6 g $d^{-1}hd^{-1}$ or 7.2 g $d^{-1}AU^{-1}$ (Grant and Boehm, 2015). The variability in emissions from the basins was influenced by the wind speeds and to a lesser extent temperatures. Consequently a complete assessment of emissions from a basin requires measurements over the entire cycle of manure handling. Predicting emissions for a given year or basin must also consider the timing of each handling phase relative to the weather conditions during the phase, since air temperature and winds influenced NH_3 emissions.

Emissions at the hog finishing farm were similar to those reported at several locations, but emissions at the breed to wean farm were much higher than reported in previous studies. Emissions from the sow farm lagoon were higher than those from the finishing farm when compared on an area or animal head basis, but were very similar on an AU (Animal Unit: a proxy for manure production) basis. Emissions were strongly influenced by air temperature at the two lagoons (Grant et al., 2013b). The apparent air temperature influence on emissions suggests that the solubility of the gas limited the emission to a greater extent than the turbulent exchange in the boundary layer over the lagoon at these farms with steady high winds (Grant et al., 2013). Daily emissions were also shown to be correlated linearly with daily mean wind speed. A semi-empirical process-based model considering the daily mean air temperature and wind speed was developed that accounted for 75% of the daily mean emissions variability on an AU basis for the two farm lagoons with a RMSE of 59 g d^{-1} AU^{-1}. The developed model would therefore not be useable where lagoon emissions are typically less than approximately 120 g d^{-1} AU^{-1}.

Clear evidence exists both for the inclusion of temperature (air or liquid) in describing the solubility of NH_3 in the water (here evident at the two hog lagoons) and the inclusion of wind speed or friction velocity in describing the turbulent transport through the boundary layer of air over the lagoon or basin surface (here most evident at the dairy basins). However the inherent stochastic variability in emissions influenced by turbulence limits the detail possible in models describing the processes transferring NH_3 from the lagoon or basin to the atmosphere. Modeling daily emissions appears more promising than that for ½ hourly emissions. Such models cannot be as complex as those developed by DeVisscher et al (2002) and Sommers et al (2006) to describe emissions into chambers. Additional work is needed to develop generalized process-based models for emissions estimation that include the lagoon water budget, N chemistry, NH_3 gas solubility controls, and turbulent gas transfer processes.

REFERENCES

ASAE. “Manure Production and Characteristics”, *ASAE Standard D384.1*, *ASAE Standards*, American Society of Agricultural Engineering, St. Joseph, MI 49085, 2003, pp. 649-651.

ASAE. “Manure Production and Characteristics”, *ASAE Standard D384.2*, *ASAE Standards*, American Society of Agricultural Engineering, St. Joseph, MI 49085, 2005, pp. 1-19.

Bicudo, J. R.; Clanton, C.J.; Schmidt, D.R.; Powers, W.; Jacobson, L.D.; Tengman, C.L. “Geotextile covers to reduce odor and gas emissions from swine manure storage ponds”, *Applied Engineering in Agriculture* 2004, 20, 65-75.

Bjorneberg, D.L.; Leytem, A.B.; Westermann, D.T.; Griffiths, P.R.; Shao, L; Pollard, M.J. “Measurement of atmospheric ammonia, methane, nitrous oxide at a concentrated dairy operation facility in southern Idaho using open path FTIR spectroscopy”, Trans. ASABE 2009, 52, 1749-1756.

Cassel, T.; Ashbaugh, L.; Flocchini, R. “Ammonia flux from open lot dairies: Development of measurement methodology and emission factors”, *J. Air Waste Manage. Assoc*. 2005a, 55, 816–825.

Cassel, T.; Ashbaugh, L.; Flocchini, R.; Meyer, D. “Ammonia emission factors for open-lot dairies: Direct measurements and estimation by nitrogen intake”, *J. Air WasteManage. Assoc*. 2005b, 55, 826–833.

Cumba, H.J.; Hamilton, D.W. “Liquid balance model for swine waste management systems using single-stage anaerobic lagoons”, *Trans. ASAE,* 2002, 45, 973-981.

DeVisscher, A.; Harper, L.A.; Westerman, P.W.; Liang, Z.; Arogo, J.; Sharpe, R.R.; VanCleemput O. “Ammonia emissions from anaerobic swine lagoons: model development”, *J. Appl. Meteorol.* 2002, 41, 426-433.

Flesch, T.K.; Wilson, J.D.; Harper, L.A.; Crenna, B.P.; Sharpe, R.P. “Deducing ground to-air emissions from observed trace gas concentrations: a field trial”, *J. Appl. Meteorol.* 2004, 43, 487-502.

Grant, R.H. “Quality Assurance Project Plan for the National Air Emissions Monitory Study: Open Source Emissions Component, US EPA Category I”, Purdue Agricultural Air Quality Laboratory, Purdue University, West Lafayette. 2006, 731p. (http://www.epa.gov/airquality/agmonitoring/pdfs/afolagooneemreport2012draftappa.pdf).

Grant, R.H.; Boehm, M.T. “National Air Emissions Monitoring Study: Data from the southwestern US pork production facility OK3A”, Final Report to the Agricultural Air Research Council. 2010a, Purdue University, West Lafayette. 167p. (http://www.epa.gov/airquality/agmonitoring/ok3a.html)

Grant, R.H.; Boehm, M.T. “National Air Emissions Monitoring Study: Data from the southwestern US pork production facility OK4A”, Final Report to the Agricultural Air Research Council, 2010b, Purdue University, West Lafayette. 174p. (http://www.epa.gov/airquality/agmonitoring/0k4a.html)

Grant, R.H.; Boehm, M.T. “National Air Emissions Monitoring Study: Data from the northwestern US milk production facility WA5A”, Final Report to the Agricultural Air Research Council, 2010c, Purdue University, West Lafayette. 121p. (http://www.epa.gov/airquality/agmonitoring/wa5a.html)

Grant, R.H.; Boehm, M.T. “National Air Emissions Monitoring Study: Data from the southeastern US pork production facility NC4A”, Final Report to the Agricultural Air Research Council. 2010d, Purdue University, West Lafayette. 154p. (http://www.epa.gov/airquality/agmonitoring/nc4a.html)

Grant, R.H.; Boehm, M.T.; Lawrence, A.F.; Heber, A.J. “Ammonia Emissions from Anaerobic Treatment Lagoons at Sow and Finishing Farms in Oklahoma”, *Agric. Forest Meteorol*. 2013, 180, 203-210. doi:10.1016/j.agrformet.2013.06.006

Grant, R.H.; Boehm, M.T.; Lawrence. A.F. “Comparison of a backward-Lagrangian Stochastic and Vertical Radial Plume Mapping methods for estimating animal waste lagoon emissions”, *Agric. Forest Meteorol.* 2013a, 180, 236-248, doi:10.1016/j.agrformet.2013.06.013.

Grant, R.H.; Boehm, M.T.; Lawrence, A.F.; Heber, A.J. “Ammonia Emissions from Anaerobic Treatment Lagoons at Sow and Finishing Farms in Oklahoma”, *Agric. Forest Meteorol*. 2013b, 180, 203-210, doi:10.1016/j.agrformet.2013.06.006.

Grant, R.H.; Boehm, M.T. “Manure NH_3 and H_2S emissions from a western dairy storage basin”, *J. Environ. Qual*. 2015, 44,127-136, doi:10.2134/jeq2014.05.0196

Harper, L.A.; Sharpe, R.R. “Ammonia emissions from swine lagoons in the southeastern U.S. coastal plains”, Final Report. Southern Piedmont Conservation Agricultural Research Center, Watkinsville, GA.

Submitted to Division of Air Quality, North Carolina Department of Environment and Natural Resources, Raleigh, NC, December 1998.

Harper, L.A.; Sharpe, R.R.; Parkin, T.B.; de Visscher, A.; van Cleemput, O.; Byers, M. "Nitrogen cycling through swine production systems: Ammonia, dinitrogen, and nitrous oxide emissions", *J. Environ. Qual.* 2004, 33, 1189-1201.

Hashmonay, R.A.; Varma, R.M.; Modrak, M.T.; Kagman, R.H.; Segall, R.R.; Sullivan, P.D. "Radial Plume Mapping: A US EPA Test Method for Area and Fugitive source emission monitoring using optical remote sensing", 21-36 In: Kim, YJ and U Platt (eds.) *Advanced Environmental Monitoring*, Springer-Verlag Press, 2008.

Laubach, J.; Kelliher, F.A. "Measuring methane emission rates of a dairy cow herd (II): results from a backward-Lagrangian stochastic model", *Agric. Forest Meteorol.* 2005, 129,137-150.

Misselbrook, T.H.; Siobhan, K.E.; Brookman, K.A.; Smith, T.C.; Williams, A.G.; McCrory, D.F. "Crusting of Stored Dairy Slurry to Abate Ammonia Emissions: Pilot-Scale Studies", *J. Environ. Qual.* 2005, 34, 411-419.

Nielsen, D.A.; Nielsen, L.P.; Schramm, A; Revsbech, N.P. "Oxygen distribution and potential ammonia oxidation in floating, liquid manure crusts", *J. Environ. Qual*. 2010, 39, 1813- 1820.

Rotz, A.C. "Management to reduce nitrogen losses in animal production", *J. Animal Sci.* 2004, 82(E. Suppl.), E119-137.

Ro, K.S.; Hunt, P.G. "A new unified equation for wind-driven surficial oxygen transfer into stationary water bodies", *Trans. Amer. Soc. Agric. Biol. Eng.* 2006, 49, 1615-1622.

Rumburg B, Mount, G.H.; Yonge, D.; Lamb, B.; Westberg, H.; Neger, M.; Filipy, J.; Kincaid, R.; Johnson, K. "Measurements and modeling of atmospheric flux of ammonia from an anaerobic dairy waste lagoon", *Atmos. Environ*. 2008, 42, 3380-3393.

Shores, R.C.; Harris, D.B.; Thompson, E.L.; Vogel, C.A.; Natschke, D.; Hashmonay, R.A.; Wagoner, K.R.; Modrak, M. "Plane-integrated open path fourier transform infrared spectrometry methodology for anaerobic swine lagoon emission measurements", *Appl. Eng. Agric.* 2005, 21, 487–492.

Smith, K.; Cumby, T.; Lapworth, J.; Misslebrook, T.; Williams, A. "Natural crusting of slurry storage as an abatement measure for ammonia emissions on dairy farms", *Biosyst. Eng.* 2007, 97, 464-471.

Sommer, S.G.; Zhang, G.Q.; Bannink, A.; Chadwick. D.; Misselbrook, T.; Harrison, R.; Hutchings, N.J.; Menzi, H.; Monteny, G.J.; Ni, J-Q.; Oenema, O.; Webb, J. "Algorithms determining ammonia emission from buildings housing cattle and pigs and from manure stores", *Adv. Agron.* 2006, 89, 261-335.

Szogi, A.A.; Vanotti, M.B.; Stansbery, A.E. "Reduction of ammonia emissions from treated anaerobic swine lagoon". In *Proceedings of the 2005 Animal Waste Management Symposium*, Research Triangle Park, NC, USA, 5-7 October 2005, Havenstein, G., Ed., North Carolina State University, NC, USA.

Wood, J.D.; Gordon, R.J.; Wagner-Riddle, C.; Dunfield, K.E.; Mandani, A. "Relationships between dairy slurry total solids, gas emissions, and surface crusts", *J. Environ. Qual.* 2012, 41, 674-704. et al, 2012

KEY WORDS

Ammonia emissions
Integrated horizontal flux
Backward Lagrangian flux
Dairy waste basin
Hog waste lagoon

ACKNOWLEDGEMENTS

Assistance with field measurements was made by J. Wolf, S. Cortus, C. Fullerton, D. Snyder, C. Diehl, A. Lawrence, P. Ndegwa, H.S. Joo and J.C. Ramirez. Without their help this work could not have been possible. Thanks also go to the anonymous producers who were very helpful in providing information and assistance at various points during the study. This research was funded by livestock producers, the Agricultural Air Research Council, Inc. , National Milk Producers and the National Pork Board.