PARTICULATE MATTER AND AMMONIA EMISSION FACTORS FOR TUNNEL–VENTILATED BROILER PRODUCTION HOUSES IN THE SOUTHERN U.S.

R. E. Lacey, J. S. Redwine, C. B. Parnell, Jr.

ABSTRACT. *Emissions rates for particulate matter less than 10 μm (PM_{10}) and ammonia (NH_3) from commercial tunnel–ventilated broiler houses in central Texas were analyzed using linear regressions to develop emission rates as a function of bird weight for broilers on litter. Interior ambient temperature and relative humidity were not found to be significant factors affecting emissions. From the regression equations, emission rates for PM_{10} and NH_3 for average weight birds in these facilities were estimated. Over a 7–week grow–out period, the average bird weight was estimated to be 1.03 kg, the average emission rate for PM_{10} was 26.5 mg PM_{10} bird^{-1} day^{-1}, and the average emision rate for NH_3 was 632 mg bird^{-1} day^{-1}. The emission factor was defined as the total emission in mass per bird for the grow–out period. For typical production conditions and management, the emission factor for PM_{10} was 1.3 g PM_{10} bird^{-1}, and for NH_3 the emission factor was 31 g NH_3 bird^{-1}. These results were compared to values found in the literature. For a facility comprised of four tunnel–ventilated broiler houses with 27,5000 birds per house and a 2–week idle time between 7–week grow–out periods, the emission inventory was calculated to be 828.2 kg PM_{10} year^{-1} and 19,780 kg NH_3 year^{-1}. The annual emissions for PM_{10} were below those required to be reported under the Federal Clean Air Act, and there is currently no requirement for NH_3 under this legislation.*

Keywords. *Ammonia, Broiler production, Emission factors, Emission inventory, PM_{10}.*

Emission factors have long been fundamental tools for air quality management. They are used for developing emission control strategies, deter–mining applicability of permitting and control programs, ascertaining the effects of sources and appropriate mitigation strategies, and a number of other related applica–tions by federal, state, and local agencies, consultants, and industry. Because of their importance, it is imperative that they reflect actual conditions as accurately as possible. The U.S. Environmental Protection Agency (EPA, 1995; EPA, 2000) defines an emission factor as:

"An emission factor is a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. These factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant (e.g., kilograms of particulate emitted per megagram of coal burned). Such factors facilitate estimation of emissions from various sources of air pollution. In most cases, these factors are simply averages of all available data of acceptable quality, and are generally assumed to be representative of long–term averages for all facilities in the source category (i.e., a population average)."

A clear distinction should be established between an emission rate and an emission factor. An **emission rate** is an expression of mass emitted per unit time, sometimes put in terms of a production unit. For example, an emission rate for a broiler operation might be in units of kg h^{-1} or in terms of kg h^{-1} 500 kg^{-1} live weight. The advantage of the second is that emissions calculations can more easily be scaled up or down as the weight of the birds varies. Emission rates are dependent on physical conditions at the source (e.g., litter moisture or litter pH) and operational considerations (e.g., type of ventilation or type of cooling systems). Variation in physical or operational conditions can change the emission rate, sometimes dramatically. However, emis-sion rates should be established under typical conditions. Comparison of emission rates can be useful in establishing the consistency of data between researchers.

An **emission factor** is expressed in terms of mass per production unit and is calculated from an emission rate. In many cases, emission rates are erroneously reported as emission factors. However, without incorporation of specific management practices, rates do not reflect "a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant." The EPA definition leaves it to the individual to define the production unit. For this study, the emission factor from broilers on litter was defined to be total mass emitted per bird (kg bird^{-1}). Since broilers are typically an all–in all–out production system with a production cycle of less than a year, this definition was convenient for further calculations. The effect of growth on emissions is included, and a time factor is implicit in the definition, generally

Article was submitted for review in September 2002; approved for publication by the Structures & Environment Division of ASAE in May 2003. Presented at the 2002 ASAE Annual Meeting as Paper No. 024212.

The authors are **Ronald E. Lacey, ASAE Member Engineer,** Associate Professor, and **Calvin B. Parnell, Jr., ASAE Fellow Engineer,** Regent's Professor, Department of Biological and Agricultural Engineering, Texas A&M University, College Station, Texas; and **Jarah S. Redwine,** Engineer, CH2M Hill, San Antonio, Texas. **Corresponding author:** Ronald E. Lacey, Texas A&M University, 201 Scoates Hall, MS2117, College Station, TX 77843–2117; phone: 979–845–3967; fax: 979–845–3932; e–mail: ron–lacey@tamu.edu.

  ISSN 0001–2351

around seven weeks to grow a broiler from chick to market weight. Thus, an emission factor carries with it assumptions about production and management. Note that for other livestock operations where the average animal weight is constant with respect to time (e.g., feedlots or layer operations), a more convenient emission factor may be in terms of mass per animal per unit time.

The third descriptive parameter commonly used is the **emission inventory**. Federal and state laws may require any commercial operation, agricultural or otherwise, to submit an annual inventory of pollutants emitted from their site. In Texas, any site within an area in attainment with air quality standards that has the potential to emit greater than: (a) 100 tons per year of any regulated air pollutant, (b) 10 tons per year of any single hazardous air pollutant (HAP), or (c) 25 tons per year of aggregate HAPs is required to submit an emission inventory (TNRCC, 2001). Because the emission inventory is a self–reporting process, an estimate of annual emissions should be calculated to determine if the facility would be required to file an emission inventory. The emission factor can be used to calculate an emission inventory by considering management and production practices at the producer's location.

The Environmental Protection Agency (EPA) regulates particulate matter (PM) in the ambient air in the U.S. (Federal Register, 2001) with maximum allowable concentrations for PM smaller than 10 μm (PM_{10}) and PM smaller than 2.5 μm ($PM_{2.5}$). The human respiratory system can filter PM larger than 10 μm in aerodynamic equivalent diameter (AED) and prevent it from reaching the alveoli in the lungs. Thus, only particulate matter smaller than 10 μm is considered respirable. Particulate matter found in broiler operations typically originates from the litter, feed, skin, and feathers (Grubb et al., 1965; Madelin and Wathes, 1989).

While not regulated under the Federal Clean Air Act, atmospheric nitrogen compounds emitted from livestock operations, primarily in the form of ammonia, have been reported as causing nitrogen enrichment and eutrophication of surface waters (Aneja et al., 2001), contributing to the formation of acid precipitation (ApSimon et al., 1995), and precursor to the formation of fine particulate material ($PM_{2.5}$) in the form of ammonium nitrate and ammonium sulfate (Barthelmie and Pryor, 1998). Additionally, ammonia is an odorant, and conditions conducive to the production of ammonia may result in the emission of other odorants (e.g., volatile fatty acids, volatile amines, indole, phenol, and sulfur–containing compounds). Ammonia is produced from the microbial breakdown of uric acid in poultry manure. The decomposition is dependent on a number of factors, including in decreasing order of importance: litter pH, temperature, and moisture content (Elliott and Collins, 1982; Carlile, 1984).

Phillips et al. (2000) identified the following four approaches to estimating emission rates for ammonia from livestock operations:

1. Feed and manure nitrogen balance (ammonia by difference).
2. Summation of local ammonia sources:
   2a. Measurements for houses and stores
   2b. Model for houses and stores.
3. Determining ammonia fluxes, either directly or indirectly, using an envelope more or less remote from the ammonia source(s):
   3a. Measuring air velocities and ammonia concentrations at the chosen envelope
   3b. Measuring the dilution of air within the chosen envelope
   3c. Modeling air velocities and ammonia concentrations at the chosen envelope
   3d. Modeling the dilution of air within the chosen envelope.
4. Ratio of ammonia source emissions to tracer gas emissions.

Approach 1 relies on accurate measurements of all other sources and sinks for N where all unaccounted for N is assumed to be lost as NH_3. While in theory this seems reasonable, in practice it is often difficult to account for all other N sources and sinks, and consequently this introduces an error into the estimate of NH_3 emissions. Approach 2 is based on individual measurements (2a) or models (2b) of NH_3 emissions from all possible sources at a given location, which are in turn summed to yield an overall estimate of NH_3 emissions. In practice, it is often difficult to determine NH_3 emissions at specific sources because of the volatility of the gas and the complexity of the sampling hoods and equipment needed.

Approach 3 relies on measuring (3a and 3b) or modeling (3c and 3d) mass flux across a defined boundary or envelope. The first two (3a and 3b) have the advantage of directly measuring NH_3 flux, but they require that the envelope be easily defined. Approach 3a is particularly conducive to measurement in a mechanically ventilated livestock building where sampling devices can be located in the building and there are a limited number of openings into the building. Concentrations of NH_3 at the sampler location are multiplied by the ventilation rate to yield an NH_3 emission rate from the building. This was the method used in this study. Approach 3b is more applicable to naturally ventilated buildings, where there are a large number of openings and complex airflow, but multiple sampling points are required. Concentrations of NH_3 are measured at the sampling locations and then combined with an estimate of ventilation rates at these points, usually based on a tracer gas like carbon dioxide, to calculate an NH_3 emission rate. The modeling approaches (3c and 3d) are similar in concept except that mathematical or empirical models are substituted for direct measurements of concentration and/or ventilation rates. Developing accurate models of both NH_3 conversion and release and air movement, particularly for naturally ventilated spaces, makes application of these methods challenging.

Approach 4 relies on emissions of a trace gas at a known rate and measurement of the concentrations of the trace gas and NH_3 at a point downwind. The ratio of trace gas concentration to NH_3 concentration at that point is assumed to be the same as the ratio of the known trace gas emission rate to the unknown NH_3 emission rate. This approach can be highly reliable in practice, but it requires extensive equipment and expertise to utilize effectively.

Of the four approaches, only approaches 3a and 3b are applicable for determining the emission rate of particulate matter (PM) from broiler housing. Approach 1 relies on mass balance on one or more components, but PM is not limited by chemical composition. Therefore, it is not possible to develop a mass balance. Approach 2 relies on summation of individual sources of PM; however, much of the PM in livestock environments is generated from large areas, such as broiler litter or bird feathers. PM is released to the atmosphere by mechanical actions such as animal motion, air velocity, or feeder operation. These two factors make it challenging to utilize approach 2a or 2b to estimate PM emissions from individual sources in livestock environments, although approach 2a is used to estimate emissions from other types of agricultural operations, such as feed mills and cotton gins. Approach 3c and 3d rely on models of PM emission, but no accurate models have yet been developed. Approach 4 relies on similar mass transport for the known tracer gas and the unknown pollutant. PM disperses solely by convective air motion and does not diffuse like gasses; therefore, convective movement and diffusion of a tracer gas cannot be assumed to occur at a fixed ratio with PM convection. Approaches 3a and 3b rely on direct measurement of the concentration of PM in the building, which can be done with gravimetric methods, but differ in the method used to estimate the ventilation rate and the number of sampling locations used to obtain a representative concentration.

Production of broiler chickens in the U.S. is primarily done within enclosed structures where the floor is covered in an absorbent material (i.e., litter) for manure collection. Conditions within these confinement buildings are managed to optimize bird health and productivity. Factors that affect the interior conditions include seasonal climate and weather conditions; building ventilation, heating, and cooling; and factors that affect the litter (e.g., feed factors, flock husbandry, and litter management). These factors are interrelated in establishing the composition of the interior air of the building. Because commercial broiler production is usually totally confined, the air in the building contains all of the materials emitted to the atmosphere, some of which are potential contaminants (e.g., ammonia, dust, and odorants).

Objectives

The first objective of this study was to estimate PM_{10} and NH_3 emission factors for tunnel–ventilated broiler production facilities using empirical data and management practices typical in the southern U.S. These estimated PM_{10} and NH_3 emission rates and emission factors were compared with emission rates and emission factors in the literature for broilers on litter. The second objective was to estimate an emission inventory for a typical modern tunnel–ventilated broiler production facility in the southern U.S. for PM_{10} and NH_3 to determine if federal or state regulations would apply.

Materials and Methods

Development of emission factors from concentration data involved a number of steps, starting with measurement of total suspended particulates (TSP) and ammonia (NH_3) concentration data and determination of the particle size distribution (PSD) of the TSP to determine the fraction of PM_{10}. Additionally, data were collected on ventilation rates of the buildings at the time of data collection. Emission rates were calculated from ventilation rates multiplied by the corresponding concentration data and divided by the number of birds in the building. All values were adjusted to a standard temperature of 21.1°C and a standard pressure of 101.3 kPa by a ratio of the actual air density to the standard air density. Results for PM_{10} and NH_3 have been previously presented in terms of mass time^{-1} bird^{-1} as a function of the age of the birds (Redwine et al., 2002). A brief summary of the data collection methodology (Redwine et al., 2002; Redwine, 2001) is presented below for the convenience of the reader.

Experimental Data

Data for this study were taken from four commercial tunnel–ventilated broiler houses in north Brazos County, Texas, during the period from June to December of 2000. Data were collected on ten days from each of four houses. Triplicate samples of TSP and NH_3 concentrations were collected from each house on each day of testing, for a total of 120 samples (3 replications × 4 houses × 10 days). PM samples for determination of the PSD were collected from two of the four houses at the same frequency. Three different flocks were included in this study (11 May to 29 June, 6 July to 27 August, and 13 November to 1 January). Ambient interior temperature and relative humidity were recorded next to the samplers every 12 s during sampling.

Concentrations of PM in the houses were determined using gravimetric sampling. High–volume TSP samplers (Graseby GMW, Smyrna, Ga.) with glass–fiber filters (G810, Graseby GMW, Smyrna, Ga.) were used to collect the TSP following the protocol in 40CFR50 (Federal Register, 2001). Volumetric flow in each TSP sampler was recorded using a calibrated orifice meter at 7 s intervals. A second sampler (Graseby GMW, Smyrna, Ga.) with a poly–web filter media (Grade 7120, Web Dynamics, East Stroudsburg, Pa.) was collocated with the TSP sampler in two of the four houses to collect PM for determination of PSD. A Coulter Counter Multisizer (Beckman–Coulter, Miami, Fla.) was used for particle size analysis. Measurement of NH3 inside the broiler houses was accomplished using a chemical analyzer (Dräger CMS, Dräger, Lubeck, Germany). Ventilation rate measurements were made using a vane thermo–anemometer (451126, Extech, Waltham, Mass.) Barometric pressure was recorded at the beginning and end of each sampling period using a digital barometer (EW–997700, Cole–Parmer, Vernon Hills, Ill.) Data loggers (HOBO H8 RH/Temp, Onset Computer Corp., Pocasset, Mass.) were mounted on the outside of each TSP sampler housing and used to record temperature and relative humidity at 12 s intervals. The mean temperature, relative humidity, and barometric pressure for each individual sampling period were used to calculate the mean air density for that particular sampling period.

All measurements were taken approximately 40 m from the exhaust end of the buildings. A schematic of the plan view of a building is shown in figure 1. Each TSP concentration was collected over approximately a 2 h sampling period. The ventilation velocity across the cross–section of the building at the location of the samplers was measured at 15 points: 0.5, 1.2, and 2.0 m above the litter at the centerline of the house, 1.2 m from each sidewall, and 3.7 m from each sidewall for each of the five tunnel ventilation stages. The velocity at the TSP sampler location was close to the average of the 15 readings for each ventilation stage. The concentrations of TSP and NH_3 in the air at the point of measurement were assumed to be the same as in the exhaust air.

The site contained four identical tunnel–ventilated broiler houses with evaporative cooling pads. The houses were 152.4 × 13.4 × 2.6 m with the long axis oriented east–west, and the center roof height was 4.85 m. The sidewalls had

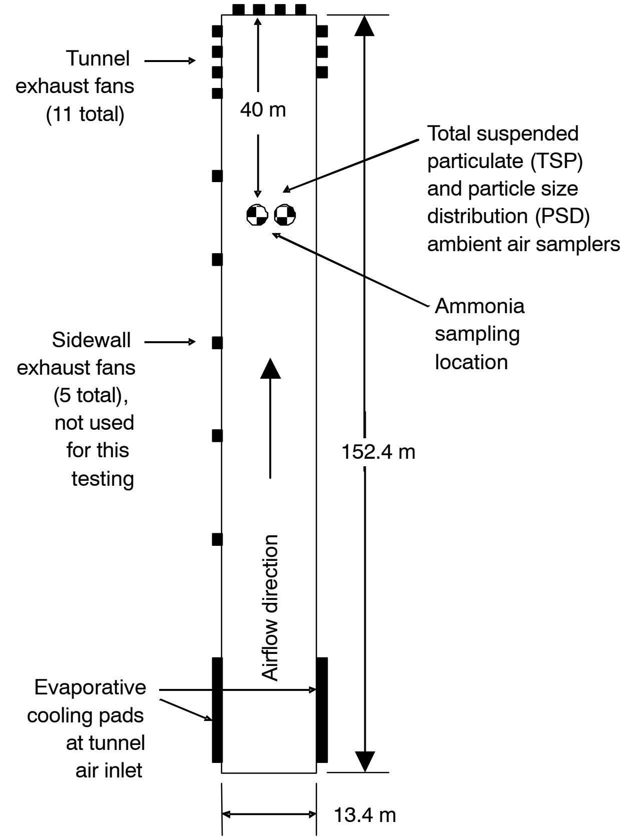

Figure 1. Schematic of the plan view of the commercial tunnel–ventilated broiler houses used in this study, showing the location of the air samplers and ventilation fans (not to scale).

ventilation openings 2.1 m in height that ran the length of the house and were equipped with moveable curtains that were closed during tunnel ventilation. The sidewalls of each house at the end opposite the tunnel ventilation fans contained two tunnel ventilation openings, 18.3 m in length, containing evaporative cooling pads. The houses did not have a ceiling, but six air baffles hung from the roof peak to approximately 3 m above the floor level and were spaced evenly through the length of the house, creating a rectangular cross–section for ventilation air movement. A 24–hour reduced lighting scheme was employed, which maintained a very low level of green light in the buildings at all times. During daylight hours, a limited amount of sunlight entered through the exhaust fan baffles, but the interior of the buildings was relatively dark at all times. Bird activity did not noticeably alter with changes in outside light between night and daylight.

Approximately 27,500 birds were placed in the houses immediately after hatching and grown until the market age of 49 days with a final average body weight of 2.4 kg. Mortality was less than 0.5% over the production cycle. After each growth cycle, the houses were vacant for approximately two weeks between flocks, with the side curtains fully open to allow natural ventilation in the buildings. The facility was operated in an all–in all–out mode, i.e., all buildings were filled with 1–day old chicks on the same day, and all finished birds were captured for market on the same day. The housing space was divided into three sections: two end sections each comprised 25% of the total floor space, and the middle section comprised the remaining 50%. During the brooding period (0 to 18 days), the birds were confined to the middle section of the house. After brooding, the birds occupied the entire length of the building at a stocking density of 13.5 birds m^{-2}. Migration fences were used to keep the birds evenly distributed throughout the house. Autofeeders and drip waterers ran the length of each house.

Wood shavings were used for litter. The litter management plan called for removing old litter and replacing it with fresh litter in the middle section after every four flocks. The litter in the two end sections of the house was changed every eight flocks. The surface cake of litter was mechanically mixed into the rest of the litter between each flock. For this study, the first flock (11 May to 29 June) was on litter that had served one previous flock, the second flock (6 July to 27 August) was on litter that had served two previous flocks, and the third flock (13 November to 1 January) was on litter that was new wood shavings in the center section (50% of the total area), and the remaining litter had served four previous flocks.

Although litter pH has been reported as a significant factor in ammonia emissions, the commercial scale used in this study created significant challenges to controlling litter pH. In a companion study, litter pH, moisture, N, and ammonia nitrogen (NH_3–N) were measured one day prior to market on two nearby farms in two identical broiler houses on each farm on two different dates. Each house used the same litter materials and feed ration as the houses in this study (Carey et al., 2000). Replicated measurements were made at 15 evenly spaced sites in each of two buildings. No statistical differences were found between farms, houses, or dates of sampling. The average litter pH was 8.48 and was found to be significantly higher on the north sides of the houses. The average litter moisture was 25.3% and was found to be significantly higher at the ventilation inlet ends of the buildings. Litter N was found to average 3.48% and was found to be higher at the ventilation exhaust ends of the buildings. Litter NH_3–N was found to average 1757 ppm and was significantly different at all sampling locations within the buildings. The conditions of the litter in this study were qualitatively compared to the litter in those studies, and no observable differences were noted.

The broiler houses were ventilated to maintain a temperature to maximize bird performance. The target temperature for the house was 31°C on day 1 and was decreased by 0.26°C per day until 20°C was reached. However, the actual temperatures were generally greater than the target temperatures, as shown in figure 2. Only tunnel ventilation was used during this study. The tunnel ventilation system consisted of eleven 1.2 m diameter tunnel fans with discharge diffuser cones mounted on the west end of the building. Variations in tunnel ventilation rate were accomplished by controlling the number of fans in operation (2, 3, 4, 5, or 11). For this study, the average cross–sectional air velocity during tunnel ventilation ranged from 0.8 to 2.6 m sec^{-1}. Evaporative cooling pads were placed at the opposite end of the building from the tunnel fans and used during tunnel ventilation to provide evaporative cooling of the incoming air.

Estimation of Emission Factors and Emission Inventories

The emission rates as reported in Redwine et al. (2002) were converted to a function of the mass of the birds. The 49–day market weight was reported by the grower as 2.4 kg $bird^{-1}$. This value was identical with an estimated weight

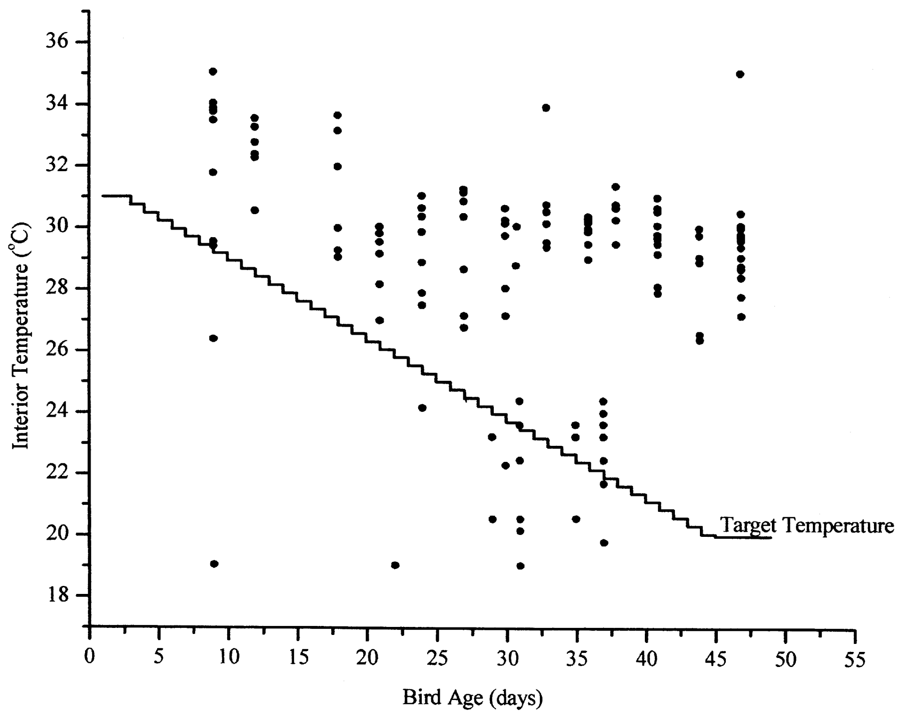

Figure 2. Average interior temperatures during each sampling period in four commercial tunnel–ventilated broiler houses in central Texas for sampling between June and December, 2000.

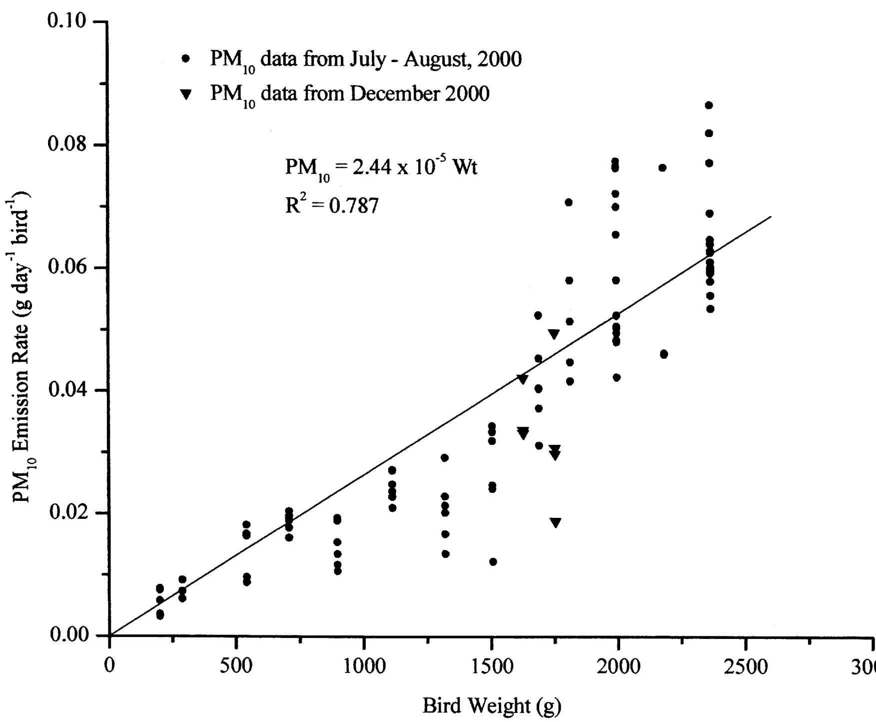

Figure 3. Emission rates for PM_{10} versus bird weight for four commercial tunnel–ventilated broiler houses in central Texas measured between June and December, 2000 (circles = data collected from June to August; triangles = data collected from December).

based on broiler growth equations in the literature (Flood et al., 1992). Thus, these equations were assumed to represent the growth during the production cycle. The average weight of a broiler during the 49–day growth cycle was calculated to be 1.03 kg. The emission data from the earlier study expressed as a function of individual bird mass are shown in figures 3 and 4 for PM_{10} and NH_3, respectively. The mortality losses were considered insignificant (less than 140 birds per house), and the total population was not corrected for those.

Multiple linear regressions were used to test for significance of bird weight, interior temperature, and interior relative humidity on PM_{10} and NH_3 emission rates. A linear regression equation was fit to the significant independent variables and used to predict PM_{10} and NH_3 emissions for an average weight bird over a 49–day production cycle. This

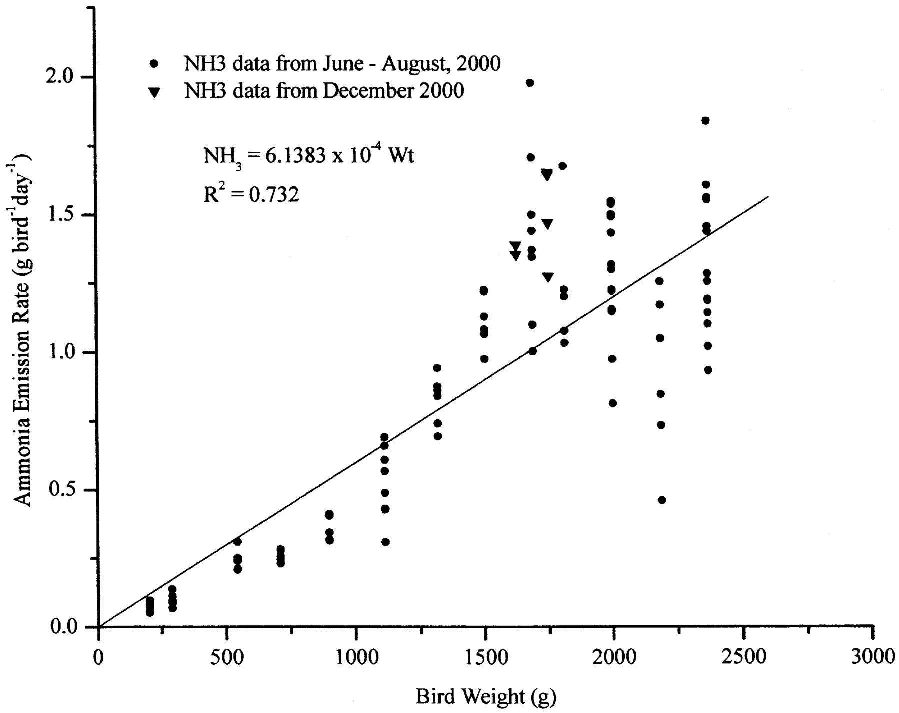

Figure 4. Emission rates for ammonia versus bird weight for four commercial tunnel–ventilated broiler houses in central Texas measured between June and December 2000 (circles = data collected from June to August; triangles = data collected from December).

resulted in PM_{10} and NH_3 emission factors that represented total emissions over the growth cycle of the bird.

The emission factors in terms of pollutant mass $bird^{-1}$ were used to calculate the total annual emissions from a typical facility. The typical production cycle for the facilities in this study was seven weeks of production followed by two weeks of idle time, which resulted in an average of 5.8 flocks $year^{-1}$. This varied slightly with market demand and processing capacity but represented the overall production goal of the facility. The site used in this study had four identical buildings housing a total of 110,000 birds per flock for a total of 638,000 birds per year.

Results and Discussion

The building temperature and relative humidity ranges for the data in this study are shown in figures 5 and 6, respectively. The maximum and minimum exterior ambient temperatures are also shown on figure 5 to give an indication of the temperature control afforded by the tunnel ventilation.

A multiple regression was performed on the data for PM_{10} and NH_3 as the dependent variables with bird weight (g), interior building temperature (°C), and relative humidity (% RH) as the independent variables. The results of the multiple regression analysis are shown in tables 1 and 2 for PM_{10} and NH_3, respectively. Only the weight of the birds was significant (α = 0.05) for either PM_{10} or NH_3 emissions. Additionally, only the intercept for PM_{10} was significant at α = 0.05 but was not significant at α = 0.01. Note that the intercept value was negative, which would reduce the estimated PM_{10} emissions if used in the equation. Since there should be no emissions when there are no birds in the houses, a linear regression was done for PM_{10} and NH_3 emission rates versus bird weight, where the intercept of each was forced through the origin. The goodness of fit as indicated by the R^2 values for the simple linear equations were comparable to the R^2 values for the multiple regressions. The linear regression equation for PM_{10} was:

$$PM_{10} = 2.574 \times 10^{-5} W$$
$$R^2 = 0.7868 \quad (1)$$

where PM_{10} is the emission rate (g $bird^{-1}$ day^{-1}), and W is the weight of the bird (g). For NH_3, the linear regression equation was:

$$NH_3 = 6.138 \times 10^{-4} W$$
$$R^2 = 0.7317 \quad (2)$$

where NH_3 is the ammonia emission rate (g $bird^{-1}$ day^{-1}). The regression lines are shown on figures 3 and 4 for PM_{10} and NH_3, respectively. Second–order linear, power law, and exponential regressions were also evaluated but did not fit the data any better than the first–order linear function.

PM_{10} Emission Factor and Emission Inventory

In this study, the average bird weight over the 7–week production cycle was estimated to be 1.03 kg based on the known market weight and broiler growth equations. The average PM_{10} emission rate was calculated from equation 1 to be 26.5 mg day^{-1} $bird^{-1}$. Thus, over the 49–day growth cycle, the PM_{10} emission factor for broilers was 1.3 g PM_{10} $bird^{-1}$. For an average production of 5.8 flocks $year^{-1}$ (a total of 638,000 birds), the emission inventory for PM_{10} from this 4–house facility was 828.2 kg PM_{10} $year^{-1}$. This is well under the 100 tons per year reporting requirement established by the U.S. Federal Clean Air Act.

No PM emission factors for broilers on litter were found in the literature. Table 3 shows PM emission rate data

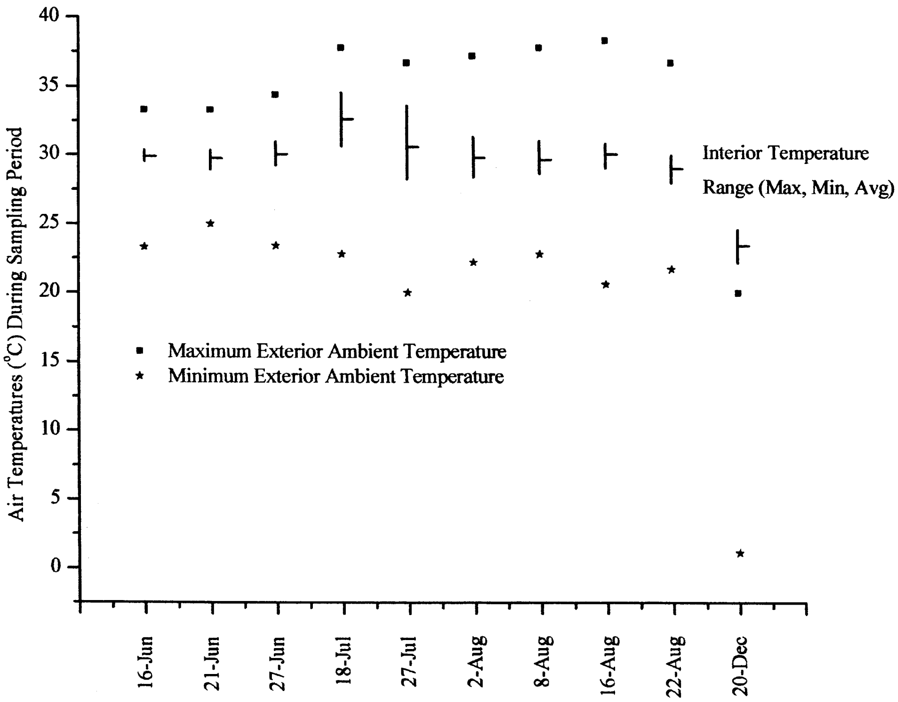

Figure 5. Mean temperature and temperature range in the buildings during data collection of total suspended particulates and ammonia concentrations from four commercial tunnel–ventilated broiler houses in central Texas sampled between June and December, 2000.

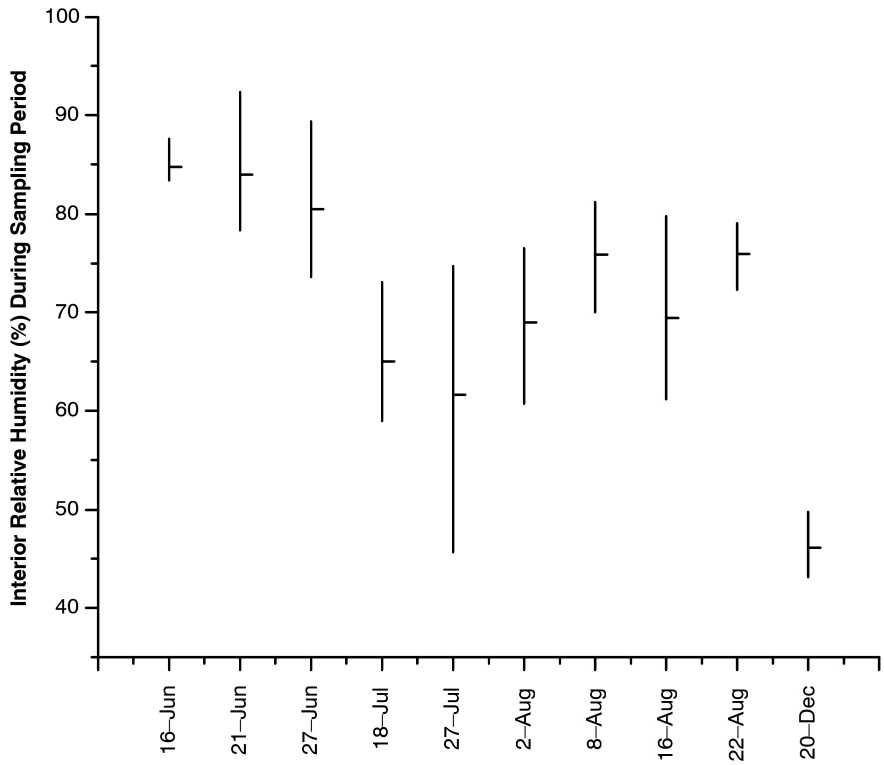

Figure 6. Mean relative humidity and relative humidity range in the buildings during data collection of total suspended particulates and ammonia concentrations from four commercial tunnel–ventilated broiler houses in central Texas sampled between June and December, 2000.

reported in the literature for broilers on litter. The PM_{10} emission rate in this study was converted to 536 mg h^{-1} 500 kg^{-1} live weight for an average–weight bird. Note that the methodology and terminology common in European studies for particulate matter do not readily translate to USEPA requirements as stated in 40CFR50 (Federal Register, 2001). Both the Institute of Occupational Medicine (IOM) and the cyclone samplers (SKC Ltd., Blandford Forum, U.K.) used in the European studies were originally designed for personal monitoring and have been adapted to measurements in broiler houses and other agricultural structures.

Table 1. Multiple regression analysis of PM_{10} for bird mass (g) and interior building temperature (°C).

Parameter	Value	Error	t–Value	Prob > | t |
Y–intercept	–0.03347	0.01542	–2.1712	0.03264
Weight	3.08013E–5	1.84205E–6	16.72126	<0.0001
RH	–6.90517E–5	1.12499E–4	–0.6138	0.54095
Temp.	0.00102	5.22249E–4	1.96004	0.05319
R^2 = 0.7966				
Adj. R^2 = 0.78959				
RMSE = 0.01041				

ANOVA table:

Item	Degrees of Freedom	Sum of Squares	Mean Square	F Statistic
Model	3	0.03695	0.01232	113.57662
Error	87	0.00943	1.08448E–4	
Total	90	0.04639		
Prob > F: <0.0001				

Table 2. Multiple linear regression results of NH_3 for bird weight (g), interior building temperature (°C), and interior relative humidity (%).

Parameter	Value	Error	t–Value	Prob > | t |
Y–intercept	0.21904	0.40197	0.54492	0.58702
Weight	6.61909E–4	4.87011E–5	13.59124	<0.0001
RH	–0.00276	0.00276	–0.99894	0.32024
Temp.	–0.00326	0.01296	–0.25186	0.80166
R^2 = 0.73517				
Adj. R^2 = 0.72722				
RMSE = 0.27655				

ANOVA table:

Item	Degrees of Freedom	Sum of Squares	Mean Square	F Statistic
Model	3	21.23014	7.07671	92.53138
Error	100	7.64791	0.07648	
Total	103	28.87805		
Prob > F: <0.0001				

Table 3. Particulate matter emission rates (mg h^{-1} 500 kg^{-1} live weight) reported in the literature and from this study for broilers on litter.

	Emission Rate (mg h^{-1} 500 kg^{-1} live weight)				
Reference	Inhalable Particulate Matter[a]	Respirable Particulate Matter[b]	TSP	$PM_{10[c]}$	Notes
Wathes et al. (1997)	5000	600			Reported for winter conditions in U.K.
	8500	850			Reported for summer conditions in U.K.
Takai et al. (1998)	6218	706			Data from U.K.[d]
	4984	725			Data from The Netherlands[d]
	1856	245			Data from Denmark[d]
	2805	394			Data from Germany[d]
This study			10,210	536	Data from southern U.S. Based on an emission factor for an average bird weight of 1.03 kg and 7– week growth cycle.

[a] Determined by IOM (Institute of Occupational Medicine, Edinburgh, U.K.) dust samplers.
[b] Determined by cyclone dust samplers (SKC Ltd., Blandford Forum, U.K.).
[c] Calculated from measured TSP and measured particle size distribution for actual PM less than or equal 10 μm aerodynamic equivalent diameter.
[d] Details on building ventilation are given in Seedorf et al. (1998a). Details on building temperature and humidity are given in Seedorf et al. (1998b).

The IOM sampler results are reported as inhalable PM, which is defined as the percentage of airborne particles of aerodynamic equivalent diameter (AED) given by a log–normal distribution (ISO 7708, 1995) with a median diameter of 100 μm. The median diameter is often referred to as the sampler cut–point, which means that 50% of the particles with an AED of 100 μm would be captured by the IOM sampler. The TSP sampler used in this study had a nominal cut–point ranging from 25 to 50 μm AED depending on the ambient wind speed (Federal Register, 2001). The TSP sampler cut–point increased with decreased air velocity. The maximum air velocity during sampling for this study was less than 60% of that used to define the sampler cut–point (Wedding et al., 1977). Therefore, the sampler cut–point was close to 50 μm. The mass median diameter (MMD) of the PM collected from the broiler houses averaged 26.1 μm, which meant that almost all of the PM was captured on the sampler filter and would also have been captured by a sampler with a larger cut–point of 100 μm (i.e., the IOM sampler). Therefore, the TSP emissions reported for this study are comparable with the inhalable emissions reported in the literature. Comparison of the TSP results to the inhalable PM values shown in table 3 shows that the PM emissions from a tunnel–ventilated broiler house in the southern U.S. could be as much as five times greater than from different buildings in cooler climates. This was not surprising considering the high ventilation velocities seen during tunnel ventilation.

Cyclone sampler results are reported in the literature as respirable PM, where respirable PM for a target population of healthy adults is defined as the percentage given by a cumulative log–normal distribution with a median diameter of 4.5 μm and a geometric standard deviation (GSD) of 1.5 (ISO 7708, 1995). The PM_{10} emissions reported in this study are comparable to those in the literature for respirable PM (table 3), although the difference between a cut–point of 10 μm and 4.5 μm would suggest that the PM_{10} emission rate be greater since the TSP emission rate is greater than the inhalable emission rates.

There is a possibility that the data in the literature overestimated the amount of respirable PM. Aerosol samplers that utilize a preseparator to obtain fractional PM concentration have been shown to over–sample in environments where the PSD is greater than the values specified in the preseparator design (Buser et al., 2002). For example, if the PM in this study, which had a MMD of approximately 26 μm and a GSD of 1.6, were sampled using a cyclone sampler operated at a cut–point of 5 μm with a slope of 1.5, then the measured PM_5 (respirable fraction) would exceed the true PM_5 by a factor of 12.9. The cyclone sampler cut–point has been shown to vary from 4.5 to 5 μm with the volumetric rate of airflow through the sampler (Harper et al., 1998). The PSD of the PM and the performance characteristics of the sampler can be used to correct the fractional PM data to accurate values for the concentration in the ambient air after Buser et al. (2002). However, these data were not reported for the studies cited in table 3.

It should also be noted that the data for these results were only for tunnel ventilation, which generates high air velocity in the buildings. However, during the brooding period, typically the first two to three weeks, tunnel ventilation is seldom used. The ventilation methods used during brooding, usually either natural ventilation or smaller sidewall fans, do not produce the higher air velocities and subsequently should not produce as much PM to exhaust. Thus, the PM_{10} emission factor based solely on data from tunnel ventilation is a conservative estimate, and the actual emissions will be less.

NH_3 Emission Factor and Emission Inventory

The average NH_3 emission rate was estimated from equation 2 to be 632 mg day^{-1} bird^{-1} for an average bird weight of 1.03 kg. Over a 49–day production cycle, the NH_3 emission factor was 31 g bird^{-1}. Based on the management parameters and facility size given earlier, the NH_3 emission inventory for this facility was 19,780 kg NH_3 year^{-1}.

There have been several reported emission factors for NH_3 from broilers on litter, as shown in table 4. Elwinger and Svensson (1996) used a flux measurement method (approach 3a in Phillips et al., 2000) to estimate an NH_3 emission factor of 0.03 kg bird^{-1}. Misselbrook et al. (2000) and Hutchings et al. (2001) used a mass balance of N (approach 1 in Phillips et al., 2000) to determine emission factors for NH_3 from broilers on litter. However, the units in several of these studies are confusing. The emission factors in Battye et al. (1994), Van der Hoek (1998), Misselbrook et al. (2000), and Hutchings et al. (2001) are in units of mass of NH_3 animal^{-1} year^{-1}. Since the growth cycle in the broiler industry is much less than one year (typically 46 to 54 days), it is not clear if these values represent a single bird or a series of birds that would be produced during a year. While either set of units can be correct, it is the opinion of the authors of this study that units of kg NH_3 bird^{-1} are less ambiguous. When annualized units are used (i.e., kg NH_3 bird^{-1} year^{-1}), information regarding the grow–out cycle should be given to allow the reader to utilize the reported values accurately.

For the mass balance approach, the total N excreted by the bird was given as 0.8 kg N bird^{-1} year^{-1} by Misselbrook et al. (2000) and as 0.5 kg N bird^{-1} year^{-1} by Hutchings et al. (2001). Hutchings et al. (2001) also reported total N production of 51.3 g N bird^{-1} (table 1 in Hutchings et al., 2001). This would imply a grow–out cycle of 5.4 weeks, assuming no idle time between the flocks (500 g N bird^{-1} year^{-1} divided by 51.3 g N bird^{-1} yields 9.75 year^{-1}, or 5.4 weeks for each flock). This is less than the typical grow–out cycle in the U.S. of 6 to 7 weeks. ASAE Standard D384.1 (*ASAE Standards*, 1999) reported the total amount of N excreted by a broiler as 1.1 kg 1000 kg^{-1} live animal mass day^{-1}. For an average bird of 1.03 kg, the total nitrogen excreted per bird over the 49–day growth cycle was calculated to be 55.5 g N bird^{-1}. Collins et al. (1999) reported data for total nitrogen from broilers that were used to calculate a production of 51.1 g N bird^{-1} over a 49–day cycle. For the 7–week grow–out plus a 2–week idle period between flocks, the annualized N excreted should be approximately 298 to 322 g N bird^{-1} year^{-1}, based on the values from Collins et al. (1999) or ASAE Standard D384.1.

Ammonia volatilizes from inorganic urea, and for poultry, urea is an intermediate product of degradation of organic uric acid from the urine and undigested proteins. To determine the amount of ammonia volatilization from poultry manure, the distribution between degraded urea N (i.e., inorganic N) and organic N is needed. The fraction of nitrogen (N) converted to NH_3 used by Misselbrook et al. (2000) was 24% and by Hutchings et al. (2001) was 40%. De Boer et al. (2000) estimated that 33.6% of the nitrogen excreted in all poultry manure in The Netherlands in 1990 was volatilized as ammonia.

There appears to be no single value in the literature that is widely accepted for the fraction of N converted to NH_3 for broilers. However, the fundamental principle of conservation of mass limits the amount of NH_3–N emitted from all locations and sources at a broiler operation to be less than or equal to the total amount of N. Thus, the figure of 0.055 kg N bird^{-1} derived from ASAE (*ASAE Standards*, 1999) or Collins et al. (1999) would represent an absolute maximum possible NH_3 release of 0.067 kg bird^{-1}, adjusted by a factor of 17/14 to account for the difference in molecular weight. If the fraction of N converted to NH_3 were 50%, then a

Table 4. Ammonia emission factors reported in the literature and from this study for broilers on litter.

Reference	Emission Factor[a]	Methodology Used to Determine the Emission Factor
Asman (1992) in Battye et al. (1994)	0.06 kg animal^{-1} year^{-1} from housing and manure storage, 0.10 kg animal^{-1} year^{-1} from land application of litter.	Not reported.
Elwinger and Svensson (1996)	0.03 kg bird^{-1} from housing.	Flux measurements. Follows approach 3a as outlined in Phillips et al. (2000).
Van der Hoek (1998)	0.15 kg animal^{-1} year^{-1} from housing, 0.02 kg animal^{-1} year^{-1} from storage, 0.11 kg animal^{-1} year^{-1} from land application.	Conversion of total nitrogen excreted. Follows approach 1 as outlined in Phillips et al. (2000).
Misselbrook et al. (2000)[a]	Calculated as 0.19 kg animal^{-1} year^{-1} from values for N excretion and NH_3–N emission (table 3 of Misselbrook et al., 2000).	Conversion of total nitrogen excreted. Follows approach 1 as outlined in Phillips et al. (2000).
Hutchings et al. (2001)[a]	Calculated as 0.2 kg animal^{-1} year^{-1} from values for N excretion and NH_3–N emission (table 7 of Hutchings et al., 2001).	Conversion of total nitrogen excreted. Follows approach 1 as outlined in Phillips et al. (2000).
This study	0.03 kg bird^{-1} from housing.	Flux measurements. Follows approach 3a as outlined in Phillips et al. (2000).

[a] Some results were rounded to two decimal places and/or converted from other units.

conservative estimate of NH_3 emissions would be 0.034 kg bird^{-1}, which is consistent with the results from this study.

Battye et al. (1994) presented data from a number of different sources and proposed an NH_3 emission factor based on these data. They referred to a 1985 emission factor from the National Acid Protection Assessment Program (NAPAP) of 0.02 kg bird^{-1} for broilers, although they discounted this value as having the lowest possible quality rating. They also cited work by Asman (1992) that presented an emission factor of 0.065 kg bird^{-1} year $^{-1}$ from housing and 0.102 kg bird^{-1} year^{-1} from land application of litter. Unfortunately, the basis for these values rested on prior work that was not readily accessible. Quoting from Battye et al. (1994):

"The inventory developed by Asman (1992) and the NH_3 emission factors published by van der Most (1992) reference the research results of De Winkel (1988) and Van der Hoek (1991). Unfortunately, the work of De Winkel (1988) is published only in Dutch and appears to be a primary reference in terms of describing the research methods and the actual derivation of the emission factors."

Battye et al. (1994) also cited a review by Lee and Dollard (1994) that compared ammonia emission factors from six other studies, including an earlier study by Asman that quoted a larger emission factor than the 1992 report. Battye et al. (1992) concurred with the Asman (1992) values and recommended a total emission factor for broilers of 0.167 kg bird^{-1} year^{-1}, although the basis as to how they reached that conclusion were not discussed.

Emission rates of NH_3 for broilers as reported in the literature are summarized in table 5. For comparison, the NH_3 emission factor of 31 g bird^{-1} determined in this study was converted to 26.3 mg NH_3 hour^{-1} bird^{-1} or 12.8 g NH_3 500 kg^{-1} live weight hour^{-1} based on an average bird weight of 1.03 kg bird^{-1} and a market cycle of 49 days. These values are larger than reported from the European studies noted in table 5. The warmer climate in Texas versus the northern European locations cited in the literature and the subsequently higher ventilation rates would promote increased NH_3 emissions. There may also be differences in bird weights that account for the greater NH_3 emissions. The study by Groot Koerkamp et al. (1998) reported values for broiler chickens in two sets of units, as noted in table 5. The data reported in mg h^{-1} bird^{-1} were divided by the data in g h^{-1} 500 kg^{-1} live weight, with appropriate unit conversion, which resulted in estimated bird weights that ranged from 0.50 to 0.84 kg. These are smaller that the 1.03 kg bird^{-1} average weight used in this study. Lastly, the litter management used in the European studies was not detailed. The litter in this study served as manure absorbance for each flock and long–term manure storage between flocks. If litter were removed more frequently in the European operations, then additional NH_3 emissions may occur elsewhere.

The use of tunnel ventilation data was considered to be less of a source of error in estimating NH_3 emissions. A number of factors previously discussed control the conversion of N to NH_3, but air velocity was not a concern. None of the data used includes birds under 18 days old, but these emissions were extrapolated from the regression equation. There is a possibility that differences exist in N excretion and NH_3 conversion between brooding chicks and young broilers, but that source of error was considered to be negligible. Lower interior temperatures that occur during the winter months may also reduce NH_3 emissions by slowing the microbial conversion of the uric acid. Since all the NH_3 data were from warmer conditions, they were considered to represent an upper boundary, making the emission factor from this study a conservative estimate.

Conclusions

Emission data for PM_{10} and NH_3 from tunnel–ventilated commercial broiler houses in central Texas were analyzed using multiple linear regressions to develop emission factors for PM_{10} and NH_3 defined in terms of mass bird^{-1}. The facility was typical of newer operations in the region and housed a total of 638,000 birds year^{-1} on litter. The buildings were cooled by mechanical ventilation operated in a tunnel mode. The methodology used in this article considered the effect of the weight of the birds on the emission factors. Interior temperature and relative humidity were not found to be significant factors for this data.

The average PM_{10} emission rate was 26.5 mg PM_{10} bird^{-1} day^{-1}, and the emission factor was 1.3 g PM_{10} bird^{-1}. Evaluation of these results against the data on PM emissions in the literature found that these values agreed with the previous work when comparing the TSP emission rate with inhalable PM emission rates. The PM_{10} emission rate was comparable to reported respirable PM emissions, although it would be expected to be higher because of the differences in

Table 5. Ammonia emission rates (g h^{-1} 500 kg^{-1} live weight) reported in the literature and from this study for broilers on litter.

Reference	Emission Rate[a] (g h^{-1} 500 kg^{-1} live weight)	Emission Rate (mg h^{-1} bird^{-1})	Estimated Average Bird Weight (kg)	Notes
Sneath et al. (1996)	7.4			Stocking density was 20.8 to 23.4 birds m^{-2}
Wathes et al. (1997)	8.5			Stocking density was 20.8 to 23.4 birds m^{-2}
Groot Koerkamp et al. (1998)	8.3	19.8	0.84	Data from U.K.
	4.2	11.2	0.75	Data from The Netherlands
	2.2	8.9	0.50	Data from Denmark
	7.5	18.5	0.81	Data from Germany
Demmers et al. (1999)	1.9			
Misselbrook et al. (2000)	6.2			
Hyde et al. (2003)	6.2			Data from Ireland
This study	12.8	26.3	1.03	Data from U.S.; stocking density was 13.5 birds m^{-2}

[a] In some cases, the units were converted from a different time base, e.g., day^{-1} or year^{-1}.

the defined cut–points (10 μm versus 4.5 μm). This was attributed to over–sampling by the PM preseparator used in the respirable PM sampler. The emissions inventory for PM_{10} from this facility was 828.2 kg PM_{10} $year^{-1}$. Annual emissions for PM_{10} would not be sufficient to classify these facilities as a major source in Texas under current law.

The average NH_3 emission rate was 632 mg NH_3 $bird^{-1}$ day^{-1}, and the emission factor was 31 g NH_3 $bird^{-1}$, which was consistent with one other published NH_3 emission factor. Other published NH_3 emission factors were based on annualized units (i.e., kg NH_3 $animal^{-1}$ $year^{-1}$), but data regarding management practices were not provided, so no comparison could be made. The NH_3 emission rate found in this study was larger than the reported NH_3 rate from the Elwinger and Svensson (1996) study, although given the climate differences, this was not unexpected. The NH_3 emission inventory from the facility in this study was 19,780 kg NH_3 $year^{-1}$. There is currently no regulatory basis for ammonia in the U.S. Federal Clean Air Act.

Both the PM_{10} and NH_3 emission factors determined in this study were conservative. That is, they were developed from data for tunnel–ventilated buildings during warmer weather and should represent an upper bound on the emissions from the facility. At the higher temperatures, higher ventilation rates were used, and thus greater concentrations of PM_{10} would be expected from the increased air velocities in the buildings. In addition, at the higher temperatures, increased microbial activity in the litter would be expected, converting more uric acid to NH_3. No data from the brooding period were included, when the birds were small and ventilation rates lower, or from cooler weather, when ventilation rates were lower. While temperature was not found to be a significant factor in this study, the daily temperatures, except for one, were from the upper end of the expected range. Emission factors that include these periods of reduced ventilation and temperature would be expected to be less than those presented here.

Acknowledgements

The authors would like to express appreciation for the cooperation of Sanderson Farms and Parks Poultry in collecting the data used in this study. Funding was provided by a grant from the Texas State Legislature for a research initiative into agricultural air quality. Additional funding was from a contract with the Texas Natural Resource Conservation Commission for a study of odor and arsenic emissions from poultry growing operations.

References

Aneja, V. P., P. A. Roelle, G. C. Murray, J. Southerland, J. W. Erisman, D. Fowler, W. A. H. Asman, and N. Patni. 2001. Atmospheric nitrogen compounds II: Emissions, transport, transformation, deposition and assessment. *Atmospheric Environment* 35(11): 1903–1911.

ApSimon, H. M., S. Couling, D. Cowell, and R. F. Warren. 1995. Reducing the contribution of ammonia to nitrogen deposition across Europe. *Water Air and Soil Pollution* 85(4): 1891–1896.

ASAE Standards. 1999. D384.1: Manure production and characteristics. St. Joseph, Mich.: ASAE.

Asman, V. A. H. 1992. Ammonia emissions in Europe: Updated emission and emission variations. Bilthoven, The Netherlands: National Institute of Public Health and Environmental Protection.

Barthelmie, R. J., and S. C. Pryor. 1998. Implications of ammonia emissions for fine aerosol formation and visibility impairment – A case study from the lower Fraser valley, British Columbia. *Atmospheric Environment* 32(3): 345–352.

Battye, R., W. Battye, C. Overcash, and S. Fudge. 1994. Development and selection of ammonia emission factors. Durham, N.C.: EC/R, Inc.

Buser, M. D., C. B. Parnell Jr., R. E. Lacey, and B. W. Shaw. 2002. PM_{10} sampler errors due to the interaction of particle size and sampler performance characteristics. Atlanta, Ga.: Beltwide Cotton Conference.

Carey, J. B., R. E. Lacey, and S. Mukhtar. 2000. Study of odors and arsenic emissions from poultry growing operations. Contract 582–0–81252. College Station, Texas: Texas A&M University.

Carlile, F. S. 1984. Ammonia in poultry houses: A literature review. *World's Poultry Science J*. 40: 99–113.

Collins Jr., E. R., J. C. Barker, L. E. Carr, H. L. Brodie, and J. H. Martin Jr. 1999. Poultry waste management handbook. Ithaca, N.Y.: Natural Resource, Agriculture, and Engineering Service.

De Boer, I. J. M., P. L. Van Der Togt, M. Grossman, and R. P. Kwakkel. 2000. Nutrient flows for poultry production in The Netherlands. *Poultry Science* 79(2): 172–179.

De Winkel, K. 1988. Ammoniak–emissiefactoren voor de veehouderij (Emission factors for ammonia from livestock). Leidschendam, The Netherlands: Ministry of Housing, Physical Planning, and the Environment.

Demmers, T. G. M., L. R. Burgess, J. L. Short, V. R. Phillips, J. A. Clark, and C. M. Wathes. 1999. Ammonia emissions from two mechanically ventilated U.K. livestock buildings. *Atmospheric Environment* 33(2): 217–227.

Elliott, H. A., and N. E. Collins. 1982. Factors affecting ammonia release in broiler houses. *Trans. ASAE* 25(2): 413–424.

Elwinger, K., and L. Svensson. 1996. Effect of dietary protein content, litter and drinker type on ammonia emission from broiler houses. *J. Agric. Eng. Research* 64(3): 197–208.

EPA. 1995. Compilation of air pollutant emission factors, AP–42, 5th ed., vol. I: Stationary point and area sources. Research Triangle Park, N.C.: U.S. Environmental Protection Agency.

EPA. 2000. Supplements to the compilation of air pollutant emission factors AP–42, 5th ed., vol. I: Stationary point and area sources. Research Triangle Park, N.C.: U.S. Environmental Protection Agency.

Federal Register. 2001. Code of federal regulations. Title 40: Protection of environment. Part 50: National primary and secondary ambient air quality standards. Washington, D.C.: General Services Administration, National Archives and Records Service, Office of the Federal Register.

Flood, C. A., J. L. Koon, R. D. Trumbull, and R. N. Brewer. 1992. Broiler growth data: 1986–1991. *Trans. ASAE* 35(2): 703–709.

Groot Koerkamp, P. W. G., J. H. M. Metz, G. H. Uenk, V. R. Phillips, M. R. Holden, R. W. Sneath, J. L. Short, R. P. White, J. Hartung, J. Seedorf, M. Schroder, K. H. Linkert, S. Pederson, H. Takai, J. O. Johnsen, and C. M. Wathes. 1998. Concentrations and emissions of ammonia in livestock buildings in northern Europe. *J. Agric. Eng. Research* 70(1): 79–95.

Grubb, W., C. A. Rollo, and J. R. Howes. 1965. Dust problems in poultry environments. *Trans. ASAE* 8(5): 338–339.

Harper, M., C.–P. Fang, D. L. Bartley, and B. S. Cohen. 1998. Calibration of the SKC, Inc., aluminum cyclone for operation in accordance with ISO/CEN/ACGIH respirable aerosol sampling criteria. *J. Aerosol Science* 29(1): 347–348.

Hutchings, N. J., S. G. Sommer, J. M. Andersen, and W. A. H. Asman. 2001. A detailed ammonia emission inventory for Denmark. *Atmospheric Environment* 35(11): 1959–1968.

Hyde, B. P., O. T. Carton, P. O'Toole, and T. H. Misselbrook. 2003. A new inventory of ammonia emissions from Irish agriculture. *Atmospheric Environment* 37(1): 55–62.

ISO 7708. 1995. Air quality – particle size fraction definitions for health–related sampling. Geneva, Switzerland: International Organization for Standardization.

Lee, D. S., and G. J. Dollard. 1994. Uncertainties in current estimates of emissions of ammonia in the United Kingdom. *Environmental Pollution* 86(3): 267–277.

Madelin, T. M., and C. M. Wathes. 1989. Air hygiene in a broiler house – Comparison of deep litter with raised netting floors. *British Poultry Science* 30(1): 23–37.

Misselbrook, T. H., T. J. Van Der Weerden, B. F. Pain, S. C. Jarvis, B. J. Chambers, K. A. Smith, V. R. Phillips, and T. G. M. Demmers. 2000. Ammonia emission factors for UK agriculture. *Atmospheric Environment* 34(6): 871–880.

Phillips, V. R., R. Scholtens, D. S. Lee, J. A. Garland, and R. W. Sneath. 2000. A review of methods for measuring emission rates of ammonia from livestock buildings and slurry or manure stores, part 1: Assessment of basic approaches. *J. Agric. Eng. Research* 77(4): 355–364.

Redwine, J. S. 2001. Emission factors for ammonia and particulate matter from broiler houses. MS thesis. College Station, Texas: Texas A&M University, Department of Biological and Agricultural Engineering.

Redwine, J. S., R. E. Lacey, S. Mukhtar, and J. B. Carey. 2002. Concentration and emissions of ammonia and particulate matter in tunnel–ventilated broiler houses under summer conditions in Texas. *Trans. ASAE* 45(4): 1101–1109.

Seedorf, J., H. J., M. Schroder, K. H. Linkert, P. S., H. Takai, J. O. Johnsen, J. H. M. Metz, P. W. G. Groot Koerkamp, G. H. Uenk, V. R. Phillips, M. R. Holden, R. W. Sneath, J. L. Short, R. P. White, and C. W. Wathes. 1998a. A survey of ventilation rates in livestock buildings in northern Europe. *J. Agric. Eng. Research* 70(1): 39–47.

Seedorf, J., H. J., M. Schroder, K. H. Linkert, P. S., H. Takai, J. O. Johnsen, J. H. M. Metz, P. W. G. Groot Koerkamp, G. H. Uenk, V. R. Phillips, M. R. Holden, R. W. Sneath, J. L. Short, R. P. White, and C. W. Wathes. 1998b. Temperature and moisture conditions in livestock buildings in northern Europe. *J. Agric. Eng. Research* 70(1): 49–57.

Sneath, R. W., M. R. Holden, V. R. Phillips, R. P. White, and C. M. Wathes. 1996. An inventory of emissions of aerial pollutants from poultry buildings in the UK. In *Proc. International Conference on Air Pollution from Agricultural Operations*, 207–211. Kansas City, Mo.: MidWest Plan Service.

Takai, H., S. Pederson, J. O. Johnsen, J. H. M. Metz, P. Koerkamp, G. H. Uenk, V. R. Phillips, M. R. Holden, R. W. Sneath, J. L. Short, R. P. White, J. Hartung, J. Seedorf, M. Schroder, K. H. Linkert, and C. M. Wathes. 1998. Concentrations and emissions of airborne dust in livestock buildings in northern Europe. *J. Agric. Eng. Research* 70(1): 59–77.

TNRCC. 2001. How to complete an emissions inventory: 2001 guidelines. Austin, Texas: Texas Natural Resource Conservation Commission.

Van der Hoek, K. W. 1991. Emission factors for ammonia in The Netherlands. Paper presented at the Workshop on Ammonia Emissions in Europe: Emission Factors and Abatement Costs, 4–6 February 1991. Laxenburg, Austria: IIASA.

Van der Hoek, K. W. 1998. Estimating ammonia emission factors in Europe: Summary of the work of the UNECE ammonia expert panel. *Atmospheric Environment* 32(3): 315–316.

van der Most, P. F. J., and C. Veldt. 1992. *Emission Factors Manual: PARCOM–ATMOS Emission Factors for Air Pollutants 1992*. Reference No. 92–235. TNO Environmental and Energy Research. Sponsored by The Netherlands Ministry of Housing, Physical Planning, and the Environment, Air and Energy Directorate, and Ministry of Transport and Water Management.

Wathes, C. M., M. R. Holden, R. W. Sneath, R. P. White, and V. R. Phillips. 1997. Concentrations and emission rates of aerial ammonia, nitrous oxide, methane, carbon dioxide, dust and endotoxin in U.K. broiler and layer houses. *British Poultry Science* 38(1): 14–28.

Wedding, J. B., A. R. McFarland, and J. E. Cermak. 1977. Large particle collection characteristics of ambient aerosol samplers. *Environ. Science and Tech.* 11(4): 387–390.