ESTIMATING VENTILATION RATES OF ANIMAL HOUSES THROUGH CO_2 BALANCE

Z. Liu, W. Powers, J. D. Harmon

ABSTRACT. *The CO_2 production rates from various animal species were measured as well as the ventilation rates (VR) in environmental rooms at Michigan State University over the course of 15 studies that considered dietary strategies to alter air emissions, including two dairy cow studies, four steer studies, two swine studies, one turkey study, four laying hen studies, and two broiler chicken studies. The objectives of this article are to summarize the baseline data on CO_2 production from various animal species and determine uncertainties of the CO_2 balance approach for estimating VR of animal houses by evaluating the model performance in these studies. In the poultry (broiler, laying hen, and turkey) and dairy studies, the CO_2 production rates per heat production of animals or respiratory quotient (RQ) showed a decreasing trend with increasing animal age or days in milk (DIM). Higher variation in CO_2 production rates per heat production of animals were observed in young broiler chicken (<3 weeks) and turkeys (<10 weeks) and in the dairy cow studies. The modeled and measured CO_2 production rates were generally comparable with each other for each species, and the standard deviation of model residuals was about 20% to 30% of the average measured CO_2 production rate for each species except dairy cows. By only including data in which the differences between exhaust and inlet CO_2 concentrations were larger than 50 ppm, the standard deviations of model residuals were less than 32% of the average measured VR in the broiler, laying hen, swine, and steer studies. Based on the results, when using the CO_2 balance approach to estimate VR for broiler, laying hen, swine, and steer operations, a minimum of ten replicate measurements is required to achieve a margin of error less than 20% in modeled VR with 95% confidence.*

Keywords. *Emission, Heat production, Metabolic rate, Respiratory quotient, Ventilation rate.*

Affordable and reliable means to estimate ventilation rates (VR) of animal house is desirable for quantifying air emissions from animal operations. Traditional methods using fans or nozzles installed in the outlets of the animal house are expensive, time-consuming, and are to some extent limited to mechanically ventilated animal houses (Pedersen et al., 2008). Various alternative methods have been proposed. Pedersen et al. (1998) compared three approaches for the calculation of VR based on the balances of animal heat, moisture, and CO_2, and they concluded that only the CO_2 balance approach is recommended for uninsulated buildings because of the difficulties in estimating the heat transmission loss from the building and in correcting for the water that evaporates from feed and wet surfaces. A sophisticated and expensive radioactive tracer gas technique has been investigated, and a good linear correlation has been reported between the results of the tracer gas technique and the CO_2 balance approach in a dairy barn (Samer et al., 2011). The CO_2 balance approach has been identified as a potential affordable alternative method to estimate VR of animal houses (Li et al., 2005; Xin et al., 2009), and it could be a viable method, especially for naturally ventilated livestock buildings, as no reliable and affordable method is currently available. However, the uncertainty of the approach is still not well understood. The CO_2 balance approach estimates VR based on the metabolic rate of animals (Van Ouwerkerk and Pedersen, 1994). The reliability of the CO_2 balance approach depends on the accuracy of the metabolic rate data of the animals and the amount of CO_2 that is not accounted for by metabolic CO_2 production, all of which requires further investigation, refinement, and validation.

The CO_2 production rates from various animal species were measured as well as VR in environmental rooms at Michigan State University over the course of 15 studies. Although some of the studies have been published on topics of various dietary strategies to alter air emissions, the CO_2 production data in these studies have never been synthesized and published. The objectives of this article are to: (1) to summarize baseline data on CO_2 production rates from various animal species in these 15 studies and (2) to determine uncertainties of the CO_2 balance approach for estimating VR of animal houses by evaluating the model performance in these studies.

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The authors are **Zifei Liu, ASABE Member,** Assistant Professor, Department of Biological and Agricultural Engineering, Kansas State University, Manhattan, Kansas; **Wendy Powers, ASABE Member,** Professor, Department of Animal Science, Michigan State University, East Lansing, Michigan; **Jay D. Harmon, ASABE Fellow,** Professor, Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, Iowa. **Corresponding author:** Zifei Liu, 154 Seaton Hall, Kansas State University, Manhattan, KS 66506; phone: 785-532-3587; email: zifeiliu@ksu.edu.

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METHODS

ANIMALS, DIETS, AND MANURE

Animals were housed and monitored in environmentally controlled rooms (H 2.60 m × W 2.37 m × L 4.11 m) in the Animal Air Quality Research Facility at Michigan State University, East Lansing, Michigan. Each room can accommodate one steer, one lactating cow, six finishing pigs, 20 turkeys, 50 broiler chickens, or up to 80 laying hens. In each study, animals from one of the species were raised in 12 rooms and fed 3 or 4 different diets (4 or 3 reps per diet). The animals were confined in a raised-deck pen. Galvanized steel manure collection pans (3.05 m × 1.52 m × 20.0 cm) were placed underneath the floor of each pen to collect urine, feces, wasted feed, and water. Fresh shavings were used as bedding for the broiler and turkey studies. Layers were in cages with no bedding. For the poultry studies, manure and litter were not removed throughout the experiments. In other studies, the manure collection pans were partially cleaned regularly (twice weekly for swine studies; daily for steer and dairy cow studies) to remove some manure and prevent overflow of the pans. Each time manure was removed, the weight of manure was taken, and a homogenous subsample was collected, frozen, and then analyzed separately by day at the end of the study. Manure nitrogen content was determined using the Kjeldahl method (AOAC, 2006). Body weights of animals were recorded at the beginning and end of each study. For the broiler, turkey, and swine studies, animals were weighed weekly. Some of the studies have been published previously on diet's effect on gas emissions (Li and Powers, 2012; Liu et al., 2011, 2012; Li et al., 2011). The species, references, study code, days of operation, animals per room, and applied diets of the 15 studies are presented in table 1.

VENTILATION RATES

Each room was individually heated and cooled using 100% ambient air, with all of the air exhausted to the outside (no recycling). Temperature within the environmental rooms was managed to enhance animal health and productivity. The air temperature in each room was programmed independently and dictated the ventilation rate. Room ventilation rates ranged approximately from 800 to 1100 m^3 h^{-1}, which allowed 32 to 43 air exchanges per hour. Ventilation rates of each room were continuously measured using a 15.24 cm orifice plate in the incoming duct of each room and a differential pressure transducer (model 239, Setra, Boxborough, Mass.). Orifice plates and pressure transducers specific to each room were calibrated in the Bioenvironmental and Structural Systems Laboratory test chamber at the University of Illinois during facility construction; no changes have taken place since construction. Throughout the studies, ventilation rates measured by the orifice plates and pressure transducers were checked against mass flowmeters (AirData Multimeter ADM-860C, Shortridge Instruments, Inc., Scottsdale, Ariz.) that were calibrated annually. The accuracy of the orifice plates and pressure transducers was expected to be on the order of 0.6%. Air temperature and relative humidity (RH) in each room were measured using a temperature and RH probe (CS500, Campbell Scientific, Inc., Logan, Utah) and recorded every 2 s.

AIR EMISSION MEASUREMENTS

Using a software control system (LabVIEW ver. 8.2, National Instruments Corp., Austin, Tex.), gas concentrations were measured in a sequential manner from rooms 1 to 12. Measurement of incoming air was followed by measurements of each of the 12 rooms' exhaust air for 15 min continuously throughout each of the 15 studies. Each measurement cycle through all 12 rooms plus the background air required 195 min to complete (13 × 15 min per room). Therefore, there were seven or eight daily observations per room, as described by Liu et al. (2011). The incoming air line and the rooms' exhaust sampling lines were purged for 9.5 min before the start of each room sampling. Following purging, data were collected for 5.5 min. All gases were measured simultaneously within the sample air stream. The air sample was pulled to a sampling manifold using a vacuum pump (Cole-Parmer, Vernon Hills, Ill.) at a rate of 30 L min^{-1} and then diverted into three gas

Table 1. Species, references, study code, days of operation, animals per room, and applied diets in the 15 studies.

Species and Reference	Study Code	Days of Operation	Animals per Room	Diet
Broiler	BR0108	42	50	A reduced nitrogen content diet compared to a control diet.
	BR0208	42	50	3×2 factorial design: three diets (control, low N, and low N with protease) and two litter amendments (PLT at 0 and 75 need units).
Laying hen	LY0108	37	80	Diets containing 0% or 15% distillers dried grains with solubles (DDGS).
	LY0109	21	55	Diets containing 0%, 10%, or 20% DDGS.
	LY0209	23	55	2×2 factorial design: 0% or 20% DDGS, with organic or inorganic trace minerals.
	LY0309	20	55	An industry control diet, a diet without supplemental methionine, or a blended diet (40% control, 60% no supplemental methionine).
Turkey (Liu et al., 2011)	TY0108	139	12	2×2 factorial design: 100% or 110% of the recommended protein content, and two or three supplemental amino acids.
Swine (Li et al., 2011)	SW0109	98	6	Diets containing 0% or 20% DDGS. The 20% DDGS diet contained either organic or inorganic mineral sources.
	SW0209	27	6	2×2 factorial design: 0% or 20% DDGS, with or without added enzymes.
Steer (Li and Powers, 2012)	ST0109	26	1	Diets containing 0%, 40%, or 60% DDGS.
	ST0209	22	1	Diets containing 0%, 60%, or 60% DDGS plus added copper and molybdenum.
	ST0110	13	1	Diets containing added quillaja extract, yucca extract, or no extract.
	ST0210	13	1	Diets containing added quillaja extract, yucca extract, or no extract.
Dairy cow (Liu et al., 2012)	DY0108	19	1	Diets representing feed ingredients typical of western, midwestern, or southeastern U.S.
	DY0208	22	1	Diets representing feed ingredients typical of western, midwestern, or southeastern U.S.

analyzers: a chemiluminescence analyzer (TEI model 17C, Thermo Fisher, Franklin, Mass.; detection limit (DL) = 0.001 ppm) that determined NH_3, NO, and NO_2 concentrations; a pulsed fluorescence SO_2-H_2S analyzer (TEI model 450i, Thermo Fisher; DL = 0.003 ppm; error = 1% of full scale at 1 ppm); and a photoacoustic analyzer (Innova 1412, Lumasense Technologies, Ballerup, Denmark) that measured CO_2 (DL = 5.1 ppm), CH_4 (DL = 0.1 ppm), NH_3 (DL = 0.2 ppm), and N_2O (DL = 0.03 ppm) concentrations. A diagram of the sampling and measurement system can be found in Liu et al. (2011). Weekly zero and span calibrations were performed on the chemiluminescence and pulsed fluorescence analyzers. The photoacoustic analyzer was calibrated at the beginning and end of each experiment, and weekly span checks were performed. Gas emission rates were calculated as the product of ventilation rates and concentration differences between exhaust and incoming air using the following equation:

$$\mathrm{ER} = Q\frac{293}{T}\times\left(C_e - C_i\right)\times 10^{-6} \quad (1)$$

where ER is CO_2 emission rate at 20°C (L min^{-1}), Q is ventilation rate at room temperature and pressure (L min^{-1}), T is air temperature in the room exhaust air (K), C_e is gas concentration in the room exhaust air (ppm), and C_i is gas concentration in the incoming air (ppm).

ESTIMATING VR USING CO_2 BALANCE APPROACH

It is expected that animal body weights and production levels, i.e., their feed intake, will directly influence their total heat production (CIGR, 2002). Equations to calculate the heat production rate (HP) of animals are presented in table 2. Using an indirect calorimetry relationship, HP can also be determined from O_2 consumption, CO_2 production, CH_4 production, and nitrogen excretion of the animal, as in the following equation (Brouwer, 1965):

$$\mathrm{HP} = 16.18O_2 + 5.02CO_2 - 2.17CH_4 - 5.99N \quad (2)$$

where HP is animal heat production rate at 20°C (W), O_2 is oxygen consumption rate (mL s^{-1}), CO_2 is carbon dioxide production rate (mL s^{-1}), CH_4 is methane production rate (mL s^{-1}), and N is nitrogen excretion rate (mg s^{-1}). By substituting the O_2 consumption with the term CO_2/RQ, equation 2 can be modified as equation 3, in which RQ is respiratory quotient of the animal (ratio of CO_2 production over O_2 consumption). The RQ can be seen as a reflection of the kind of substrate of the feed that is being oxidized (Van Ouwerkerk and Pedersen, 1994). For example, an RQ value is 1.0 for carbohydrates, 0.8 is for proteins, and 0.7 is for fats (Nienaber et al., 2009). The RQ of animals varies theoretically from 0.71 to 1.3 depending on metabolic rate, feed intake, and individual status of the animals (Van Ouwerkerk and Pedersen, 1994; Brouwer, 1957):

$$\mathrm{HP} = (16.18/\mathrm{RQ} + 5.02)CO_2 - 2.17CH_4 - 5.99N \quad (3)$$

Therefore, the CO_2 production rate can be estimated using the following equation:

$$CO_2 = (\mathrm{HP} + 2.17CH_4 + 5.99N) / (16.18/\mathrm{RQ} + 5.02) \quad (4)$$

In this study, the CH_4 production rates were estimated from measured CH_4 emission rates. The nitrogen excretion rates were estimated from measured nitrogen content in manure. Assuming all of the measured CO_2 production is from animals, the VR can be estimated using equation 5 (Xin et al., 2009) from modeled CO_2 production rates (calculated based on eq. 4) and measured differences between exhaust and inlet CO_2 concentrations:

$$\mathrm{VR} = CO_2 / ([CO_2]_e - [CO_2]_i) \quad (5)$$

where VR is the ventilation rate of the animal house (m^3 s^{-1}), and $[CO_2]_e$ and $[CO_2]_i$ are the measured CO_2 concentrations in exhaust and inlet air, respectively (ppm). In our study, daily average CO_2 concentrations were used.

DATA ANALYSIS

The measured CO_2 production rates per heat production of animals for each species were synthesized based on measurements of daily average values of CO_2 concentrations. The RQ were then determined from the average values of the measured CO_2 production rates per heat production of animals for each species using equation 3, assuming that the contributions of the CH_4 and N terms are negligible. The daily average CO_2 production rates were modeled using equation 4 from HP of animals; and then the daily average VR were modeled using the CO_2 balance approach (eq. 5). The overall average values and standard deviations of the CO_2 production rates or VR for each species were estimated respectively on measured or modeled values. Plots of model residuals were checked for model performance, and standard deviations of model residuals were calculated to represent uncertainties of the model for each species. R^2 values were calculated between the measured and modeled CO_2 production rates or VR on a daily basis for each species.

RESULTS

MEASURED CO_2 PRODUCTION RATES AND RESPIRATORY QUOTIENTS

The overall average measured CO_2 production rates with standard deviations were compared with the range of CO_2

Table 2. Equations to calculate heat production of animals (adapted from CIGR, 2002).

Species	Equation[a]
Broiler	$\mathrm{HP} = 10.62m^{0.75}$
Laying hen in cages	$\mathrm{HP} = 6.28m^{0.75} + 25Y_2$, where Y_2 = egg production (normally 0.050 kg d^{-1} for consumer eggs)
Turkey	$\mathrm{HP} = 9.86m^{0.77}$
Swine (fattening pigs)	$\mathrm{HP} = 5.09m^{0.75} + [1 - (0.47 + 0.003m)] \times (n - 1) \times (5.09m^{0.75})$
Steer (beef cattle)	$\mathrm{HP} = 7.64m^{0.69} + Y_2(23/M - 1) \times [(57.27 + 0.302m) / (1 - 0.171Y_2)]$, where Y_2 = daily gain (0.7 to 1.1 kg d^{-1})
Dairy cow	$\mathrm{HP} = 5.6m^{0.75} + 22Y_1 + 1.6 \times 10^{-5}p^3$, where Y_1 = milk production (kg d^{-1})

[a] HP = animal heat production rate (W), m = animal body mass (kg), M = energy content of feed (MJ kg^{-1} dry matter), p = number of days of pregnancy, and n = daily feed energy in relation to maintenance requirement.

production rates reported in the literature for each species (table 3). Because the CO_2 production rates are associated with the heat production of animals, the unit of $m^3\ h^{-1}\ hpu^{-1}$, where 1 hpu is equivalent to 1000 W of total heat production at 20°C, was used for comparison purposes. The CO_2 production rates per heat production of animals are related with RQ through equation 3. The variation of the CO_2 production rates in table 3 could be due to different RQ resulting from different species, different stages of production, or different management practices.

In the poultry (broiler, laying hen, and turkey) and dairy studies, the CO_2 production rates per heat production of animals or RQ showed a decreasing trend with increasing animal age or days in milk (DIM). The results were in agreement with the findings of Pedersen et al. (2008), who stated that RQ will be low if animals are fed close to maintenance, and RQ will increase with higher feed intake. The lower CO_2 production rates or RQ could be related to the reduced feed intake associated with later stages of production. When an average value of RQ was used in modeling CO_2 production for the 139-day turkey study, the model residuals indicated an obvious overestimation when bird ages were high. In order to improve model performance, different RQ values were determined for different ages in the poultry studies and for different DIM in the dairy studies, as shown in table 3. The coefficients of variance of the measured CO_2 production rates in the broiler (>3 weeks), laying hen (>28 weeks), turkey (>10 weeks), swine, and steer studies were approximately 0.17, 0.24, 0.27, 0.18, and 0.24, respectively. Higher variation in CO_2 production rates per heat production of animals were observed in young broiler chicken (<3 weeks) and turkeys (<10 weeks) and in the dairy cow studies.

Comparison of Measured and Modeled VR

The modeled and measured CO_2 production rates were generally comparable with each other for each species (table 4). The standard deviations of model residuals were about 20% to 30% of the average values of measured CO_2 production rates for each species except dairy cows. In the broiler chicken, turkey, and swine studies, both the modeled and measured CO_2 production rates per head increased as body weight increased during the experiments. Strong correlations between the modeled and measured CO_2 production rates were observed in these studies. Nevertheless, in the laying hen, steer, and dairy cow studies, the modeled CO_2 production rates had little variation due to stable body weights during the experiments. Most of the variation in the measured CO_2 production rates in these studies was not captured by the model, although average values of the

Table 3. Measured CO_2 production rates and respiratory quotients (RQ) for each species.

Species	Body Weight of Animal (kg head^{-1})	Age or Days in Milk (DIM)	Measured CO_2 Production Rates ($m^3\ h^{-1}\ hpu^{-1}$)[a]	Coefficient of Variance of Measured CO_2 Production Rates	RQ	Range of CO_2 Production Rates in Literature ($m^3\ h^{-1}\ hpu^{-1}$)	Range of RQ in Literature
Broiler	0.1 to 2.7	Age <3 weeks	0.201 ±0.144	0.71	1.25	0.154 to 0.182[b]	0.89 to 1.10[b]
		Age >3 weeks	0.195 ±0.033	0.17	1.20		
Laying hen	1.36 to 1.47	Age <28 weeks	0.155 ±0.046	0.30	0.88	0.137 to 0.191[c]	0.76 to 1.17[c]
		Age >28 weeks	0.145 ±0.035	0.24	0.82		
Turkey	0.1 to 18.4	Age <10 weeks	0.220 ±0.164	0.75	1.42	-	-
		Age >10 weeks	0.141 ±0.039	0.27	0.79		
Swine	25 to 119	-	0.171 ±0.030	0.18	1.01	0.152 to 0.201[d]	0.86 to 1.25[d]
Steer	262 to 325	-	0.192 ±0.046	0.24	1.18	0.142 to 0.195[e]	0.8 to 1.2[e]
Dairy cow	~600	DIM <200 days	0.180 ±0.119	0.66	1.08	0.174 to 0.181[f]	1.02 to 1.08[f]
		DIM >200 days	0.165 ±0.072	0.44	0.96		

[a] Values are means ± standard deviations.
[b] Pederson et al., 2008; Zheng et al., 2006; Zhao et al., 2001; Pedersen and Thomsen, 2000; Jørgensen et al., 1996b; Jørgensen et al., 1990.
[c] Pederson et al., 2008; Eerden et al., 2006; Li et al., 2005; Parmentier et al., 2002; Mashaly et al., 2000.
[d] Bolhuis et al., 2008; Pederson et al., 2008; Hansen et al., 2007; Jørgensen et al., 2007; Theil et al., 2007; Blanes and Pedersen, 2005; Chwalibog et al., 2004; Sousa and Pedersen, 2004; Wang et al., 2004; Gerrits et al., 2001; Jørgensen et al., 2001; Jørgensen, 1998; Jørgensen et al., 1997; Jørgensen et al., 1996a; Jørgensen et al., 1996c.
[e] Van Ouwerkerk and Pedersen, 1994.
[f] Pederson et al., 2008; Knegsel et al., 2007; Straalen et al., 2007.

Table 4. Comparison of measured and modeled CO_2 production rates.

Species	Age or Days in Milk (DIM)	(1) Measured CO_2 Production Rates (mL s^{-1} head^{-1})[a]	(2) Modeled CO_2 Production Rates (mL s^{-1} head^{-1})[a]	(2)/(1)	(3) Standard Deviation of Residuals (mL s^{-1} head^{-1})	(3)/(1)	R^2 between Measured and Modeled CO_2
Broiler	Age <3 weeks	0.23 ±0.14	0.25 ±0.14	108%	0.09	39%	0.90
	Age >3 weeks	0.88 ±0.26	0.88 ±0.21	100%	0.15	17%	
Laying hen	Age <28 weeks	0.43 ±0.13	0.43 ±0.01	100%	0.13	30%	<0.01
	Age >28 weeks	0.42 ±0.10	0.42 ±0.00	100%	0.10	24%	
Turkey	Age <10 weeks	1.28 ±0.90	1.39 ±0.92	109%	0.46	36%	0.70
	Age >10 weeks	2.89 ±0.55	3.01 ±0.62	104%	0.80	28%	
Swine	-	11.59 ±3.82	11.47 ±2.75	99%	1.95	17%	0.76
Steer	-	25.50 ±6.57	25.54 ±2.28	100%	6.13	24%	0.13
Dairy cow	DIM <200 days	74.52 ±48.9	75.26 ±4.74	101%	49.8	67%	<0.01
	DIM >200 days	70.03 ±30.40	70.30 ±5.58	100%	30.8	44%	

[a] Values are means ± standard deviations.

modeled and measured CO_2 production rates were generally comparable with each other.

The measured and modeled VR using the CO_2 balance approach for each species are compared in table 5. The uncertainties in the measured CO_2 concentrations contributed to the uncertainties in the modeled VR. When the differences in CO_2 concentrations between exhaust and inlet air are not large enough, even small uncertainties in the measured CO_2 concentrations can result in huge errors in modeled VR. Van Ouwerkerk and Pedersen (1994) suggested that there should be a good measureable difference (>200 ppm) in CO_2 concentrations between exhaust and inlet air as a prerequisite for application of the CO_2 balance approach. This prerequisite may put some limitations on the application of the approach. In table 5, various thresholds of differences between exhaust and inlet CO_2 concentrations (0, 50, 100, and 200 ppm) were used to decide the eligibility of data points to be included in the VR modeling. Generally, higher thresholds will result in better model performance. For the broiler, laying hen, swine, and steer studies, by only including data in which the differences between exhaust and inlet CO_2 concentrations were larger than 50 ppm, the standard deviations of model residuals were less than 32% of the average values of measured VR. By increasing the threshold to 100 ppm, the standard deviations of model residuals were reduced to less than 21% of the average values of measured VR. However, if the threshold is increased to a point at which the number of eligible data points is significantly reduced (e.g., less than 80% of the total number of data points), the model performance will also be reduced, and the model will tend to underestimate VR because the remaining data points are no longer representative. Based on the results, a threshold of 50 ppm can be used with understanding of the associated uncertainties, and the threshold can be increased for better model performance as long as the number of data points is still considered representative. Relatively high R^2 values were observed in the broiler and turkey studies because of the relatively high variation of VR due to the wide ranges of bird age in these studies. In other studies, the R^2 values for correlations between the measured and modeled VR were low, mainly due to low day-to-day variation of VR.

UNCERTAINTY ANALYSIS

The uncertainties in the modeled VR arise from the uncertainties in the modeled CO_2 production rates, which include two parts. The first part is due to uncertainties in the RQ used. The RQ of animals varies theoretically from 0.71 to 1.3. The modeled CO_2 production rates increase with increasing RQ. According to equation 4, a 10% error in RQ values used in the model can result in approximately 7% error in the modeled CO_2 production rates. The second part is due to the variation in CO_2 production rates that is not captured by the RQ in the model. This was measured by the coefficients of variance of the measured CO_2 production rates, which were between 0.17 and 0.27 in the broiler (>3 weeks), laying hen (>28 weeks), turkey (>10 weeks), swine, and steer studies but can be much higher in the broiler (<3 weeks), turkey (<10 weeks), and dairy cow studies (table 3).

The uncertainties in the measured differences in CO_2 concentrations between exhaust and inlet air also contribute to the uncertainties in the modeled VR. When the measured differences in CO_2 concentrations are around 50 ppm, a 1% error of a single CO_2 concentration measurement around 500 ppm can result in a 20% error in the modeled VR. By

Table 5. Comparison of measured and modeled VR using the CO_2 balance approach.

Species	Data Points	Threshold of Differences between Exhaust and Inlet CO_2 Concentrations	(1) Measured VR (L s^{-1} head^{-1})[a]	(2) Modeled VR (L s^{-1} head^{-1})[a]	(2)/(1)	(3) Standard Deviation of Residuals (L s^{-1} head^{-1})	(3)/(1)	R^2 between Measured and Modeled VR
Broiler	206	>200 ppm	3.29 ±1.86	3.30 ±1.78	100%	0.50	15%	0.92
	492	>100 ppm	3.36 ±1.89	3.53 ±1.98	105%	0.69	21%	0.88
	600	>50 ppm	3.36 ±1.85	3.63 ±2.15	108%	1.08	32%	0.75
	713	>0 ppm	3.45 ±1.83	412 ±5406	11,900%	5,406	156,700%	<0.01
Laying hen	9	>200 ppm	3.02 ±0.80	1.95 ±0.19	65%	0.89	29%	0.13
	480	>100 ppm	3.57 ±0.79	3.47 ±0.55	97%	0.75	21%	0.18
	941	>50 ppm	4.05 ±0.88	4.40 ±1.24	109%	1.00	25%	0.36
	978	>0 ppm	4.07 ±0.88	74 ±1531	1,800%	1,531	37,600%	<0.01
Turkey	49	>200 ppm	10.9 ±3.0	13.7 ±5.0	125%	3.66	34%	0.48
	742	>100 ppm	20.3 ±7.9	22.8 ±15.2	112%	9.96	49%	0.49
	1234	>50 ppm	20.1 ±7.1	22.5 ±12.8	112%	8.78	44%	0.57
	1488	>0 ppm	18.9 ±7.6	24.3 ±32.8	129%	31.6	170%	0.07
Swine	962	>200 ppm	46.0 ±6.2	47.5 ±8.0	103%	6.09	13%	0.44
	1466	>100 ppm	46.3 ±6.1	50.3 ±9.7	109%	8.15	18%	0.31
	1497	>50 ppm	46.4 ±6.1	51.3 ±11.8	110%	10.4	22%	0.23
	1499	>0 ppm	46.4 ±6.1	55.8 ±174.4	120%	174	380%	<0.01
Steer	2	>200 ppm	112 ±17	103 ±4	92%	21.2	19%	-
	288	>100 ppm	244 ±49	219 ±39	90%	34.1	14%	0.53
	829	>50 ppm	265 ±41	290 ±74	109%	62.4	24%	0.30
	868	>0 ppm	266 ±40	315 ±203	118%	196	74%	0.07
Dairy cow	255	>200 ppm	269 ±58	258 ±87	96%	65	24%	0.31
	356	>100 ppm	279 ±54	328 ±147	118%	115	41%	0.32
	379	>50 ppm	281 ±54	386 ±290	137%	250	89%	0.21
	411	>0 ppm	286 ±56	611 ±904	213%	821	290%	0.14

[a] Values are means ± standard deviations.

only including data in which the differences between exhaust and inlet CO_2 concentrations were larger than 50 ppm, the standard deviations of model residuals were less than 32% of the average values of measured VR in the broiler, laying hen, swine, and steer studies (table 5). Based on the observed standard deviations, when using the CO_2 balance approach to estimate VR for broiler, laying hen, swine, and steer operations with 95% confidence, a minimum of ten replicate measurements is required to achieve a margin of error less than 20% in modeled VR, and a minimum of 41 replicate measurements is required to achieve a margin of error less than 10%. The CO_2 production rates and RQ for turkeys and dairy cows demonstrated larger variations at different stages of production and resulted in higher uncertainties. Therefore, for turkey and dairy cow studies, more replicate measurements may be needed. In addition, for dairy cow studies, a higher threshold of differences between exhaust and inlet CO_2 concentrations is recommended due to the observed overestimation with the 50 ppm threshold.

In the steer and dairy cow studies, manure was removed from the environmental rooms on a daily basis, and therefore no contribution of CO_2 from the manure was accounted for. In the poultry studies, bedding material was used, and manure was kept in the environmental rooms for the entire experiment periods. The higher CO_2 production rates observed in the broiler studies could be partly due to the CO_2 contributions from the manure system. Pedersen et al. (2008) conducted a literature review and suggested that the CO_2 contribution from manure systems could add about 10% at house level as compared with CO_2 production data collected from respiration chambers. Ni et al. (1999) reported that housing with manure stored indoors for more than three weeks can result in up to 35% CO_2 contribution from manure. In applications of CO_2 balance, another possible source of CO_2 is the exhaust of the heating system, which is not the case in our studies because the natural gas heating system was vented outside and for young animals supplemental heat was provided using electricity.

Contributions of CH_4 and N excretion to modeled HP are usually much less than that of CO_2 in equations 3 and 4. Nienaber et al. (2009) reported that, for chickens and turkeys, the terms for CH_4 and N excretion can be neglected and result in an error of less than 1.5%. In our studies (table 6), in the poultry and swine studies, contributions of the CH_4 term were less than 0.1% of HP, and therefore CH_4 can be neglected in the model. In the steer and dairy cow studies, contributions of the CH_4 term were in the range of 0.3% to 0.8% of HP. Contributions of the N term were in the range of 0.8% to 1.4% of HP. When both the CH_4 and N terms are neglected in equations 3 and 4, the modeled CO_2 production rates could be underestimated by 0.8% to 1.4% in the poultry and swine studies and by 1.1% to 2.4% in the steer and dairy cow studies.

CONCLUSION

Gas emissions of CO_2 were measured in environmental rooms in 15 animal operation studies, including two dairy cow studies, four steer studies, two swine studies, one turkey study, four laying hen studies, and two broiler chicken studies. A CO_2 balance approach was used to estimate VR of the environmental rooms based on the metabolic rate of the animals. The measured CO_2 production rates and VR were compared with the modeled CO_2 production rates and VR. Based on the results, the following conclusions can be made:

(1) The measured CO_2 production rates, in units of m^3 h^{-1} hpu^{-1}, were comparable with literature values in the broiler (>3 weeks), laying hen (>28 weeks), swine, and steer studies. The CO_2 production rates for turkeys were determined, and this could be a significant contribution to the very limited data in the literature. In the poultry (broiler, laying hen, and turkey) and dairy studies, the CO_2 production rates per heat production of animals or RQ showed a decreasing trend with increasing animal age or DIM. To improve model performance, difference RQ values were provided for different ages in the poultry studies and for different DIM in the dairy studies. The coefficients of variance of the measured CO_2 production rates in the broiler (>3 weeks), laying hen (>28 weeks), turkey (>10 weeks), swine, and steer studies were between 0.17 and 0.27. Further investigation of the relationship between RQ and animal age, feed intake, or individual status of the animals could improve the estimation

Table 6. Contributions of the CH_4 and N terms to the modeled HP in equations 3 and 4.

Species	Study Code	(1) Modeled HP (W head^{-1})	(2) 2.17CH_4 (W head^{-1})	(3) 5.99N (W head^{-1})	(2)/(1)	(3)/(1)	[(2) + (3)]/(1)
Broiler	BR0108	13.9 ±6.0	<0.01	0.18 ±0.06	<0.1%	1.4%	<1.5%
	BR0208	10.4 ±6.4	<0.01	0.13 ±0.07	<0.1%	1.2%	<1.3%
Laying hen	LY0108	9.8 ±0.1	<0.01	-	<0.1%	-	-
	LY0109	10.2 ±0.0	<0.01	0.10 ±0.01	<0.1%	1.0%	<1.1%
	LY0209	10.3 ±0.1	<0.01	0.11 ±0.00	<0.1%	1.1%	<1.2%
	LY0309	10.4 ±0.0	<0.01	0.10 ±0.00	<0.1%	1.0%	<1.1%
Turkey	TY0108	52.6 ±28.8	0.01 ±0.01	0.47 ±0.19	<0.1%	0.9%	<1.0%
Swine	SW0109	261.3 ±48.5	0.14 ±0.08	-	<0.1%	-	-
	SW0209	169.0 ±17.3	0.06 ±0.02	-	<0.1%	-	-
Steer	ST0109	453.1 ±35.5	1.3 ±0.5	-	0.3%	-	-
	ST0209	523.7 ±32.5	2.4 ±0.9	-	0.4%	-	-
	ST0110	482.0 ±2.3	2.0 ±0.5	-	0.4%	-	-
	ST0210	445.1 ±5.5	2.9 ±0.7	-	0.6%	-	-
Dairy cow	DY0108	1496.8 ±82.8	12.6 ±2.4	15.1 ±2.4	0.8%	0.8%	0.6%
	DY0208	1536.7 ±122.7	15.1 ±2.8	13.0 ±2.7	1.0%	0.8%	1.8%

of CO_2 production rates and reduce uncertainties. The observed higher variation in CO_2 production rates per heat production of animals in young broiler chicken (<3 weeks) and turkeys (<10 weeks) and in the dairy cow studies also requires further investigation.

(2) The modeled and measured CO_2 production rates were generally comparable with each other for each species, and the standard deviations of model residuals were about 20% to 30% of the average values of measured CO_2 production rates for each species except dairy cows. Various thresholds of differences between exhaust and inlet CO_2 concentrations were used to decide the eligibility of data points to be included in the VR modeling. Based on the results, a threshold of 50 ppm can be used with understanding of the associated uncertainties. The standard deviations of model residuals were less than 32% of the average values of measured VR in the broiler, laying hen, swine, and steer studies, which indicated that, when using the CO_2 balance approach to estimate VR for these species, a minimum of ten replicate measurements is required to achieve a margin of error less than 20% in modeled VR with 95% confidence. For the turkey and dairy cow studies, more replicates and a higher threshold of differences between exhaust and inlet CO_2 concentrations are recommended. In the model to estimate CO_2 production rates, the N term can be neglected with an error of 0.8% to 1.4%. The CH_4 term can be neglected with an error of less than 0.1% in the poultry and swine studies and with an error of 0.3% to 0.8% in the steer and dairy cow studies.

This study investigated the uncertainties of the CO_2 balance approach based on data from environmentally controlled rooms. Higher uncertainties should be expected for applications in commercial barns. In addition, for commercial livestock houses, especially naturally ventilated buildings, the air exchange rates are often much less than those in our environmental rooms, and therefore larger differences between exhaust and inlet CO_2 concentrations can be expected. In these cases, higher thresholds of differences will be feasible and are recommended to improve model performance.

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