The influence of broiler activity, growth rate, and litter on carbon dioxide balances for the determination of ventilation flow rates in broiler production

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ABSTRACT Carbon dioxide balances are useful in determining ventilation rates in livestock buildings. These balances need an accurate estimation of the CO_2 produced by animals and their litter to determine the ventilation flows. To estimate the daily variation in ventilation flow, it is necessary to precisely know the daily variation pattern of CO_2 production, which mainly depends on animal activity. The objective of this study was to explore the applicability of CO_2 balances for determining ventilation flows in broiler buildings. More specifically, this work aimed to quantify the amount of CO_2 produced by the litter, as well as the amount of CO_2 produced by the broilers, as a function of productive parameters, and to analyze the influence of broiler activity on CO_2 emissions. Gas concentrations and ventilation flows were simultaneously measured in 3 trials, with 1 under experimental conditions and the other 2 in a commercial broiler farm. In the experimental assay, broiler activity was also determined. At the end of the experimental trial, on the day after the removal of the broilers, the litter accounted for 20% of the total CO_2 produced, and the broilers produced 3.71 L/h of CO_2 per kg of metabolic weight. On the commercial farm, CO_2 production was the same for the 2 cycles (2.60 L/h per kg of metabolic weight, $P > 0.05$). However, substantial differences were found between CO_2 and broiler activity patterns after changes in light status. A regression model was used to explain these differences ($R^2 = 0.52$). Carbon dioxide increased with bird activity, being on average 3.02 L/h per kg of metabolic weight for inactive birds and 4.73 L/h per kg of metabolic weight when bird activity was highest. Overall, CO_2 balances are robust tools for determining the daily average ventilation flows in broiler farms. These balances could also be applied at more frequent intervals, but in this case, particular care is necessary after light status changes because of discrepencies between animal activity and CO_2 production.

Key words: broiler, carbon dioxide balance, broiler activity, gas emissions

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INTRODUCTION

Quantifying ventilation rates in animal houses is crucial to the management of environmental controls in intensive livestock production. The establishment of proper ventilation rates is necessary in order to maintain appropriate conditions in the buildings, which determine the productivity and welfare of the animals. In broiler production, indoor environments must be strictly controlled, which involves a proper determination of the ventilation rates (Wathes and Charles, 1994). Likewise, the determination of ventilation rates is needed for the quantification of airborne emissions from animal buildings, in which the building itself is considered the control volume for mass balance (Phillips et al., 1998). This task requires the simultaneous measurement of gas concentrations and ventilation rates.

In mechanically ventilated buildings and under well-controlled conditions, ventilation rates in poultry houses can be determined using direct methods with precision better than 10% (Gates et al., 2004; Calvet et al., 2010). However, in naturally ventilated buildings and in buildings with a large number of fans, indirect methods are necessary to determine ventilation rates because direct measurement methods are either impractical or not possible. Among indirect methods, CO_2 balances have been widely used in the past (Pedersen et al., 1998). These balances use CO_2 as a tracer gas, which is naturally emitted by the animals and their litter, in order to determine the ventilation rates in buildings. To do this, CO_2 production from the animals and from their litter must be well known. Carbon dioxide produced by the animals depends on animal weight and

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daily gain, and is strongly affected by variations in animal activity, given that this gas is produced as a result of animal metabolism.

The basis of CO_2 balances was first proposed by Feddes et al. (1984) who measured the CO_2 production of broilers as a function of animal age. Later, Van Ouwerkerk and Pedersen (1994) estimated the ventilation rate in pigs and cattle according to their metabolic reactions, establishing a relationship between animal heat, expressed in watts (W), and volumetric CO_2 production, expressed in L/h. These authors proposed a CO_2 production rate of between 0.17 and 0.20 L/h per W of energy, considering that manure accounted for 4% of the total CO_2 production for animal houses with regular manure removal. However, in traditional broiler production, manure removal occurs at the end of the cycle, resulting in deep litter. The CO_2 production from deep litter is expected to be higher than 4%. This CO_2 methodology has been adapted for most livestock species by the International Commission of Agricultural Engineering (CIGR), which takes into account temperature changes, animal activity, and CO_2 production rate per animal heat production (CIGR, 2002; Pedersen et al., 1998, 2008).

The CO_2 balance method consists of 4 main steps. First, animal heat production is calculated as a function of animal weight and productive performance. Second, a correction for ambient temperature is applied to obtain a corrected heat production. Third, a correction for daily variation of animal activity is used to obtain more detailed information for the ventilation pattern within a given day. Finally, the ventilation rate is calculated according to the measured CO_2 concentrations and the CO_2 production rate by the animals. Thus, the ventilation rate calculated by the balance method, expressed in m^3/h per animal (V_{CO_2}) can be calculated by means of equation 1:

$$V_{CO_2} = \frac{F_{CO_2} \times \phi^*_{tot}}{\left(CO_{2outlet} - CO_{2inlet}\right) \times 10^{-6}}, \qquad [1]$$

where F_{CO_2} is the CO_2 produced per heat production unit (m^3/W). The CO_2 concentrations (CO_{2oulet} and CO_{2inlet}) are expressed in parts per million (ppm), and Φ^*_{tot} is the total heat production (W), which in turn depends on animal live weight, ambient temperature, and animal activity. For pigs, some models have been proposed to adjust daily variation of activity (Blanes and Pedersen, 2005). However, the model currently proposed for broilers by CIGR (2002) only considers a situation of permanent lighting, which is no longer allowed in the European Union for most of the rearing period, according to Council Directive 2007/43/CE. On the contrary, a strong influence of the lighting program on animal activity has been described for broilers (Calvet et al., 2009), which may be associated with relevant changes in CO_2 emission during the day.

The main parameters involved in the CO_2 balances (equation 1) were reviewed by Pedersen et al. (2008). These parameters are animal heat, CO_2 production per heat unit, and the effect of animal activity. However, these parameters have associated errors ranging from 10 to 20% (Zhang et al., 2010), leading to relatively uncertain results for estimated ventilation rates. Furthermore, errors in the estimation of these parameters may lead to systematic over- or underestimations of ventilation rates. Therefore, further research is necessary in order to determine these parameters accurately.

Three main concerns still arise when applying CO_2 balances in broiler production. The first is related to the calculation of total heat produced by each broiler, given that the metabolic activity of broilers may be affected by the evolution of animal genetics; for example, improved weight gain rates in modern strains. In broilers, advances in genetics in recent years have induced a precise and substantial change in BW gain and feed consumption (Havenstein et al., 2003; Schmidt et al., 2009), which is probably related to increased CO_2 production. This effect was not considered for broilers in the CIGR methodology because too few experimental data were available. However, for fattening pigs, the effect of weight gain was indeed explicitly considered.

The second concern is that the influence of bird activity on CO_2 emission in broiler production is not fully understood. Finally, the contribution of litter throughout the growing period of the broilers should be further explored because it remains unclear how litter contributes to global CO_2 emissions.

The main objective of this study was to evaluate the effect of 3 critical parameters in CO_2 balances for the determination of ventilation rates in broiler production: 1) the amount of CO_2 produced by the litter at the end of the broiler growing period; 2) the CO_2 produced by broilers as a function of bird weight; and 3) the influence of broiler activity on this emission, as affected by the lighting program.

MATERIALS AND METHODS

Two experiments were conducted to evaluate the applicability of the CO_2-balance method in broiler production. Experiment 1 corresponded to a broiler facility on a laboratory scale, whereas experiment 2 was conducted in a commercial farm. Experiment 2 evaluated 2 separate growing periods (one in summer and one in winter). In these 2 experiments, the CO_2 produced by the broilers was quantified and the CO_2 balance was evaluated on a daily basis. This estimation was used to evaluate the relationship between CO_2 production and bird weight, among others. The design of experiment 1 allowed for the examination of additional parameters for CO_2 balances: the proportion of CO_2 produced by the deep litter, and the influence of broiler activity on the emission of this gas. The buildings were cleaned and disinfected before new bedding was added at the

beginning of each growing cycle. No new bedding was incorporated during a cycle.

Experiment 1

The broiler facility on a laboratory scale was located in the Division of Process Engineering (Georg-August University of Goettingen, Germany). A total of 158 one-day-old Ross broilers were distributed into 12 pens (each 2 m^2) in a 6 × 8 m room. The cycle started in November 2006 and the birds were reared until 35 d of age (Figure 1). Each pen had 1 manual feeder, 2 nipple drinkers, and approximately 6 cm of wood shavings for bedding material. Temperature and lighting were adjusted to animal requirements (Aviagen, 2002). A target temperature was assigned as a function of the age of the broilers, which decreased from 29°C at the beginning of the cycle to 22°C at the end. To achieve these temperatures, inlet air was heated as needed. The light regimen consisted of 2 dark and 2 light periods during the day. During the first 10 d of the cycle, the dark periods were from 2300 to 0500 h and from 1130 to 1530 h, whereas during the rest of the experiment the dark periods were from 2100 to 0500 h and from 1130 to 1530 h. Bird weight and feed consumption were determined weekly.

The room was ventilated by a 3-level constant ventilation system: level 1 (d 1–8), level 2 (d 9–28), and level 3 (d 29 to end of cycle). The ventilation exhaust was conducted in 2 PVC tubes (153.6 mm diameter) and the ventilation rate of each level was measured by means of a fan-wheel anemometer (MiniAir6/S6Mik20, Schiltknecht, Switzerland), resulting in 347, 387, and 414 m^3/h for levels 1, 2, and 3, respectively. Air temperature and RH at air exhaust and bird heights were measured using temperature and humidity sensors (Hydroclip, Rotronics, Bassersdorf, Switzerland), and were continuously recorded in a data logger (Mikromec-multisens, Technetics, Freiburg, Germany). The CO_2 concentration was determined every 30 min using an FTIR analyzer (ThermoNicolet 470 ED, Waltham, MA).

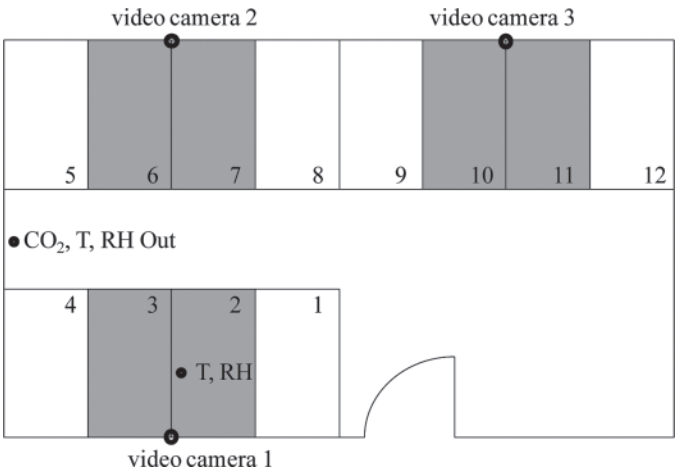

Figure 1. Experiment 1 design, including the distribution of pens, monitoring of broiler activity (gray areas), and measurement point for CO_2, temperature (T), and RH in the experimental farm.

To determine broiler activity, 6 pens were continuously monitored and video recorded using 3 infrared-sensitive cameras, located as shown in Figure 1. Three infrared lights were used for monitoring night broiler activity. Each of these 6 pens housed 13 broilers during the entire experiment, incorporating 1 broiler from the remaining pens when any broiler in a monitored pen died. Broiler activity was quantified every 15 min by observation of the video tapes as explained in Calvet et al. (2009). Six animal activities were identified: lying, standing, moving (either walking or running), drinking, eating, and scratching. For each observation, the number of animals performing each activity was counted and the percentage of occurrence for each activity was calculated. Finally, animal activity was quantified using an activity index (**Ai**), defined as the proportion of active birds; that is, birds not lying down.

Experiment 2

In the second experiment, CO_2 concentrations and ventilation rates were quantified in 2 growing cycles in a commercial, mechanically ventilated broiler farm located in Villarreal (Castellón, Spain). One cycle corresponded to summer conditions (July and August 2006) and the other to winter (December 2006 and January 2007).The evaluated period was the same as in experiment 1 (d 1-35). The building was equipped with 16 one-speed fans. Rice hulls (approximately 8–10 cm deep, 4 kg/m^2) were used as bedding material, and the deep litter was removed at the end of each cycle. The summer experiment started with 10,000 male and 10,100 female broiler chicks on July 20, 2006, and the winter experiment started with 12,000 male and 12,000 female chicks on December 15, 2006. Bird weight and feed consumption were determined weekly; 50 broilers were weighed every week, whereas feed consumption was obtained from farm records.

To determine the ventilation rate, the operation time of each fan was recorded hourly during the 2 cycles. Each fan was calibrated at 4 different pressure drops (0, 15, 30, and 45 Pa), both at the beginning and the end of the experiment. During the calibration, the exhaust air from each fan was ducted 50 cm downstream, and the air speed was measured using a hot-wire anemometer (Testo 425, range 0–20 m/s, precision 5% of reading; Testo AG, Lenzkirch, Germany) using the measurement protocol established by ASHRAE (2001). Each pressure drop was measured and recorded every 5 min using the 0–2.5 V analog output of a differential pressure transducer (Setra model 267, range 0–100 Pa, Boxborough, MA), located as specified in Figure 2. More details on ventilation measurements are provided by Calvet et al. (2010).

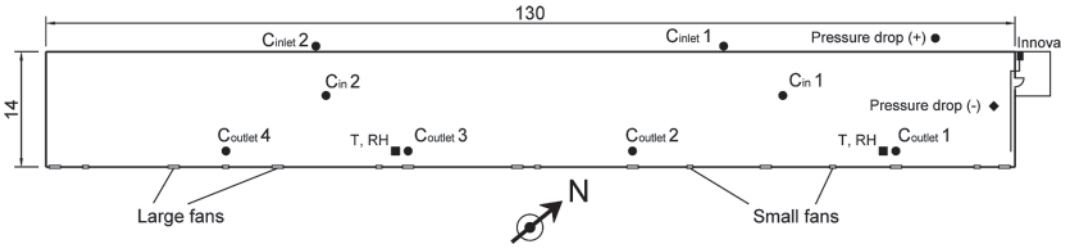

Figure 2. Distribution of the commercial farm with the location of exhaust fans, the gas concentration sampling points, and measurement locations of temperature, RH, and pressure drop.

The CO_2 concentration was measured using a photo acoustic gas monitor (INNOVA 1412, LumaSense Technologies, Ballerup, Denmark) equipped with a gas multipoint sampler, allowing for sequential measurement of 8 different points in a 2-h sequence (15 min/ measurement). To determine the exhaust-gas concentrations, 4 sampling points were placed next to the extraction fans; 2 points were at the air-inlet openings for the characterization of outside air, and the other 2 points were in the middle of the building (Figure 2). In order to have general information about the ambient conditions, indoor and outdoor temperatures and RH were recorded using 4 data loggers and a weather station (H8–004–002 and HOBO Weather Station, Onset Computer Corp., Pocasset, MA).

Data Analysis

The CO_2-balance method for estimating ventilation rates was evaluated using the methodology established by CIGR (2002). The following expression (equation 2) was used to estimate the average ventilation rate (V_{CO_2}, m^3/h per bird):

$$V_{CO_2} = \frac{F_E \times LW^{0.75} \times F_T \times F_{CO_2} \times F_A \times \frac{1}{(1-F_{litter})}}{(CO_{2outlet} - CO_{2inlet}) \times 10^{-6}}, \quad [2]$$

where F_E is the heat production factor (W/kg of metabolic weight), LW is the live weight (kg), F_T is the dimensionless correction factor for temperature (CIGR, 2002), F_{CO_2} is the CO_2 production (m^3/W), F_A is the dimensionless correction for animal activity, CO_2 is the concentration of the gas ($CO_{2outlet}$ and CO_{2inlet}; ppm), and F_{litter} is the proportion of total CO_2 produced by the litter. This variable was estimated in the first experiment, considering the average proportion of CO_2 production during the first 24 h after slaughter, in relation to the last 4 d of the rearing period, and assuming a constant value for F_{litter} (Xin et al., 2009).

Ideally, the model results are similar to measured ventilation rates. Therefore, we can use measured values of ventilation rates to estimate the CO_2 balance model parameters. In equation 3 all directly measured values of the model were grouped in the left part of the following expression:

$$V_{measured} \times (CO_{2outlet} - CO_{2inlet}) \times \frac{(1-F_{litter})}{F_T} \times 10^{-6} = F_A \times F_E \times F_{CO_2} \times LW^{0.75}. \quad [3]$$

The left part of equation 3 refers to the measured CO_2 produced by animals (E_{CO_2}), expressed in L/animal and h. If the unknown variables in the right part of equation 3 are grouped, the following regression model (equation 4) relates the emission of CO_2 to animal live weight (LW):

$$E_{CO_2} = \alpha \times LW^{0.75} + \varepsilon, \quad [4]$$

where α is the regression slope representing the CO_2 production rate (L/h per kg of metabolic weight), and ε is the model error. Statistical differences between the experiments were evaluated using a multiple regression model, which combined daily average CO_2 emissions from the 2 experiments using dummy variables. This model was evaluated with average daily values using the PROC REG of SAS (SAS Institute, 2001). Given that daily average values were used, the correction for animal activity variation during the day (F_A) is, by definition, not necessary, then $\alpha = F_E \times F_{CO_2}$.

To assess the influence of animal activity on CO_2 production per kg of metabolic weight (E_{CO_2}), 2 models were tested using average values every 30 min from the experimental assay (experiment 1). The first model (equation 5) is an ANOVA that considers the effect of light status ($Light$), whereas the second model is a linear regression (equation 6) that considers the influence of animal activity (Ai), where β_1 and β_2 are the regression parameters:

$$E_{CO_2 MW_i} = \mu + Light_i + \varepsilon_i, \quad [5]$$

and

$$E_{CO_2 MW_i} = \beta_1 + \beta_2 \cdot Ai_i + \varepsilon_i. \quad [6]$$

However, observed data indicated that the sudden transition from light to dark, and vice versa, involved a sudden change in animal activity, but CO_2 emission changes were delayed in time. Therefore, an extended

Table 1. Climate and productive parameters during the studied growing periods[1]

Parameter[2]	Wk 1	Wk 2	Wk 3	Wk 4	Wk 5	Average
Experiment 1 (laboratory scale)						
Indoor T (°C)	28.4 ± 2.1	25.2 ± 0.4	24.1 ± 0.3	23.0 ± 0.3	22.3 ± 0.4	24.7 ± 2.4
Outdoor T (°C)	8.7 ± 3.8	8.9 ± 3.6	8.7 ± 3.2	7.2 ± 2.6	6.2 ± 3.5	8.0 ± 3.5
Indoor RH (%)	38.4 ± 3.0	48.6 ± 4.7	54.3 ± 2.1	55.5 ± 2.1	59.8 ± 3.4	51.1 ± 8.0
Outdoor RH (%)	89.1 ± 7.4	88.6 ± 8.5	86.1 ± 8.6	86.1 ± 6.9	87.3 ± 9.4	87.4 ± 8.2
Ventilation (m^3/animal per h)	1.16 ± 0.00	1.24 ± 0.06	1.29 ± 0.00	1.29 ± 0.00	1.35 ± 0.04	1.26 ± 0.07
Indoor CO_2 (ppm)	1,420 ± 177	1,830 ± 210	2,415 ± 269	3,039 ± 405	3,623 ± 328	2,431 ± 834
Final weight (kg)	0.198	0.497	0.935	1.513	2.120	—
Feed intake (kg)	0.129	0.364	0.654	0.983	1.106	3.236[3]
Experiment 2 (summer cycle)						
Indoor T (°C)	30.9 ± 2.2	29.8 ± 1.9	28.5 ± 2.1	27.4 ± 1.8	25.6 ± 1.7	28.4 ± 2.7
Outdoor T (°C)	26.8 ± 3.9	26.6 ± 3.8	25.6 ± 3.6	24.4 ± 3.1	23.6 ± 3.9	25.4 ± 3.8
Indoor RH (%)	50.1 ± 9.3	56.7 ± 8.0	50.4 ± 11.3	51.0 ± 10.7	53.8 ± 11.3	52.4 ± 10.5
Outdoor RH (%)	66.7 ± 16.0	68.1 ± 15.9	60.0 ± 18.7	60.5 ± 18.1	59.9 ± 20.2	63.0 ± 18.1
Ventilation (m^3/animal per h)	0.86 ± 0.86	1.76 ± 1.12	3.78 ± 1.85	5.23 ± 1.92	7.11 ± 2.40	3.87 ± 2.84
Indoor CO_2 (ppm)	1,229 ± 782	1,237 ± 469	1,084 ± 217	1,025 ± 150	1,037 ± 144	1,122 ± 437
Final weight (kg)	0.115	0.341	0.698	1.139	1.617	—
Feed intake (kg)	—	—	—	—	—	2.974[3]
Experiment 2 (winter cycle)						
Indoor T (°C)	28.9 ± 1.5	26.2 ± 0.8	24.5 ± 0.8	23.6 ± 0.8	21.9 ± 1.1	24.9 ± 2.5
Outdoor T (°C)	10.0 ± 3.5	8.3 ± 3.6	10.0 ± 4.3	10.8 ± 4.2	10.8 ± 3.9	10.0 ± 4.0
Indoor RH (%)	55.1 ± 10.4	68.6 ± 3.1	64.1 ± 6.4	57.8 ± 8.2	58.0 ± 8.4	60.9 ± 9.0
Outdoor RH (%)	59.1 ± 17.1	62.1 ± 18.2	78.1 ± 15.9	72.8 ± 17.8	74.9 ± 17.3	69.5 ± 18.7
Ventilation (m^3/animal per h)	—	0.46 ± 0.17	0.86 ± 0.40	1.48 ± 0.58	2.58 ± 1.02	1.37 ± 1.02
Indoor CO_2 (ppm)	—	4,459 ± 769	2,913 ± 664	2,406 ± 495	2,032 ± 405	2,920 ± 1,085
Final weight (kg)	0.128	0.374	0.767	1.255	1.783	—
Feed intake (kg)	—	—	—	—	—	3.183[3]

[1]Expressed as weekly average values ± SD

[2]T = temperature.

[3]Accumulated feed consumption at the end of the growing period.

model based on a decay curve was proposed in order to model the influence of animal activity on CO_2 emission (equation 7). The model was evaluated using the Procedure NLIN of SAS (SAS Institute, 2001):

$$E_{CO_2 MW_i} = \beta_0 + \beta_1 \times Light \times Ai + (-1)^{Light} \times \beta_1 \times Ai \times e^{\left(-\frac{1}{\beta_2} \times t\right)}. \quad [7]$$

In this model, $E_{CO_2 MW}$ is the CO_2 emission rate (L/h per kg of metabolic weight), β_0 is the CO_2 emission rate for nonactive birds (L/h per kg of metabolic weight), β_1 is the effect of animal activity on CO_2 emission (L/h per kg of metabolic weight), β_2 is the decay constant (h), Ai is the activity index (dimensionless), *Light* is a bivariate function defining the light status (0 for dark; 1 for light), and t is the time (h) after the light status changes.

RESULTS

Production Results

According to the production parameters shown in Table 1, the broilers in experiment 1 grew faster compared with those in experiment 2. In experiment 1, the average weight gain from d 1 to 35 was 62.1 g/d, whereas in experiment 2 the average weight gain during the same period was 46.4 and 50.0 g/d in summer and winter, respectively. Despite the higher feed intake in experiment 1, the feed conversion ratio was slightly lower than in experiment 2.

Litter Emissions

The relationship between the average amount of CO_2 produced before and after broiler slaughter was obtained in experiment 1 from the CO_2 production curve (Figure 3). Before slaughter (d 30–33), average CO_2 production was 6.81 L/h per bird, which originated both from the broilers and the deep litter, whereas during the first 24 h after slaughter the average amount of CO_2 produced was 1.36 L/h per bird. Assuming that differences in the CO_2 produced by the deep litter between these 2 estimations are negligible, we obtained that 20% of the global CO_2 production in the laboratory trial (experiment 1) originated from deep litter reactions ($F_{litter} = 0.20$).

Broiler CO_2 Production Rate

The daily average CO_2 productions are represented in Figure 4 against the metabolic weight of the broilers for experiments 1 and 2. In all cases, a linear tendency was observed, and linear regression parameters according to equation 4 are shown in Table 2. According to Table 2, in experiment 1 the CO_2 production rate of the birds was 3.71 L/h per kg of metabolic weight. In experiment 2 (commercial farm), no differences in daily average CO_2 production were found between the summer and winter cycles ($P > 0.05$). The average CO_2

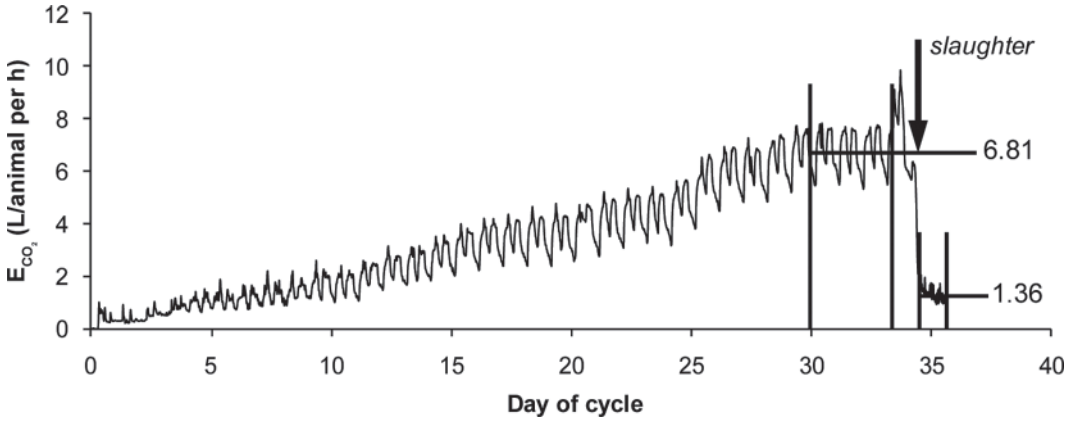

Figure 3. Evolution of CO_2 production and estimation of average productions before and after broiler slaughter.

emission rate for experiment 2 was 2.60 L/h per kg of metabolic weight. However, the CO_2 production rate was significantly higher in experiment 1 compared with experiment 2 ($P < 0.01$).

The parameters to be used in the balance method for the CO_2 produced by the broilers are indicated in Table 3. According to these results, the estimation for the heat production from birds in experiment 1 (21.82 W/kg$^{0.75}$) was substantially higher than in experiment 2 (15.32 W/kg$^{0.75}$).

Effect of Broiler Activity

In experiment 1, the light status affected the CO_2 production significantly ($P < 0.01$), with an average emission value of 3.03 ± 0.02 and 3.85 ± 0.02 L/h per kg of metabolic weight during the dark and light periods, respectively. Carbon dioxide emission per kg of metabolic weight (E_{CO_2MW}) was also significantly affected by broiler activity ($P < 0.01$), as indicated in equation 8:

$$E_{CO_2MW} = 2.94\ (\pm 0.02) + 1.56\ (\pm 0.02) \cdot Ai \quad \left(R^2 = 0.40\right). \qquad [8]$$

According to this equation, the expected CO_2 emission rate was 2.94 and 4.50 L/h per kg of metabolic weight for inactive and active birds, respectively. However, we found a discrepancy between the observed broiler activity and the measured CO_2 emission rates, particularly after changing the light status (turning lights on and off). Therefore, we investigated the rationale behind this fact.

After the lighting status changed, the evolution of broiler activity was not in accordance with the CO_2 produced (Figure 5). More specifically, it was observed that the changes in CO_2 were delayed in time with respect to the changes in broiler activity. An expanded model based on a decay curve was adjusted according to equation 7, obtaining the regression parameters indicated in Table 4. The extended model explained the influence of broiler activity on CO_2 emission (R^2 = 52.6%) better than the model in equation 8. As a result, the expected CO_2 emission rate was 3.02 and 4.73 L/h per kg of metabolic weight for inactive and active birds, respectively. According to this model, a 95% change in CO_2 production was achieved within the first 2.28 h and a 99% change was achieved within 3.50 h.

Table 2. Linear regression estimates of CO_2 production (L/h per bird) as a function of metabolic weight (kg$^{0.75}$)[1]

Experiment[2]	R^2	α	SE	*P*-value
1	0.98	3.71	0.03	<0.01
2	0.99	2.60	0.03	<0.01

[1]α = CO_2 emitted by broilers.

[2]Experiment 1 took place on an experimental farm and experiment 2 took place on a commercial farm.

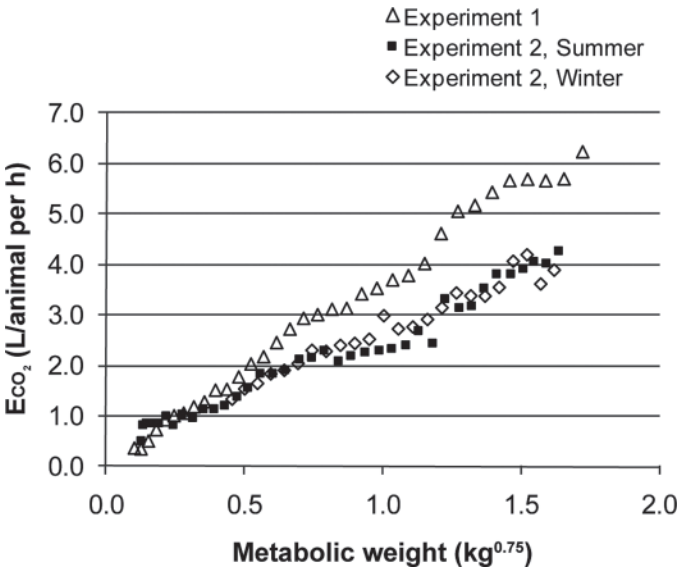

Figure 4. Relation between daily average CO_2 production and bird weight in experiment 1 (experimental farm) and experiment 2 (commercial farm in summer and winter).

Table 3. Estimation of CO_2 emitted by broilers (α), CO_2 production rate per energy unit (F_{CO_2}), and heat production of broilers (F_E)[1]

Experiment[2]	α (L/h per kg of metabolic weight)	F_{CO_2}[3] (L/h per W)	F_E[4] (W/kg$^{0.75}$)
1	3.71	0.170	21.82
2	2.60	0.170	15.32

[1] $\alpha = F_E \cdot F_{CO_2}$.

[2]Experiment 1 took place on an experimental farm and experiment 2 took place on a commercial farm.

[3]Estimated according to Pedersen et al. (2008).

[4]Indirectly estimated from F_E and F_{CO_2}.

DISCUSSION

Litter Emissions

Determining the CO_2 produced by the deep litter is crucial for avoiding biased ventilation rate estimations. For this reason, several authors have proposed correction factors that are applied to the CO_2 produced by the animals in order to account for the CO_2 produced by the litter. However, there are discrepancies in the results reported so far, likely because of variations in animal species, manure handling systems, substrate humidity, stocking density, weather, and other factors. Van Ouwerkerk and Pedersen (1994) proposed a general correction factor of 4% CO_2 produced by manure, whereas Pedersen et al. (2008) indicated that the contribution of manure is expected to be lower than 10%, unless manure is stored for considerable time periods (more than 3 wk). However, in many situations, including the usual litter management in broiler production, manure is stored indoors over a longer time period, resulting in higher CO_2 contribution. Ni et al. (1999a) found as much as a 35% contribution of CO_2 from manure in pigs. This contribution can reach a comparable amount to animal respiration in deep-litter systems (Jeppsson, 2000).

For broilers, Xin et al. (2009) indicated the difficulty in accounting for the CO_2 contributed by the litter in the CO_2 balance in order to estimate ventilation rates. Although this contribution is normally expressed as a percentage of the bird respiration rate of CO_2, the emission dynamics directly depend on litter properties, which in turn depend on litter management. Carbon dioxide in the litter is a product of the aerobic breakdown of uric acid and other organic compounds (Carlile, 1984). At the end of the cycle, a significant contribution of CO_2 produced by the litter (20%) to total CO_2 produced was found in our study. At present, it is commonly accepted that this percentage is constant throughout the cycle, but it seems realistic that the contribution of CO_2 by the litter may vary depending on the litter material, the C:N ratio in the substrate, and the litter management. This contribution may be particularly affected by the use of built-up litter, that is, a reused mixture of bedding and bird feces, compared with new bedding material. Miles et al. (2006) found relevant CO_2 emissions from 1-d-old chickens using built-up litter. However, when new litter is used in each flock, as in this study, it can be expected that microbial activity is lower at the beginning of the cycle, leading to lower CO_2 emissions from the litter in relation to the end of the cycle. Therefore, understanding the evolution of CO_2 emissions from the litter, under different litter-management systems, is crucial in the estimation of more precise ventilation rates using CO_2 balances.

Carbon Dioxide Production Rate of Broilers

As obtained in previous studies, CO_2 production has been positively related with metabolic weight. However, the values of heat and CO_2 production obtained in this study (Table 3) differ from previous research. According to CIGR (2002), a value of 10.62 W/kg$^{0.75}$ is proposed for F_E, and 0.185 L/W for F_{CO_2}, thus, α equals 1.96 L/kg$^{0.75}$, which is almost half of the value obtained in our study (experiment 1). It seems that inaccuracies in the measurements are not enough to explain these differences. However, F_E and F_{CO_2} may be higher than

Table 4. Regression parameters of the decay curve proposed to model changes of CO_2 following sudden changes in light status ($R^2 = 52.6\%$)

			CI	
Parameter[1]	Estimate	SE	Lower	Higher
β_0 (L/h per kg of metabolic weight)	3.03	0.02	2.99	3.07
β_1 (L/h per kg of metabolic weight)	1.71	0.06	1.59	1.83
β_2 (h)	0.76	0.10	0.56	0.97

[1]β_0 = is the CO_2 emission rate for nonactive birds; β_1 = is the effect of animal activity on CO_2 emission; β_2 = is the decay constant.

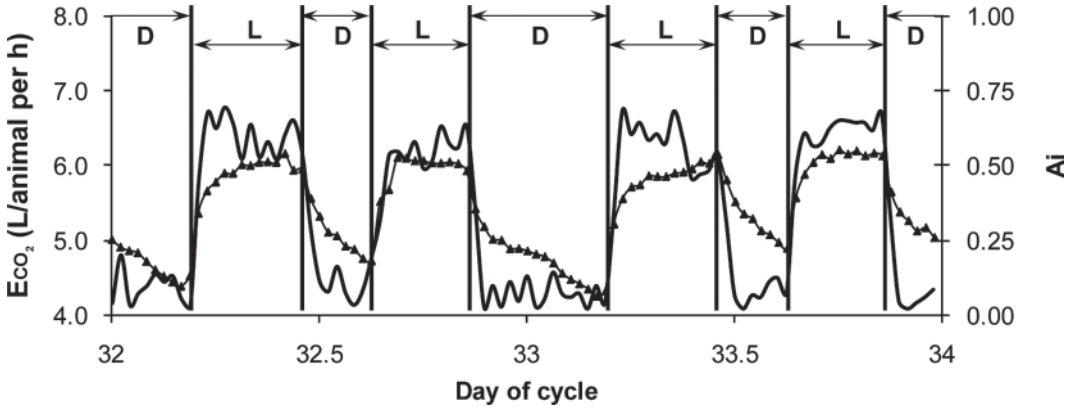

Figure 5. Evolution of CO_2 production (E_{CO_2}, —▲—) and the animal activity index (Ai, —) during d 32 and 33 of the rearing cycle. Light status is indicated as L (light) and D (dark).

those previously reported values because of the increased animal growth rates over the last decades, as reported for pigs by CIGR (2002).

In broilers, advances in genetics in recent decades have induced a substantial change in BW gain and feed consumption. According to Havenstein et al. (2003) broiler growth rate in terms of BW increased by approximately 73 g/yr from 1976 to 1991. This tendency was also demonstrated by the same authors when comparing poultry strains differing by 44 years (1957 vs. 2001 strains). They found strong differences in weight gain (2001 broilers grew about 4 times faster than 1957 broilers at 42 d of age), and feed conversion rate (being on average 1.47 and 4.42 for 2001 and 1957 strains, respectively). This higher metabolic activity of modern strains is probably related to significant increases of CO_2 production.

In experiment 1 of this study, for example, the broilers grew faster than in the commercial farm, and this could have caused greater CO_2 production. Considering the estimation of α in the experimental study (3.71 L/h per kg of metabolic weight), and assuming F_{CO_2} is 0.170 L/h per W (according to Pedersen et al., 2008) the F_E estimated in this study would be 21.82 W/kg$^{0.75}$, which is about 2 times the value proposed by CIGR (2002). This disagreement is large enough that more specific studies for the determination of how F_E may be affected by changes in genetics and nutrition should be considered. In experiment 2 (commercial farm), the estimation of F_E was 33% higher than the value proposed by CIGR. The emission, however, was lower compared with experiment 1, likely owing to differences in growth rates.

In a similar study, Xin et al. (2009) compared measured and estimated ventilation rates, considering a carbon dioxide balance, in 2 flocks of broilers. They found a good agreement between measured and estimated flow when considering $F_E = 10.62$ W/kg$^{0.75}$, according to CIGR (2002), and $F_{CO_2} = 0.157$ L/h per W, based on the principle of animal calorimetry. However, F_{CO_2} increases with daily gain, as a consequence of the increased respiratory quotient. This quotient represents the relationship between CO_2 production and O_2 consumption. In this study, calorimetric studies would be necessary in order to quantify how respiratory quotient and, thus, F_{CO_2} are affected by changes in broiler productive parameters.

Differences between studies could be explained by significant differences in daily BW gain (Figure 6). Although this figure shows estimated values, and there is not enough information to establish a linear relationship between daily weight gain and F_E, there is strong evidence that heat production (and, thus, CO_2 emission rate) may be affected by animal growth rate. In fact, this effect is already included in the CO_2 model proposed for fattening pigs by CIGR (2002). It is also reasonable that feed consumption could affect the CO_2 production; unfortunately this information is scarcely available in the literature. Therefore, it seems interesting to further explore how recent changes in animal growth parameters affect CO_2 production, which could be accounted for when conducting the CO_2 balances to estimate ventilation rates in animal buildings.

Broiler Activity

As obtained in experiment 1, light status influenced broiler activity, and therefore had an indirect effect on CO_2 production. The results of the expanded model (equation 7 and Table 4), in which the time after a change in light status is considered, can be interpreted as follows. The first term of the equation ($\beta_0 = 3.03$ L/animal per kg of metabolic weight) represents the tranquil CO_2 exhalation rate proposed by Ni et al. (1999b) for pigs. From this basal value, the activity of the birds can cause an increase of as much as 57% in the CO_2 produced, depending on the Ai.

If only broiler activity was considered (equation 8), only 40% of CO_2 variation during the day could be explained, in contrast with the 52% of the expanded model. Therefore, observed broiler activity may not be a suitable direct estimator for the variation in CO_2 pro-

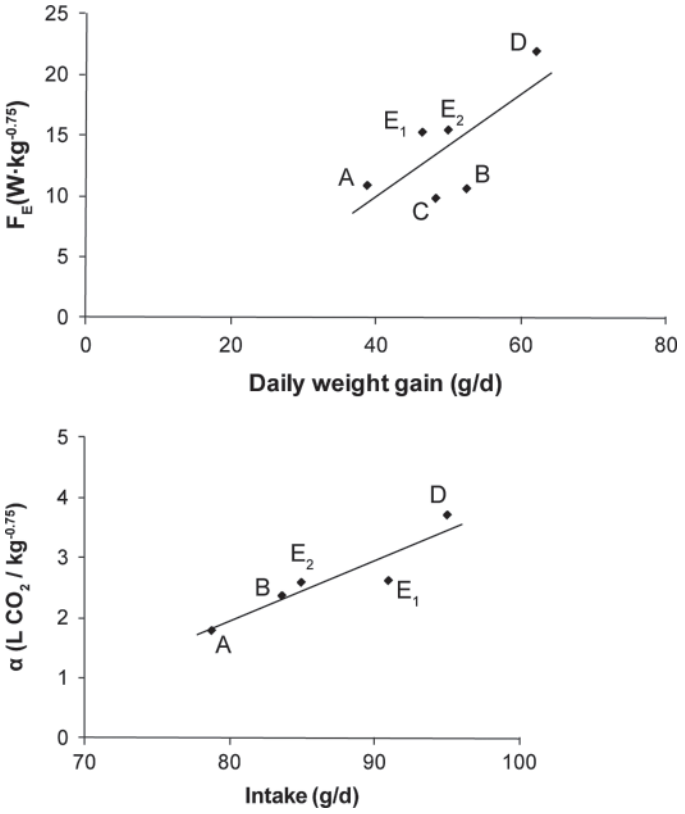

Figure 6. The influence of daily weight gain on heat production F_E (top) and the feed intake on carbon dioxide production (bottom). A. Feddes et al. (1984); B. Pedersen and Thomsen (2000); C. adapted from Xin et al. (2009); D. this study (experiment 1); E1. this study (experiment 2 in the summer); E2. this study (experiment 2 in the winter).

duction in cases of on-off controlled light programs. According to our findings, it seems that observed broiler activity and CO_2 production can be directly related from light status changes after about 2 to 3 h.

A possible reason for the progressive change in CO_2 emission between light and dark periods is the fact that CO_2 concentrations change according to transitory state conditions, therefore concentrations cannot change drastically. Applying the transitory state curve of gas concentrations in the measured ranges of gases, ventilation rates and building volume in the experimental study resulted in 99% of the change in CO_2 concentration within the first 20 min after the light status changed. In contrast, measured values indicated a 99% change within 3.5 h. This indicates that the CO_2 pattern showed in Figure 5 is not a consequence of the gas decay in the volume space.

The most probable reason for the lack of coincidence between broiler activity and CO_2 emission patterns is that when a change in the light status occurs, a change in broiler activity is perceived, and the *Ai* changes. Nevertheless, the metabolic status may not be reflected by the observed activity. This is particularly significant in the first hours of sleep. According to Shapiro and Flanigan (1993), there is a transition from wakefulness to sleep, characterized by active brain activity, which could explain the smooth transition in CO_2 production by animals. According to these authors, one of the functions of sleep is energy conservation, decreasing the metabolic rate (oxygen consumption, heart rate, body temperature, and, thus, CO_2 production) by 5 to 25%.

These findings indicate that for broiler production under conventional management there is a sharp change in the observed broiler activity as a function of the light status, which is not directly followed by similar changes in CO_2 production. The main consequence of these findings in the use of CO_2 balances is that a specific correction for observed broiler activity and time after light change is necessary in order to estimate ventilation rates. This is particularly important in lighting programs that are on-off operated. In contrast, in other species, such as pigs, activity variations throughout the day are of lower magnitude than in broilers, and are also defined by sinusoidal models (Blanes and Pedersen, 2005). However, if the CO_2 from the litter and the animals is properly estimated, these balances seem like a realistic solution for the estimation of daily average ventilation rates, given that in this case the correction for animal activity is not necessary.

Conclusions

For broiler houses with new litter (6 cm of wood shavings), the litter accounted for 20% of the total CO_2 production at the end of the growing period (35 d). However, there is evidence that this percentage may change depending on the litter material, management, and substrate humidity. Therefore, understanding the evolution of CO_2 emissions from the litter is crucial in avoiding biased predictions of ventilation rates that are based on the use of CO_2 balances.

Average daily CO_2 production varied linearly with the metabolic weight of the broilers from d 1 to 35 of the growing cycle. The average emission was 3.71 and 2.60 L/h per kg of metabolic weight for experiment 1 (experimental farm) and experiment 2 (commercial farm), respectively. These values are 89% and 33% higher, respectively, than those according to CIGR. This increase can partly be explained by higher feed intake and daily gain owing to genetics and different housing conditions.

In contrast with previous measurements with slower changes from light to dark, low correlations were found between broiler activity and CO_2 production. An expanded model was proposed for modeling CO_2 emission rates after changes in light status. It can be concluded that particular care should be taken when applying correction factors for animal activity in the estimation of ventilation rates using CO_2 balances in broilers, particularly when lights are on-off controlled. Using daily average ventilation rates, however, is a realistic solution if the CO_2 production model from the animals and their litter is properly estimated.

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