Quantification of nitrogen balance components in a commercial broiler barn

K. von Bobrutzki, C. Ammon, W. Berg, M. Fiedler

Department of Engineering for Livestock Management, Leibniz Institute for Agricultural Engineering Potsdam-Bornim, Potsdam, Germany

ABSTRACT: Characterizing the respective nitrogen (N) use efficiency requires understanding the N flow of inputs and outputs from a commercial broiler barn. In this study, an N mass balance was performed for one entire growing cycle. The objectives were to quantify, sample, and analyze all N components entering and leaving the barn. The N from feed, chickens, and bedding material was considered as inputs, the outputs included the N accretion in mature broilers, the total N emissions (N_{TNE}), the N accumulation in litter, and the N of mortality. Of particular relevance was the determination of an appropriate method to mirror the heterogenic texture of the litter. Litter samples were collected weekly according to a defined procedure. The major N input was feed N, accounting for 99% of the total N input. After the 36-day growing cycle, the N outputs were portioned as follows: 59% (1741.3 kg N) in mature broilers, 37% (1121.3 kg N) accumulated in litter, and 4% in NTNE (114.3 kg N). The N accumulations in broiler tissue and litter agree well with other studies. The measured emissions were consistently lower compared to other references, due to the fact that these references were mainly based on studies where broilers were raised on built-up litter. In contrast to *in situ* quantified N emissions in this study, other published values were assumed to be the difference of N between inputs and outputs. This study illustrates that extensive sampling of litter is a prerequisite for calculating litter masses. The accurate specification of the litter texture proved to be crucial within the mass balance approach. With this information, the feasible improvements within management practices can be identified.

Keywords: ammonia; emissions; mass balance; litter sampling

In Europe, the livestock sector strongly influences the nitrogen (N) cycle because large amounts of nutrients, water, and energy are related to the actions of that sector (Steinfeld and Wasenaar, 2007; Erisman et al., 2008). Broiler operations have become larger and more concentrated in recent years due to a growing demand for broiler meat, the production of which is the second largest worldwide (Niu et al., 2009). As a result, the concentration of nutrients in the form of waste products such as manure (litter) and gaseous emissions (Gous, 2010) has increased. The nutrient of the greatest concern in gaseous emissions is nitrogen (N) in the form of ammonia (NH_3). Ammonia is formed from the breakdown of nitrogenous waste products in broiler manure (undigested proteins and uric acid) by exogenous enzymes produced by microorganisms (Atapattu et al., 2008).

One abatement strategy of NH_3 involves the optimization of dietary composition (protein level) by providing the best feed conversion ratio for broilers and minimizing the excretion of manure (Elwinger and Svensson, 1996; Ferguson et al., 1998; Robertson et al., 2002). Additionally, feeding additives can improve the feed conversion rate of broilers (Ritz et al., 2004; Schiavone et al., 2008). Ammonia is removed from the broiler barn and exhausted into the atmosphere by the ventilation system. Misselbrook et al. (2005) stated that more than half of the N in the manure can be volatilized in the form of NH_3. Therefore, to determine the fertilizing value, one must distinguish between excreted N and the amount of N in the manure. The factors that directly control the NH_3 formation inside the barn are litter pH, litter temperature, and litter moisture (Redwine et al., 2002).

In general, NH_3 release is depressed at pH < 7 but is high at pH > 8 (Lahav et al., 2008). Inside commercial broiler barns, the pH of the litter falls between 7.5 and 8.5 (Ritz et al., 2004). Therefore, Coufal et al. (2006) concluded in their study for re-used litter that pH > 8 is not a driving factor in determining the NH_3 volatilization inside the barn. Thus, temperature and moisture remain the most important factors affecting the variability of NH_3 volatilization in a broiler barn. As a result, various factors, such as farm operational parameters (ventilation system, management), animal conditions (age, weight, health, diet), and litter management could influence the temperature and moisture inside the barns (Seedorf and Hartung, 2002; Mosquera et al., 2005; Bessei, 2006; Coufal et al., 2006). The emitted NH_3 may affect animal and human health (Ritz et al., 2004; Meluzzi and Sirri, 2009). However, NH_3 is a precursor for secondary particulate matter, which represents a critical air pollutant (Wu et al., 2008). Moreover, excessive release of NH_3 contributes to various negative environmental impacts, such as eutrophication and acidification of the ecosystem, and can cause direct damage to vegetation near the sources (Fangmeier et al., 1994; Krupa, 2003; Erisman et al., 2007).

The concept of a farm-gate balance of N, when different N flows on a farm were quantified, was used in various studies (Bassanino et al., 2007; Fangueiro et al., 2008). The approach of using mass balance on a livestock level is a recommended method to determine and follow the fate of nutrients and the emissions of substances such as N throughout livestock production systems (Phillips et al., 2000; Reidy et al., 2009). The purpose of calculating mass balances is to monitor the N use efficiency as a ratio between the outputs and inputs. The differences between the N inputs and outputs of agricultural systems are defined as surpluses (van Eerdt and Fong, 1998). Using this technique, different broiler production systems can be compared and options for improvements identified (Kratz et al., 2004). A number of studies have been performed to quantify the N budget from broiler barns. Patterson et al. (1998) reported an N budget calculation integrating feed N, broiler carcass N, and litter N from two farms in the USA. Coufal et al. (2006) compared the N mass balance of 18 broiler growing cycles of 40–42 days each. Mitran et al. (2008) used the N mass balance and measured all N inputs and outputs. These authors reported that 99% of the total input was feed N. According to estimates by Van der Hoek (1998), the average N assimilation efficiency is approximately 34% for poultry. However, Phillips et al. (2000) stated that a mass balance has limitations because the animal weight, amount of feed consumed, and feed accumulation must be estimated. Further, other practical problems include the collection and handling of representative samples and the measurement of the N excreted by the animals. One critical assumption is that all losses of N would be in the form of NH_3. Some N is lost in other forms, such as nitrous oxide (N_2O), dust, etc. (Coufal et al., 2006). Besides broilers, mass balances were also calculated for other livestock animals, such as rabbits (Calvet et al., 2008) and pigs (Dourmad et al., 1992), and for the global animal production (Van der Hoek, 1998).

The main objective of this paper was to quantify the N components from a commercial broiler barn using the approach of a complete mass balance. By measuring the N content of all the inputs and outputs, it was possible to distinguish between the portion of N in the litter and the volatilized N in the air. Thus, the fate and use efficiency of the N inputs throughout a broiler growing cycle can be characterized and evaluated with previous studies.

MATERIAL AND METHODS

General approach

The mass balance method was proposed to evaluate the components of the N balance during the growing cycle of broilers' fattening. Thus, monitoring the N use of the inputs with respect to the N outputs was possible. The balance is based on the approach that the N intake (N_{feed}) by the broilers is accumulated in the broiler tissues (N_{tissue}) (adding the broiler chicken tissues on day 0; $N_{tissue(d0)}$). The N mass of the broiler tissues (N_{tissue}, $N_{tissue(d0)}$) was estimated according to the commonly accepted recommendations for the N concentration in protein, which was used by Kirchgessner (1997) and Patterson et al. (1998). Kirchgessner (1997) stated that the contents of the crude protein of broiler rise from 16% at the beginning of the growing cycle to 19% at the end of the cycle. Crude protein was calculated as the product of the crude protein percentage and the broiler mass. Dividing the crude protein mass by 6.25 (e.g. Patterson et al., 1998) yields the N mass of

the broiler tissue (N_{tissue}). Mortalities were recorded and removed from the barns daily ($N_{mortality}$). Part of the N was lost as excreta in the litter (N_{litter}). The N mass of the bedding material (sawdust with 0.9 kg/m^2) was added ($N_{litter(d0)}$). Further, gaseous N was removed as the total N emissions (N_{TNE}) as expressed in Equation (1):

$$N_{TNE} = NH_3 - N + N_2O - N + N_2 \quad (1)$$

(N_2 could not be measured, but can also be produced in solid manure systems.)

From these data, calculations were made to partition the inputs entering and the outputs leaving the broiler barn as expressed in Equation (2):

$$N_{feed} + N_{litter(d0)} + N_{tissue(d0)} = N_{tissue} + N_{mortality} + N_{litter} + N_{TNE} - c_{out} \quad (2)$$

The N loss by N_{TNE} was adjusted by a factor of 14/17 and 28/44 to account for the difference in molecular weight between N and NH_3 or N and N_2O, respectively. Both concentrations of NH_3 and N_2O were corrected by subtracting a corresponding atmospheric background concentration. For atmospheric background concentration of NH_3 (c_{out}) we used a mean value of 0.02 mg/m^3, which was determined during previous measurements at the same study site (von Bobrutzki et al., 2011). The atmospheric background concentration (c_{out}) for N_2O based on general acceptance was set to 325 ppb.

Broiler husbandry

The experiment was performed during a growing cycle that ran October 20–November 26, 2010. Approximately 57 000 commercial broilers were raised in the subject barn (length 93 m, width 29 m, height 4.5 m). This barn was subdivided into two pens of 28 600 broilers each. In each pen, the broilers (*Cobb* strain) were provided with *ad libitum* access to feed and water. A multiphase feeding regime consisting of four diets, supplied by a commercial integrator, was kept over the growing cycle of 36 days to a market mass of approximately 1.8–2.1 kg. In one pen, the broilers received only plain water (control group; pen 1). In the other pen, water supplemented with a liquid additive (Biopolym®; Schulze & Hermsen GmbH, Dahlenburg, Germany) was provided 15 days after the start of the growing cycle (treated group; pen 2). Thereby, 3 g of water additive per 100 kg live weight per day of growing cycle dissolved in water in a ratio of 1 : 5 was added. Sawdust was used as the bedding material (0.9 kg/m^2) once at the beginning of the growing cycle. Further, the broilers were weighed in-house on permanently installed electronic scales (two in each pen). The cumulated feed conversion (in g/g) was calculated as Equation (3):

$$\text{Feed conversion}_{cumulated} = \frac{\text{feed}_{cumulated}}{\text{broiler mass}_{cumulated}} \quad (3)$$

The mechanical ventilation system with 18 rooftop stacks was controlled by the inside air temperature of the broiler barn, which was adjusted between 22 and 34°C, depending on the age of the broilers. After each growing cycle, the barn was cleaned and sterilized. Each pen of the barn was equipped with three pan feeding lines (*F*) and four nipple watering lines (*W*), alternating from side to side, beginning with a nipple watering line each. Between each pair of those seven functional rows and the walls of the long pen sides, eight rows were left (Figure 1). These remaining areas (*R*) are influenced neither by the dampness of the nipple watering lines, nor by the increased scratching around the pan feeding lines. By this procedure, both pens could be divided into 15 stripes each. The widths of the stripes influenced by the pen feeding and nipple watering lines were taken into account. Further, each pen was divided into 5 blocks of the same length, orthogonally to the stripes (Figure 1, blocks designated A–E).

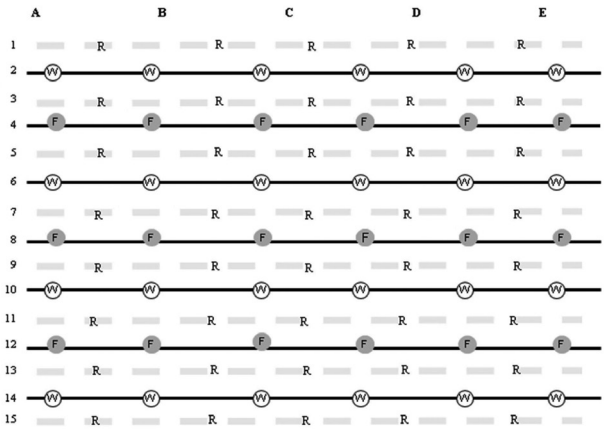

Figure 1. Schematic layout of one pen, showing in total 15 stripes of feeding lines (*F*), watering lines (*W*), and remaining areas (*R*). The pen is divided into 5 blocks marked A–E. During the study, 35 samples were collected weekly in each pen (5 *F*, 10 *W*, 20 *R*)

Emission and litter sample collection

Inside the two broiler pens, the NH_3 and N_2O concentrations (c_{in} in mg/m^3) and the air-volumetric flow rate (q in m^3/h) were measured using Innova type 1312 photo-acoustic multi-gas analyzer (INNOVA AirTech Instruments, Ballerup, Denmark) and by ventilators of MVP63 type (Hotraco Group, Hegelsom, the Netherlands). The sampling of NH_3 and N_2O was performed close to the exhaust air outlets at the bottom of the rooftop stacks (1 min sampling rate at each of the six places in both pens using a multiplexer to switch between places), whereby the gases were sucked through PTFE-hoses to the multi-gas analyzer. The mass-flow (m in g/h) was calculated according to Equation (4):

$$m = c_{in} \times q \quad (4)$$

During pretests, it was determined that the texture of the broiler litter differs among the areas inside the barn. The areas beneath the nipple watering lines were considerably wet, whereas the areas around the pan feeding lines were rather dry and scratched free from litter to some extent. During the experiment, litter samples from seven stripes per block in each pen were taken in the middle of each week during the 36-day growing cycle: one sample from a pen feeding line (*F*), two samples from a nipple watering line (*W*), and four samples from the remaining area (*R*). The litter samples from each stripe were collected at random. This resulted in 35 litter samples for the barn (5 *F*, 10 *W*, 20 *R*) (Figure 1). The samples were collected using short plastic pipes of 50 or 100 mm in diameter. The litter was cut down to the concrete floor in a cylindrical form, and the height of the litter from the floor was noted. For gathering the height for broiler litter at various sampling points in both pens we compared different statistical data of mean minimum values (5th percentile) and maximum values (95th percentile). This approach of gathering the height enabled us to calculate the volume for the samples by multiplying the height by the area covered by the pipes.

Statistical analysis

Based on the gathered height data for broiler litter at various sampling points in both pens by using short plastic pipes, a generalized linear model was used to (*i*) test differences between both pens and areas within the pens, (*ii*) use the factor estimates and their standard errors to get confidence intervals for litter height. Fixed influence factors in the model were pen (*ST*; i = 1, 2) and area (*AR*; j = 1, 2, 3). The course of the growing cycle was considered in form of a covariate "cumulative animal units" (*CAU*). The animal unit refers to 500 kg of broilers in a pen and is given daily by multiplying the number of broilers in the pen with the average mass of a broiler in kg and dividing by 500 kg. To get the cumulative value, the animal units calculated per day in each pen are summed up from the first day of the fattening period to the various days of measurement, respectively. The resulting model for the analysis of covariance only included the main effects – Equation (5):

$$y_{ijk} = \mu + ST_i + AR_j + x \times CAU + \varepsilon_{ijk} \quad (5)$$

where:

y_{ijk} = observed litter height in stable i and area j at measurement k
μ = general mean litter height
ST_i = fixed effect of pen i
AR_j = fixed effect of area j
CAU = regression coefficient for cumulative animal units given as x
ε_{ijk} = normally distributed random residuals

The model was fitted using the MIXED procedure of SAS (Statistical Analysis System, Version 9.3, 2012). The null hypotheses were that *ST*, *AR*, and *CAU* would have no influence on litter height, and they were tested at a significance level of 5%. Tests of pair-wise differences between the area levels were performed using the LSMEANS statement, and the SIMULATE option was used to adjust *P*-values for multiple testing to keep the global significance level.

Sample analysis

Samples from the *F, W,* and *R* areas were pooled before further processing. After weighing the pooled litter samples, their density was obtained by dividing mass by volume. Assuming that the heights were representative for the given stripe when averaged within the stripe, the total volume of each stripe was estimated by multiplying the stripe height, stripe width, and pen length. Then,

Table 1. Litter conditions during the growing cycle

Week	Dry matter (%)		pH value		C/N ratio	
	pen 1	pen 2	pen 1	pen 2	pen 1	pen 2
1	68.1 ± 1.14[1]	77.5 ± 1.28	6.38 ± 0.16	6.09 ± 0.05	15.3 ± 1.29	16.7 ± 2.29
2	70.3 ± 2.28	68.3 ± 0.81	6.98 ± 0.05	7.13 ± 0.09	11.6 ± 0.50	11.7 ± 0.74
3	65.0 ± 0.55	59.0 ± 1.09	8.49 ± 0.14	6.83 ± 0.24	9.75 ± 0.46	9.22 ± 0.27
4	57.9 ± 0.77	64.0 ± 0.61	8.17 ± 0.31	7.64 ± 0.25	8.91 ± 0.20	8.57 ± 0.24
5	62.5 ± 1.00	59.5 ± 0.74	8.20 ± 0.16	7.65 ± 0.22	8.76 ± 0.47	8.44 ± 0.29

[1]standard deviation

the total litter volumes of *F, W,* and *R* were multiplied by the respective calculated densities to obtain the litter masses. Afterwards, these results were used to determine the mass ratios between the *F, W,* and *R* areas. To mirror the total litter composition in each pen of the barn, these mass ratios were used to mix the sample material gained from each area to a single composite sample. After homogenization, the composite samples for both pens were divided into 15 sub-samples each.

In total, 30 samples of feed and fresh litter were ground (GRINDOMIX GM 200; Retsch GmbH, Haan, Germany) and analyzed for dry matter (drying at 105°C for 24 h in a convection oven), N (Kjehldahl procedure; DIN EN 25663), and carbon (C) (Dumas procedure; Vario EL III). The pH of the litter samples was determined immediately after collection by adding 100 ml of distilled water to 10 g of fresh litter, stirring and measuring the pH with an electronic pH meter Cond 720 (WTW inoLab, Koblenz, Germany).

RESULTS

Litter conditions

The litter dry matter content decreased during the time of the growing cycle from approximately 68 to 62% in pen 1 and from 78 to 60% in pen 2 (Table 1). New sawdust bedding had a pH between 6.38 (pen 1) and 6.09 (pen 2). The pH had been rising until the end of week 4, after which the litter pH did not change. Comparing the pH value in weeks 4 and 5 in pen 1, the pH was approximately by 0.85 higher than in pen 2. The C/N ratios showed a steady decrease from values of approximately 16 to 8.5 on the average.

Broiler performance

Within the first week of the growing cycle in each pen, 28 600 broilers of approximately 175 g body mass per broiler were kept. The broilers were removed after 36 days (week 5), and the mean masses of the broilers were 2.016 and 1.982 g for pen 1 and 2, respectively (Table 2). During the growing cycle, approximately 1.87% of the broilers in pen 1 died, and, consequently, 24 054 broilers were reared in pen 1. In the third week of the growing cycle in pen 2, approximately 1000 broilers died. This incident cannot be fully explained by the authors but may be related to an external accidental disturbance whereby the broilers were crushed to death. Thus, the mortality rose to 5.45% and, consequently, 23 023 broilers were produced in pen 2. The feed conversion (Equation 2) in both

Table 2. Broiler performance during the growing cycle

Week	Mass of broilers (g)		Cumulated mortality (%)		Cumulated feed conversion (g/g)	
	pen 1	pen 2	pen 1	pen 2	pen 1	pen 2
1	176	175	0.74	0.99	1.32	1.17
2	496	484	1.02	1.27	1.20	1.15
3	938	973	1.23	5.00	1.35	1.23
4	1510	1502	1.48	5.19	1.50	1.41
5	2016	1982	1.87	5.45	1.70	1.66

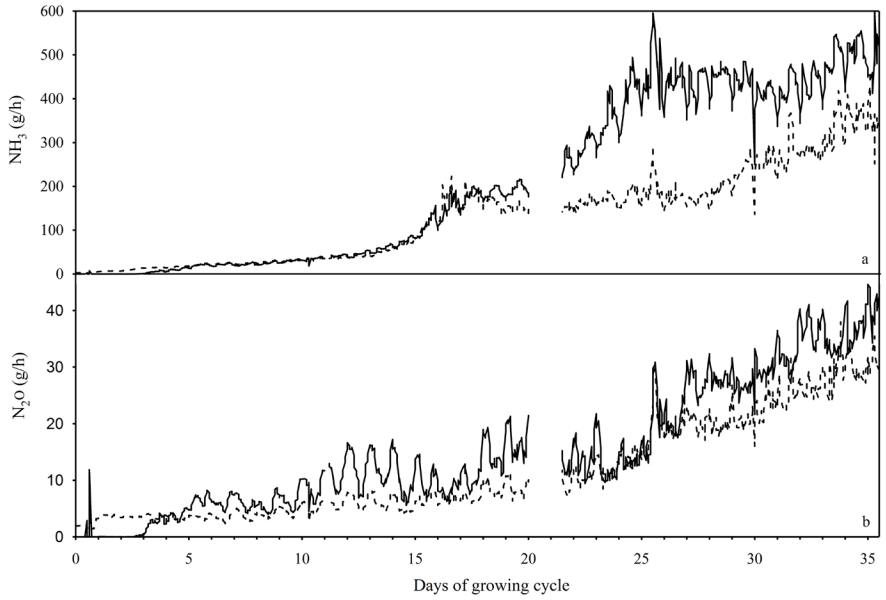

Figure 2. Time-series of (**a**) NH_3 and (**b**) N_2O mass-flow (*m*) from both pens with 28 600 broilers each

solid line = control group in pen 1, dashed line = treated group in pen 2

pens increased over the five weeks of the growing cycle. In contrast to pen 1, the feed conversion in pen 2 was consistently lower.

NH_3 and N_2O emissions

The directly measured air-volumetric flow rates and the concentrations of NH_3 and N_2O, shown as mass-flows (Equation 4), increased during the 36 days of broiler rearing (Figure 2). The sum of the NH_3 and N_2O mass-flows represents the total N emissions (N_{TNE}), which is an important output portion of the calculated N balance of the barn. The NH_3 mass-flow varied between 0 and 100 g/h in both pens during the first 15 days. For pen 1, the NH_3 mass-flow rose close to 600 g/h until day 25. Subsequently, the NH_3 mass-flow was nearly constant for the last 11 days and ranged 400–550 g/h. For pen 2, from day 15 to 28, the NH_3 mass-flow stagnated at approximately 180 g NH_3/h. In the following days, the NH_3 mass-flow continuously increased until the end of the growing cycle up to 400 g NH_3/h. Figure 2b shows the time series of the N_2O mass-flows during the growing cycle. For both pens, the mass-flows continuously increased until the end of the growing cycle, up to 45 g N_2O/h out of pen 1. It is worth noting that

Table 3. Weekly N masses of the cumulative N balance components for pens 1 and 2

Week	N inputs (kg)			N outputs (kg)				N balance (kg)		
	N_{feed}	$N_{litter\ (d0)}$	$N_{broiler\ (d0)}$	N_{tissue}	$N_{mortality}$	N_{litter}	N_{TNE}	N inputs (total)	N outputs (total)	rest
Pen 1										
2	494.4	4.20	27.1	382.2	1.2	129.3	7.3	525.7	520.6	5.1
3	1108.1	4.20	27.1	721.2	2.5	708.2	24.7	1139.5	1464.8	–317.2
4	1892.5	4.20	27.1	1158.1	4.9	773.5	78.7	1923.8	2015.2	–91.4
5	2848.4	4.20	27.1	1738.5	10.7	1163.3	140.7	2879.7	3053.3	–173.6
Pen 2										
2	470.1	4.20	25.6	372.0	1.4	153.5	8.2	500.0	535.1	–35.1
3	1043.5	4.20	25.6	719.6	17.6	703.5	24.3	1073.3	1464.8	–391.5
4	1730.4	4.20	25.6	1108.6	19.4	830.4	48.3	1760.2	2006.7	–246.5
5	2645.1	4.20	25.6	1777.9	23.1	1079.2	87.9	2674.9	2968.1	–293.2

week 1 insufficient for sampling

Table 4. Estimates for mean broiler litter masses for pens 1 and 2 derived from the statistical model and their lower (min) and upper (max) boundaries given by 95% confidence limits

Week	Output N_{litter} mean (kg)		Output N_{litter} min (kg)		Output N_{litter} max (kg)	
	pen 1	pen 2	pen 1	pen 2	pen 1	pen 2
2	129.92	153.54	97.14	124.91	162.69	182.16
3	708.24	703.45	617.38	623.49	799.11	783.40
4	773.50	830.44	716.30	770.19	830.70	890.68
5	1163.26	1079.17	1107.94	1030.15	1218.58	1128.19

*week 1 insufficient for sampling

the N_2O mass-flow of pen 1 was always higher than that of pen 2.

N mass balance

Summaries of the collected components of the N mass balance according to Equation (2) are shown in Table 3. The data are presented separately for both pens.

Table 4 shows the results of applying the estimated litter heights to calculating litter volume and thereafter calculating litter mass per pen, for mean height, minimum height, and maximum height. Minimum and maximum are given by the 95% confidence limits of the mean.

All three factors in the model (see Equation 5) had significant influence on litter height (*ST*: $P = 0.0058$; *AR*: $P < 0.0001$; *CAU*: $P < 0.0001$). Mean litter height in pen 1 was lower by 0.22 ± 0.08 cm (mean ± SE) compared to pen 2. Litter height was 1.87 ± 0.11 cm, 2.23 ± 0.07 cm, and 2.58 ± 0.05 cm in areas *F, W*, and *R*, respectively. Per *CAU* an increase of litter height by 0.002 ± 0.0001 cm was estimated.

DISCUSSION

Broiler performance

The average weekly feed conversions showed a steady increase with broiler age over the observed growing cycle with a maximum of 1.65 g/g on average in week 5 (Table 2). These findings for the feed conversions agree with the results of Coufal et al. (2006) and Dong et al. (2011). Coufal et al. (2006) reported an average feed conversion of 1.67 kg/kg for 18 consecutive flocks reared over days 40–42. Dong et al. (2011) calculated an overall feed conversion of 1.75 kg/kg for caged broiler production. Comparing the present results of both pens, the feed conversion of the treated group in pen 2 is slightly lower with similar slaughter weights (Table 2). This effect is assumedly attributed to the water additive deployed in pen 2. Thus, the water additive Biopolym® can be rated as a method of abatement of NH_3 emissions, as recommended by Ferguson et al. (1998) and Robertson et al. (2002).

N mass balance

The purpose of calculating mass balances is to monitor the fate of N inputs and outputs. In addition to all feed, the broilers and bedding material entering the barn from the beginning of the growing cycle were considered as N inputs. The feed accounted for 99% of all the N inputs, which confirms the results of Mitran et al. (2008). The broiler masses and the N mass of the tissues presented relatively consistent values, which ranged 1.739–1.778 kg N at the end of the growing cycle in pens 1 and 2, respectively (Tables 1 and 3). This is equal to an average 59% transformation of the cumulative N intake to the broiler tissue (Table 5). Figure 3a, b clarifies the proportion of N outputs per broiler for both pens. The main output of the feed N source was the N accretion in the broiler tissue, averaging 75 g for pens 1 and 2 in week 5 of the growing cycle. The secondary output was the N accumulation in the litter. These observations are similar to the results of previous studies listed in Table 5.

The amount of N in the outputs varied with broiler age and increased with time, which agrees with the findings of Dong et al. (2011). The term Rest between the total N inputs and measured N outputs varied between 7 and 13 g N per broiler at the end of the growing cycle. This Rest has to

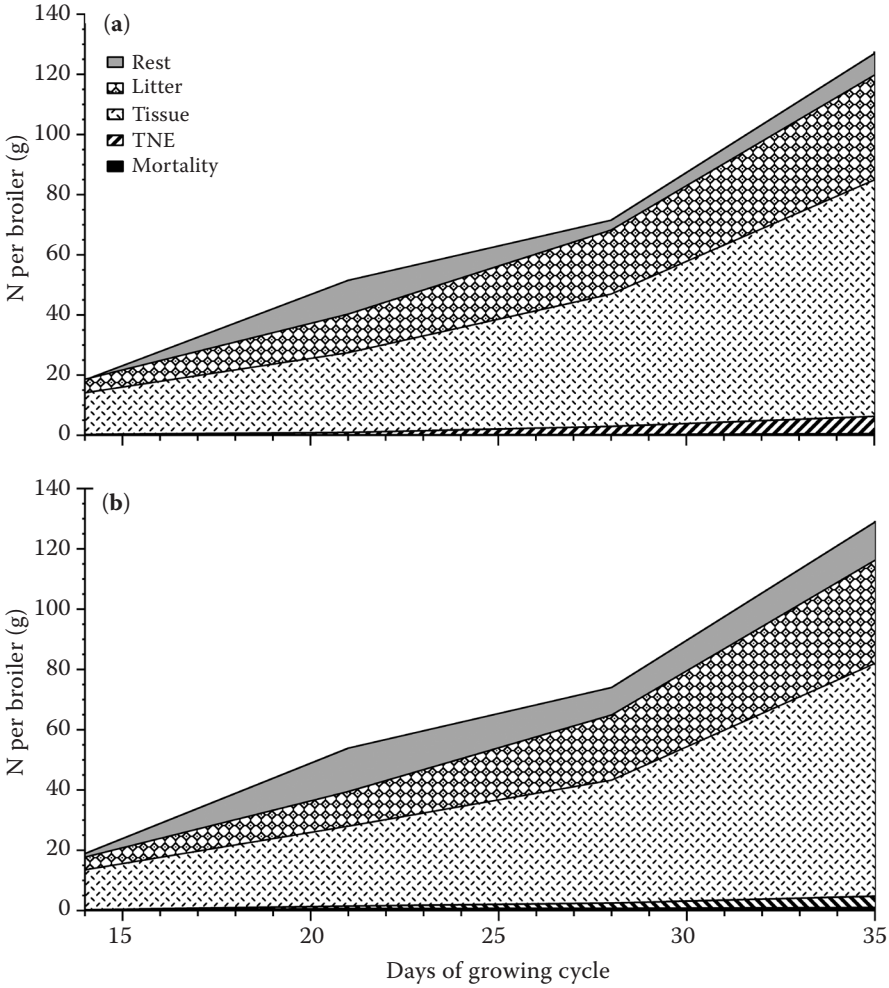

Figure 3. Accumulated N output components during growing cycle in (**a**) pen 1 and (**b**) pen 2

be rated as an imbalance within the mass balance, marked with grey colour in Figure 3a, b. The variations in estimating the N in the broiler tissue were assumed to be modest, according to the commonly accepted recommendations for N concentration in protein. This was already used in previous works, e.g. Elwinger and Svensson (1996). Moreover, the N_{TNE} emissions were measured with a reliable and approved method. Thus, as N is the most uncertain component, we presumed the N accumulation in the litter, which amounted to 38% of the mean at the end of the growing cycle.

From the very beginning of the present study, we took this issue into account, employing pretests to determine the differences in the broiler litter texture. Then, during the experiment, the focus was directed to accurately mirror the heterogenic variability of the litter by an intensive collection of samples in different stripes (see Emission and litter sample collection). In addition to this pro-

Table 5. Summary of N output components of different mass-balance studies

Reference	Broiler age (days)	N in tissue (%)	N in litter (%)	N in emission (%)
von Bobrutzki (present study)	36	59	37	4
Dong et al. (2011)[1]	42	59	34	3
Mitran et al. (2008)[2]	42	67 ± 2	26 ± 2	13 ± 0.4
Coufal et al. (2006)	40–42	57	22	21
Guiziou and Béline (2005)	35	59	21	20
Patterson et al. (1998)	57	51	31	18

[1]discrepancy of 4% in N outputs

[2]discrepancy 3–5% in N outputs

cedure, we assumed that the heights of the litter estimated by the statistical model were representative for the given areas and calculated the litter masses. Despite these extensive sampling efforts, the calculation of the N accumulation in the litter can be assumed to be the major source of error, as can be seen in the still large confidence intervals for the mean litter masses in Table 4. Thus, the N accumulation in the litter is presumed to be the overestimated component within this mass balance. For future experiments, determining the height of the litter in the cylindrical pipes used to calculate the volume of the samples should be one central aspect, and it can be reached by increasing the reading accuracy of the height of the litter inside the pipes. Another central aspect is to estimate the total volume of litter inside the barn as good as possible. This could be achieved by not only using the heights of the litter samples to estimate average litter heights, but also measuring litter heights in additional places in the barn, e.g. in every stripe instead if just in the ones selected for sampling. By subtracting the term Rest from the N output in the litter (Figure 3a, b), the imbalance would be corrected. As a result, it can be noted that a careful and thorough analysis (especially of the volume) of the litter must be a prerequisite of any reliable N mass balance for broilers. This fact should be assessed as a major uncertainty compared to the limitation of estimating broiler weight and feed consumption, as stated by Phillips et al. (2000).

Despite the fact that the results from this study agree well with those obtained in other studies, the N_{TNE} in our experiment were consistently lower compared to the other references (Table 5). An exception was outlined by a recent study of Dong et al. (2011), where a complementary approach was used, while including the same instrument for measuring N_{TNE}. Comparing the results of this study and those of Dong et al., the recorded N_{TNE} were in line with each other.

It is important to note that the mentioned literature values in Table 5 were mainly applicable for broilers raised on built-up litter, where the N loss in the form of emissions was higher. Moreover, the listed N in the emissions was assumed to be the difference between the inputs and outputs. This paper reports a mass balance where the components were quantified by *in situ* measurements. Therefore, it can be expected that the stated lower percentage of N_{TNE} from this study is a more appropriate attempt.

The percentage of N in broiler tissue was consistent throughout all of the studies listed in Table 5 except Mitran et al. (2008), who reported a higher partition of N outputs (67%) in the broilers. The authors explained this fact by an improved genetic selection of broilers and better formulation of diets. In general, Mitran et al. (2008) stated that a higher N accumulation in broilers minimizes the N in the litter and the N emissions. As a consequence, the lower N_{TNE} found in this study can be assumed to result in a higher proportion of N in the litter. This case should be targeted to improve the subsequent fertilizing value and benefit sustainable broiler management. In contrast, Patterson et al. (1998) reported that the N in the tissue accounted for only 51% of the total output. Van der Hoek (1998) estimated an average N accumulation of approximately 34% for poultry. These prior results do not properly reflect the contemporary state of broiler breeding in which an improvement of 2–3% per year in the efficiency of meat production must be assumed (Gous, 2010).

NH_3 and N_2O emissions

The increased NH_3 emission mass-flow (m) over the growing cycle (Figure 2) is consistent with the studies of Elwinger and Svensson (1996) and Redwine et al. (2002). This increase of NH_3 is caused by the accumulation of excreta from the broilers and a microbial growth in the litter. Calculated from the sum of m over the growing cycle, as shown in Figure 2, the emissions ranged 3.8–6.0 g NH_3 per broiler for pen 2 and 1, respectively. Previous emission rates for the same barn yielded 2.4 g NH_3 per broiler and growing cycle (von Bobrutzki et al., 2011). This lower value can be explained by the changed temperature conditions due to the different season of the year in the two experiments, which can be assumed to be an important factor contributing to the variability of the overall N (Coufal et al., 2006). Further, Bicudo et al. (2004) found that the NH_3 emission rates from broiler barns varied as widely as by a factor of 50. Guiziou and Beline (2005) reported an average emission rate of 5.74 g NH_3 per broiler for a 35-day growing cycle. The NH_3 emission estimated by Elwinger and Svensson (1996) was equal to 29.5 g NH_3 per broiler during a 41-day growing cycle. Patterson et al. (1998) used an N balance approach to estimate the NH_3 emissions from two commercial broiler facilities with 16.6

and 28.5 g per broiler in 44 and 57 days of fattening, respectively. In this context, the present results can be rated as relatively low NH_3 emissions. Nevertheless, it must be noted that the data gap, which occurred on day 20 for approximately 36 h (Figure 2), slightly minimized the real emissions. The measured N_2O emissions varied between 0.34 and 0.44 g N_2O per broiler during the growing cycle, which equates to 0.12 and 0.15 g N_2O/h per 500 kg in pen 2 and 1, respectively. These findings showed lower N_2O emissions than previous research that showed an emission of 0.59 g N_2O/h per 500 kg (Wathes et al., 1997). Possible explanations are likely the improved genetic selection in commercial broilers and better formulation of diets, such as phase feeding and better balancing of amino acids. Further, the lower N_2O emissions can be explained by the different climatic conditions during the two experiments.

Ammonia emission is influenced by the temperature, dry matter content, and pH of the litter (Redwine et al., 2002). The observation that the pH in the litter rose until the end of week 4 and did not change after that time (Table 1) is in line with the results of Coufal et al. (2006). The modest NH_3 volatilization during the first 15 days, shown in Figure 2a, occurred at pH 7 and below (Table 1). This fact is supported by the general statement that the NH_3 release is depressed at pH < 7 (Lahav et al., 2008). Further, the tendency of lower pH values in pen 2 during the whole time of the growing cycle (Table 1) can be rated as a depression of the NH_3 emission in pen 2. Nevertheless, the ventilation rate is the most influential factor concerning the variability of NH_3 inside the barn. More and more ventilation became necessary as the cycle progressed because a certain internal air temperature had to be maintained to keep pace with the broilers' physical growth and because the NH_3 concentrations rose as the birds grew in size.

Further, with the progressed age of the broilers, the dry matter content of the litter showed an expected decrease, which corresponds to the findings of Robertson et al. (2002). The C/N ratio was reduced to 8.6 on the average at the end of the growing cycle. Elwinger and Svensson (1996) observed a higher C/N ratio of approximately 10 at the end of their study. However, a lower C/N ratio in the litter reduces the microbial activity. Such a decrease in microbial activity results in a decreased release of NH_3 from the litter (Coufal et al., 2006). Thus, less N in the litter was volatilized as NH_3. By comparing both pens of the barn, it became apparent that most of the characteristics listed in Tables 1–3 appeared higher in pen 1. This finding points to the fact that the water additive deployed in pen 2 exerted a positive impact on broiler performance and litter conditions. Therefore, better N use efficiency and N accretion in the broiler tissue can be expected, which represents one feasible abatement strategy for NH_3. Nevertheless, future work will be required to further verify this enhanced decreasing effect.

CONCLUSION

In conclusion, this study presents a mass balance approach for characterizing the fate of N for a commercial broiler barn. The N inputs in the feed, chickens, and bedding material were related to the N outputs in mature broilers by directly measured N_{TNE} emissions and the N accumulation in the litter. The feed N input was mainly accumulated in the broiler tissue (59%), followed by the N accumulation in the litter (37%). These findings agreed well with previous studies. Nevertheless, the comparison of the percentage of volatilized N emissions with previous research showed up to 5-times lower values. This research demonstrated that the calculation of N accumulation in the litter can be assumed to be a major uncertainty within the mass balance approach. For future studies, determining a more appropriate representation of the heights of the litter, representative of the areas of varying litter characteristics within the barn, should be attempted to calculate the litter masses. As a further important outcome, it can be noted that an extensive sampling of the litter during the cycle is a prerequisite for characterizing the occurring temporal variability of the litter. Then, it becomes possible to identify and establish feasible innovations within the management practices. However, the deployed water additive showed a tendency to reduce N_{TNE} emissions and to enhance broiler and litter performance. Thus, this study encourages ongoing measurements, valuable for improvements in a sustainable broiler production.

Acknowledgement

We greatly appreciate the support of the farmer who encouraged the extensive measurements in

the broiler barn. Further, we wish to acknowledge the technical and logistical support of the Department of Engineering for Livestock Management. Special thanks go to K. Schröter, U. Stollberg, and D. Werner.

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Received: 2012–12–31
Accepted after corrections: 2013–07–14

Corresponding Author

Dr. Ing. Kristina von Bobrutzki, Leibniz Institute for Agricultural Engineering Potsdam-Bornim, Department of Engineering for Livestock Management, Max-Eyth-Allee 100, 14469 Potsdam, Germany
Tel. +493 315 699 521, fax +493 315 699 849, e-mail: kvbobrutzki@gmail.com