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The effect of manure and litter handling and indoor climatic conditions on ammonia emissions from a battery cage and an aviary housing system for laying hens

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Abstract

Ammonia emissions from both traditional and new welfare-based housing systems for laying hens must be reduced to prevent detrimental effects on the environment. In a comparative study the effect of only manure handling (variation in drying and removal frequency) in a battery cage and the effect of manure handling (as in battery cage system) and litter treatment (removal of litter) in a Tiered Wire Floor (TWF) aviary system on the emission of ammonia were investigated. Each system housed 6480 hens, treatments were varied in time, and effects were analysed by means of time-series analysis.

The hens in the TWF system dropped 22.5% of their excreta in the litter and the remaining part, like all manure in the battery cage system, was dropped on the manure belts. The estimated emission from the manure on the belts in both systems was 18.8 g h^{-1} (daily mean, manure removal twice a day), whereas the emission from the litter in the TWF system amounted to 62.5 g h^{-1}. Emission from the belt manure on a typical day increased with 14, 39, 109 and 177% from the 1st until the 4th day after manure removal. The effect of temperature and water vapour pressure difference on emission was +17 and −22% per degree and per kPa, respectively. Drying of manure on the belts increased the dry matter content of the manure and showed a tendency to lower emissions.

The dry matter content of the litter varied between 780 and 840 g kg^{-1}, the mean total nitrogen content was 3.3% of the dry matter, and the layer thickness varied between 2 and 9 cm. Both the unionised ammonia content, which ranged between 20 and 190 mg kg^{-1}, and the layer thickness of the litter influenced the emission from the litter positively.

Keywords: ammonia emission, laying hens, battery cage, aviary housing, manure and litter handling

Introduction

Ammonia emissions from both traditional and new welfare-based housing systems for laying hens have to be reduced to prevent detrimental effects on the environment (Heij & Schneider, 1991). This implies that the level of ammonia emission will be an important factor for the acceptance of these systems and their sustainability in the future. Blokhuis & Metz (1992) concluded that aviary housing systems for laying hens meet most of the behavioural needs of the hens and seem promising in terms of egg production. However, one of the drawbacks of these housing systems is a high ammonia emission. Preliminary research into the emission of ammonia from the Tiered Wire Floor (TWF) aviary system showed emission rates that were about three times higher than the rates from battery houses (Groot Koerkamp & Metz, 1992). Further research into the factors that are involved in the emission of ammonia is necessary to develop solutions so that ammonia emissions from these housing systems can be reduced.

Manure handling and litter conditions strongly affect the emission of ammonia from housing systems for laying hens. The degradation process of uric acid and undigested proteins in the manure and litter to ammonia is mainly influenced by dry matter content, temperature and pH. The drying of manure and litter is influenced by the temperature, water vapour pressure difference and velocity of the air. The total nitrogen and ammonia concentrations in the manure and litter are influenced by the degradation process and the volatilization of ammonia (Groot Koerkamp, 1994).

This paper summarizes a comparative study of the effects of manure handling in a battery cage and a TWF system and the effects of litter treatment in the TWF system on ammonia emissions. Its' purpose is to present insight about the quantitative effects of the various factors influencing the ammonia emission and explain differences between the two housing systems.

Materials and methods

Housing systems

The hen house in this experiment consisted of two completely separate rooms of 14 by 23 m. The rooms were identical except for exterior insulation of the floor of the room with the aviary system. Each room had its own light regulation and a mechanical ventilation system. Outside air entered the rooms through inlets under the ridges, mixed with the indoor air and was blown outside by means of ventilators in the ceiling. The room temperatures were set at 22 °C. One room was equipped with a conventional battery cage system with manure belts. The cages were 0.50 m wide and 0.45 m deep, could house up to five hens and were placed in six rows of three tiers. The other room was equipped with the Tiered Wire Floor (TWF) aviary system. It consisted of four rows of stacked wire floors and four rows of laying nests. The concrete floor was completely covered with approximately 5 cm of sand at the beginning of the laying period. The characteristics of both systems are given in Table 1. A

Table 1. Characteristics of the battery cage system and the Tiered Wire Floor (TWF) system.

	Battery cages	TWF
Number of hens (20 weeks of age)	6480	6480
Stocking density (hens m^{-2} groundfloor)	20.1	20.1
Stocking density (m^{-2} hen)	0.045	0.100
Ventilation capacity (m^3 h^{-1} per room)	30,000	30,000
Number of rows of tiers	6	4
Number of levels (cages or wire floors)	3	3
Litter area (m^2)	0	303

cross-section of the TWF system is given in Figure 1. The TWF system is extensively described by Ehlhardt *et al.* (1988, 1989) and Blokhuis & Metz (1992).

The manure produced by the hens dropped onto the conveyer belts underneath the cages in the battery cage system and underneath the wire floors of the tiers in the TWF system. All belts were equipped with a manure drying system (Kroodsma *et al.*, 1985). Air from outside was warmed up in a heat exchanger, one for each room, and blown through tubes with holes above the manure belts (holes with a diameter of 3 mm and a distance between them of 10 cm). The conveyer belts transported the belt manure outside the house where it was taken away by means of containers. The hens in the TWF system deposited their fresh droppings partly in the litter.

Both the cage and the TWF system were, in length, divided into two sections. In the TWF system sections were separated by means of wire netting. In each system one section was used for 3240 light-weight White Leghorn hens (LSL) and the other for 3240 middle-weight Brown Leghorn hens (ISA Brown). Hens were fed a commercial diet at a restricted level. Water was supplied during the lighting period by means of nipple drinkers. At night the water supply was cut off. Light schemes based on optimal management were used: 16 hours light (L): 8 hours dark (D) in the TWF

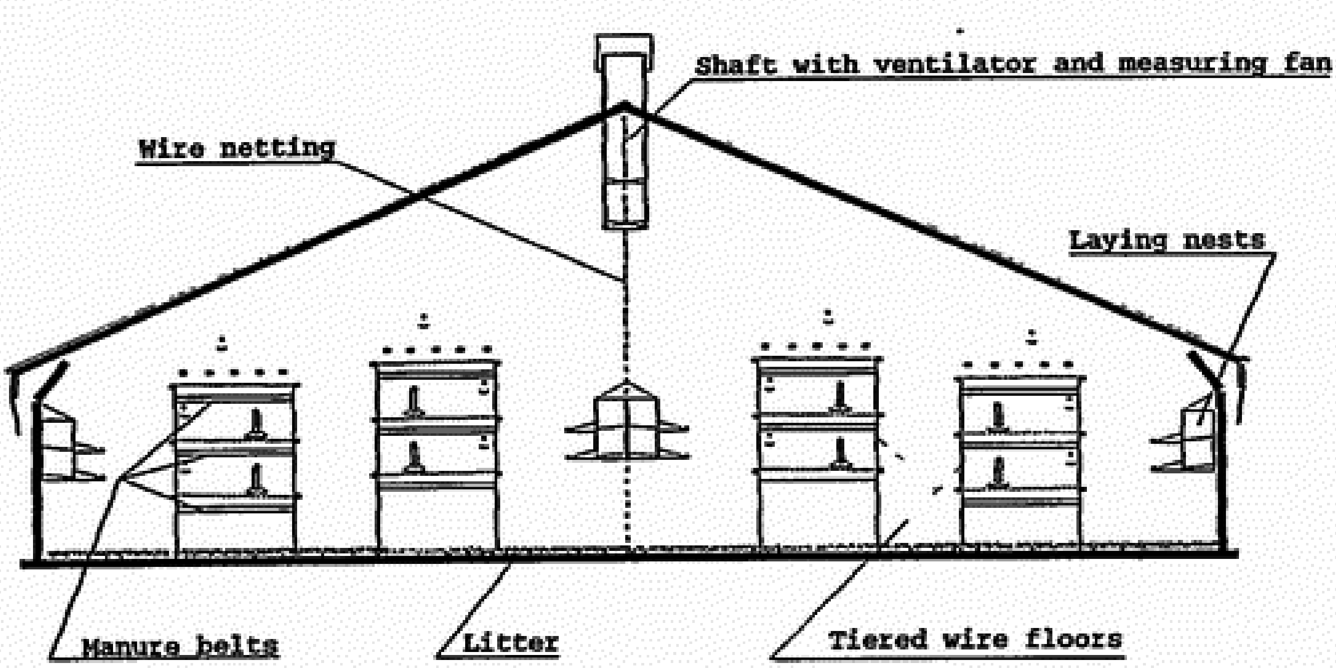

Figure 1. Cross-section of the Tiered Wire Floor (TWF) system.

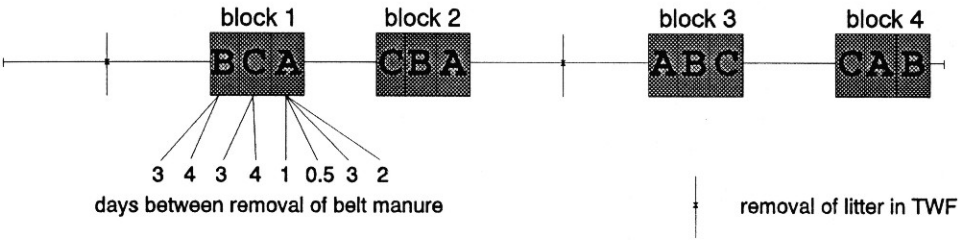

Figure 2. Treatment scheme with the treatments of manure on the belts for the Tiered Wire Floor (TWF) system and battery system; without manure drying (A) or with manure drying on the belts with equal (B) or adjusted (C) distribution of drying air and manure removal interval in days. The litter treatments in the TWF system are also indicated.

system, and an intermitting scheme of 1L:3D per hour during 16 hours in the cage system. Both cage and TWF hens were debeaked to prevent problems with cannibalism.

Treatments

The experiments were carried out with hens that were 41 weeks old at the start of the experiment. The experiment lasted a total of 173 days (March until September 1992). The treatment schedule is given in Figure 2. The age of the hens (weeks) was used as the time basis. The handling of manure on the belts in both systems was varied and repeated in four blocks, beginning in weeks 45, 50, 59 and 63. Three drying treatments were applied: A (no drying), B and C (drying). Drying treatment C was only applied in the TWF system and differed from treatment B. In treatment C most of the drying air was passed over the manure on the belt of the upper floors. Each drying treatment lasted 7 days and was randomly carried out within a block. Within a drying treatment the removal frequency was varied. For drying treatments B and C, manure was removed after 3 or 4 days; for drying treatment A manure was removed after .5, 1, 2 and 3 days. These removal frequencies were assigned randomly within a drying treatment. All days in the experiment were given a letter-number combination. The letter indicated the drying treatment, whereas the number indicated the number of days since the belt manure had been removed. For example, code B3 was used for the 3rd day after manure removal when manure drying treatment B was applied. This day was preceded by days with code B2 and B1. Manure was removed between 1100 and 1200 hours, and for treatment A0.5 also between 2000 and 2100 hours. To reduce the thickness of the layer, most of the litter in the TWF system was removed at week 43 and again at week 55. Manure drying treatment B was applied during the periods of the litter treatment and between the blocks.

Measurements

Measurements of ammonia concentrations and ventilation rates were continuously carried out in all ventilation shafts according to the method described by Scholtens

(1993). Temperature and relative humidity were measured by means of combined sensors (Rotronic I–100) that were placed in the centre of each room: one above the manure belt of each tier, one at a height of approximately 2.5 m and in the TWF room also one above the litter. The temperature in the litter was measured at four spots, two in each section (AD-592 sensors). A combined sensor was placed underneath the ridge in the centre of the house at a height of 2 m, so that the temperature and humidity outside could be measured as well. Hourly averages of ammonia concentration, ventilation rate, temperature and humidity were automatically recorded (Bleijenberg & Ploegaert, 1994). The ammonia emission was calculated to be the difference between the concentration of ammonia in the exhaust air and in the inlet air multiplied with the volume of exhaust air. The following data were calculated: total ventilation rate, mean ammonia concentration of the exhaust air, total ammonia emission, mean temperature and humidity above the manure belts and mean temperature in the litter. Air temperature and humidity above the manure belts and the litter were used to calculate the saturated and the actual water vapour pressure of the air (Anon., 1993a). The water activity of manure and litter with a dry matter content above 20% (wet base) and temperatures between 20 and 30 °C is 0.9 (Beeking *et al.*, 1994). The water vapour pressure in the manure and litter was therefore calculated to be 0.9 times the saturated water vapour pressure. Daily means were calculated from noon until noon. Egg production and feed and water intake by the hens were daily registered per section.

Manure and litter samples were taken separately in the sections. Samples of belt manure were taken during the drying and removal treatments in all blocks. During the removal of the belt manure approximately 10 samples of manure were taken from the conveyer belt at a fixed time interval and mixed. This sample was taken for analysis of dry matter content (NEN 6620). Manure samples of days with treatment A0.5 were also analysed on the content of total nitrogen (NEN 6481), total ammoniacal nitrogen (TAN) (NEN 3235 4.1), inorganic matter (NEN 6620) and pH. The pH was determined in a mixture of two parts demineralised water and one part manure. The amount of belt manure per section was weighed after each treatment A2 (a total of four times). Litter samples were taken during each treatment block, before and after litter removal (total nine times) from 10 designated spots that were evenly distributed per section. The samples were mixed and analysed on total nitrogen, TAN, dry and inorganic matter content and pH. Along with the litter samples, the quality of the litter and the thickness of the layer were measured (total eight times). The quality was subjectively estimated on a linear scale from 1 (wet and soppy) to 9 (dry and friable).

Statistical analysis

All singular manure and litter data were statistically analysed (ANOVA) on an arithmetic scale whereas the measurements in time were used as pseudo-repetitions. The trends in TAN content (NH_3 plus NH_4^+) and pH in the litter were modelled with spline-functions of order 6 with time as the independent variable. The unionised ammonia content of the litter (NH_3) was calculated with the empirical relation for poultry manure of Hashimoto (1972). The pK_a of this empirical relation is 10.1 instead of 9.4 that is used for aqueous solutions. The rate of increase of the thickness of the layer of litter was estimated with a linear model with time as the independent variable.

The differences between the battery cage and the TWF system in the ventilation rate, the ammonia concentration in the outgoing air and the ammonia emission were quantified by using the natural logarithm of these variables. The use of the logarithmic scale implies that proportional effects were studied instead of absolute effects. The logistic curve was used to describe the fixed effects of the outside temperature on the ventilation rate in both housing systems. The deviation was assumed to follow an autoregressive process of order 1. The calculation method was essentially the same as the one used for the ammonia emission.

Model for the ammonia emission

The ammonia emission process is influenced by time-dependent processes such as air temperature and ventilation rate. Thus statistical techniques involving time-series analysis were used. The natural logarithm of the daily mean ammonia emission (called log emission), instead of the absolute level of emission was modelled. In this way the emission is kept positive. The variance is assumed constant on the log scale and corresponds to a constant coefficient of variation of the emission. It is our experience that this is more realistic than the assumption of constant variance for the emission itself. A linear model for log emission means a multiplicative model for emission. Let z_t be the log emission at time t, η_t be its mean and ε_t be the deviation, then

$$z_t = \eta_t + \varepsilon_t. \tag{1}$$

Hence, η_t will depend on time-dependent explanatory variables and ε_t will represent the deviation of observation z_t from its mean. The mean and the deviation are functions of time. For ease and clarity of notation the index t is omitted in the equations below. The emission was considered to be the result of two separate and independent processes. The first was the emission from the belt manure and the other was the emission from the litter. Belt manure existed in both systems, but litter existed only in the TWF system. Define η_{bm} and η_{litter} as the mean log emission from the belt manure and from the litter respectively. The mean log emission from both processes together then becomes:

$$\eta = \log\left(e^{\eta_{bm}} + \delta_{TWF} \cdot e^{\eta_{litter}}\right) \tag{2a}$$

in which δ_{TWF} indicates which observation belongs to the TWF system (δ_{TWF}=1) and which to the battery cage system (δ_{TWF}=0). In this way it was possible to model the measurements of both systems in one analysis. The separate processes were represented by the following equations:

$$\eta_{bm} = C_{BC,\,bm} + E_{TWF,\,bm} + E_{A,B,C} + E_{DAR} + \alpha_1 \cdot T_{bm} + \alpha_2 \cdot P_{diff,\,bm} \tag{2b}$$

and

$$\eta_{litter} = C_{TWF,\,litter} + \alpha_1 \cdot T_{litter} + \alpha_4 \cdot P_{diff,\,litter} + \alpha_5 \cdot C_{NH_3,\,litter} + \alpha_6 \cdot D_{litter} \tag{2c}$$

In this way the daily mean emission from both systems for each day in the experiment was estimated. The letter-number combination of each day was used for the estimation of the effect of the drying treatment and removal frequency.

The deviation ε_t was assumed to follow an autoregressive process of order 1:

$$\varepsilon_t = \phi\, \varepsilon_{t-1} + a_t \tag{3}$$

with a_t being independently distributed errors called innovations, with zero mean and variance σ^2_a, the innovation variance. The ϕ is the correlation between successive observations. The ε_t is a weighed sum of past innovations. The relationship between σ^2_ε, the variance of ε_t, and σ^2_a is:

$$\sigma^2_\varepsilon = \frac{\sigma^2_a}{1-\phi^2} \tag{4}$$

Estimation and inference

The relationship between η_t and the explanatory variables, expressed in equations (2a) to (2c) is partly nonlinear. To keep as much of the linearity as possible the model was considered a generalised linear model (GLM) that links η to the contribution of the belt manure η_{bm}, whereas η_{litter} is the contribution of the litter, which was considered to be the nonlinear part, containing the parameters of the link function. The advantage of this is that the general solution of GLM can be used, being an iterative reweighed regression, with adjusted response and explanatory litter variates and weights depending on the relative contribution of the belt manure. Appendix 2 derives and describes the algorithm in detail.

The solution for the fixed part of the model has been formulated as a linear regression, therefore the complete model is linear with autoregressive errors. For this model a maximum likelihood solution can be obtained with existing software, such as the time-series facilities of Genstat 5, Release 3 (Anon., 1993b). The analysis results in estimates of regression coefficients with standard errors.

The assumption of constant innovation variance after fitting of the model was checked by inspecting residual plots and found to be adequate for the purpose of this research. The assumption of an autoregressive process of order 1 was checked by inspecting the partial correlogram and the spectrum and was also found to be adequate.

The σ^2_ε was used as measure for the goodness of fit, which resulted from the innovation variance σ^2_a and autoregressive parameter ϕ. The amount of variance explained by the regression parameters in equations (2a) to (2c) was indicated by the percentage of σ^2_ε. Estimated standard errors (s.e.) of parameter estimates of time-series analyses were multiplied by 1.96 to calculate 95%-confidence intervals. A sensitivity analysis of the model was carried out where explanatory variables were varied between the minimum and maximum value of the measurements.

Results

Production results

The production results of the hens in the two housing systems are shown in Table 2. Statistical analysis of the production results was not found to be useful due to the lack of repetitions. Hens in the TWF system produced almost the same number of eggs as the hens in the battery cage system. The egg weight of the hens in the TWF system was 1.6% lower and their feed intake was 2.6% higher. This resulted in a 4.6% higher feed conversion ratio. The water:feed ratio was almost equal for the hens in both system, as was mortality, which was low.

Manure and litter

Table 3 shows the production and composition of belt manure. The amount of dry matter of manure on the belts in the TWF system was about 80% of the manure production in the battery cage system. The dry matter content of the belt manure sampled after 12 hours, which from now on will be called faeces, was 48 g kg^{-1} higher in

Table 2. Mean production results of the laying hens in the battery cage system and the Tiered Wire Floor (TWF) system from 20 to 84 weeks of age.

	Battery Cages			TWF		
	LSL	Isabrown	Total	LSL	Isabrown	Total
Number of hens housed	3240	3240	6480	3240	3240	6480
Egg production (number of eggs housed-hen^{-1})	366.3	352.5	359.4	364.1	350.7	357.4
Egg production (kg egg housed-hen^{-1})	23.65	23.09	23.37	23.45	22.52	22.99
Feed consumption (g hen^{-1} day^{-1})	118.3	116.8	117.6	120.5	120.6	120.6
Feed conversion ratio (kg feed kg^{-1} egg)	2.18	2.21	2.19	2.25	2.32	2.29
Water: feed ratio (g g^{-1})	2.04	2.00	2.02	2.02	1.97	2.00
Mortality (%)	7.19	6.02	6.61	7.27	9.67	8.47

Table 3. Mean production (during treatment A2) and composition (during treatment A0.5) of belt manure for the battery cage system and the Tiered Wire Floor (TWF) system.

Manure		Battery cages mean	TWF mean	s.e.d.
Production	g hen^{-1} day^{-1}	137.5	89.4***	4.52
	g dry matter hen^{-1} day^{-1}	38.3	30.5***	1.80
Dry matter content	g kg^{-1} manure	244	292***	8.0
Total N	kg^{-1} dry matter	50.5	45.1**	1.92
Total Ammoniacal Nitrogen	% of toatal N	21.3	18.9	2.56
pH	–	6.7	6.8	0.09
Ash content	% of dry matter	24.3	22.9*	0.52

* $P<0.05$, ** $P<0.01$, *** $P<0.001$

Table 4. Mean dry matter content (g kg^{-1}) of belt manure of four blocks after 8 drying and removal treatments (see Figure 2) for the battery cage system and the Tiered Wire Floor (TWF) system.

Treatment	Battery cages	TWF
A0.5	245.9[c]	290.3[c]
A1	278.9[b]	323.4[b]
A2	288.7[b]	333.2[b]
A3	286.7[b]	331.2[b]
A4	300.2[b]	344.6[b]
B3	351.2[a]	395.6[a]
B4	364.6[a]	409.1[a]
C3	–	400.1[a]
C4	–	413.6[a]

[a–c] Column means without a common superscript differ significantly ($P<0.05$).

Table 5. Quality, thickness of the layer and composition of the litter in the Tiered Wire Floor (TWF) system (means and s.e.).

Quality	Layer thickness	Dry matter content	Total N	Total Ammoniacal Nitrogen	pH	Ash content % of dry matter
–	10^{-2} m	g kg^{-1}	g kg^{-1} dry matter	% of total N	–	
(n=16)	(n=16)	(n=18)	(n=18)	(n=18)	(n=18)	(n=18)
8.9 (0.06)	5.4 (0.50)	805 (6.3)	33.3 (0.36)	7.1 (0.60)	8.5 (0.10)	27.6 (0.31)

the TWF system and the total nitrogen content was 5.4 g kg^{-1} lower. These differences were significant. About 20% of the nitrogen was present as ammoniacal nitrogen, and the pH was less than 7. Table 4 shows that for all drying treatments and removal frequencies, higher dry matter contents were found in the TWF system. In both systems, dry matter contents of the manure on the belts increased as it remained in the house longer. Through drying of manure, treatment B, the dry matter contents in both systems were raised significantly as compared to not drying. The adjusted air flow in treatment C in the TWF system did not result in higher dry matter contents than in treatment B.

The litter in the TWF was dry (805 g kg^{-1}) and friable (quality 8.9 units), see Table 5. The total nitrogen content was 33.3 g kg^{-1} dry matter, which was considerably lower than the concentration in the faeces. The mean ash content and pH were higher in the litter than in the faeces, and the relative TAN concentration was lower. The mean thickness of the litter was 5.4 cm, but varied in the course of time. Removal of the litter reduced the thickness 6.5 and 2.5 cm for the first and second time respectively, whereafter it increased 5.65 mm day^{-1}. Figure 3 shows the variation of the dry matter, the total nitrogen and unionised ammonia content in the litter during the experiment. The highest dry matter content coincided with the highest total nitrogen content and the lowest unionised ammonia content and vice versa. The highest dry matter contents also coincided with the highest ventilation rates (not shown).

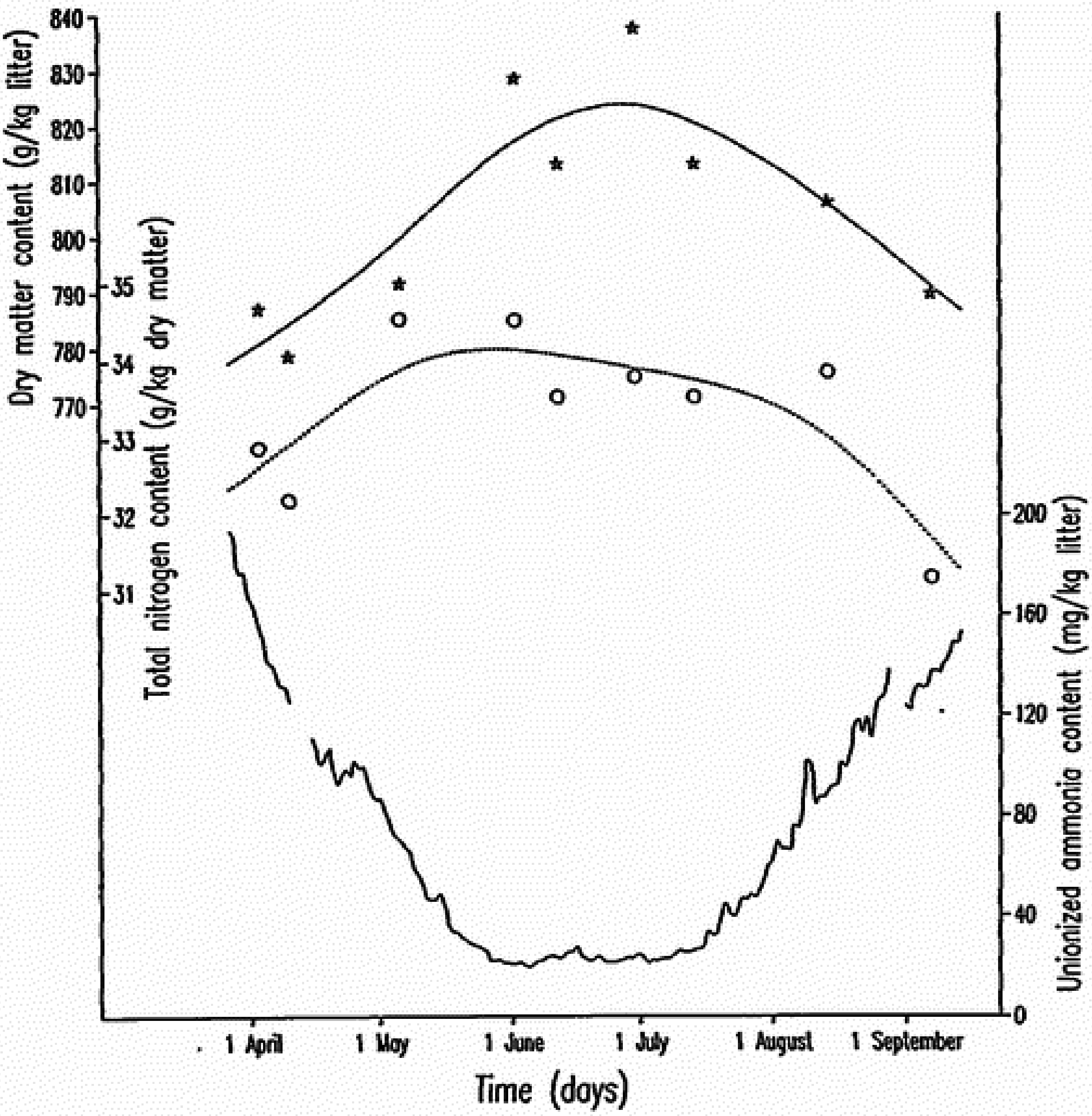

Figure 3. The dry matter (points: *, trend: —), the total nitrogen (points: o, trend: ···) and the unionized ammonia content (—) of the litter in the Tiered Wire Floor (TWF) system during the experiment. The points are the mean values of the samples in the two sections.

Ammonia emission

The coefficients of the logistic curves of the ventilation rate vs the outside temperature were not significantly different for the two housing systems, except for the steepness of the curves. They were 1269 and 836 m^3 h^{-1} per degree Celsius for the battery cage and TWF system, respectively. This resulted in lower ventilation rates in the TWF system when the daily mean outside temperature was above 12°C and vice versa.

Ammonia concentrations in the exhaust air of the battery system varied between

0.50 and 5.51 mg m^{-3} with the mean being 1.91 mg m^{-3}. These concentrations were significantly lower than the concentrations in the TWF system, which varied between 1.68 and 12.82 mg m^{-3} and a mean of 4.59 mg m^{-3}.

Table 6 shows the time-series coefficients of the model for ammonia emissions from the two housing systems. The effects per system are given in relationship to the mean emission from the belt manure and the litter. The mean for the belt manure represents the emission for the first level of the factors $E_{A,B,C}$ and E_{DAR} and the mean value of the co-variables temperature, water vapour pressure difference, unionised ammonia content and layer thickness. The mean emission from the belt manure in the TWF system ($e^{(2.93-0.12)} = 16.6$ g h^{-1}) was not significantly lower than from that in the battery cage system ($e^{2.93} = 18.8$ g h^{-1}). Drying treatment B and C decreased the emission from the belt manure by 6 and 27% respectively, but neither of these effects were significant. The emission from the belt manure increased by 14, 39, 109 and 177% from the first until the fourth day after manure removal. The effects of temperature and water vapour pressure difference of the air above the manure were significant and amounted to 17% °C^{-1} and –22% kPa^{-1} respectively.

The litter in the TWF system increased the mean emission from the aviary system with 62.5 g h^{-1} ($e^{4.14}$). The effect of the temperature in the litter on the emission, 3% °C^{-1}, was smaller than the effect of temperature above the manure belt. The effect of the water vapour pressure difference above the litter was –17% kPa^{-1}, similar to the effect it had above the manure belt. Neither the effect of temperature nor the effect of water vapour pressure was significant. The unionised ammonia content in the litter (mg/kg^{-1}), which is shown in Figure 3, increased the emission from the TWF system by 0.5% per unit of concentration. The emission from the litter increased significantly with the layer thickness of the litter (5% cm^{-1}). A numerical example of the use of the model is given in Appendix 3.

Figure 4 illustrates the predicted emission of the model along with the measurements for the battery cage and TWF system for the first block of drying and removal treatments. The model predictions follow the pattern of the measurements in both systems fairly well, but the deviations in the TWF system are greater.

A sensitivity analysis of the model for ammonia emission is given in Figure 5. All effects on the emission from the belt manure are relative to the predicted ammonia emission for a typical day with treatment A0.5. The daily mean ammonia emission from the belt manure increased greatly for the treatment without drying (A) from the level of a typical day when belt manure was removed twice (A0.5) to the level of the 4th day after manure removal (A4). Drying treatment B and C showed a tendency towards lower emissions from the first until the fourth day after manure removal compared to not drying (not shown in Figure 5). Air temperature had a strong positive effect on the emission from the belt manure, wheras the content of unionised ammonia in the litter influenced the emission from the litter much stronger than temperature and layer thickness. The water vapour pressure difference decreased the emission from both the belt manure and the litter. This effect was, however, relatively small.

Table 6. Results (means and s.e.) from the time-series regression analysis of the natural logarithm of the ammonia emission rate from two housing systems for laying hens. The means are also given on the linear scale (g NH_3 h^{-1} or %).

Parameter	Symbol	Level or measured range	Battery Cages			Tiered Wire Floor		
			log scale		linear scale	log scale		linear scale
			mean	s.e.	mean	mean	s.e.	mean
Mean ammonia emission belt manure battery cage system	$C_{BC,bm}$	–	2.93	0.13	18.8 g h^{-1}	–	–	–
Effect of TWF system on ammonia emission belt manure	$E_{TWF,bm}$	–	–	–		–0.12	0.37	–11%
Drying treatment belt manure	$E_{A,B,C}$	A	–	–	–	–	–	–
		B	–0.06	–0.06	–6%	–0.06	–0.06	–6%
		C	–0.32	0.32	–27%	0.32	0.32	–27%
Day After Removal belt manure	E_{DAR}	day 0.5	–	–	–	–	–	–
		day 1	0.13	0.06	14%	0.13	0.06	14%
		day 2	0.33	0.07	39%	0.33	0.07	39%
		day 3	0.74	0.07	109%	0.74	0.07	109%
		day 4	1.02	0.07	177%	1.02	0.07	177%
Temperature belt manure	α_1	21-29°C	0.15	0.02	17%	0.15	0.02	17%
Water vapour pressure difference belt manure	α_2	0.4-1.7 kPa	–0.25	0.10	–22%	0.25	0.10	–22%
Mean ammonia emission litter	$C_{TWF,litter}$	–	–	–	–	4.14	0.07	62.5g/h
Temperature litter	α_3	19–29°C	–	–	–	0.03	10.024	3%
Water vapour pressure difference litter	α_4	0.9–1.6 kPa	–	–	–	–0.19	0.18	–17%
Volatile NH_3 concentration litter	α_5	20–190 mg kg^{-1}	–	–	–	5.4 E-3	1.4 E-3	0.5%
Layer thickness litter	α_6	2–9 10^{-2} m	–	–	–	0.053	0.038	5%
ø		–	0.89	0.03		0.89	0.03	

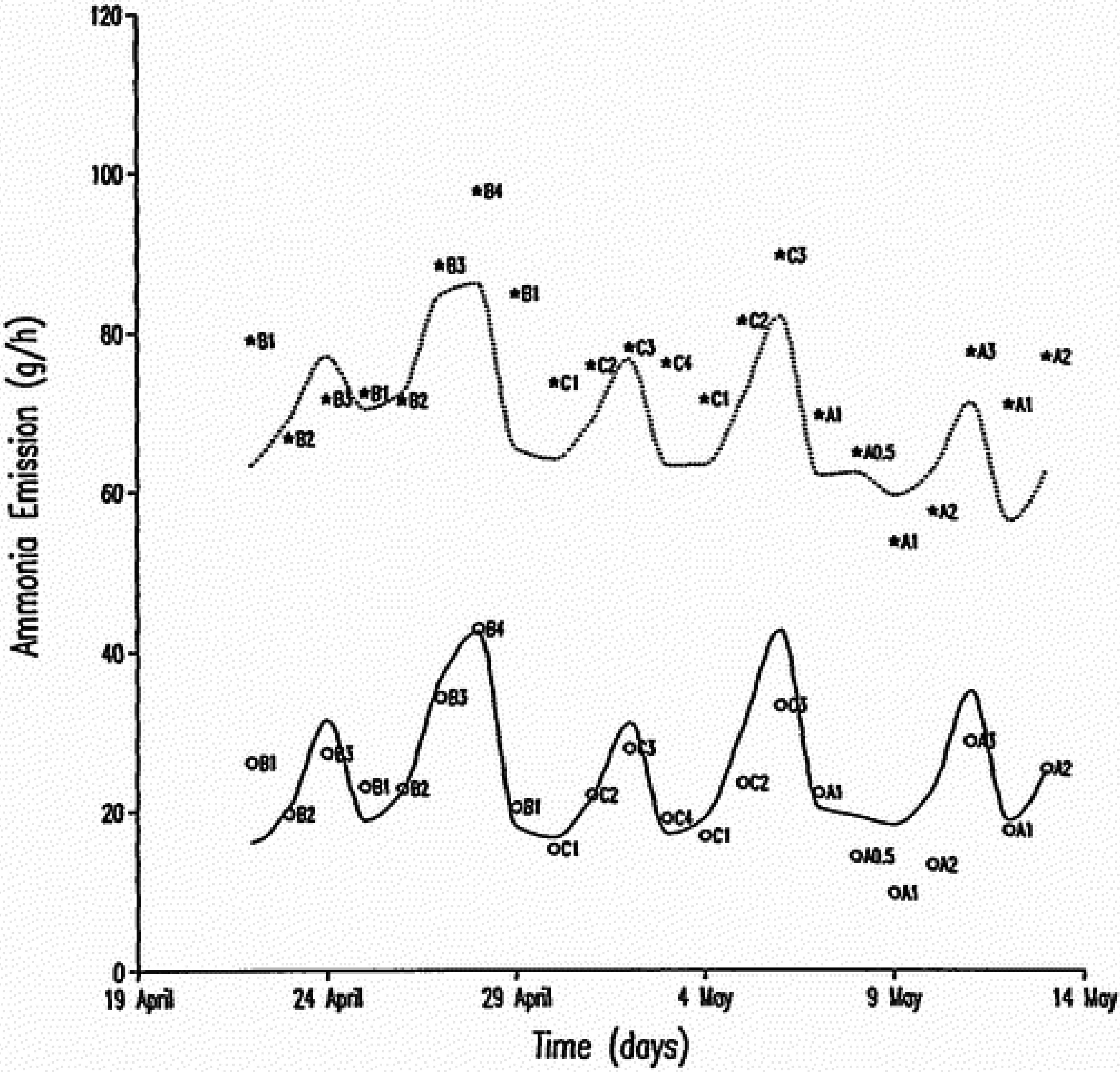

Figure 4. The predicted (lines) and measured (points) mean ammonia emission per day (g $hour^{-1}$) for the battery cage (—— and o) and the Tiered Wire Floor (TWF) system (··· and *) during the first block with drying treatments and removal frequencies. The measurements are indicated along with the treatment-code.

Discussion

Production

The production results of both caged hens and TWF hens were in accordance with production standards in practice. The higher feed intake and the lower egg mass production agrees with earlier results of Ehlhardt *et al.* (1989) who found a 4.75% higher feed conversion ratio for the TWF hens. The higher feed conversion ratio can be explained by the higher energy requirements for activity. The mortality rate of this experiment was slightly higher than in a previously reported experiment (Blokhuis & Metz, 1992), but because this one lasted 8 weeks longer it was to be expected.

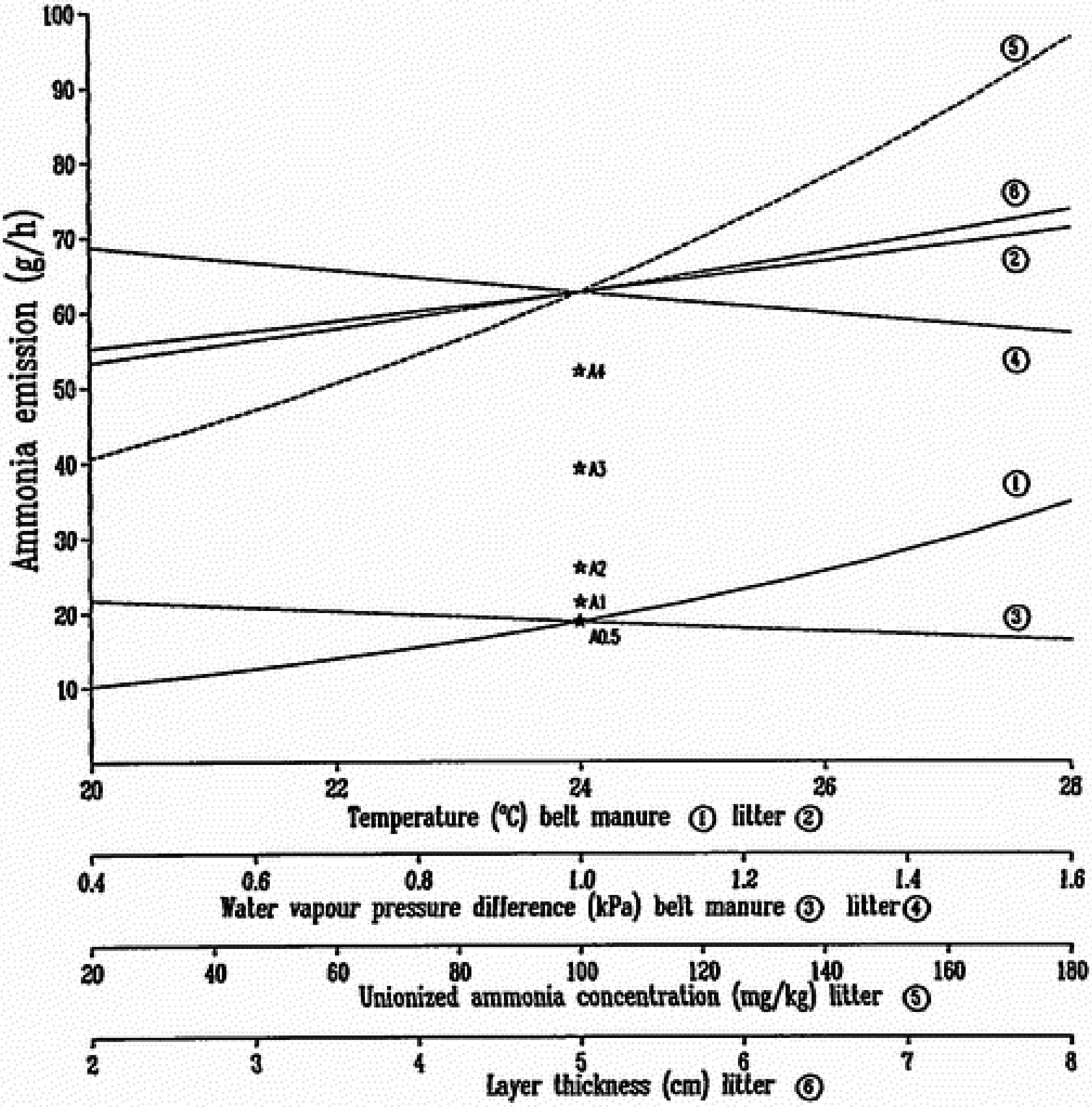

Figure 5. Sensitivity analysis of the ammonia emission model. The points (*) represent the predicted emission from the belt manure for drying treatment A from the first until the fourth day for the mean value of the co-variables shown on the x-axes. The effect of the co-variables on the emission from the belt manure is given relative to the treatment A0.5 (18.8 g h^{-1}). The effect of the co-variables on the emission from the litter is given relative to the mean (62.5 g h^{-1}).

Manure and litter

The 2.5% higher feed intake of the TWF hens will have resulted in a higher manure production. About 22.5% of the manure of the hens in the TWF system was dropped in the litter when it was assumed that the hens in the TWF systems also excreted 2.5% more dry matter. The faeces dropped in the litter in two commercial hen houses was roughly estimated to be 36 and 32% of the total manure production (Evers *et* *al.*, 1992a and 1992b). The distribution of faeces will depend on the distribution of the hens in space, for example the sojourns of the hens on the different functional locations, and in time, for example the variation of the faeces production during a day. The amount of manure transported from the litter to the manure belts in the TWF system by the hens (between their feathers) was estimated to be negligible. At least 20% of the nitrogen in the belt manure was degraded to ammonia within 12 hours, whereas it is assumed that fresh droppings hardly contain any ammonia. This means that degradation processes in the manure start immediately after excretion by the hens. Complete volatilization of this amount of ammoniacal nitrogen would cause an emission of 126 g NH_3 h^{-1}. Only a relatively small amount of this is actually emitted from the manure, because the predicted emission on a day with treatment A0.5 was 18.8 g h^{-1}.

The water:feed ratio was not significantly different in the battery cage system and the TWF system. It could therefore be expected that the droppings of both groups contained about the same percentage of dry matter at the time of excretion. It can therefore be concluded that the differences found in the composition of the manure on the belts were a result of the type of housing system and manure drying system. The higher dry matter content of faeces on the belts in the TWF system compared to the battery cage system (Table 3) could be explained by a higher water evaporation rate as a result of higher air velocities above the manure due to the open structure of the tiers and the free movement of the hens. Also, because part of the manure fell into the litter area and because of the larger manure belt area in the TWF system, the mean density of manure on the belts (kg dry matter m^{-2}) in the TWF system was 71% of that in the battery cage system. The difference in the dry matter content of the faeces (treatment A0.5) caused the differences between the dry matter contents of the TWF and the battery cages for the other drying and removal treatments (Table 4). The dry matter content of the belt manure after three and four days drying was higher than without drying, but was lower than that measured by Kroodsma *et al.* (1988) (40 to 60% after 7 days drying). The shorter drying time was partly responsible for the difference. Besides this, the static pressure in the drying systems was lower than recommended by Kroodsma *et al.* (1985). This will have had a negative influence on the drying process. Drying treatment C was applied because most of the manure on the belts in the TWF system was found on the belt of the upper floors underneath the perches where the hens rest. The mean dry matter content after three and four days drying according to treatment C was not higher than with treatment B despite the adjustment of the air flow above the belt manure.

The sand, which was for more than 90% ash, in the litter area at the start of the laying period could hardly be distinguished in the litter during the experiment. The ash content at the start of the experiment had already dropped to a constant level a few percent higher than the ash content of the faeces. This higher ash content of the litter was the result of the degradation of organic material. This process decreased the amount of dry matter, whereas the amount of inorganic matter remained constant. The lower total nitrogen content of the belt manure in the TWF system could not be explained by differences in ammonia volatilization or addition of feed as a result of spilling from the feeding pans. It was calculated that the nitrogen excretion of the hens in the TWF system amounted to 55% of the nitrogen uptake by the feed, resulting in a nitrogen retention of about 45%. This was far above normal values, so that is was concluded that the measured concentrations in the manure in the TWF system must have been low. The mean total nitrogen content in the litter showed that a substantial part of the nitrogen, 17.2 (50.5 minus 33.3) g kg^{-1} dry matter of the faeces, was volatilised. This is equivalent to an ammonia emission of about 50 g NH_3 h^{-1}. This was close to the predicted mean level of the model, being 62.5 g NH_3 h^{-1}. The mean relative TAN content of 7.1% in the litter resulted from the discharge of ammonia by means of volatilization and supply by means of degradation of uric acid and proteins. The opposite trend of the unionised ammonia content in the litter during the experiment as compared with the trend of total nitrogen and dry matter contents could be explained as follows: higher dry matter contents diminished the degradation rate of uric acid and proteins considerably, resulting in a lower unionised ammonia content in the litter. The lower volatile ammonia content reduced the ammonia emission from the litter and led to a small increase of the total nitrogen content (Figure 5). The dry matter content of the litter might have been influenced by the water vapour pressure difference and the ventilation rate.

Ammonia emission

The higher maximum rate of increase of the ventilation rate in the battery cage system meant that higher ventilation rates were necessary to maintain the set temperature in this room (22°C). This data as well as the observations and calculations of Van Ouwerkerk *et al.* (1994) in these rooms, showed that the air velocity patterns in the two housing systems differed greatly. The difference in the ventilation rate and the air velocity pattern could have had an effect on the ammonia emission rate. Any possible effect however is included in the difference between the emission from the belt manure in the two housing systems. Room temperatures below 20°C were not measured due to the temperature controlled ventilation system, but the increase in room temperatures up to 28°C on days with high outside temperatures, could not be prevented. The difference in the ammonia concentrations in the exhausted air between the battery cage and TWF system corresponded to the difference in the ammonia emission. The difference in the ammonia emission, which is the product of concentration and ventilation rate, was therefore mainly caused by the concentration difference and for a minor part by the difference in the ventilation rate.

The daily increase of ammonia emissions after removal of the belt manure, and with increasing amount of manure on the belts, was also reported by Kroodsma *et al.* (1988). They also found that drying reduced the emission compared to not drying and that the ammonia emission from manure belts strongly decreased if dry matter contents rose above 40%. In this experiment manure drying had a positive effect on the dry matter content of the belt manure. The emission however was not significantly decreased, probably caused by the fact that the dry matter content of the belt manure did not raise above 41%. Inadequate functioning of the drying installation could very well have been the reason for the lower dry matter contents. However, the lower manure density on the belts and the higher dry matter contents of the belt manure in the TWF system than the battery cage system, did not decrease the mean ammonia emission from the belt manure in the TWF system (16.6 g h^{-1}) significantly as compared to the battery cage system (18.8 g h^{-1}). The daily mean ammonia emission of 18.8 g NH_3 h^{-1} was equivalent to a nitrogen volatilization of about 1.8% of the nitrogen intake by the hens.

The effect of the local climate in the houses on the ammonia emission was reflected by the temperatures above the belt manure and the litter and the water vapour pressure differences (Groot Koerkamp, 1994). The effect of the temperature on the emission from the belt manure represents the combined effect of temperature on the degradation and the volatilization process, which was also found by Oldenburg (1989). The evaporation of water from manure and litter particles was enhanced by a higher water vapour pressure difference. A higher volatilization rate of water resulted in dryer manure, which in turn diminished the degradation rate of nitrogen compounds and hence the volatilization of ammonia. The variation between the measured minimum and maximum ammonia emission from the belt manure in the battery cage system, 9 and 74 g NH_3 h^{-1} respectively, was well explained by the model. The reported mean ammonia emission over longer periods from belt batteries with different drying treatments and removal frequencies in other experiments were all within this range (Groot Koerkamp, 1994; Groot Koerkamp *et al.*, 1994). It could be concluded that by means of control of the indoor temperature and regular removal of the manure, ammonia emission from manure on belts can be reduced.

The daily mean ammonia emission from the litter in the TWF raised the total emission to 79.1 g NH_3 h^{-1} (16.6 + 62.5) and confirmed results of earlier measurements (Groot Koerkamp & Metz, 1992). It was remarkable that the 22.5% of the faeces of the hens that were dropped in the litter in the TWF system caused 79% of the ammonia emission of this system. However, the effect of temperature and water vapour pressure difference on the emission from the litter was not significant. But temperature and water vapour pressure difference might have had a long term effect on the emission rate of ammonia. The unionised ammonia content in the litter on a typical day resulted from degradation and volatilization rates in the past. Both processes were then influenced by local climatic conditions. Unionised ammonia contents below 20 mg kg^{-1} litter were necessary to substantially reduce the emission from the litter in the TWF system. The positive relationship between emission and layer thickness (a 5% increase in emission for every cm layer thickness) could be explained by the larger amount of manure and thus larger amount of unionised ammonia in the litter in the TWF system. This meant that the volatilization of ammonia from the litter not only depends on the surface area, but also on the volume of the litter. This was logical because as a result of the scratching and dust bathing of the hens, the litter was friable and mixed many times per day. Therefore, unionised ammonia may have diffused through the litter. Another, and possibly more important, adverse effect of thicker litter layers is the development of inadequate conditions for water evaporation from small particles of faeces in the sublayers of the litter. The drying of these particles will be hampered if the water has to pass a thicker layer. It was concluded that the degradation process in the litter must be minimized to reduce emission from the litter. Control of the layer thickness and the dry matter content of the litter are possibilities to achieve this. Technical measures that increase the water volatilization from the litter have thus to be developed.

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APPENDIX 1

Notation:

η_t	*Natural logarithm of the daily mean ammonia emission (g NH_3/h)*
ε_t	*Deviation between the measured and predicted daily mean ammonia emission*
$C_{BC, bm}$	*Mean ammonia emission from the belt manure in the battery cage system*
$E_{TWF, bm}$	*Effect of the TWF system on the mean ammonia emission from the belt manure*
$E_{A,B,C}$	*Effect of drying of belt manure, treatment A, B and C*
E_{DAR}	*Effect of removal frequency of belt manure, i.e. number of Days After Removal*
$T_{bm/litter}$	*Mean temperature of the air above the belt manure in both systems or in the litter in the TWF system (°C)*
$P_{dif,bm.litter}$	*Difference between the saturated water vapor pressure times 0.9 and the actual water vapor pressure of the air above the belt manure in both systems or of the air above the litter in the TWF system (kPa)*
$C_{TWF, litter}$	*Mean ammonia emission from the litter in the TWF system*
$C_{NH_3, litter}$	*Unionized ammonia content in the litter in the TWF system (mg/kg)*
D_{litter}	*Layer thickness of the litter in the TWF system*
α_i	*Regression coefficient for co-variable i*

APPENDIX 2 Estimation of regression coefficients for emission

For ease and clarity of notation index t is omitted. Log stands for natural logarithm. Equations (2a) to (2c) represent the formulation of a generalised linear model (GLM) in η_{bm}, with link function , containing as unknown parameters the regression coefficients of η_{litter}.

Estimation when η_{litter} is known

For a given η_{litter} the standard algorithm is Iterative Reweighed Least Squares (IRLS) with link-adjusted response variate:

$$\zeta = \eta_{bm'} + (z-\eta)\frac{\partial\eta_{bm}}{\partial\eta}$$

and weights:

$$w = \left(\frac{\partial\eta_{bm}}{\partial\eta}\right)^{-2}$$

With $\mu = e^{\eta}$:

$$\frac{\partial\eta_{bm}}{\partial\eta} = \frac{e^{\eta}}{e\eta - \delta_{TWF} \cdot e^{\eta litter}} = \frac{\mu}{\mu - \mu_{litter}} = \frac{\mu}{\mu_{bm}}$$

the link-adjusted response variate and weights are:

$$\zeta = \eta_{bm'} + (z-\eta)\frac{\mu}{\mu_{bm}} \text{ and } w = \left(\frac{\mu_{bm}}{\mu}\right)^{-2} \tag{4}$$

z can be taken as the starting value for η. Weighed regression with explanatory variates for belt manure emission yields an estimate of η_{bm}. Then, ζ and w are updated and the regression can be repeated. Convergence is obtained if the change in η_{bm} between iterations is negligible.

Estimation of the litter contribution

Note that η_{bm} depends on η_{litter} and therefore on the regression coefficients β_{litter} of the explanatory variates for litter emission. This is emphasized in the notation $\eta_{bm}(\beta_{litter})$. Parameters of β_{litter}, β_j, j=1...J in which J represents the number of explanatory variates for litter emission, are estimated according to a linear approximation, using only the first term of the Taylor series expansion (Pregibon, 1980):

$$\eta_{bm}(\beta_{litter}) \approx \eta_{bm}(\beta^*_{litter}) + \sum_j (\beta_j - \beta_j^*)\left(\frac{\partial\eta_{bm}(\beta_{litter})}{\partial\beta_j}\right)^*$$

The partial derivative $\frac{\partial\eta_{bm'}(\beta_{litter})}{\partial\beta_j}$ can be found by applying the chain rule:

$$\frac{\partial \eta_{\mathrm{bm}}}{\partial \beta_{\mathrm{litter}}} = \frac{\partial \eta_{\mathrm{bm}}}{\partial \eta} \cdot \frac{\partial \eta}{\partial \eta_{\mathrm{litter}}} \cdot \frac{\partial \eta_{\mathrm{litter}}}{\partial \beta_{\mathrm{litter}}}.$$

Because: $\frac{\partial \eta_{\mathrm{bm}}}{\partial \eta} = \frac{\mu}{\mu_{\mathrm{bm}}}$ (see above),

$$\frac{\partial \eta}{\partial \eta_{\mathrm{litter}}} = \frac{\delta_{\mathrm{TWF}} \cdot e^{\eta_{\mathrm{litter}}}}{e^{\eta_{\mathrm{bm}}} = \delta_{\mathrm{TWF}} \cdot e^{\eta_{\mathrm{litter}}}} = \frac{\mu_{\mathrm{litter}}}{\mu},$$

$$\frac{\partial \eta_{\mathrm{litter}}}{\partial \beta_{\mathrm{j}}} = x_{\mathrm{j}},$$

in which x_j is the explanatory variate with regression coefficient β_j. An estimate of the parameter of β_{litter} can be calculated by multiplying each explanatory variate for litter emission with $\frac{\mu_{\mathrm{litter}}}{\mu_{\mathrm{bm}}}$ (for the observations of the TWF system) and then carry out regression with all explanatory variates, for the belt manure emission as well as for the litter emission. For the regression coefficients of the litter emission, the difference with the previous value is estimated. The new estimate is the sum of the previous value and the estimate of the difference. Iteration is continued until the estimated difference is negligible.

APPENDIX 3 Numerical example of the use of the emission model

The model predicts the daily mean ammonia emission in g h^{-1} depending on the housing type (TWF or battery cage system), the handling of belt manure (drying and removal frequency), climatic conditions (temperature and humidity), the litter condition (unionised ammonia content) and the litter management (layer thickness).

Circumstances:
* drying treatment B, the third day after removal
* belt manure: temperature 22.0°C (mean 24.0), water vapour pressure difference 1.4 kPa (mean 1.0)
* litter: temperature 21.0°C (mean 24.0), water vapour pressure difference 1.6 kPa (mean 1.0)
* litter: 20 mg unionised ammonia per kg litter (mean 100)
* litter: layer thickness 2.0 cm (mean 5.0)

Battery Cage system:
$$e^{(2.93-.06+.74+(22.0-24.0)*.15+(1.4-1.0)*-.25)} = 24.8 \text{ g } NH_3 \text{ h}^{-1}$$

Tiered Wire Floor system:
$$e^{(2.93-.06+.74+(22.0-24.0)*.15+(1.4-1.0)*-.25)} +$$
$$e^{(4.14+(21.0-24.0)*.031+(1.6-1.0)*-.19+(20-100)*5.4E-3+(2.0-5.0)*.053)} =$$
$$24.8 \text{ g} + 28.3 = 53.1 \ NH_3 \text{ h}^{-1}$$