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Sensitivity Analysis of a Mechanistic Model for the Ammonia Emission of Dairy Cow Houses

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***Abstract*.** Emission of ammonia (NH_3) from animal husbandry, and specially from the dairy sector, contributes significantly to acidification and eutrophication, and affects sensitive natural areas. In the nineties Monteny (1998) introduced a mechanistic model to understand and predict the NH_3 emissions from cubicle dairy cow houses. Although a limited sensitivity analysis was carried out, we still lack information that essential for further development of the model. Our aim is that the model can predict and assess the NH_3 emission from dairy cow houses under practical circumstance.

The objective of this research was 1) to determine the relevance and irrelevance of a limited set of input factors, and 2) assess options for further development of the model for use in practice.

A full factorial sensitivity analysis was carried out for eight variables related to NH_3 emission from a urine puddle on the floor. Relative importance and R^2 of the regression model factors were determined.

The NH_3 emission varied strongly with both high and low emissions. Strongly contributing process variables were puddle pH, initial urea concentration, urination frequency, puddle depth and puddle area. We conclude that deviations in these influencing variables lead to large fluctuations in the NH_3 emission, which means that precise quantification of these variables in practice is essential for accurate predictions. Moreover, the results also show that the model may be over-parameterized, having several inputs that seem hardly relevant for the level of NH_3 emission.

Keywords. Ammonia emission, sensitivity analysis, mechanistic model, dairy cow, cow houses

Introduction

In the late eighties of the previous century it became clear that acidification of the environment was mainly caused by deposition of ammonia (NH_3) in the air. Recent figures from The Netherlands show that NH_3 emission of the dairy sector decreased since 1990 from 120.9 kton NH_3 to 34.8 kton in 2009 (36.3% and 32.3% respectively of total agriculture) (van Bruggen et al., 2011). In 2008 the total NH_3 emission level of The Netherlands was still 5% higher than the national NH_3 emission ceiling of 128 kton in 2010 (EEA, 2010).

A typical dairy cow house in The Netherlands contains both a housing and storage facility. The storage facility is generally underneath a concrete, slatted floor, and is called a slurry pit. The floor is used as walking and living area for the dairy cows, besides cubicles are used to rest. In these dairy cow houses it is difficult to measure the actual NH_3 emission, because they are naturally ventilated by large openings in the sidewalls and in the ridge.

In the late nineties Monteny (1998) introduced a conceptual mechanistic model to understand and predict NH_3 emissions from free stall cubicle dairy cow houses; an approach that is followed by several groups and authors. Since the year 2000 this model is used by the Ministry of Economic Affairs, Agriculture and Innovation (EL&I) in The Netherlands to assess the NH_3 emission of newly developed dairy cow houses and emission reducing methods. This model based assessment is generally followed by full scale measurements. Monteny performed a limited sensitivity analysis of this model, of being a One-Factor-at-a-Time analysis for seven variables of the model. However, we still lack information on a larger number of variables (either input variables of the model or parameters within the model), a wider range of values, and the interactions between variables. This knowledge is essential for further development of the model for use in practice to predict and assess the ammonia emission from dairy cow houses.

The objective of this research was 1) to determine the relevance and irrelevance of a limited set of input variables, and 2) assess options for further development of the model for use in practice.

Material and Methods

Mechanistic model for the ammonia emission of dairy cow houses

To determine the NH_3 emission from dairy cow houses, Monteny et al (2008) described a mechanistic model. In this model urine puddles with initial concentration of urea nitrogen are randomly distributed in time and place at floor level. After deposition of a urine puddle the NH_3 emission process start. The NH_3 emission process consists of three steps (Monteny et al., 1998). The first step is the enzymatic conversion of urea to ammonia , with an equilibrium between ammonia-nitrogen (NH_3-N) and ammonium-nitrogen (NH_4-N) influenced by the dissociation constant, pH and temperature. Secondly, the concentration of gaseous NH_3-N in the boundary layer of the urine puddle is determined by Henry's constant, depending on temperature. Finally, the evaporation of gaseous NH_3-N from the puddle to the air is determined by the concentration difference between air and puddle and the mass transfer coefficient for NH_3, dependent on temperature and air velocity. The NH_3 emission from the slurry pit is determined according to the same process, except that there is no enzymatic conversion modeled. Instead a constant TAN concentration in the top layer of the slurry at all times is assumed. In this research only NH_3 emission at floor level and only the input variables of the model are taken into account. Table 1 shows the number and the name of these variables.

Table 1. List with variables and their extreme low and high value based on practical data from literature. As used for the sensitivity analysis of the NH_3 emission from urine puddles on a floor.

nr	Variable	Low	High	References
1	Urination frequency [#/day*cow]	2	19	(Villettaz Robichaud et al., 2011)
2	Initial urea nitrogen concentration [kg/m^3]	2.4	16.4	(Monteny et al., 2002; van Duinkerken et al., 2003)
3	Area of the floor [m^2/cow]	2	5	(Ursinus et al., 2009)
4	Temperature above puddle [K]	273	308	(Scholtens et al., 1997)
5	Air velocity above puddle [m/s]	0.05	0.50	(Schrade et al., 2012)
6	Area covered by puddle [m^2]	0.4	1.4	(Braam et al., 1996; Monteny et al., 1998)
7	Depth of puddle [m]	1.5E-4	8.5E-4	(Braam et al., 1996; Monteny et al., 1998)
8	pH of puddle	5.93	9.70	(DeGroot et al., 2010; Monteny et al., 2002)

Sensitivity analysis

A full factorial sensitivity analysis was carried out with the mechanistic model. This sensitivity analysis included any possible combinations of a low and high value for each variable (tab. 1)(Montgomery, 2009). Table 2 shows the combinations where "-" and "+" represent a low and high value respectively for the variables. Each combination was called a scenario which resulted in a NH_3 emission level from the floor. In total there were 2^8 = 256 scenarios and thus 256 simulations of the model. The number of dairy cows was 100 in every scenario.

Table 2. Design of the sensitivity analysis with the NH_3 model with all unique combinations of low "-" and high "-" variable values (scenarios) and there NH_3 emission level.

	Variable								
Scenario	1	2	3	4	5	6	7	8	NH_3
1	-	-	-	-	-	-	-	-	...
2	-	-	-	-	-	-	-	+	...
3	-	-	-	-	-	-	+	-	...
4	-	-	-	-	-	-	+	+	...
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
256	+	+	+	+	+	+	+	+	...

Data analysis

The contribution in terms of percentage was determined for each single variable and for each possible interaction for two up to five variables, based on the Sum of Squares (eq. 1). The R^2 was determined for the regression model. The regression model (eq. 2) contained one up to all variables and interactions.

$$contribution = \frac{SS_i}{SS_t} * 100\% \tag{1}$$

where,

i = Variable or interaction between variables

SS_i = Sum of Squares for one variable or interaction i

SS_t = Sum of Squares for total model with all variables and interactions t

$$\hat{y} = \beta_0 + \beta_i c x_i + ... + \varepsilon \tag{2}$$

where,

$\hat{y}$ = Result regression model

β_i = Coefficient related to variable or interaction i (0 = mean)

cx_i = Coded variable or interaction i (value = -1 or +1)

ε = Residual error

Results

The NH_3 emission varied strongly between the scenarios. Average emission was 1.9E-5 kg/s (SD is 4.9E-5). With a minimum and maximum of 4.3E-9 kg/s and 3.4E-4 kg/s respectively. Skewness was 4.6 (left sided peak) and Kurtosis 23.5 (high peak), as shown by the normal distribution in figure 1.

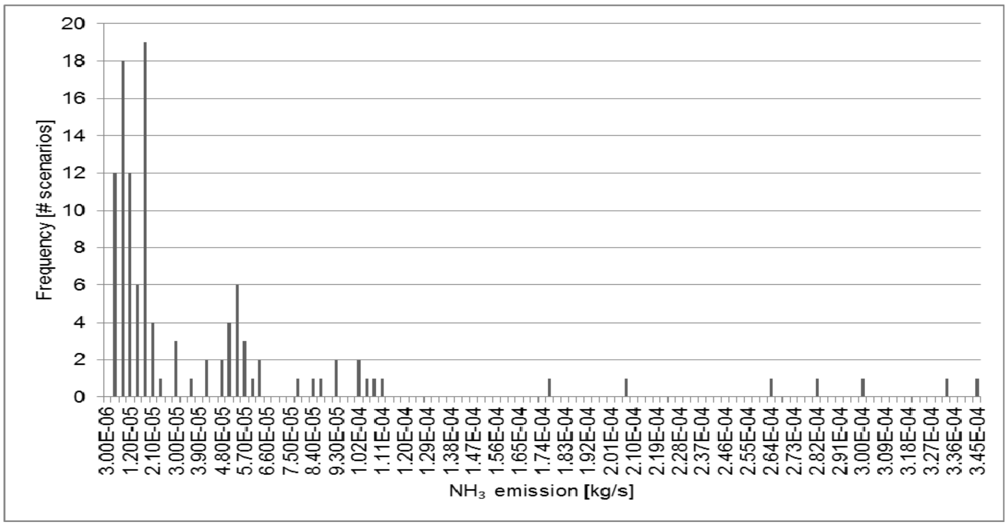

Figure 1. Histogram with number of scenarios per emission category. Emission levels lower than 3.0E-6 were excluded for reasons of readability (=143 scenarios).

Table 3. Each single variable or interaction between variables and there relative contribution. The number of variables/interactions in the regression model and the R^2.

Variable or interaction[1]	Single Contribution[2]	Vars	R^2 model	Variable or interaction[1]	Single Contribution[2]	Vars	R^2 model
-	%	#	-	-	%	#	-
8	12.82	1	0.128	2-6	1.54	16	0.773
2	7.94	2	0.208	2-6-8	1.46	17	0.787
1	6.98	3	0.277	1-6-8	1.35	18	0.801
1-8	6.53	4	0.343	1-6	1.29	19	0.814
2-8	6.48	5	0.408	1-2-7-8	1.27	20	0.827
7	5.81	6	0.466	1-2-7	1.24	21	0.839
7-8	5.40	7	0.520	6-7-8	1.18	22	0.851
1-2	3.42	8	0.554	6-7	1.16	23	0.862
6	3.25	9	0.586	4	0.66	24	0.869
1-2-8	3.20	10	0.618	1-2-6-8	0.60	25	0.875
6-8	3.07	11	0.649	1-2-6	0.57	26	0.881
2-7	2.96	12	0.679	2-6-7-8	0.56	27	0.886
2-7-8	2.74	13	0.706	2-6-7	0.55	28	0.892
1-7-8	2.59	14	0.732	All[3]	-	246	1.000
1-7	2.54	15	0.757	-	-	-	-

[1] Number of the variables according Table 1, either the single variable or an interaction.
[2] Table 3 show result for single contribution of 0.5% or higher.
[3] "All" contained all single variables and interactions between two up to five variables.

The contribution of the single variables and interactions decreased from 12.82 (pH) to 0.55%, (interaction 2-6-7), whereas the R^2 of the model increased from 0.128 to 0.892 (tab. 3). The contribution of the single variables 8, 2, 1, 7 and 6 was highest. These five single variables and their interactions result in a R^2 of 0.862 (vars = 23).

The effects of the variables 3 and 5 (area of the floor and air velocity) are not given in table 3, because their contribution on the overall ammonia emissions was lower than 0.5%. Variable 4 (temperature) contributed for 0.66%, interaction effects with 4 were lower than 0.5% as well.

Discussion

The low and high values used for the variables were based on a literature search. For some variables (4, 5, 6, 7 and 8) there was hardly information. For two others (2 and 8) data was obtained from papers about feed additives which resulted in extreme values. Therefore, neither the used values, nor their combined values in practice do necessarily represent practical circumstances.

All the simulations with the mechanistic model were performed for a situation with 100 dairy cows. The chosen values for the variables hold for each cow. In a practical dairy cow house the variables related to the urination of one cow (1, 2, 4, 6, 7 and 8) will vary between different cows. So one set of variable values, the same for each cow, doesn't necessarily happen in practice. As a result the low and high NH_3 emission levels in this research do not represent practical emission levels exact.

In this research the NH_3 emission is assessed only from the floor. In a typical dairy cow house in The Netherlands this is a slatted floor. This floor doesn't close the slurry pit. To use a NH_3 emission model in practice the slurry pit cannot be neglected.

Monteny (1998) showed a linear relation of NH_3 emission with variables 1, 4, 5, 6, 7 or 8. Increasing values resulted in higher emissions (one-factor-at-a-time analysis). The result of this research show also higher emissions for higher variable values. Based on two input values per variable it is not possible to conclude the type of relation.

We think that the afore mentioned issues about the high and low values of the variables as used in this study had a limited effect on the selection of the less relevant variables on the NH_3 emission from dairy cow houses. The contribution of temperature, air velocity and total area of the floor was very limited. The exact quantitative effect of the most influencing variables on the ammonia emission from dairy cow houses (puddle pH, initial urea concentration, urination frequency, puddle depth and puddle area) was certainly affected by the chosen high and low values, however we expect that the extent of the effects will remain stable for small changes of input values. Further in depth analyses have to confirm this.

Conclusion

From the results can be concluded that pH of the urine puddle is the most important input variable to determine the level of NH_3 emission. Other relevant variables are initial urea concentration, urination frequency, puddle depth and puddle area. Less or hardly relevant are temperature, air velocity and total area of the floor.

To develop the mechanistic model for use in practical situations it has to be possible to measure the values for puddle pH, initial urea concentration, urination frequency, puddle depth and puddle area precisely.

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