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Research Paper

Non-linear temperature dependency of ammonia and methane emissions from a naturally ventilated dairy barn

Sabrina Hempel [a,*], *Chayan Kumer Saha* [a,b], *Merike Fiedler* [a], *Werner Berg* [c], *Christiane Hansen* [d], *Barbara Amon* [c], *Thomas Amon* [a,e]

[a] *Department Engineering for Livestock Management, Leibniz-Institute for Agricultural Engineering Potsdam-Bornim e.V. (ATB), Max-Eyth-Allee 100, 14469 Potsdam, Germany*

[b] *Department of Farm Power and Machinery, Bangladesh Agricultural University, Mymensingh 2202, Bangladesh*

[c] *Department Technology Assessment and Substance Cycles, Leibniz-Institute for Agricultural Engineering Potsdam-Bornim e.V. (ATB), Max-Eyth-Allee 100, 14469 Potsdam, Germany*

[d] *Mecklenburg-Vorpommern State Research Institute for Agriculture and Fisheries, Wilhelm-Stahl-Allee 2, 18196 Dummerstorf, Germany*

[e] *Institute of Animal Hygiene and Environmental Health, Department of Veterinary Medicine, Free University of Berlin, Robert-von-Ostertag-Str. 7-13, 14163 Berlin, Germany*

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Ammonia (NH_3) and methane (CH_4) emissions from naturally ventilated dairy barns affect the environment and the wellbeing of humans and animals. Our study improves the understanding of the dependency of emission rates on climatic conditions with a particular focus on temperature. Previous investigations of the relation between gas emission and temperature mainly rely on linear regression or correlation analysis.

We take up a preceding study presenting a multilinear regression model based on NH_3 and CH_4 concentration and temperature measurements between 2010 and 2012 in a dairy barn for 360 cows in Northern Germany. We study scatter plots and non-linear regression models for a subset of these data and show that the linear approximation comes to its limits when large temperature ranges are considered. The functional dependency of the emission rates on temperature differs among the gases. For NH_3, the exponential dependency assumed in previous studies was proven. For methane, a parabolic relation was found. The emissions show large daily and annual variations and environmental impact factors like wind and humidity superimpose the temperature dependency but the functional shape in general persists.

Complementary to the former insight that high temperature increases emissions, we found that in the case of CH_4, also temperatures below 10 °C lead to an increase in emissions from ruminal fermentation which is likely to be due to a change in animal activity. The improved prediction of emissions by the novel non-linear model may support more accurate economic and ecological assessments of smart barn concepts.

* *Corresponding author.*
E-mail address: SHempel@atb-potsdam.de (S. Hempel).

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Nomenclature

SP	sampling point
THS	temperature-humidity sensor
LU	livestock unit (1 LU = 500 kg animal mass)
E	emission in g LU^{-1} h^{-1}
E_a	ammonia emission
E_m	methane emission
N	number of cows
m	average mass of a cow
C_i	gas concentrations inside
C_o	gas concentrations outside
Q	air exchange rate
A	animal activity
T	outdoor temperature
F	relative air humidity
W	wind speed
θ	wind direction
D	day of the year (cyclic with period 365.25)
H	hour of the day (cyclic with period 24)
μ, a, b, c, d, e, f, g, h, i	coefficients of the multilinear model
j, k	coefficients of the exponential model
l, n, p	coefficients of the parabolic model
q, r	coefficients of the linear model
ε	remaining model error

1. Introduction

Emissions from livestock production are a main concern to farmers, environmentalists and government representatives due to the negative impacts on the surrounding environment and the global climate that are associated with ammonia (NH_3) or greenhouse gases like methane (CH_4) (IPCC, 2013; Sutton et al., 2011a,b). Farming, particularly dairy farming, is regarded as one of the most important sources of these gaseous pollutants (FAO, 2006). In Germany, for example, according to the Federal Environment Agency about 95% of the NH_3 emissions and 54% of the CH_4 emissions are attributed to agriculture (Umweltbundesamt, 2013/2014). Cattle, which are typically housed in naturally ventilated buildings (NVB), cause about half of these NH_3 emissions and more than 90% of the CH_4 emissions. Different studies in moderate and cold climates have found average emission rates from naturally ventilated dairy buildings in the order of magnitude 1 g LU^{-1} h^{-1} NH_3 and 10 g LU^{-1} h^{-1} CH_4 with significant diurnal, seasonal and (inside and among buildings) spatial variations (Ngwabie, Vander-Zaag, Jayasundara, & Wagner-Riddle, 2014; Samer et al., 2011; Schrade et al., 2012).

The transport of pollutants, humidity and heat inside and out of NVB and thus the air exchange rate is mainly determined by the turbulent airflow (Rong, Liu, Pedersen, & Zhang, 2014; Saha et al., 2013; Schrade et al., 2012). Moreover, the production of polluting gases is affected by airflow, temperature and humidity inside the barn which strongly depend on the continuously changing weather conditions and are typically spatially heterogeneous and non-stationary (Amon, Amon, Boxberger, & Alt, 2001; Bjerg et al., 2013; Fiedler et al., 2013; Saha et al., 2014a,c, 2013,; Schrade et al., 2012). Long-term measurements of gas concentrations are needed to obtain statistically representative results for defined boundary conditions. The measurements must be spatially distributed and temporally highly resolved in order to obtain accurate emission factors. This highlights the necessity to better characterise the emission sources and their interrelation with different environmental factors at the barn scale to further increase also the accuracy of emission factors in general (i.e., averaged over a particular farm or region).

In the past decades, several authors investigated different aspects of the complex relation between climate conditions and emission rates. In this context, temperature is a common reference variable for the climate. Amon et al. (2001), for example, investigated NH_3 emissions from slurry-based and straw-based cattle houses and found strong variations in the course of the year and a linear correlation between indoor temperature and average emission (Amon et al., 2001). In the case of CH_4 the authors found, however, no significant linear correlation to the season or temperature. Schrade et al. (2012) investigated the dependency of NH_3 emission factors on external wind speed and temperature and found in both cases strong linear correlations in the log-transformed averaged emission values, which indicates that the underlying dependency is exponential (Schrade et al., 2012). Moreover, Saha et al. (2013) showed that the inflow in general, i.e. speed and direction of the incoming wind, strongly affects the spatial distribution of gas concentrations (Saha et al., 2013). The authors found a significant influence of wind, temperature and humidity on the log-transformed emission values of NH_3 and CH_4 in the temperature range between about 10 °C and 20 °C. Strong diurnal and seasonal variations were observed. In another study, Saha et al. considered again log-transformed emission values of NH_3 and CH_4 and showed that the prediction of the emissions can be improved if wind direction, time of the day and day of the year are included as cyclic variables in the modelling process in addition to temperature, humidity and wind speed (Saha et al., 2014a).

The previous studies mentioned above focused on linear relationships (in most cases Pearson correlation) between emission factors and climate conditions. In some cases, non-linearity was considered indirectly via cyclic variables or log-transformed values, but non-linear modelling was not discussed (Saha et al., 2014a, 2013; Schrade et al., 2012). A low Pearson correlation, however, does not necessarily imply that there is no relation or interaction. In particular, in the case of non-monotonic functional relations (e.g., cycles or parabola) the Pearson correlation can be very low. In such cases, the