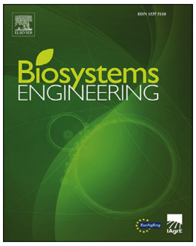
Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110



Research Paper

Calculation of ventilation rates and ammonia emissions: Comparison of sampling strategies for a naturally ventilated dairy barn

David Janke [a,*], *Dylia Willink* [a], *Christian Ammon* [a], *Sabrina Hempel* [a], *Sabine Schrade* [c], *Peter Demeyer* [d], *Eberhard Hartung* [f], *Barbara Amon* [a,g], *Nico Ogink* [e], *Thomas Amon* [a,b]

[a] *Leibniz Institute for Agricultural Engineering and Bioeconomy(ATB), Max-Eyth-Allee 100, 14469 Potsdam, Germany*
[b] *Institute of Animal Hygiene and Environmental Health, Department of Veterinary Medicine, Free University of Berlin, Robert-von-Ostertag-Str. 7-13, 14163 Berlin, Germany*
[c] *Agroscope, Ruminant Research Unit, Taenikon, 8356 Ettenhausen, Switzerland*
[d] *Flanders Research Institute for Agriculture, Fisheries and Food (ILVO), Technology and Food Science Unit, Belgium*
[e] *Wageningen UR Livestock Research, Wageningen, the Netherlands*
[f] *University of Kiel, Institute of Agricultural Engineering, Kiel, Germany*
[g] *University of Zielona Góra, Faculty of Civil Engineering, Architecture and Environmental Engineering, Poland*

ARTICLE INFO

Article history:
Received 18 December 2019
Received in revised form
6 July 2020
Accepted 14 July 2020

Keywords:
Air exchange rate
CO_2 balance method
Long-term measurements
FTIR
Sampling positions

Emissions and ventilation rates (VRs) in naturally ventilated dairy barns (NVDBs) are usually measured using indirect methods, where the choice of inside and outside sampling locations (i.e. sampling strategy) is crucial. The goal of this study was to quantify the influence of the sampling strategy on the estimation of emissions and VRs. We equipped a NVDB in northern Germany with an extensive measuring setup capable of measuring emissions under all wind conditions. Ammonia (NH_3) and carbon dioxide (CO_2) concentrations were measured with two Fourier-transform infrared spectrometers. Hourly values for ventilation rates and emissions for ammonia over a period of nearly a year were derived using the CO_2 balance method and five different sampling strategies for the acquisition of indoor and outdoor concentrations were applied. When comparing the strategy estimating the highest emission level to the strategy estimating the lowest, the differences in NH_3 emissions in winter, transition, and summer season were +26%, +19% and +11%, respectively. For the ventilation rates, the differences were +80%, +94%, and 63% for the winter, transition and summer season, respectively. By accommodating inside/outside concentration measurements around the entire perimeter of the barn instead of a reduced part of the perimeter (aligned to a presumed main wind direction), the amount of available data substantially increased for around 210% for the same monitoring period.

---

* *Corresponding author.*
E-mail address: djanke@atb-potsdam.de (D. Janke).

https://doi.org/10.1016/j.biosystemseng.2020.07.011

1. Introduction

Agriculture contributes up to 92% of the European ammonia emissions, where 11% are related to the manure management of dairy cattle (EEA, 2016). Accurate measurements are a basis for efficient emission mitigation measures. Dairy cows are mainly housed in naturally ventilated barns (NVB). In NVBs, air exchange rates and gaseous emissions are usually measured by indirect gas balancing methods, where the air exchange rates can be derived from measuring the dilution of a tracer gas with a known release rate. The emission rate of the target gas can then be derived as the product of the air exchange rate and the target gas concentration. A common approach is to use CO_2 (which is produced by the animals with a known release rate) as a tracer gas to estimate the air exchange rate (Ogink et al., 2013). Due to their large openings, NVBs are directly influenced by outside climatic conditions. This results in complex flow fields inside and around the building, where the concentrations of gases like CO_2 and NH_3 are distributed highly heterogeneously, both in time and space. Since the estimation of ventilation rates (VR) and ammonia emissions (E_{NH3}) relies on indirect balancing methods, the differences of measured outdoor and indoor concentrations of CO_2 (for the VR) and NH_3 (for the E_{NH3}) have a major influence on the accuracy of the results. The magnitude of the difference is directly dependent on the choice of sampling location for the outdoor and indoor concentration measurements (Edouard et al., 2016; König et al., 2018).

When using indirect CO_2 balancing methods, measurements of the NH_3 and CO_2 concentrations are required which are representative for the exhaust, barn leaving gas concentrations. The same applies to the measurements of NH_3 and CO_2 concentrations that are entering the barn. The challenge is to identify the position(s), where a representative measurement of exhaust and entering concentrations is possible. In the following, the exhaust gas concentrations will be called *inside gas concentrations* and the barn entering concentrations will be called *outside gas concentrations*.

Another important aspect is the time resolution and duration of the measurements. It needs to be chosen in a way, that representative results can be expected. Although important, this aspect will not be investigated in this study. This study considered hourly wind and concentration conditions.

1.1. *Measuring inside gas concentrations*

Van Buggenhout et al. (2009) conducted experiments in a laboratory test room with mechanical ventilation to investigate the influence of the sampling location on the accuracy of the estimation of VRs with a tracer gas technique. They found that the positioning of sampling points had a significant influence on the result of the ventilation rate estimation, and can cause errors up to 86%, due to heterogeneously distributed gas concentrations inside the building. The best results were derived when the sampling was done directly at the outlet, where the error was always lower than 10%.

König et al. (2018) and Ngwabie et al. (2009) investigated gas concentrations with point wise measurements inside a NVB. They found variations for the VRs up to 46% (König et al., 2018) and variations for NH_3 concentrations up to 35% (Ngwabie et al., 2009), when only individual sampling points were taken into account. Both authors suggest therefore the use of multipoint measurements to measure the gas concentrations inside the barn.

An intensive variant of these multipoint measurements is the use of so-called sampling lines. Here, the sampling air is sucked through tubes with many orifices over their length, that allow a high spatial resolution of sampling locations. Their use is published e.g. by Wu et al. (2012), where sampling lines were positioned at the two side openings and the ridge opening of a NVB. They chose these positions following the studies of Demmers et al. (2001) and Demmers et al. (1998), who concluded that due to no identifiable representative zone inside the building, the best location to measure the concentrations was at the outlets.

Edouard et al. (2016) used both, individual sampling points and sampling lines to investigate the influence of different spatial sampling strategies on the estimation of the VR. The sampling points and sampling lines under investigation were all positioned at the central axis in the middle of the barn, based on previous studies by Shen et al. (2012) optimization and Mendes et al. (2015) and on the assumption, that in NVBs the outlets can also act as inlets, which would bias the results.

Mohn et al. (2018) measured NH_3 of a compartment in a NVB and used a net of sampling lines, that were connected with each other, so that physically mixed sample was generated and measured as inside gas concentration.

Schrade et al. (2012) measured NH_3 in several different NVB, where they installed sampling lines either at every opening (ridge, gate, windows), or net-like over the animal occupied zones. In contrast to Mohn et al. (2018), the mean value of all sampling lines was not formed directly by physically mixing the concentrations of all lines, but sequentially measuring line after line and then forming the mean value afterwards. Both Schrade et al. (2012) and Mohn et al. (2018) used the artificial tracer gases SF_6 and SF_5Cf_3 instead of the naturally produced CO_2.

The VERA test protocol (VERA, 2018) gives a guideline on the measurement strategy for naturally ventilated buildings. For measuring the inside concentrations, it recommends either to place a sampling line in the middle of the building (for symmetrical houses), or for more open barns towards the side walls (that are described here as outlet openings), with a minimum distance of 2 m to the walls.

Concerning the measurement of gas concentrations within the barn, it can be summarised that multi-point sampling is preferable to single-point sampling. Sampling lines with many orifices provide a good opportunity to sample gas concentrations in a high spatial resolution over a long distance. No clear trend in the literature is recognisable whether these sampling lines should (i) cover only the outlets, (ii) be placed in the middle of the barn or (iii) cover as many regions inside the barn as possible.

1.2. *Measuring outside gas concentrations*

The measurement of the outside concentrations can be categorised in three approaches. In the first approach, the mean value of several point measurements positioned outside the barn is used. It is based on the idea that the more sampling points, the more representative the result will be. Examples can be found e.g. in Saha et al. (2013), Saha, Fiedler, et al. (2014) and Ngwabie et al. (2011). In the second approach, a sampling point is located at the approaching wind direction and measures the concentrations transported with the actual wind direction. This can be done either for only one main wind direction where situations with deviating wind directions are not taken into account (Schmithausen et al., 2018) or with several sampling points, taking into account variations of the approaching wind direction (König et al., 2018). The third approach takes into account several measurement points around the barn (e.g. one at each side opening) and uses the point with the lowest concentration for the outside gas concentration. The assumption behind this approach is that the sampling point positioned at the respective inlet opening must be the one with the lowest concentration. This strategy was used by e.g. by Ngwabie et al. (2009) and Wu et al. (2012), and is also recommended in the VERA test protocol (VERA, 2018). The only study we found that investigated the influence of different outside sampling locations was done by König et al. (2018). Four outside concentration sampling points were positioned at each side opening of a NVB. The VR was estimated based on each single point and based on the point at the respective approaching flow direction, defined by wind direction measurements. Compared to the wind direction strategy, the median values for VRs estimated by the fixed single points differed between −15% and +4%.

1.3. *Combination of measuring outside and inside gas concentrations*

We define the *sampling strategy* as the combination of outside and inside sampling locations that are used to calculate the difference of gas concentrations. With many sampling locations (or sampling lines) inside and outside the barn, many sampling strategies are possible to quantify the concentration differences. All sampling strategies found in the literature rely on comprehensible assumptions regarding the flow behavior and the transport of gas concentrations, and they combine different degrees of information to estimate VRs and E_{NH3}. In summary, an increase in accuracy is expected by increasing the quantity (more sampling locations) and/or quality of information (additional sources of information such as wind measurements or previous smoke tests) to reduce the risk of systematic errors. So far, the influence of different sampling strategies on the estimation of VR and E_{NH3} is insufficiently understood.

Our hypotheses are (1) The sampling strategy has a significant influence on the estimation of VR and E_{NH3}; and (2) Different sampling strategies lead to systematic deviations (over- or underestimation of VR and E_{NH3}) due to their design. The corresponding objectives of this study are to test these hypotheses and to quantify the influence of the sampling strategy on VR and E_{NH3} estimates.

To achieve the objectives, a set of five sampling strategies was considered and applied to a dataset of measurement values generated from long term measurements in a NVB, which will be described in the following in chapter 2.4.

2. Material and methods

2.1. *Barn and site description*

Measurements were carried out in an experimental dairy barn located in Dummerstorf in the northeast of Germany (54°1′ 0″ N, 12° 13′ 60″ E, altitude 43 m) near the city of Rostock. The barn's dimensions are 96.15 m length and 34.2 m width; its metal roof has a triangular shape, with the gable top reaching a maximum height of 10.7 m, decreasing to 4.2 m at the lowest point (on the sides). The total volume of the barn is 25,499 m^3. The floor is made of solid concrete and is cleaned every 90 min by automatic scrapers that push the slurry into four manure pits outside the barn. The barn is naturally ventilated, with open side walls and a ridge opening with a width of around 0.5 m. Only at very cold winter nights the side walls are closed using a polyethylene film. For air movements inside the barn, four additional ceiling fans (Powerfoil X2.0, Big Ass Fans HQ, Lexington, KY, USA) are installed on a height of 5.6 m above the floor over the feeding alley. They have a diameter of 7.34 m and operate temperature controlled under partial load for $10\ ^\circ C > T > 5\ ^\circ C$, and under full load for $T > 10\ ^\circ C$. The barn capacity was 375 dairy cows, which are free to move inside the barn. In north eastern direction, the barn is partly surrounded by other buildings, including a milking parlour, storage tanks, a young stock house and another NVB. In south western direction, the barn is surrounded by open field.

2.2. *Instrument setup and data collection*

2.2.1. *Measuring instruments description*

For the current work, more than 900 m of sampling lines made of PTFE with an inner diameter of 6 mm were installed inside and around the barn. Figure 1 presents a detailed plan of the distribution of the sampling lines. Table 1 lists the distances of the lines to the respective walls. Every 8–10 m, the lines were equipped with critical orifices, which ensured a constant volume flow over the length of each line. Carbon dioxide and ammonia concentrations were measured every hour from four sample lines representing outdoor concentrations, and from six sample lines for indoor concentrations. Two high-resolution Fourier-transform infrared (FTIR) spectrometers (Gasmet CX4000, Gasmet Technologies Oy) were used for measurements, each equipped with a multichannel to switch between the lines. The FTIR spectrometer had a standard uncertainty of 5–8% and worked in parallel, each connected to six sampling lines. The lines were measured one after another. In total, each line was measured 10 min. Seven minutes were used to flush the line and the measuring cell and 3 min were used for concentration measurements. By this, all 12 lines were measured within one hour, and hourly values for VR and emissions could be derived. Table 2 shows one example measurement cycle. It has to be mentioned that, due to wind variation within the period of the 1-h measurement cycle, this procedure might also involve an additional uncertainty in the measurements, which will not be investigated in this study. Before the measurements, additionally to the in-built libraries, both FTIR were calibrated for CO_2 with calibrating gas containing a concentration of 500 ppm for CO_2 and

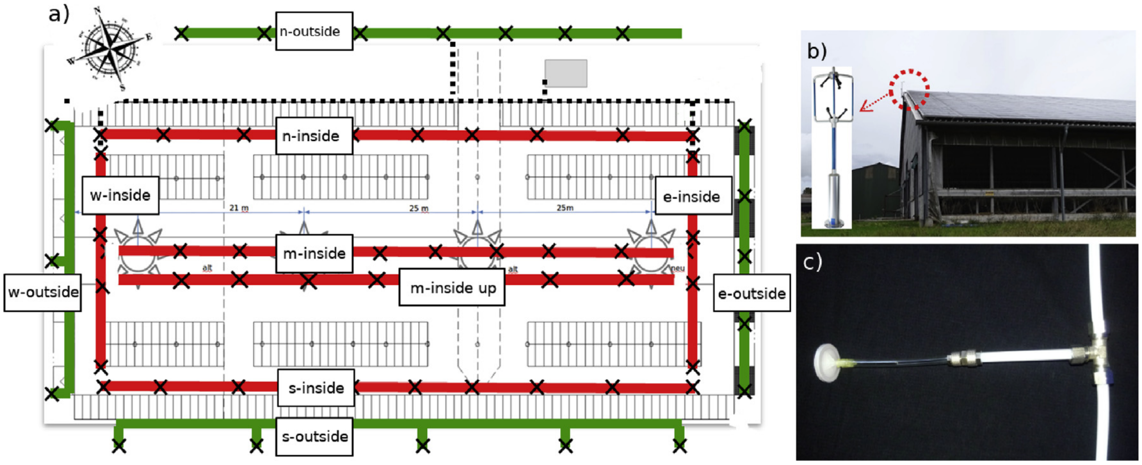


Fig. 1 – a) Plan of the location of measurement sample lines inside (red line) and outside (green lines) the barn. The first letters in the captions refer to north, east, south, west and middle, the second for inside and outside the barn. All lines were positioned at a height of 3.2 m, except line 'm-inside up', which was positioned at a height of 6.8 m. Every x represents a critical orifice. Grey stars mark the positions of the ceiling fans. b) Position and detailed view of the outside positioned ultrasonic anemometer. c) detailed view on the critical orifice.

Table 1 – Positions of the sampling lines. Distances are defined as distance from a line to it's corresponding building wall. The names of the sample lines indicate the cardinal directions with which they are aligned (n - north, e - east, s - south and w - west) as well as whether the lines are outside or inside the building.

Line	Distance (m)	Height (m)
n-outside	6	3.2
e-outside	4	3.2
s-outside	3	3.2
w-outside	3	3.2
n-inside	4	3.2
e-inside	8	3.2
s-inside	4	3.2
w-inside	8	3.2
m-inside	17	3.2
m-inside-up	17	6.8

Table 2 – One example measurement cycle of one hour with the two measurement devices FTIR1 and FTIR2. The lines 'extra 1' and 'extra 2' were additional lines, that were not taken into account for this study.

Time (min)	FTIR 1	FTIR 2
	Line	Line
10	n-outside	e-outside
20	s-inside	w-inside
30	m-inside	extra 1
40	s-outside	w-outside
50	n-inside	e-inside
60	m-inside-up	extra 2

calibrating gases containing concentrations of 0.5 ppm, 3 ppm and 5 ppm for NH_3. An ultrasonic anemometer (USA, Windmaster Pro ultrasonic anemometer, Gill Instruments Limited, Lymington, Hampshire, UK) was installed on the roof of the barn to measure the approaching wind velocity and direction. Inside the barn, temperature and relative humidity was measured with four EasyLog USB 2+ sensors (Lascar Electronics Inc., USA).

2.2.2. *Animal data*

CO_2 balance method calculations require information on the animals, including number of cows in the barn, their live weight (kg), average pregnancy length (days) and average milk production (kg day^{-1}). This data was collected by the administration of the Dummerstorf barn who kindly provided it to us for the current study. The cows had an average mass of 682 kg, the mean herd milk yield was 39.2 kg d^{-1} per animal. On average, 355 lactating Holstein-Friesian cows were in the barn and no dry cows were present. The cows were fed on totally mixed ration (TMR), consisting of corn and maize silage. For the computation of the CO_2 production term, the respective daily herd mean values were taken.

2.3. *Air exchange rate and emissions calculations via indirect method*

The ventilation rate was estimated from calculations of the mass balance of CO_2:

$$Q_t = \frac{C_{prod}}{(CO2_{inside} - CO2_{outside})} \cdot N_{animals}, \tag{1}$$

where $Q_t$is the total ventilation rate (m^3 h^{-1}), $CO2_{inside}$ and $CO2_{outside}$ are the concentrations of CO_2 inside and outside the barn respectively, C_{prod} is the estimated CO_2 production rate per animal and provided in g h^{-1}, and $N_{animals}$ is the number of animals inside the barn. The sources of CO_2 inside the barn were divided into two types: gas produced by animals and gas emitted from manure and bedding material. The gas produced by animals was considered to make up 95%, and the manure together with the bedding straw was considered to produce 5%, following the approach of Wang et al. (2016).

The CO_2 mass balancing method has been previously described in detail (Bjerg et al., 2012; Estellés et al., 2011; Pedersen, 2002, pp. 1–46; Pedersen et al., 1998; Samer & Abuarab, 2014; Wang et al., 2016), and is based on the estimation of animal heat production. Heat production varies due to animal physiology, different actions (milking, feeding, rumination), and animals' physical activity (Calvet et al., 2013). Those parameters must also be considered during calculations with the CO_2 balance method. The formula for calculating CO_2 production rate is presented as Equation (2). Heat production per cow (W) is multiplied by a factor of 0.185 and by an animal activity factor which varies depending on time of the day and type of animal, and can be identified as shown in Equation 6 (Pedersen, 2002).

$$C_{prod} = \frac{0.185 \cdot Heat_{prod} \cdot A}{1000} \tag{2}$$

$$Heat_{prod} = \Phi_{tot} \cdot t_{factor} \tag{3}$$

$$\Phi_{tot} = \Phi_{LM} + \Phi_{MY} + \Phi_{p} = 5.6m^{0.75} + 22Y_1 + 1.6 \cdot 10^{-5} p^3 \tag{4}$$

$$t_{factor} = 1000\left(1 + 4 \times 10^{-5}(20 - t)^3\right) \tag{5}$$

$$A = 1 - a \cdot (\sin(2 \cdot \pi / 24) \cdot (h + 6 - h_{min})) \tag{6}$$

where A is the relative animal activity; a is a constant expressing the amplitude with respect to the constant 1; $h_{min}$is the time of the day with minimum activity (hours after midnight); $\Phi_{LM}$is heat dissipation due to maintenance of essential function (W); $\Phi_{MY}$is heat dissipation due to milk yield (W); m is body mass of the cow (kg); Y_1 = milk production, (kg day^{-1}); t is the temperature inside the barn (°C), and p is days of pregnancy. Y_1 and p were provided by the barn operators, t was measured with the TH-logger inside the barn (see section 2.2.1).

Formula 3 provides the corrected total heat production $Heat_{prod}$ (W), calculated per cow at a temperature of 20 °C.

The total emission rate E_t (g h^{-1}) can be defined using the following equation:

$$E_t = Q_t \cdot (NH3_{inside} - NH3_{outside}) \tag{7}$$

where Q_t is the total ventilation rate (Eq. 1) and $NH3_{inside}$ and $NH3_{outside}$ are the NH_3 concentrations inside and outside the barn, respectively, in g m^{-3}. In order to make the results comparable to other studies, the measured NH_3 emissions will be provided as the emissions per livestock unit LU in g h^{-1} LU^{-1}, where 1 LU is the body mass equivalent of 500 kg, N is the number of animals and m is the average mass of one animal:

$$E = \frac{E_t \cdot LU}{N \cdot m}. \tag{8}$$

2.4. Sampling strategies

The approaching flow was divided into four sectors, each with an angle of 90°. The angles were adjusted to the orientation of the barn (+17° spin to the north–south axis), thus, each sector's symmetry line was perpendicular either to the longitudinal or the lateral openings. In the following text, flow entering the barn at the longitudinal side openings will be called north or south, and flow entering at the lateral openings at the gable walls will be called west or east. Consequently, in the following text flows from east or west will be called lateral flows, flows from south or north will be called cross flows.

Figure 1 shows the location of the sample lines, four on the outside and five inside the barn. Theoretically, there are 26 possible combinations to represent the value for the inside concentration (e.g. only the middle line or the mean value of all lines) and 15 possible combinations to represent the value for the outside concentration. This leads to $26 \cdot 15 = 390$ possible combinations for creating the inside - outside concentration difference. Based on the literature survey summarised in chapter 1 and additional assumptions regarding the flow characteristics inside the barn, we reduced this multitude of combinations to five different sampling strategies, that are summarised in Table 3 and further explained in the following subsections.

2.4.1. *Strategy 1 - based on wind direction*

Sampling strategy 1 was based on observed hourly wind directions. A visual description of this strategy is presented in Fig. 2 (M1). According to the wind direction, we defined every hour an actual inlet (green line) and outlet (red line) of the barn. The outside concentrations were then taken from the inlet sample line, the inside concentration from the outlet sample line.

2.4.2. *Strategy 2 – based on combined wind directions and spatial averaging*

Like strategy 1, sampling strategy 2 used hourly observed wind directions to determine the sample line for outside concentrations. In contrast to strategy 1, the inside concentrations were estimated for each hour as an average of all sample lines inside the barn, independent of the wind direction.

2.4.3. *Strategy 3 – based on spatial average of sampling lines*

This approach did not use any information about the wind direction. Instead, the mean values from all inside sampling lines were averaged to characterise the inside concentration, and the mean values from all outside sampling lines were averaged to characterise the outside concentrations.

2.4.4. *Strategy 4 – based on spatial average for inside, lowest concentration for outside concentrations*

In this strategy, the inside concentrations were estimated as an average of all sample lines inside the barn. For the outside concentration, the sample line with the respective hourly minimum concentration value was chosen.

2.4.5. *Strategy 5 – based on spatial average for inside without the middle sampling line, lowest concentration for outside*

This approach is a modified version of strategy 4, without taking into account the middle sample line $m - inside$ for inside concentrations. It was done because during the warm period in the middle of the barn, 4 huge cooling fans were constantly switched on. Those fans are installed in the middle of the barn (see Fig. 1 under line $m - inside$). We assume a high dilution of the concentrations at the position of sampling line $m - inside$, which may result in an underestimation of actual

Table 3 – Description of the applied sampling strategies.

Strategy	Inside sampling	Outside sampling	Assumption	Used by
M1	line in downwind direction	line in wind direction	The incoming flow pushes the gas concentrations in wind direction through the barn.	Schmithausen et al. (2018)
M2	mean value of all lines[a]	wind ward line	Using more sampling lines inside makes M2 more error-resistant than choosing only one line at the suspected outlet	König et al. (2018)
M3	mean value of all lines[a]	mean value all lines[a]	Robust strategy through smoothing out high concentration gradients	Saha et al. (2013), Saha et al. (2014b), Ngwabie et al. (2011)
M4	mean value of all lines[a]	line with minimum CO_2 concentration	The incoming flow must consist the lowest CO_2 concentrations, hence the outside line with lowest CO_2 concentrations must be at the inlet.	Ngwabie et al. (2009), Wu et al. (2012)
M5	mean value of lines positioned at openings[a]	line with minimum CO_2 concentration	Measuring concentrations at the openings is sufficient, no sampling in the middle is needed.	VERA (2018)

[a] The mean concentration values were computed every hour by forming the mean value of the individual sampling lines concentrations.

gas concentrations; thus, the central concentration line was skipped in this strategy.

2.5. *Climate conditions*

Weather in Germany is more or less stable with strongly-pronounced seasons and moderate climate, with deviation from North to South and from West to East due to geographical unevenness, surrounding by Baltic and Northern seas and the Alps located in the south of the country. The experimental barn is in the north-east, 20 km southern-east from a relatively big port city named Rostock and around 30 km away from Baltic sea. That makes the experimental place subjected to northern climate processes.

In order to investigate the role of wind direction on the estimation of VR and NH_3 emissions, wind vectors were measured with the anemometer described in chapter 2.2.1. They are presented as wind roses in Fig. 3. Wind roses are presented in several ways: for the whole researched year (Fig. 3 a); for November (Fig. 3 b) and by season (Fig. 3 c-e). The wind situation changes with the seasons; for example, in winter, winds are observed with near-equal frequencies from a spectrum of directions between east-south-east and north-north-west. In spring, more north-westerly winds were observed, while in summer, winds observed to blow primarily in western and south-eastern directions. A total of 6093 hourly values (described below as *events*) were taken into consideration. The wind data obtained during the measurement period were distributed as follows: 737 events from the north, 1862 from the south, 2004 events from the west, and 1490 events from the east. Thus, we can conclude that western and southern winds were the most frequently observed.

2.6. *Data treatment and overview*

Measurements took place throughout the period from November 2016 until September 2017 and hence covered all seasons. An overall amount of 5604 hourly data sets for gas concentrations in each sampling line was collected. In accordance to the recording date, the data was divided into the seasons winter (Dec–Feb), summer (Jun–Aug) and transition (Mar–May & Sep–Nov). Corresponding to the alignment of the barn, these data sets were further divided into northern, eastern, southern and western sectors, as depicted in Fig. 3. Table 4 shows the number of measurement values divided in seasons and wind directions.

The whole dataset with hourly measured gas concentrations in the sampling lines and additional ambient and animal parameters can be found in Janke et al. (2020).

2.7. *Statistics*

For statistical analysis the software packages SAS 9.4 (SAS Institute Inc., Cary, NC, USA) and Matlab were used. The derived results both for VR and E_{NH3} followed a skewed, non-Gaussian distribution. As a consequence, they were harmonised using a natural logarithmic transformation (Wilks, 2011). Repeated measures covariance analysis models were used to estimate the VR and E_{NH3} by strategy as well as to test differences between the five strategies while taking into account

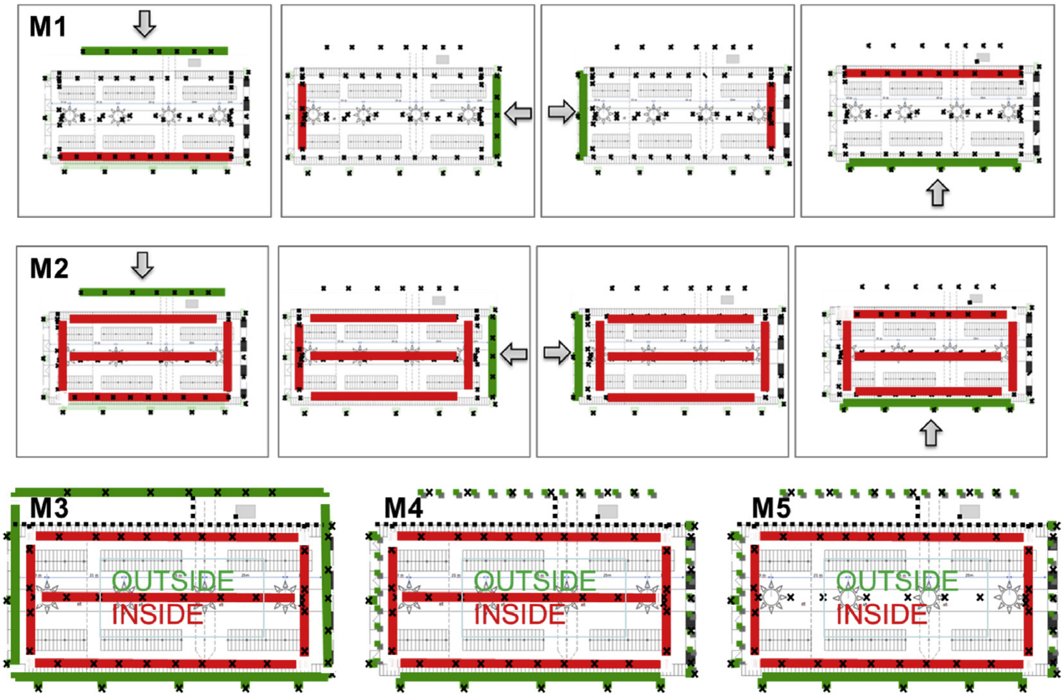


Fig. 2 – Schematic view of the sampling strategies M1, M2, M3, M4 and M5. Green lines correspond to outside measurements, red lines to inside measurements. The grey arrow marks the respective wind direction. Dashed colored lines for strategies M4 and M5 represent possible outside sampling lines, dependent on the concentration minimum.

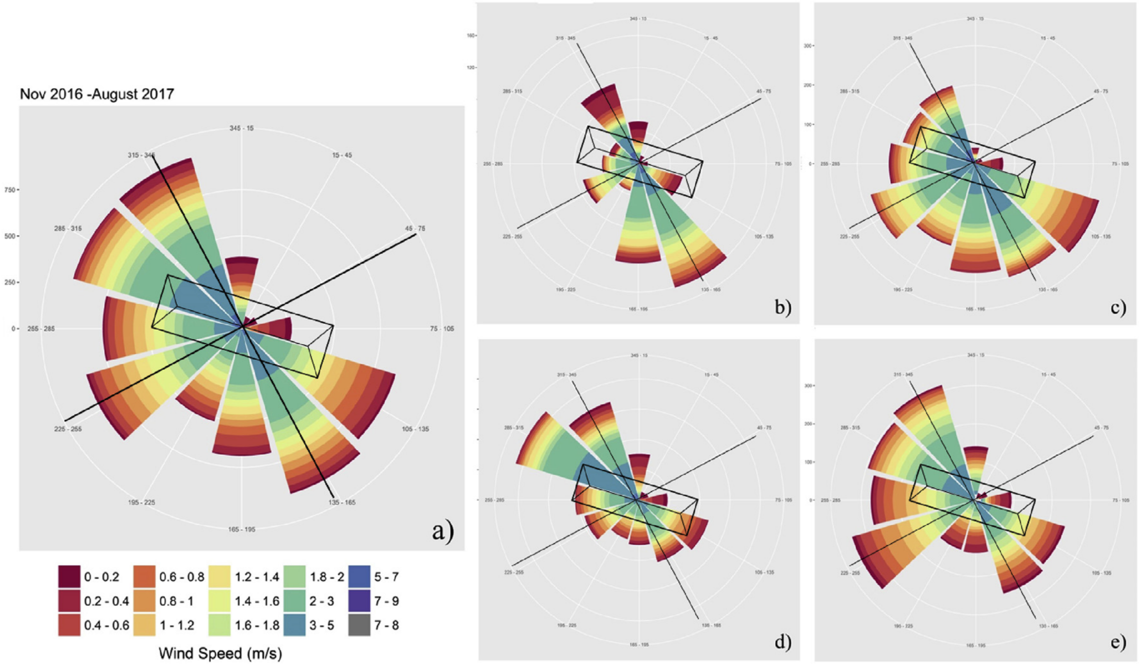


Fig. 3 – Wind roses obtained from the ultrasonic anemometer placed over the barns roof for a) November 2016–August 2017; b) November 2016; c) Winter 2016–2017; d) Spring 2017; e) Summer 2017. According to the alignment of the barn, the data sets were divided into four 90°-sectors, that were rotated 17° from the normal north, east, south and west sectors.

wind direction, wind speed and temperature, separately for each season. Fixed effects were strategy, wind direction and the interaction between strategy and wind direction. Wind speed and temperature were included as linear regression covariables. The repeated hourly measures within each strategy were considered with a spatial power covariance structure of the R matrix (variance-covariance matrix of the residuals). Hypotheses were tested at a significance level of

Table 4 – Number of hourly gas concentration measurements, sorted for wind direction and season.The second column shows the average temperatures and standard deviation.

	T (°C)	N	E	S	W	Overall
Winter	1.8±3.8	163	571	790	617	2141
Transition	10.3±5.9	404	574	650	717	2345
Summer	19.1±4.3	71	233	320	494	1118
Overall	638	1378	1760	1828	5604	

5%. After analysis, the results were transformed back into normal space and are presented here as mean values with the upper and lower limits of their respective 95% confidence intervals (CI).

3. Results and discussion

The five strategies introduced in section 2.4 were used to calculate VRs and E_{NH3} for the whole dataset. In the following, the results will be presented and discussed.

3.1. Ventilation rates

3.1.1. Comparison with the literature

Figure 4 shows the mean ventilation rates in m^3 per hour and livestock unit estimated by the five strategies, sorted by seasons and wind directions. For all seasons and strategies, a wide spread of estimated values for VRs is visible, from 1190 m^3 h^{-1} LU^{-1} (lowest CI-limit of strategy 1 in winter season from northern wind directions) to 4267 m^3 h^{-1} LU^{-1} (highest CI-limit of strategy 3 in transition season with northern wind directions). In Saha et al. (2013) and König et al. (2018), the same barn as in this study was measured, but with a different instrumental setting and in different time periods. König et al. (2018) used a sampling strategy equal to our strategy 2 and published a total yearly mean value for the VR in the range between 1811 and 2012 m^3 h^{-1} LU^{-1}. This corresponds well with our measurements with a yearly mean value computed with strategy 2 in the range between 1576 and 2127 m^3 h^{-1} LU^{-1}.

In Saha et al. (2013), a sampling strategy equal to our strategy 5 was used. Their published results for VRs in a summer season were sorted after wind direction. Following values were estimated: 1122–1500 m^3 h^{-1} LU^{-1} for northern winds, 1112–1301 m^3 h^{-1} LU^{-1} for eastern winds, 2109–2922 m^3 h^{-1} LU^{-1} for southern winds, and 1433–1920 m^3 h^{-1} LU^{-1} for western winds. The results for VRs from our study agree well with the results from Saha et al. (2013) for wind directions from south and west (no significant differences). Slightly higher VRs are estimated in our study for wind directions from east, and significantly higher VRs (appr. +60%) are estimated for northern winds. A reason for the high deviation for northern winds could be the relatively low number of data samples for the summer period with northern winds (71 in our study, 62 in the study of Saha et al. (2013)), that can lead to over- or underestimation of gusts or calms or simply different weather conditions in the different years of the studies (2012 and 2017).

3.1.2. Intercomparison of the strategies

According to Fig. 4b), significant differences can be identified between the results of strategy 1, strategy 3, and the group of strategies 2, 4 and 5. For all wind directions and seasons, strategy 3 estimates the highest values for VRs, strategy 1 the lowest. When comparing strategy 3 to strategy 1, differences between the mean values of +80% in the winter, +94% in the transition, and +63% in the summer period are estimated, respectively.

The high VR values estimated with strategy 3 can be explained by the sampling of outside concentrations with this strategy. By forming the mean value of all outside lines, the outside concentration value for CO_2 is artificially increased, which leads to smaller inside-outside differences, resulting in very high VR values. It can be concluded, that using strategy 3 results in an immense overestimation of the VR, independently of season and wind direction.

The low results for VRs estimated with strategy 1 can be explained by the assumption of a flow pushing the gas through the barn, where the CO_2 concentrations are accumulated with the flow direction. Strategy 1 uses for outside concentrations the line, where the flow enters the barn and as inside concentration the line, where the flow leaves the barn. Hence, the inside-outside concentration differences must be maximum, which results in minimum estimated VRs.

No significant differences exist between the estimated VRs of strategies 2, 4 and 5. This allows two conclusions to be drawn. Firstly, since strategy 4 and strategy 5 only differ by the use of the sampling line in the middle of the barn, it can be concluded that this line does not provide any extra information and could be skipped when measuring the ventilation rate. Secondly, since strategy 2 and strategy 4 only differ in the strategy for estimating the outside concentration - strategy 2 uses the line towards the wind direction, strategy 4 uses the line with the minimum CO_2 concentration - it can be concluded that the extra information about the wind direction for outside sampling does not change the estimation of ventilation rates and choosing the line with the minimum concentration is sufficient.

In all cases, strategy 2 estimates higher VRs than strategy 1. This is because strategy 2 is forming the value for the inside concentration as a mean value from all inside sampling lines. By this, upwind positioned sample lines inside the barn with lower concentrations are also taken into account and will dilute the average value. This lower inside concentration value leads to lower inside-outside concentration differences, which result in higher VRs.

3.2. Emissions

3.2.1. Comparison with the literature

Figure 5a) shows the mean NH_3 emissions estimated by the five strategies in grams per hour and livestock unit, sorted by seasons and wind directions. The numerical values from the figures can be found in Tables A.7, A.8 and A.9 in Appendix A. For the winter season, the estimated emissions throughout all five strategies are in a range between 0.67 g h^{-1} LU^{-1} (strategy 4 for eastern winds) and 1.10 g h^{-1} LU^{-1} (strategy 1 for western winds). These values agree with the results published by Saha,

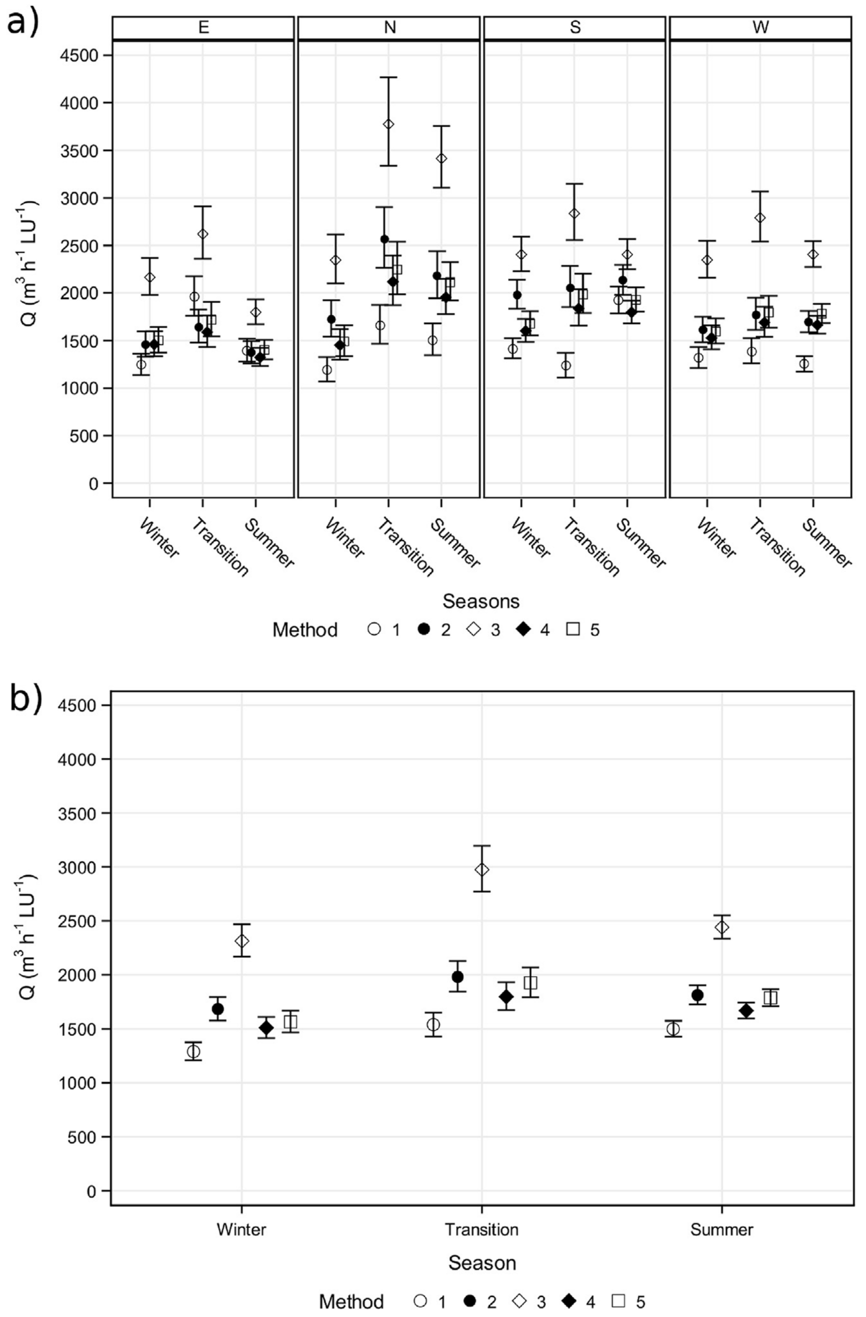


Fig. 4 – Ventilation rates per hour and livestock unit, computed by the five strategies. Symbols mark the mean values, error bars the upper and lower border of the 95% confidence interval. a) sorted by wind direction and seasons. b) sorted only by seasons and aggregated wind directions.

Ammon, et al. (2014), who measured the same barn that was the object of this study. For the winter period, their measured NH_3 emissions were in a range from 0.33 to 1.47 g h^{-1} LU^{-1}. The emissions for a NVB with a solid floor in the winter season were also measured by Schrade et al. (2012) and are in the range from 0.25 to 0.96 g h^{-1} LU^{-1}, which is slightly lower but still in agreement with this study. Winter measurements in a NVB with solid floor were published by Zhang et al. (2005) with emissions in a range from 0.51 to 0.64 g h^{-1} LU^{-1}, which is lower than our results, probably due to the colder climate conditions in Denmark.

For the transition season, the estimated emissions are in a range from 1.07 g h^{-1} LU^{-1} (strategy 4 for northern winds) and 1.73 g h^{-1} LU^{-1} (strategy 3 for eastern winds). This range is completely covered by the results for transitional period measurements in the before mentioned studies of Schrade et al. (2012) (0.67–1.83 g h^{-1} LU^{-1}) and Saha, Ammon, et al. (2014) (0.23–3.89 g h^{-1} LU^{-1}) and partially covered by the results of Zhang et al. (2005), which are slightly lower with ranges between 0.50 and 1.45 g h^{-1} LU^{-1}.

For the summer season, the estimated emissions are in a range from 1.77 g h^{-1} LU^{-1} (strategy 4 for northern winds) and

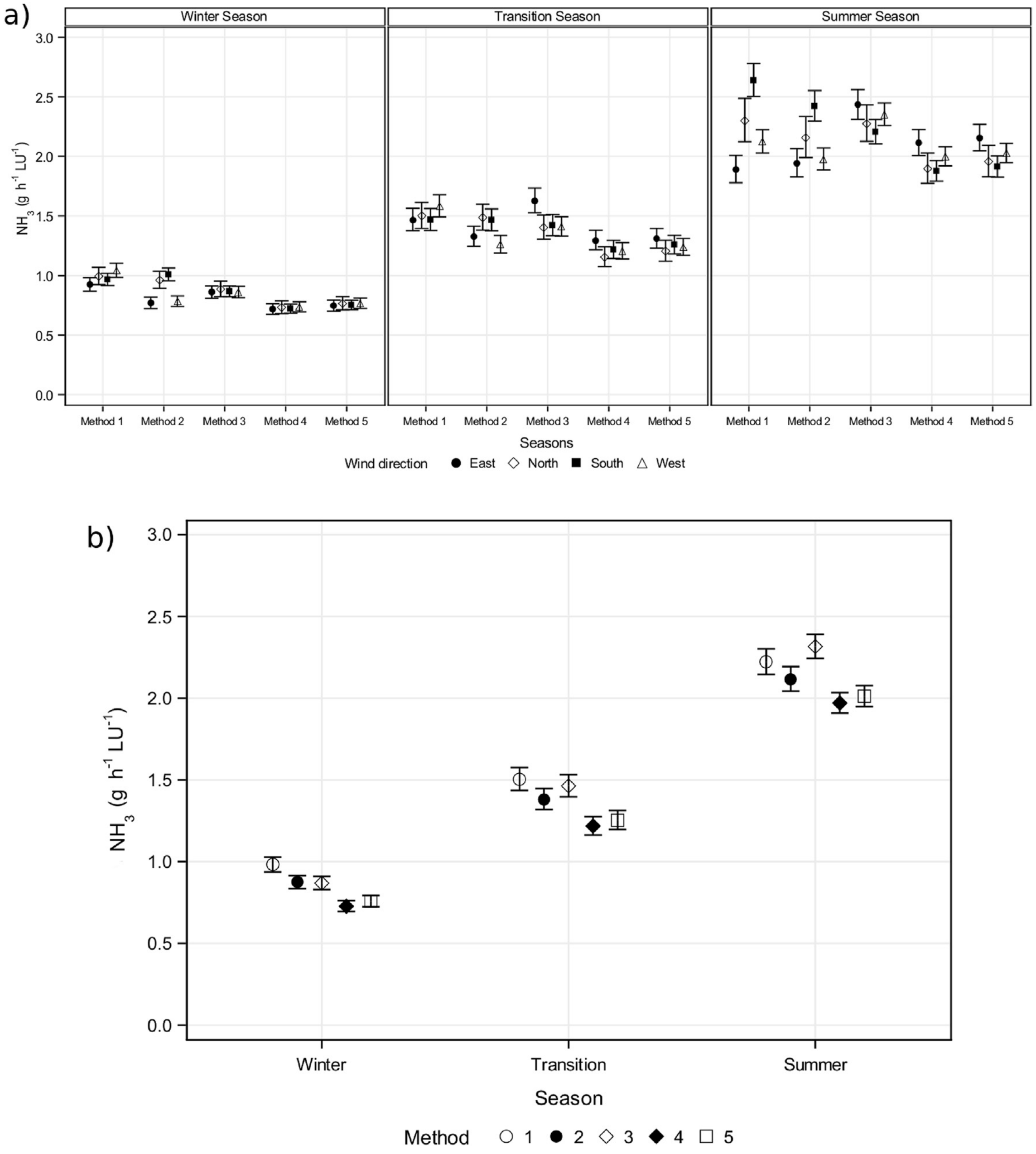


Fig. 5 – Ammonia emissions computed by the five strategies, a) sorted by wind direction and method for every season and b) sorted for season with aggregated wind directions. Symbols mark the mean values, error bars the upper and lower border of the 95% confidence interval.

2.78 g h^{-1} LU^{-1} (strategy 1 for southern winds). These values are completely covered by the results for summer period measurements in the before mentioned studies of Schrade et al. (2012) (1.29–2.79 g h^{-1} LU^{-1}), Saha, Ammon, et al. (2014) (0.367–4.41 g h^{-1} LU^{-1}), and Zhang et al. (2005) (1.12–4.21 g h^{-1} LU^{-1}).

Regardless of the wind direction and strategy, ammonia emissions were highest in the summer and lowest in the winter. The reason for that is the temperature-dependent production of ammonia and the higher temperatures in the transition- and summer season. Similar to this, the variances in the estimated values increases from the winter season over the transition season to the summer season. The reason for that is the higher temperature fluctuations in the transition- and summer season. Both, the seasonal increase in emissions and in variance (high in summer, low in winter) were also reported in Saha, Ammon, et al. (2014), Schrade et al. (2012), and Zhang et al. (2005).

3.3. *Intercomparison of the strategies*

Referring to Fig. 5a), in none of the 12 cases (four wind directions with three seasons), a significant difference between the estimated values from strategy 4 and strategy 5 is visible.The only difference between these two strategies was the sample line in the middle (*m-in* in Fig. 1), which was taken into account for strategy 4 and not taken into account for strategy 5. Hence, it can be concluded that when deriving the inside concentration as a mean value of all sampling lines inside (strategy "the-more-the-better"), the use of the middle sampling line does not deliver any extra information and is therefore not needed.

Regarding the results sorted for seasons shown in Fig. 5b), strategies 4 and 5 show the lowest values for NH_3 emissions for all seasons. The highest values are estimated by strategy 1 for the winter and transition season, and by strategy 1 and 3 (no significant difference) for the summer season. If strategy 1 (highest) is directly compared to strategy 4 (lowest, reference), the resulting differences of the mean values are +26% for the winter, +19% for the transition, and +11% for the summer season. Table 5 shows the p-values for the differences between the estimated mean values of each method, sorted for winter, transition and summer season, corresponding to Fig. 5b).

When deriving a whole-year emission value from the actual dataset, strictly using strategy 1 would result in a value of 13.74 kg y^{-1} LU^{-1}, while strictly using strategy 4 would result in 11.43 kg y^{-1} LU^{-1}. As a consequence, the predicted emissions per year per LU would be +20% higher when using strategy 1 instead of strategy 4. We can therefore conclude that hypotheses 1 and 2 have proven to be correct: the sampling strategy has a significant influence on the estimation of NH_3 emissions (hypothesis 1) and the different sampling strategies lead to systematic errors (hypothesis 2).

When comparing strategy 2 with strategy 4, the influence of the outside sampling strategy can be investigated: both strategies use the same strategy for sampling the inside concentrations (mean value of all inside sampling lines). Hence, any differences between their estimated emissions must be caused by the choice of the outside concentration line. In strategy 2, this choice is wind-driven, in strategy 4, the line with the minimum CO_2 level is chosen. The results for NH_3 emissions shown in Fig. 5a) show a behavior dependent on the wind direction, or more precisely, dependent on whether the flow is entering the barn cross-wise (north/south) or lateral-wise (east/west). For the lateral cases, no difference between strategy 2 and 4 can be seen. For the cross-wise cases, significant differences with a clear trend towards higher values for strategy 2 are present for all seasons except northern winds in the summer (same trend, but no significance). Expressed as relative differences, with strategy 4 as reference, strategy 2 delivers for southern winds +40%, +20% and +29% higher values for the winter, transitional and summer season, respectively. For northern winds, the differences are +31% for the winter and +28% for the transitional season (no significant difference for the summer season). This leads to overall differences of +20% for the winter, +14% for the transition, and +7% for the summer season, to be seen in Fig. 5b). For the whole dataset, strictly using wind direction information for the choice of the outside sampling line as in strategy 2, would result in an emission factor of 12.77 kg y^{-1} LU^{-1}, which corresponds to a difference of +12%. These differences did not show up when the ventilation rates were estimated with strategies 2 and 4 and only the concentration of CO_2 was considered.

It was concluded in the previous chapter, that both, choosing the sampling line with the minimum concentration or choosing the sampling line based on wind direction, deliver the same estimates of ventilation rates. Consequently, for CO_2, the outside sampling line towards the approaching flow was always the one with the CO_2 minimum. For NH_3, this appears not to be the case, otherwise strategy 2 would not estimate different NH_3 emissions than strategy 4. A possible reason for that might be wind directions in between two sectors or rapidly changing wind directions, combined with outside positioned additional sources of NH_3, like manure pits. The differences are only visible for cross-wise directions; for strategy 4 this would e.g. mean, that a wind from south-east shows minimum CO_2 values in the eastern line, which is then consequently chosen, while strategy 1 would choose the southern outside line. The western outside line, positioned over the manure pits, could show in this case higher NH_3 concentrations, which would decrease the inside-outside difference and lead to lower E_{NH3} levels. It can be concluded, that in the case of existing outside sources of NH_3, and unstable, rapidly changing wind conditions, the outside sampling line should rather be determined by the wind direction than by the concentration minimum.

Strategy 3 was, when estimating the ventilation rates, the strategy with the by far highest values. This behavior can not be noticed when strategy 3 is used to estimate the NH_3 emissions. According to equations 1 and 7, a decrease of inside-outside concentrations leads to an increase of ventilation rates and a decrease of NH_3 emissions. This means, that the increase of VRs due to the artificial increase of outside CO_2 concentrations in strategy 3 is compensated by the same artificial increase of NH_3 concentrations.

3.4. *Discussion and assessment of the different strategies*

The strategy-induced differences in estimated VRs and NH_3 emissions have been quantitatively determined. In the following, the applicability for each strategy under given

Table 5 – p-values for the differences of the mean values estimated by the five strategies, shown in Fig. 5b).

Winter Season					Transition Season				Summer Season			
	M2	M3	M4	M5	M2	M3	M4	M5	M2	M3	M4	M5
M1	0.0053	0.0018	<.0001	<.0001	0.0834	0.9175	<.0001	<.0001	0.3090	0.4253	<.0001	0.0006
M2	–	0.9998	<.0001	0.0002	–	0.4252	0.0011	0.0256	–	0.0027	0.0259	0.2229
M3	–	–	<.0001	0.0004	–	–	<.0001	<.0001	–	–	<.0001	<.0001
M4	–	–	–	0.7187	–	–	–	0.9115	–	–	–	0.8913

circumstances will be assessed. The assessment of the strategies will be based on the following assumptions.

The first is the assumption of an accumulation of gas concentrations aligned with the flow direction inside the barn. That means the lowest gas concentrations can be measured directly at the inlet of the barn, the highest at the outlet. This assumption is especially related to strategy 1, since this strategy presupposes the existence of a defined outlet. At this outlet, the inside gas concentrations are measured with only one sampling line. If the assumption is not fulfilled, it means that the flow inside the barn is not straightly following the direction of the incoming wind direction. This might happen when the flow is drifted laterally due to complex flow pattern or obstacles inside the barn. In these cases, strategy 1 would be a weak choice, because the "wrong" outlet sampling line would be considered.

The second assumption is that the release rate of NH_3 is independent of the wind direction. Apart from shifts in local flow velocities over emission-active surfaces that slightly shift the chemical equilibrium, the direction of the flow should have no influence on the level of NH_3 emissions. This was already published by Saha et al. (2013), who investigated the same barn as in this study and found no significant influence of the wind direction on the NH_3 emissions. As a consequence, the NH_3 estimates of a strategy should not vary significantly within the four wind directions. This assumption is related to all strategies.

Figure 6 shows the gradients of the CO_2 and NH_3 concentrations in the lines over the whole measurement period, sorted by the four approaching wind directions. In the left (blue) box of each figure, the concentration levels of the lines aligned in the main flow direction are shown, e.g. for a flow from south, first the outside southern line is shown, followed by southern inside, middle, northern inside and northern outside line. In the right (white) box, the concentrations of the lines aligned to the left and right of the flow direction are shown, meaning that e.g. for southern flow direction, the inside east, then outside east, inside west and last the outside west line concentrations.

For winds from the south, north, and west, the concentrations both for NH_3 and CO_2 show increasing values along the flow direction, which confirms assumption 1. For eastern winds, the concentrations show higher values at the middle line which then stagnate or even decrease towards the outlet. The reason for that might be the formation of more complex flow structures for lateral flows from east, that accumulate the gas concentrations at the middle line location. Another explanation could be the distribution of wind directions for the eastern sector, shown in Fig. 3a). The incoming flow direction in

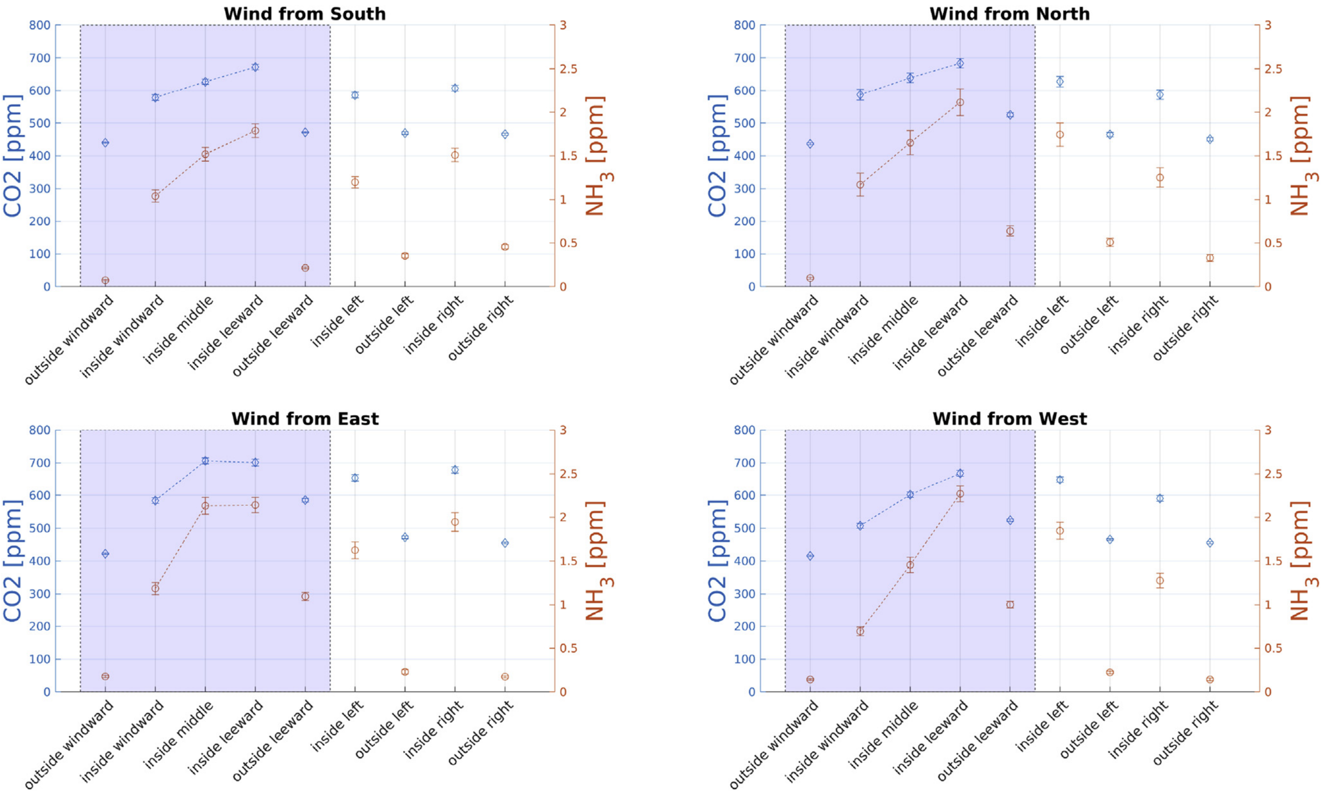


Fig. 6 – Accumulation of the gas concentrations along the flow direction. The dataset was sorted by the wind directions south, north, east and west. For each wind direction, the mean values of the gas concentrations in each sample line were computed. Blue dots and bars show the mean concentrations and confidence intervals of CO_2, red dots present the values for NH_3. The respective sample lines are ordered for each wind direction and renamed after their position relative to the flow direction, e.g. *inside windward* is the sample line positioned at the inlet inside the barn, *outside right* is the sample line outside the barn on the right side when facing in direction of the flow (starboard side). The blue area marks values from sample lines positioned along the flow, where an accumulation of concentrations is expected. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 6 – Suitability of the different strategies for certain wind- and site conditions and general tendencies of the strategies for the estimation of ventilation rates and ammonia emissions. $CO2_{in}$ and $NH3_{in}$ are carbon dioxide and ammonia concentrations for the inside concentration values, $CO2_{out}$ and $NH3_{out}$ for the outside concentration values. Scenario Sc1: straight and stable flow through the barn, either cross or lateral. Sc2: unstable and weak wind conditions and ambiguous wind directions. Sc3: building and wind combination leading to flow deflection or complex flow pattern (e.g. long barns with mainly lateral flow, large flow obstacles inside the barn). Sc4: incoming flow is contaminated with gas concentrations from different outside sources. Sc5: measurement campaigns with multiple barns with different geometries and wind conditions.

Strategy	Sc1	Sc2	Sc3	Sc4	Sc5	tendency VR (explanation)	tendency E_{NH3} (explanation)
M1	+	−	−	o	o	lowest (estimates maximum $CO2_{inside}$ - $CO2_{outside}$)	highest (uses maximum $NH3_{inside}$)
M2	−	−	+	+	o	moderate	moderate
M3	−	+	o	o	o	highest$^{!}$ (artificial maximum of $CO2_{outside}$)	moderate
M4	−	+	+	−	+	moderate	lowest (uses low $NH3_{inside}$−$NH3_{outside}$)
M5	−	+	+	−	+	moderate	lowest (uses low $NH3_{inside}$−$NH3_{outside}$)

$^{+}$Recommended for the scenario $^{-}$Not recommended for the scenario ^{o}No general recommendation possible $^{!}$Strong overestimation, not recommended for estimation of VR.

this sector is not equally distributed around the barns eastern opening, but has a trend to south-east directions. This could lead to less definite flow regimes. Instead of a clear lateral flow, a mix of cross flow and lateral flow would be the result. Based on these observations, it can be concluded that strategy 1 should be applied under clear wind conditions (either cross- or lateral flow). Here, the chance of a well defined outlet is high, and the sampling line would measure the indeed leaving concentrations, giving the most accurate results. For rather unclear wind conditions, another strategy should be considered. Imaging wind conditions with very low incoming speeds, or even a lull, strategy 1 should be avoided. In these cases, a more robust strategy like strategy 3, which does not consider inlets or outlets at all, should be the first choice.

To use the second assumption as an evaluation of the strategies, the strategy-wise results for NH_3 emissions are shown in Fig. 5, sorted after season and wind direction. If we assume the emission rates are independent of the wind direction, then a strategy performs well when the estimated emission rates show no dependency on the wind directions. For the winter season, the results estimated with strategies 1, 3, 4 and 5 do not show any significant differences within the wind directions. Strategy 2 estimates significantly higher values for cross-wind directions. In the transition season, strategies 1, 4 and 5 do not show significant differences within the wind directions. Strategy 2 shows the same behavior as in the winter season with higher values for cross-winds and lower values for lateral winds. In the summer season, the only strategy estimating values independently of the wind direction is strategy 3. Strategy 1 and 2 show the highest variations with significantly higher values for southern winds and lowest values for lateral wind directions. The higher variation for strategy 1 and 2 can be explained by the summer weather, where less stable wind conditions with generally lower wind speed and more changing wind directions are present. This affects the strategies that use information about the wind direction most, while strategies using only information about the gas concentrations (strategy 4 and 5) or no information at all (strategy 3) seem to be more robust. Hence, under unstable, weak wind conditions, strategies relying on information about the wind direction (for inside or outside concentrations) should be avoided.

In case of designing several measurement campaigns with different barns, e.g. for the collection of data for national inventories, a strategy should be considered, which delivers as many useable samples as possible in a given time frame. For example, Schmithausen et al. (2018) used a setup similar to strategy 1, with the constraint of a given main wind direction. This led, depending on the wind conditions, to a rejection of data in the amount of around 80%. With the actually installed setup for this study, every wind direction could be taken into account, which means a gain of data of around 210%, if beforehand conditions with only straight southern wind directions were considered (see Table 4). This could be even enhanced, if an adaption of strategy 2 would be applied, where all sampling lines inside the barn would be physically connected, and the mean value for inside concentration would be determined by physically mixing the single line concentrations. By that, the needed time for a whole measurement circle with all lines could be reduced by the factor 2, because only one value for inside concentrations would be measured. The suitability of each strategy for certain wind and site conditions is summarised in Table 6.

Finally, no influence of the surroundings on the estimation of the emissions can be found. In the north, the barn is surrounded by several other barns and buildings, in the south, it is surrounded by free field. However, the different roughness is not noticeable, since no strategy (except strategy 1 in the summer season) estimates differences between the values from north and south.

4. Conclusions

The sampling strategy has a significant influence on the estimation of ventilation rates and ammonia emissions, which leads to systematic errors, depending on the applied strategy.

The choice for the outside sampling (either wind-dependent or choosing the minimum CO_2 level) influences the estimation of ammonia emissions up to 20%, but does not affect the estimation of ventilation rates, probably as a consequence of outside NH_3 sources combined with unstable inflow conditions.

The strictly wind-dependent strategy 1 estimates the highest values for ammonia emissions, the concentration (outside), and mean value (inside) based strategies 4 and 5 estimate the lowest values.

Using the mean value of all outside lines for the outside concentration value (strategy 3), leads to unrealistically high ventilation rates. However, the estimation of ammonia emissions is not affected by this strategy, probably because the artificial decrease of CO_2 concentration difference induced by this strategy is compensated by inducing an artificial decrease of NH_3 concentration difference in the same relative magnitude.

Neither for the estimation of VRs nor the estimation of ammonia emissions, the use of a sampling line in the middle of the barn delivers any extra information and can therefore be skipped.

No influence of the surrounding of the barn in terms of flow obstacles (buildings or free field) could be found.

All investigated strategies followed reasonable assumptions, so none can be considered superior to the other. The main problem when trying to assess the strategies is the lack of a highly accurate reference dataset to compare against and validate the investigated strategies. Hence, the interpretation of the results and the assessment of the strategies had to be done based on some basic assumptions concerning the flow and the transport of gas.Following conclusions could be drawn: The wind-dependent strategy 1 should be used for stable wind conditions, either clear cross or lateral flow. Under these conditions, this strategy quantifies the barn-leaving emissions most accurately. Under unstable or indifferent wind conditions strategy 1 should be avoided.

Strategies 3, 4 and 5 show a robust behavior towards unstable wind conditions. In cases of lateral flow, where a more complex flow pattern inside the barn is expected, the inside sampling should not rely on only one line at the expected outlet, but on more lines like in strategies 3, 4, and 5. Therefore, for these cases, either strategy 3 or strategy 4 is recommended.

This study focused on the spatial distribution of sampling locations. The important aspect of the distribution in time was not considered. The frequency of sampling, the duration of measurement periods and the number of repetition of measurements will have a major influence on the estimation of VRs and E_{NH3}. Further investigations should therefore be done regarding these aspects.

The systematic investigation of different sampling strategies under different influencing factors will help to set up a robust measurement design with an optimised sampling strategy, adjustable to the respective conditions. By this, the outcomes of this study will help to improve the CO_2 balancing method, which is widely used to estimate ventilation rates and emissions from naturally ventilated barns.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We like to acknowledge Uli Stollberg and Andreas Reinhard, technicians at ATB, for technical support during the measurements. Also we like to thank the Landesforschungsanstalt für Landwirtschaft und Fischerei (LFA), namely PD Dr. Anke Römer, Dr. Bernd Losand, and Christiane Hansen for the comprehensive provision of climate and animal data. Further this article is based upon cooperation from COST Action LivAGE (CA16106), supported by COST (EuropeanCooperation in Science and Technology). Finally, we like to thank the members of the KTBL working group *EmiDaT* for always fruitful discussions and the exchange of experience.

Appendix A. Tables Emission Factors and ventilation rates

Table A.7 – Winter Season: ammonia emissions and ventilation rates. “up” and “low” mark the upper and lower limit of the 95% confidence interval.

		NH_3 (g h^{-1} LU^{-1})					Q (m^3 h^{-1} LU^{-1})				
		M1	M2	M3	M4	M5	M1	M2	M3	M4	M5
	Up	0.98	0.82	0.91	0.76	0.79	1363	1595	2370	1598	1644
East	Mean	0.92	0.77	0.86	0.72	0.75	1245	1456	2165	1460	1502
	Low	0.87	0.72	0.81	0.67	0.70	1138	1329	1979	1334	1372
	Up	1.07	1.04	0.95	0.79	0.82	1327	1926	2617	1619	1662
North	Mean	1.00	0.96	0.89	0.73	0.77	1190	1723	2346	1452	1490
	Low	0.92	0.89	0.82	0.68	0.71	1067	1542	2102	1302	1336
	Up	1.02	1.06	0.91	0.76	0.79	1526	2138	2593	1728	1808
South	Mean	0.97	1.01	0.87	0.72	0.75	1415	1981	2404	1602	1677
	Low	0.92	0.96	0.82	0.69	0.71	1312	1835	2229	1486	1555
	Up	1.10	0.83	0.91	0.78	0.81	1429	1750	2549	1660	1733
West	Mean	1.04	0.78	0.86	0.74	0.77	1316	1611	2347	1529	1596
	Low	0.99	0.74	0.81	0.70	0.72	1211	1482	2162	1408	1469
	Up	1.03	0.92	0.91	0.76	0.79	1375	1795	2468	1610	1669
Overall	Mean	0.98	0.87	0.87	0.73	0.76	1289	1682	2312	1509	1564
	Low	0.94	0.84	0.83	0.69	0.72	1208	1577	2169	1415	1466

Table A.8 – Transition Season: ammonia emissions and ventilation rates. "up" and "low" mark the upper and lower limit of the 95% confidence interval.

		NH_3 (g h^{-1} LU^{-1})					Q (m^3 h^{-1} LU^{-1})				
		M1	M2	M3	M4	M5	M1	M2	M3	M4	M5
	Up	1.57	1.42	1.74	1.38	1.40	2175	1826	2911	1764	1909
East	Mean	1.47	1.33	1.63	1.30	1.31	1957	1644	2621	1588	1718
	Low	1.38	1.25	1.53	1.22	1.23	1761	1479	2359	1430	1547
	Up	1.62	1.60	1.51	1.24	1.30	1875	2904	4268	2394	2539
North	Mean	1.50	1.49	1.40	1.16	1.21	1658	2564	3775	2118	2247
	Low	1.40	1.38	1.31	1.08	1.12	1466	2264	3340	1874	1988
	Up	1.56	1.56	1.51	1.30	1.34	1370	2284	3148	2038	2202
South	Mean	1.47	1.47	1.42	1.22	1.26	1234	2058	2837	1837	1985
	Low	1.38	1.38	1.34	1.14	1.18	1111	1853	2557	1656	1789
	Up	1.68	1.34	1.49	1.278	1.31	1527	1951	3066	1856	1972
West	Mean	1.58	1.26	1.41	1.21	1.24	1388	1774	2791	1690	1796
	Low	1.49	1.19	1.33	1.14	1.17	1261	1612	2541	1539	1635
	Up	1.44	1.32	1.40	1.16	1.20	1649	2128	3196	1931	2069
Overall	Mean	1.50	1.38	1.46	1.22	1.25	1535	1980	2975	1798	1926
	Low	1.58	1.45	1.53	1.28	1.31	1429	1843	2770	1674	1793

Table A.9 – Summer Season: ammonia emissions and ventilation rates. "up" and "low" mark the upper and lower limit of the 95% confidence interval.

		NH_3 (g h^{-1} LU^{-1})					Q (m^3 h^{-1} LU^{-1})				
		M1	M2	M3	M4	M5	M1	M2	M3	M4	M5
	Up	2.01	2.07	2.56	2.23	2.27	1519	1495	1933	1425	1508
East	Mean	1.90	1.94	2.43	2.11	2.16	1394	1372	1798	1325	1402
	Low	1.78	1.83	2.31	2.01	2.05	1280	1259	1672	1232	1304
	Up	2.49	2.34	2.43	2.02	2.09	1683	2439	3756	2149	2323
North	Mean	2.30	2.16	2.28	1.90	1.96	1505	2178	3415	1955	2113
	Low	2.13	1.99	2.13	1.78	1.83	1347	1946	3105	1778	1922
	Up	2.78	2.55	2.31	1.97	2.00	2069	2297	2567	1919	2059
South	Mean	2.64	2.42	2.21	1.88	1.91	1922	2132	2404	1797	1928
	Low	2.50	2.30	2.11	1.79	1.83	1786	1979	2252	1683	1806
	Up	2.22	2.07	2.45	2.08	2.11	1336	1810	2545	1760	1886
West	Mean	2.12	1.98	2.35	2.00	2.03	1252	1695	2406	1664	1783
	Low	2.03	1.89	2.26	1.92	1.95	1174	1588	2275	1573	1686
	Up	2.30	2.19	2.39	2.03	2.08	1574	1904	2551	1743	1867
Overall	Mean	2.22	2.12	2.32	1.97	2.01	1499	1812	2441	1668	1787
	Low	2.15	2.04	2.24	1.91	1.95	1428	1726	2336	1596	1710

REFERENCES

Bjerg, B., Zhang, G., Madsen, J., & Rom, H. B. (2012). Methane emission from naturally ventilated livestock buildings can be determined from gas concentration measurements. *Environmental Monitoring and Assessment, 184*, 5989–6000.

Calvet, S., Gates, R. S., Zhang, G., Estelles, F., Ogink, N. W., Pedersen, S., & Berckmans, D. (2013). Measuring gas emissions from livestock buildings: A review on uncertainty analysis and error sources. *Biosystems Engineering, 116*, 221–231.

Demmers, T., Burgess, L., Short, J., Phillips, V., Clark, J., & Wathes, C. (1998). First experiences with methods to measure ammonia emissions from naturally ventilated cattle buildings in the UK. *Atmospheric Environment, 32*, 285–293.

Demmers, T., Phillips, V., Short, L., Burgess, L., Hoxey, R., & Wathes, C. (2001). Se—structure and environment: Validation of ventilation rate measurement methods and the ammonia emission from naturally ventilated dairy and beef buildings in the United Kingdom. *Journal of Agricultural Engineering Research, 79*, 107–116.

Edouard, N., Mosquera, J., van Dooren, H. J., Mendes, L. B., & Ogink, N. W. (2016). Comparison of CO^2-and SF^6-based tracer gas methods for the estimation of ventilation rates in a naturally ventilated dairy barn. *Biosystems Engineering, 149*, 11–23.

EEA, E. E. A. (2016). *European Union emission inventory report 1990-2016 — European Environment Agency* (vol. 6). https://www.eea.europa.eu/publications/european-union-emission-inventory-report-1.

Estellés, F., Fernandez, N., Torres, A., & Calvet, S. (2011). Use of CO^2 balances to determine ventilation rates in a fattening rabbit house. *Spanish Journal of Agricultural Research, 9*, 713–720.

Janke, D., Dilya, W., Hempel, S., Amon, B., Römer, A., & Amon, T. (2020). High resolution long-term measurements af carbon dioxide and ammonia concentrations in a naturally ventilated dairy barn. *PUBLISSO Repository for Life Sciences*. https://doi.org/10.4126/FRL01-006420709

König, M., Hempel, S., Janke, D., Amon, B., & Amon, T. (2018). Variabilities in determining air exchange rates in naturally ventilated dairy buildings using the CO^2 production model. *Biosystems Engineering, 174*, 249–259.

Mendes, L., Ogink, N., Edouard, N., van Dooren, H., Tinôco, I., & Mosquera, J. (2015). Ndir gas sensor for spatial monitoring of carbon dioxide concentrations in naturally ventilated livestock buildings. *Sensors, 15*, 11239–11257.

Mohn, J., Zeyer, K., Keck, M., Keller, M., Zähner, M., Poteko, J., Emmenegger, L., & Schrade, S. (2018). A dual tracer ratio method for comparative emission measurements in an experimental dairy housing. *Atmospheric Environment, 179*, 12–22.

Ngwabie, N., Jeppsson, K.-H., Gustafsson, G., & Nimmermark, S. (2011). Effects of animal activity and air temperature on methane and ammonia emissions from a naturally ventilated building for dairy cows. *Atmospheric Environment, 45*, 6760–6768.

Ngwabie, N., Jeppsson, K.-H., Nimmermark, S., Swensson, C., & Gustafsson, G. (2009). Multi-location measurements of greenhouse gases and emission rates of methane and ammonia from a naturally-ventilated barn for dairy cows. *Biosystems Engineering, 103*, 68–77.

Ogink, N. W., Mosquera, J., Calvet, S., & Zhang, G. (2013). Methods for measuring gas emissions from naturally ventilated livestock buildings: Developments over the last decade and perspectives for improvement. *Biosystems Engineering, 116*, 297–308.

Pedersen, S. S. K. (2002). *Climatization of animal houses. heat and moisture production at animal and house levels*. Horsens, Denmark: Danish Inst of Agric Sci.

Pedersen, S., Takai, H., Johnsen, J. O., Metz, J., Koerkamp, P. G., Uenk, G., Phillips, V., Holden, M., Sneath, R., Short, J., et al. (1998). A comparison of three balance methods for calculating ventilation rates in livestock buildings. *Journal of Agricultural Engineering Research, 70*, 25–37.

Saha, C., Ammon, C., Berg, W., Fiedler, M., Loebsin, C., Sanftleben, P., Brunsch, R., & Amon, T. (2014a). Seasonal and diel variations of ammonia and methane emissions from a naturally ventilated dairy building and the associated factors influencing emissions. *Science of the Total Environment, 468*, 53–62.

Saha, C. K., Ammon, C., Berg, W., Loebsin, C., Fiedler, M., Brunsch, R., & von Bobrutzki, K. (2013). The effect of external wind speed and direction on sampling point concentrations, air change rate and emissions from a naturally ventilated dairy building. *Biosystems Engineering, 114*, 267–278.

Saha, C. K., Fiedler, M., Ammon, C., Berg, W., Loebsin, C., Amon, B., & Amon, T. (2014b). Uncertainty in calculating air exchange rate of naturally ventilated dairy building based on point concentrations. *Environmental Engineering and Management Journal (EEMJ), 13*.

Samer, M., & Abuarab, M. E. (2014). Development of CO^2 balance for estimation of ventilation rate in naturally cross-ventilated dairy barns. *Transactions of the ASABE, 57*, 1255–1264.

Schmithausen, A., Schiefler, I., Trimborn, M., Gerlach, K., Südekum, K.-H., Pries, M., & Büscher, W. (2018). Quantification of methane and ammonia emissions in a naturally ventilated barn by using defined criteria to calculate emission rates. *Animals, 8*, 75.

Schrade, S., Zeyer, K., Gygax, L., Emmenegger, L., Hartung, E., & Keck, M. (2012). Ammonia emissions and emission factors of naturally ventilated dairy housing with solid floors and an outdoor exercise area in Switzerland. *Atmospheric Environment*, 47, 183–194. https://doi.org/10.1016/j.atmosenv.2011.11.015

Shen, X., Zong, C., & Zhang, G. (2012). Optimization of sampling positions for measuring ventilation rates in naturally ventilated buildings using tracer gas. *Sensors, 12*, 11966–11988.

Van Buggenhout, S., Van Brecht, A., Özcan, S. E., Vranken, E., Van Malcot, W., & Berckmans, D. (2009). Influence of sampling positions on accuracy of tracer gas measurements in ventilated spaces. *Biosystems Engineering, 104*, 216–223.

VERA. (2018). *Vera test protocol: For livestock housing and management systems*.

Wang, X., Ndegwa, P. M., Joo, H., Neerackal, G. M., Stöckle, C. O., Liu, H., & Harrison, J. H. (2016). Indirect method versus direct method for measuring ventilation rates in naturally ventilated dairy houses. *Biosystems Engineering, 144*, 13–25.

Wilks, D. S. (2011). *Statistical methods in the atmospheric sciences* (3rd ed.). Oxford: Academic Press.

Wu, W., Zhang, G., & Kai, P. (2012). Ammonia and methane emissions from two naturally ventilated dairy cattle buildings and the influence of climatic factors on ammonia emissions. *Atmospheric Environment, 61*, 232–243.

Zhang, G., Strøm, J. S., Li, B., Rom, H. B., Morsing, S., Dahl, P., & Wang, C. (2005). Emission of ammonia and other contaminant gases from naturally ventilated dairy cattle buildings. *Biosystems Engineering, 92*, 355–364.