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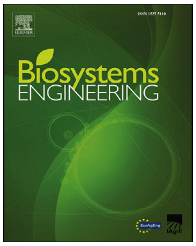

Research Paper

Comparison of CO_2- and SF_6- based tracer gas methods for the estimation of ventilation rates in a naturally ventilated dairy barn

Nadège Edouard [a,b,*], Julio Mosquera [c], Hendrik J.C. van Dooren [c], Luciano B. Mendes [c,1], Nico W.M. Ogink [c]

[a] INRA UMR1348 PEGASE, F-35590 Saint Gilles, France
[b] Agrocampus Ouest UMR1348 PEGASE, F-35590 Saint Gilles, France
[c] Wageningen UR Livestock Research, P.O. Box 135, 6700 AC Wageningen, The Netherlands

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Livestock production is a source of numerous environmental problems caused by pollutant gas emissions. In naturally ventilated buildings, estimating air flow rate is complicated due to changing climatic conditions and the difficulties in identifying inlets and outlets. To date no undisputed reference measurement method has been identified. The objective of this paper was to compare CO_2- and SF_6-based tracer gas methods for the estimation of ventilation rates (VR_{CO_2} *vs.* VR_{SF_6}) in naturally ventilated dairy barns both under conventional and very open ventilation situations with different spatial sampling strategies. Measurements were carried out in a commercial dairy barn, equipped with an injection system for the controlled release of SF_6, and measurement points for the monitoring of SF_6 and CO_2 concentrations to consider both horizontal and vertical variability. Methods were compared by analysing daily mean VR_{CO_2}/VR_{SF_6} ratios. Using the average gas concentration over the barn length led to more accurate ventilation rates than using one single point in the middle of the barn. For conventional ventilation situations, measurements in the ridge seem to be more representative of the barn average than in the middle axis. For more open situations, both VR_{CO_2} and VR_{SF_6} were increased, VR_{CO_2}/VR_{SF_6} ratios being also more variable. Generally, both methods for the estimation of ventilation rates gave similar results, being 10–12% lower with the CO_2 mass balance method compared to SF_6 based measurements. The difference might be attributed to potential bias in both methods.

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* *Corresponding author.* INRA UMR1348 PEGASE, F-35590 Saint Gilles, France. Tel.: +33 2 23 48 70 58; fax: +33 2 23 48 50 80.
E-mail addresses: nadege.edouard@rennes.inra.fr (N. Edouard), julio.mosquera@wur.nl (J. Mosquera), hendrikjan.vandooren@wur.nl (H.J.C. van Dooren), mendes@iiasa.ac.at (L.B. Mendes), Nico.Ogink@wur.nl (N.W.M. Ogink).

[1] Present address: Mitigation of Air Pollution and Greenhouse Gases/Ecosystems Services and Management, International Institute of Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria.

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Nomenclature

VR	Ventilation rate
CIGR	International Commission of Agricultural Engineering (CIGR, Commission Internationale du Génie Rural)
PTFE	Polytétrafluoroéthylène
GC	Gas chromatography (method used for the measurement of SF_6 concentrations)
NDIR	Non-dispersive infrared sensor (method used for the measurement of CO_2 concentrations)
OP-laser	Open-path laser (method used for the measurement of CO_2 concentrations)
PAS	Photo acoustic multi-gas monitor (method used for the measurement of CO_2 concentrations)
VR_{CO_2}, VR_{SF_6}	Ventilation rate calculated using either CO_2 or SF_6 as a tracer gas
PCO_2	amount of CO_2 produced (in $m^3\ h^{-1}$) at the barn level
hpu	Heat production unit = 1000 W at 20 °C
VR_{CO_2}/VR_{SF_6}	Ratio between Ventilation rates calculated using either CO_2 or SF_6 as a tracer gas
VR_{CO_2NDIR}, VR_{CO_2laser}, VR_{CO_2PAS}	Ventilation rates calculated using CO_2 as a tracer gas, with CO_2 concentrations measured either with NDIR sensors, OP-laser or PAS methods
CV	Coefficient of variation
ANOVA	Analysis of variance
AOZ	Animal occupied zone
H	Height dimension
RMSE	Root mean square error of the model
SEM	Standard error of the mean

1. Introduction

Livestock production is a source of a number of environmental problems (acidification, eutrophication, loss of biodiversity) through ammonia emissions, and is a significant contributor to climate change through the emission of greenhouse gases. In order to implement and evaluate the use of technologies and practices to reduce these pollutant emissions, reliable and standardised measurement methods are required. Although gaseous emissions from livestock have been studied for decades over the world, it is acknowledged that their quantification still is a challenge. This is particularly the case for naturally ventilated buildings, prevailing in cattle systems, where estimation of air flow rates is complicated by the considerable effects of wind speed and direction, temperature, air inlet and outlet constructions as well as roof inclination angle on the air movement inside the building and the resulting net air flow rate (Calvet et al., 2013; Ogink, Mosquera, Calvet, & Zhang, 2013; Perén, van Hooff, Leite, & Blocken, 2015; Takai et al., 2013).

Among the variety of direct and indirect methods developed for the measurement of air flow rates, as reviewed by Ogink et al. (2013), none has been identified as an undisputed reference method. More recently, new approaches based on direct measurements of velocity profiles (using ultrasonic anemometers) have been developed. However, these methods either have not yet been validated by comparison against existing methods (Joo et al., 2014) or were developed in laboratory/prototype conditions and are not yet readily transferable to conditions in commercial animal houses (Van Overbeke, De Vogeleer, Brusselman, Pieters, & Demeyer, 2015; Van Overbeke, De Vogeleer, Pieters, & Demeyer, 2014; Van Overbeke, Pieters, De Vogeleer, & Demeyer, 2014). More research is therefore needed to validate their applicability and improve measurement accuracy in naturally ventilated barns. Until now, comparative studies from the literature have identified tracer gas techniques as the most robust method to investigate emissions in naturally ventilated buildings, even if improvements are required (Ogink et al., 2013; Phillips, Lee, Scholtens, Garland, & Sneath, 2001; Samer et al., 2011; Scholtens, Dore, Jones, Lee, & Phillips, 2004). The principle of the tracer gas method was extensively described in Phillips et al. (2001). It consists of releasing a tracer at a known rate, monitoring its concentration in the building and deducing the resulting air exchange rate. The tracer gas should be injected close to the emission source and disperse in a similar way as the target gas. To estimate ventilation rates (VR), concentrations measured at the sampling point(s) should be representative of the average building concentration (Ogink et al., 2013). This technique, however, assumes good air mixing conditions inside the building, which is often not the case in naturally ventilated buildings. This has resulted in some studies inferring that the uncertainty in ventilation rate estimations in very open building can exceed 50%, compared to 5–20% in mechanically ventilated buildings (Calvet et al., 2013; Zhang, Pedersen, & Kai, 2010).

The tracer used can be either artificially injected in the building (e.g. SF_6, Ikeguchi & Hideki, 2010; Scholtens et al., 2004; Schrade et al., 2012; Snell, Seipelt, & Van den Weghe, 2003; Zhang et al., 2005; or ^{85}Kr, Kiwan et al., 2013; Muller et al., 2007; Samer et al., 2011, 2012) – or released as metabolic products by the animals and the manure (e.g. CO_2, Bjerg, Zhang, Madsen, & Rom, 2012; Kiwan et al., 2013; Muller et al., 2007; Ngwabie, Jeppsson, Gustafsson, & Nimmermark, 2011; Ngwabie, Jeppsson, Nimmermark, Swensson, & Gustafsson, 2009; Phillips et al., 2001; Rong, Liu, Pedersen, & Zhang, 2014; Saha et al., 2014; Samer et al., 2011, 2012; Zhang et al., 2005). The CO_2 mass balance is a particular form of tracer gas method which is considered reliable, quite simple, fast and cheap for the estimation of ventilation rates and gaseous emissions in animal housings when compared to the use of artificial tracers. The rate of metabolically produced CO_2 can be estimated from CIGR equations (Pedersen & Sällvik, 2002; Pedersen et al., 2008) using information on animal numbers and production levels. This tracer benefits from the relatively homogeneous distribution of CO_2 by animal sources throughout the building, resulting in a better mixing between the tracer and air (Ogink et al., 2013). Several uncertainties have, however, been identified which relate to the prediction of CO_2 production, such as CO_2 produced per energy unit, the amount of CO_2 emitted by manure and the location of sampling points (Samer et al., 2011).

Van Buggenhout et al. (2009) demonstrated that the outlet sampling position was the one location where, as to be expected, the ventilation rate could be estimated with the best accuracy (less than 10% error) in mechanically ventilated buildings. However, the location of exhaust air can be difficult to determine in naturally ventilated buildings as it may be subject to cross ventilation from variable directions. From an experimental study conducted by Shen, Zong, and Zhang (2012), it appeared that the optimal sampling position for indoor gas concentration measurement was found to lie close to the centre of the building, at approximately 30% of the barn height. Similarly, using one sampling point situated in the middle of the barn was shown to be equivalent to using the mean of 5 sampling points throughout the house (Bjerg et al., 2012). On the contrary, Wu, Zhai, Zhang, and Nielsen (2012) concluded from their computational fluid dynamics analysis that the mean CO_2 concentration of the entire room might not accurately represent the outlet concentration in very open barns. Besides, they concluded that gas sampling positions should be located adjacent to all the openings to reduce uncertainty related to wind direction. New dairy barns, especially in Northern Europe, are more often constructed with large inlet openings, changing ventilation management from conventional ridge ventilation with restricted side inlets to combinations of cross flow and ridge ventilation. Consequently, there is a need for a better understanding of spatial variability of tracer-pollutant ratios in the building and its relation with ventilation management to improve tracer gas method reliability (Ogink et al., 2013).

The objective of this paper was to compare CO_2- and SF_6-based tracer gas methods for the estimation of ventilation rates in a naturally ventilated dairy barn with ridge outlet and side wall inlets. Firstly, both methods were compared when side inlet openings were reduced to a minimum. In this way, air was supposed to be well mixed and leaving the barn through the ridge, ensuring clear inlet and outlet points for sampling. The purposes of this first analysis were (a) to check whether or not both methods perform similarly under these conventional ventilation conditions and (b) to investigate the influence of horizontal (number and location of sampling points) and vertical (central axis *vs.* ridge) sampling strategies. Secondly, CO_2 and SF_6 methods were compared in more open situations (large inlet openings), when air may leave the barn both through the ridge and side openings. The applicability of these methods in barns with restricted or very open inlet configurations was discussed.

2. Material and methods

2.1. *Barn description and animal management*

Measurements were carried out over periods between May 2012 and December 2013 in a naturally ventilated dairy barn considered to be representative for modern dairy buildings in the Netherlands (Bunschoten, province of Utrecht, NL). A precise description of the barn characteristics can be found in Mendes, Edouard, et al. (2015). Side walls openings were protected with fabric nets (mesh 50 × 50 mm). The building was equipped with manually operated curtains to enable the farmer to modulate temperature inside the building through ventilation rate (Fig. 1). During the measurement periods, 192–201 Holstein dairy cows (131–159 lactating, 6–31 dry, 18–37 young stock) were housed in this free stall design barn which contained six rows of cubicles with paper chips used as bedding (replaced approximately every 4 month) and concrete slatted walking alleys. Feeding alleys were located on both sides of the barn (see Figs. 2 and 3). Remaining manure and urine on the slats were automatically scraped every 3 h and stored in the slurry pit under the slats. On the east side of the barn, a calving area was covered with straw litter evacuated once a year with a tractor mounted scraper (faeces manually removed daily). The lactating cows had permanent access to 3 milking robot systems. All the cows were kept in the building all year long and were fed with roughage (grass and maize silage) and concentrate. Between May 2012 and December 2013, mean live weight was 661 ± 10 kg cow^{-1} for lactating and dry cows; young cows were not weighed regularly and were estimated to weigh 500 kg; mean milk yield per cow was 28.7 ± 1.2 kg d^{-1}.

2.2. *Description of the SF_6 injection system*

The barn was equipped with an injection system for the controlled release of SF_6. The SF_6 injection system was described in detail by Mendes, Edouard, et al. (2015). A pure SF_6 tank and an air compressor system were kept in a shelter placed outside of the barn. SF_6 was mixed at a controlled mass flow rate of 22.4 ± 0.8 ml min^{-1} (GFM 571, Aalborg Instruments & Controls, Orangeburg, NY, USA) with compressed air at a flow rate of 10 l min^{-1}. The mixture was channelled into the barn through polyethylene tubing (6.3 mm inside diameter) and released through injection points along both feeding fences, along the cubicles area and beyond the automatic milking systems, with a total of 114 injection points placed at approximately 0.5 m above the floor (Fig. 2). The injection points were equipped with capillary tubes and a thin plate orifice (9.8 mm internal diameter with a 217 μm diameter orifice; 0.5 mm thick) to allow equal release of a specific amount of tracer gas. The distribution of the SF_6 flow over the different points within an injection line was occasionally checked measuring the pressure at individual injection points, to ensure that pressure was the same between injection lines and also between the end and the beginning of each of these lines.

2.3. *Description of the CO_2 and SF_6 concentration measurements*

The barn was provided with several spatially dispersed measurement points for the monitoring of SF_6 and CO_2 concentrations to consider both horizontal and vertical variability. SF_6 and CO_2 concentrations were monitored using different methods and sampling strategies, either based on individual sampling points, collective multi-sampling points or the average of the barn length (see Tables 1 and 2). Inside the barn, sampling took place in the centre, distributed over its full length (64 m) at two heights: 3 m above the slats, further designated as sampling of the central axis, and at 10 m above the slats and as such positioned 1 m below the ridge, further

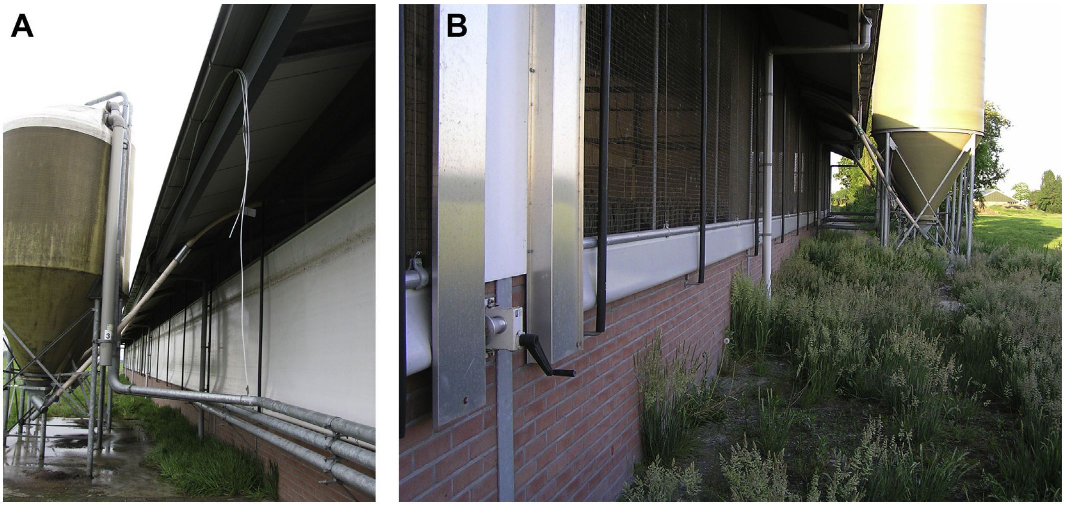

Fig. 1 – **Images of the manually operated curtain on one side of the dairy barn in its "restricted" (A) and "open" position (B).**

designated as sampling in the ridge (Fig. 3). Background gas (CO_2) concentration was monitored with sampling points located outside the barn (Fig. 3). All sampling tubes were made of polytetrafluoroethylene (PTFE, 6.3 mm inside diameter).

2.3.1. *Equipment for the measurement of SF_6 concentration*

Five evenly distributed individual sampling points (one point every ~10 m), each with their own sampling line, were installed in the central axis of the barn (Fig. 3). Sampling in the ridge was based on one collective line with five evenly distributed inlet points (equipped with a glass capillary restricting the flow to 1000 ml min^{-1}) providing one collective multi-sampling point connected to a pump (>5000 ml min^{-1}). SF_6 concentrations were semi-continuously monitored at each individual or collective sampling points with a specific gas chromatograph analyser (Interscience CompactGC with Electron Capture Detector, see Table 2 for technical specifications) with the same measurement point measured every 40 min (Table 1) thanks to a rotary multi point selection valve.

2.3.2. *Equipment for the measurement of CO_2 concentration*

In the central axis of the barn, CO_2 concentrations were recorded continuously using 2 different methods and sampling strategies (see Tables 1 and 2 for descriptions). Five portable non-dispersive infrared (NDIR) type CO_2 gas sensors (model SD-GAS-025, Sensor data B. V., Rijswijk, The

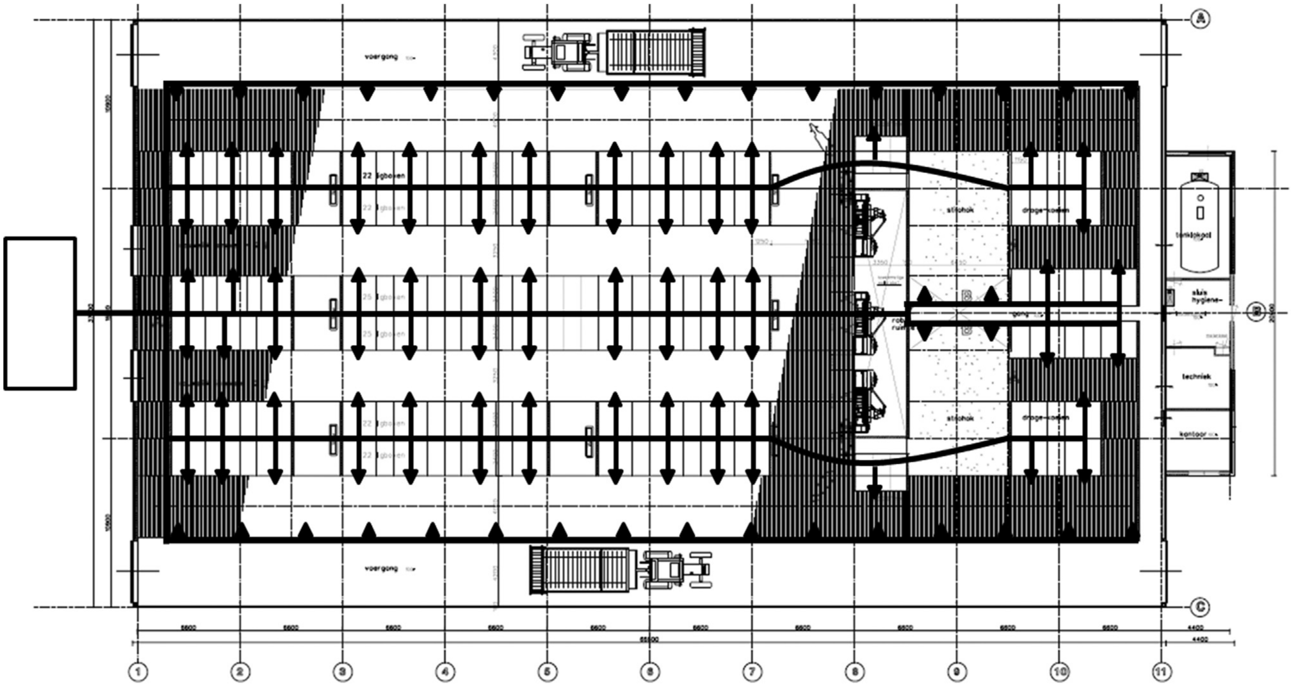

Fig. 2 – **Position of the SF_6 distribution lines (plain lines) and 114 injection points (triangles) dispersed along the dairy cow barn. The rectangle on the left side of the barn represents the placement of the instrument shelter.**

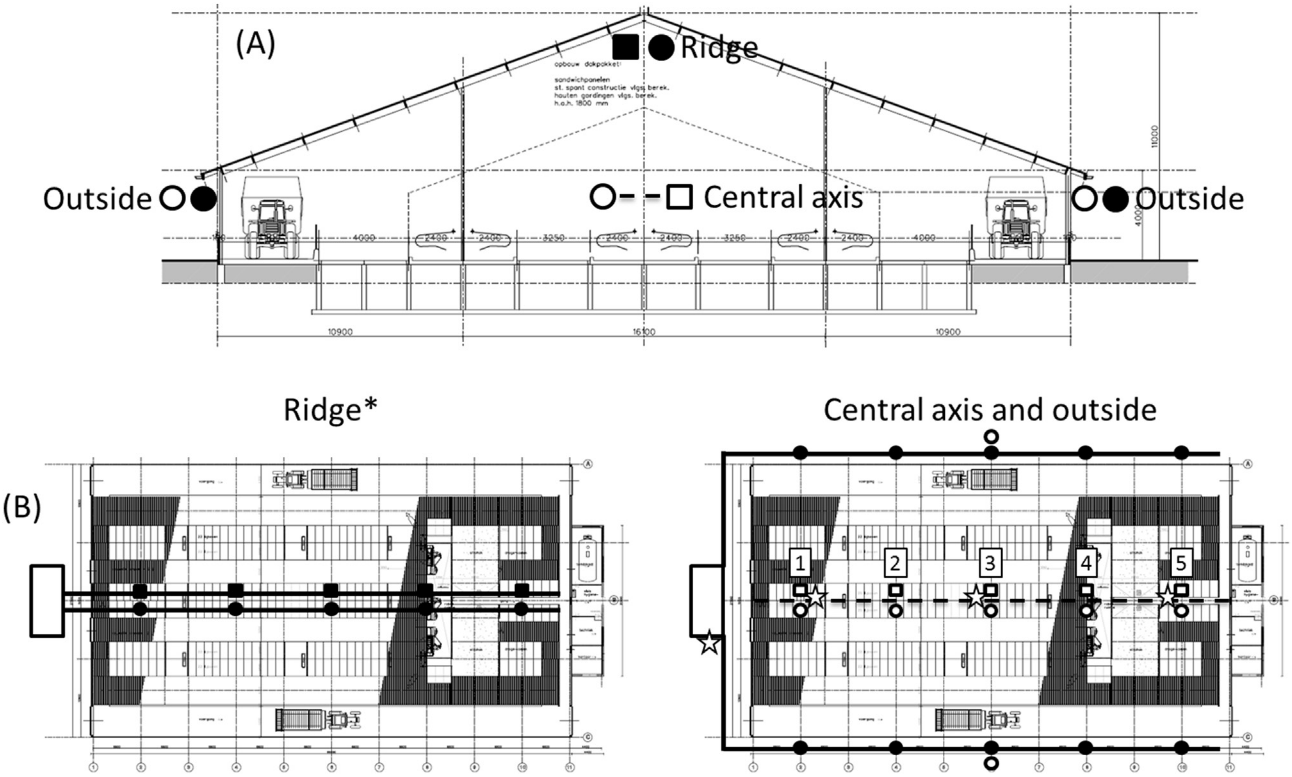

Fig. 3 – Position of sampling points on cross-sectional (A) and plan (B) views of the dairy cow barn either in the ridge, central axis and outside for the measurement of SF_6 concentration (squares), CO_2 concentrations (circles), temperature and relative humidity (stars). Full symbols represent collective multi-sampling lines including 5 inlet points each. Open symbols represent individual sampling points (1–5). The dotted line represents the open-path laser for the monitoring of CO_2 concentrations over the barn length. The rectangle on the left side of the barn represents the placement of the instrument shelter. *In the ridge, 2 sampling lines are shown for ease of understanding (CO_2 and SF_6 concentration measurements). In reality, air was pumped via one unique multi-sampling collective line. The purge line of the pump was then split in two lines, one for CO_2 concentration measurement and one for SF_6 concentration measurement.

Netherlands) were evenly distributed over the barn length (one every ~10 m) and monitored CO_2 concentration at each location every 5 min. As described in Mendes, Ogink, et al. (2015), their measurement principle is based on gas absorption of radiation at a known wavelength. The NDIR sensors were connected to a datalogger system (CR1000, Campbell Scientific, Inc., Logan, UT, USA) located in a shelter placed outside the barn (Fig. 3). In parallel, an open-path (OP) laser (model GasFinderFC, Boreal Laser, AL, Canada) was installed at one side of the barn to measure CO_2 concentrations over the whole length of the barn (64 m) every 5 min (Fig. 3, Table 1). A remote retro-reflector (prism-like mirror) was installed on the opposite wall for reflection of the laser beam back to the source. The OP-laser held a self-calibration check mechanism, including a reference calibration cell (crystal sphere containing CO_2 at known concentration; see Table 2 and Mendes, Ogink, et al., 2015 for a complete description of the CO_2 measurement systems and their calibration).

Sampling in the ridge was based on the same collective line as used for SF_6 concentration measurements, with five evenly

Table 1 – Summary of sampling characteristics for the monitoring of CO_2 and SF_6 concentrations inside and outside the barn.

Sampling site	Gas	Equipment[a]	Sampling characteristics	Measurement frequency at each point (min)
Central axis	CO_2	NDIR sensor	5 individual points	5
		OP laser	Average of the path length	5
	SF_6	GC	5 individual points	40
Ridge	CO_2	PAS	1 collective line, 5 inlet points	5
	SF_6	GC	1 collective line, 5 inlet points	40
Outside	CO_2	NDIR sensor	1 individual point per side	5
		PAS	1 collective line per side, 5 inlet points	5

[a] NDIR sensor: non-dispersive infrared type CO_2 gas sensors; OP laser: open-path laser; GC: gas chromatography; PAS: photo acoustic multi gas monitor.

Table 2 – Technical specifications of the gas measuring devices used in this study.

Equipment[a]	Measured gas	Detection limit[b]	Accuracy	Calibration
NDIR sensor	CO_2	0.2 ppm_v	±30 ppm_v ±2%	Two-points calibration at laboratory
OP laser	CO_2	2000 ppm_m	500 ppm_m	Continuous self-calibration with a reference gas crystal cell
PAS	CO_2	1.5 ppm_v	±1%	Two-points calibration at factory
GC	SF_6	0.08 ppb	±0.4%	One-point calibration (16.1 ppb) at laboratory every 6 months

[a] NDIR sensor: non-dispersive infrared type CO_2 gas sensors; OP laser: open-path laser; GC: gas chromatography; PAS: photo acoustic multi gas monitor.

[b] ppm_v: parts per million by volume; ppm_m: parts per million per meter; ppb: parts per billion.

distributed inlet points providing one collective multi-sampling point (purge line of the pump split in two lines, Fig. 3). CO_2 concentrations were measured every 5 min using a photo acoustic multi-gas monitor (PAS; Innova model 1312, INNOVA AirTech Instruments A/S, Ballerup, Denmark; filter model UA0982, AirTech Instruments). Dew point temperature was also monitored by the PAS analyser in order to account for cross-interference with moisture in the air (see Table 2 and Mendes, Ogink, et al., 2015 for more technical descriptions and calibration).

Background concentrations were recorded every 5 min both using two NDIR sensors (one on each side of the dairy barn, in the middle of the barn length; Fig. 3) and two collective multi sampling lines (one on each side of the barn, each including 5 inlet points; Fig. 3) providing average measurements points for the determination of CO_2 concentrations with the PAS. Both NDIR sensors and inlet points from the collective lines were located outside the barn, approximately 1 m from side screens and 1 m below the barn roof gutters (Fig. 3).

2.4. *Climate and side screen opening*

Temperature and relative humidity were continuously measured inside and outside the barn using combined sensors (Rotronic Instrument Corp., Hauppauge NY, USA; Fig. 3). Hourly mean values were stored in a data-logging system (CR1000, Campbell Scientific, Inc., Logan, UT, USA). Outside wind speed and direction data were derived from the nearest meteorological station (KNMI, station De Bilt, at 10 m height and located 19 km from the measurement site) which was considered as representative of the local conditions in this flat area near sea level.

The opening percentage of both side wall screens was continuously monitored by a sensor (homemade based on a rotary multi-turn position sensor connected to the curtain axle giving a signal between 0 and 1V, ranging from fully closed to fully opened) and logged. When the daily mean signal was less than 0.25, the opening size of the side screens was “restricted” and the ventilation management called conventional, representing the ventilation situation of an ordinary dairy barn in the Netherlands where most of the air leaves the barn through the ridge; when the signal was more than 0.25, the side screens were considered to be “open” resulting in a very open ventilation where air may leave the barn both through the ridge and as a cross-flow through the side openings (Fig. 1). During the measurement periods, both side screens were open or closed in the same manner. Table 3 describes animal and climate characteristics (temperature, relative humidity and wind) relative to periods when VR were measured and when side screens were either open or restricted.

2.5. *Data processing and ventilation rate calculations*

Due to instrument failure and revision, not all data between May 2012 and December 2013 was available (Table 3). The

Table 3 – Description of animal and climate characteristics (minimum; mean; maximum) for the measurement days when both methods could be compared, when side screens were either open (N = 27) or restricted (N = 47).

Side screens	Open			Restricted		
Measurement periods: Month (consecutive days)	June 2012 (11 d) July 2012 (3 d) August 2012 (4 d) November 2012 (9 d)			December 2012 (3 d) October 2013 (24 d) November 2013 (13 d) December 2013 (7 d)		
	Minimum	Mean	Maximum	Minimum	Mean	Maximum
Number of cows	190	196	200	188	194	199
Milk production (kg d^{-1} cow^{-1})	27.6	29.4	30.8	25.8	27.2	30.6
Live weight adult cows (kg)	650	660	670	653	673	685
Temperature barn (°C)	5.3	14.7	23.4	4.2	15.5	27.1
Temperature outside (°C)	2.2	12.9	22.1	2.5	9.6	16.9
Delta Temp. (barn – out, °C)	0.73	1.84	3.91	0.54	5.90	12.24
Relative humidity barn (%)	70.6	88.8	100	82.7	95.4	100
Relative Humidity outside (%)	64.3	80.0	98.5	76.3	88.4	99.6
Wind speed (m s^{-1})	1.75	3.55	6.54	1.33	3.88	8.50
Wind direction (°)	118	210	324	126	202	280

dataset was further filtered to consider only days where at least 19 out of 24 h of data were available for the calculation of ventilation rates (i.e. 80% of hourly measurements, a criterion derived from the VERA test protocol for Livestock Housing and Management Systems, 2011).

Ventilation rate calculations were performed on an hourly basis using either the naturally emitted (CO_2) or the artificially injected (SF_6) tracer gas. Previous and related work indicated that the influence of mean integration time (5, 15, 30 and 60 min) on concentrations was negligible (Mendes, 2014). Ventilation rates were reported on a daily basis in order to integrate intra-day variations due to climate parameters and/or cow activity patterns (Pedersen & Sällvik, 2002).

2.5.1. *Natural tracer gas (CO_2)*

The amount of CO_2 produced (and emitted) by the animals acted here as the tracer gas. Ventilation rate (VR_{CO_2}) based on this tracer method was calculated by the following equation:

$$VR_{CO_2} = \frac{\frac{PCO_2}{[CO_2]_{barn} - [CO_2]_{outside}}}{N_{animals}}$$

where VR_{CO_2} is expressed in $m^3\ h^{-1}\ animal^{-1}$; PCO_2 is the amount of CO_2 produced (in $m^3\ h^{-1}$) at the barn level; $[CO_2]_{barn}$ represents the barn concentration (in $m^3\ m^{-3}$), derived from spatial sampling options provided by the measurement points at the central axis and the ridge line (for ease of presentation and clarity, the specific spatial sampling strategies applied for determining $[CO_2]_{barn}$ are described in the results section); $[CO_2]_{outside}$ represents the outside CO_2 concentration (in $m^3\ m^{-3}$); $N_{animals}$ is the number of animals present in the barn.

PCO_2 was calculated using the CIGR equations provided by Pedersen and Sällvik (2002). The method is based on the calculation of total heat production (in W) by the animals (from maintenance, milk production and pregnancy) at "normal" indoor temperature of 20 °C. A coefficient is then applied ($0.20\ m^3\ h^{-1}\ hpu^{-1}$; hpu = heat production unit = 1000 W at 20 °C; Pedersen et al., 2008) to estimate the amount of CO_2 produced in $m^3\ h^{-1}$ at barn level (PCO_2). The factor 0.20 takes into account a small constant percentage of emissions from the manure (Pedersen et al., 2008). The estimated CO_2 production from the CIGR equations are representative for the mean daily CO_2 production (no diurnal effects included), but are expressed on an hourly basis.

This procedure can be described by the following equations:

$$PCO_2(dairy\ cow) = \frac{0.2 \times (5.6m^{0.75} + 22 \times Y_1 + 1.6 \times 10^{-5} \times p^3)}{1000}$$

$$PCO_2(dry\ cow) = \frac{0.2 \times (5.6m^{0.75} + 1.6 \times 10^{-5} \times p^3)}{1000}$$

$$PCO_2(heifer) = \frac{0.2 \times \left(7.64m^{0.69} + Y_2 \times \left(\frac{23}{M} - 1\right) \times \left(\frac{57.27 + 0.302m}{1 - 0.171Y_2}\right) + 1.6 \times 10^{-5} \times p^3\right)}{1000}$$

where m is the average weight of the animals (kg); Y_1 is the cow daily milk production ($kg\ d^{-1}$); p is the cow pregnancy state (d); M is the energy content of feed ($MJ\ kg\ dry\ matter^{-1}$); Y_2 is the heifer daily gain ($kg\ d^{-1}$).

When information was not available, the following constant values were used (Pedersen & Sällvik, 2002): m was set to 500 kg for heifers; M was fixed at 10 $MJ\ kg\ dry\ matter^{-1}$; Y_2 was 0.6 $kg\ d^{-1}$; dairy and dry cows were considered to be 160 d of pregnancy and heifers 140 d of pregnancy (Smits, personal communication).

The total CO_2 production in the barn (PCO_{2tot}; $m^3\ h^{-1}$) was determined every day as:

$$\begin{aligned} PCO_{2tot} = {} & PCO_2(dairy\ cow) \times number\ of\ dairy\ cows \\ & + PCO_2(dry\ cow) \times number\ of\ dry\ cows + PCO_2(heifer) \\ & \times number\ of\ heifers \end{aligned}$$

Finally, PCO_{2tot} was corrected for barn temperature (t_{barn}, °C) as deviations from the standard condition of 20 °C that is assumed for estimating heat production, according to Pedersen and Sällvik (2002):

$$PCO_2 = \frac{PCO_{2tot} \times (1000 + 4 \times (20 - t_{barn}))}{1000}$$

2.5.2. *Artificial tracer gas (SF_6)*

In the constant tracer gas injection technique, the barn is initially charged with tracer gas and then the injection rate is set to a constant value that produces a measurable concentration within the detection range of the measuring equipment. In this method it is necessary to precisely control the injection rate at a known rate and measure the tracer gas concentration in the barn. As with the method adopted for CO_2, SF_6 barn concentrations were measured using a variety of sampling options (Fig. 3). The barn ventilation rate (VR_{SF_6}), expressed in $m^3\ h^{-1}$, was determined by the injection rate (I, in $m^3\ h^{-1}$) and the concentration (C, in $m^3\ m^{-3}$) of the tracer gas in the building envelope (derived from Demmers et al. 2001), assuming perfect mixing, negligible concentrations of the tracer gas inside and outside the barn before the gas is injected, and steady-state conditions. The resulting ventilation rate calculated at building level is then divided by the number of animals present ($N_{animals}$).

$$VR_{SF6} = \frac{\frac{I}{C}}{N_{animals}}$$

2.6. *Codification and statistical analyses*

To compare ventilation rates estimated using either SF_6 (VR_{SF_6}) or CO_2 (VR_{CO_2}) as tracers, the daily ratios between both methods (VR_{CO_2}/VR_{SF_6}) were calculated for the days when both methods could be applied (see Table 3). For VR_{CO_2} a distinction was made according to the equipment used for the measurement of CO_2 concentrations: VR_{CO_2NDIR}; VR_{CO_2Laser}; VR_{CO_2PAS}. *VR* ratios were then compared between measurement strategies (number of measurement points or ventilation situation) using means, minimum and maximum, and also coefficient of variation (CV) as an indicator of the variability.

Grubbs' tests (maximum normed residual test) were used to detect outliers (2 ratios were removed from the dataset corresponding to abnormal VR_{CO_2} above 15,000 $m^3\ h^{-1}$ animal^{-1}).

VR_{CO_2}/VR_{SF_6} ratios were compared to the theoretical value of 1 using Student's *t*-tests (Minitab 17, Minitab, State College, Pennsylvania, USA). To determine the influence of the “horizontal” sampling strategy (number of points considered for concentration measurements, only for restricted ventilation situations) or of the ventilation strategy (side screens restricted or open) for a given “horizontal” sampling strategy (based on the previous analysis), one-way analyses of variance (one-way ANOVA, Minitab 17) were performed following the statistical models below:

$$Y_i = \mu + NbPoints_i + e_i$$

$$Y_i = \mu + Ventilstrategy_i + e_i$$

where Y_i is the studied variable (VR ratio), μ is the average, $NbPoints_i$ is the number of points considered for concentration measurements using NDIR sensors (1 *vs.* 2, *vs.* 3, *vs.* 5 individual sampling points; 3 df), $VentilStrategy_i$ is the ventilation strategy (side screens restricted or open; 1 df); and e_i is the error associated with each Y_i. Pairwise test comparison between every level of sampling (1 *vs.* 2, *vs.* 3, *vs.* 5 individual sampling points) or ventilation (open *vs.* restricted) strategies was also realised with p-values adjusted with Tukey–Kramer corrections. One-way ANOVA was only performed for intra-equipment comparisons of CO_2 concentrations. This is the reason why the “vertical” sampling strategy was not tested (CO_2 monitored with NDIR sensors or OP laser in the central axis *vs.* PAS in the ridge). Normality of the residuals was checked visually.

3. Results and discussion

3.1. *Some constraints in the calculation of* VR_{CO_2}

This study compared ventilation rates estimated using either CO_2 or SF_6 as tracers and different sampling strategies for gas concentration measurements. One particular aspect of this study was that CO_2 concentrations were measured using NDIR sensors, a PAS or an OP-laser depending on the sampling location (Table 1). Mendes, Ogink, et al. (2015) showed that the NDIR sensors measured systematically higher CO_2 concentrations in the barn (average + 13%) compared with the PAS analyser. They consequently advised users of NDIR sensors to use the same equipment for background measurement, thereby eliminating the bias in the background corrected CO_2 concentrations. Here, some sensors were placed outside the barn to measure background concentrations but they did not produce reliable results and their records therefore could not be used. The sensors appeared to be positioned too close to the outlets, and as such were occasionally subject to direct effects of outgoing barn air, thus overestimating background concentrations. Bias was also observed in outside CO_2 concentrations measured with the PAS analyser, and they also could not be used for same reasons. Zhang et al. (2010) determined that deviations were limited if a fixed value was estimated from outdoor measurements and was used for the inlet gas concentrations. It was therefore decided to use a constant value of 417 ppm for background CO_2 concentration based on outdoor measurements around dairy barns (CV between daily means, 8%), from previous experiments in similar conditions (Mosquera, Smits, & Ogink, in prep.). The value of 417 ppm was, however, obtained using a PAS analyser. This probably resulted in higher CO_2 concentration gradients than would have been calculated using NDIR sensors placed indoors and outdoors, thus lowering the resulting VR_{CO_2NDIR}. The use of this constant value could lead to higher variability in the estimation of VR_{CO_2PAS} and VR_{CO_2Laser} compared with direct measurements of background concentration.

3.2. *Spatial sampling strategies*

Considering only restricted ventilation situations representing conventional ventilation management, air flow rate estimates, based on either using CO_2 or SF_6 as a tracer, were compared using different spatial sampling strategies.

3.2.1. *Horizontal sampling strategy*

To study the influence of the use of one or more sampling points and their horizontal distribution, ventilation rate ratios (VR_{CO_2}/VR_{SF_6}) were calculated from different series of measurement points, comparing concentration measurements obtained from one (n°3 in the central axis), two (n°2 and 4), three (n°1, 3 and 5) or all 5 individual sampling points in the central axis (Fig. 3). At this spatial resolution (individual points), only VR_{CO_2NDIR} could be used (Table 1). Depending on the number of considered sampling points, mean VR_{CO_2NDIR}/VR_{SF_6} ratios varied between 0.52 and 0.70 (Table 4). This indicates that ventilation rates calculated with CO_2 as a tracer were on average between 50 and 30% lower than when SF_6 was used. As mentioned in Section 3.1, this difference could partly be related to the combined use of NDIR sensors and background measurement based on the PAS analyser. The use of a corrected CO_2 background concentration of 471 ppm (to take into account the 13% mean higher estimation of CO_2 concentrations by NDIR sensors estimated in Mendes, Ogink, et al., 2015) indeed leads to VR_{CO_2} being increased by 30% (±33%).

Ventilation rate estimates have been shown to be highly dependent on the measurement position (Ikeguchi & Hideki, 2010). Some authors judged that the best position for tracer gas sampling was the outlet and that neither a single point nor the mean of the entire barn are representative of the outlet concentration (Van Buggenhout et al., 2009; Wu et al., 2012). However, in naturally ventilated barns, outlets can also act as inlets depending on wind direction, leading to large errors in the calculation of ventilation rates (Bjerg et al., 2012; Van Buggenhout et al., 2009; Wu et al., 2012). Using an optimisation procedure with different simulated barn sidewalls opening situations, Shen et al. (2012) determined that the universal

Table 4 – Ratios of ventilation rates calculated using CO_2 (monitored with NDIR sensors) or SF_6 as a tracer gas (VR_{CO_2NDIR}/VR_{SF_6}, dimensionless) when inlet side screens were restricted; days of measurement (N), mean, standard error of the mean (SEM), minimum, maximum and coefficient of variation (CV, %) for each spatial sampling strategy (sampling points) in the central axis and results from the variance analysis.

Sampling point(s)	N[a]	VR_{CO_2}/VR_{SF_6} (dimensionless)				CV (%)
		Mean	SEM	Minimum	Maximum	
Point 3	46	0.52[b]	0.03	0.14	1.14	41
Points 2 and 4	40	0.63[b]	0.03	0.31	1.16	34
Points 1, 3 and 5	45	0.69[b]	0.04	0.24	1.12	36
5 points	38	0.70[b]	0.03	0.37	1.04	25

[a] Different numbers of N result from missing data for individual NDIR sensors at some days.

[b] Different letters refer to significant differences ($p < 0.05$) from the ANOVA.

optimal sampling position was close to the centre of the barn (i.e. near the central axis, at 27% of the barn height). This recommended sampling position corresponds to measurements just above the animal occupied zone (AOZ) and is in agreement with conclusions of Mendes, Edouard et al. (2015). On the basis of this information, five sampling points, evenly distributed along the central axis at approximately $H = 3.0$ m (i.e. 27% of the barn height), were chosen. When measurements are made frequently over long periods, Ngwabie et al. (2009) showed that a good choice of single sampling locations may give satisfactory results. Using one single point in the centre of the barn was therefore investigated and compared to estimates of ventilation rate using the mean of 2, 3 or 5 points. The ratio calculated using concentrations measured at one location (sampling point n°3; Fig. 3) was significantly lower than the ratios using measurements from 3 or 5 locations ($P < 0.01$, $RMSE = 0.21$). VR_{SF_6} was quite similar whatever the individual point considered since SF_6 was evenly distributed across the barn. This lower ratio was therefore related to a lower VR_{CO_2} calculated at point n°3 because of the higher CO_2 concentration measured due to the presence of dairy cows at this location. Using only one sampling point, though it was located in the middle of the barn, led to highly variable ventilation rates being calculated (CV of ratios = 41%; Table 4) especially when using CO_2 as a tracer. This suggests that this point was not very representative of gaseous concentrations inside the whole of the building. As previously discussed by Mendes, Ogink, et al. (2015), gaseous concentrations can vary widely inside the barn depending on multiple factors, including barn geometry, occupation and wind flow patterns as well as inter-sensor variability; the use of several sampling locations should therefore be favoured to represent the average concentration of the barn. The mean ratio of ventilation rates was the highest using the average of 5 points (0.70 ± 0.03) and it gave the lowest coefficient of variation (25% see Table 4). This result shows that to calculate the accurate ventilation rate for the barn using an average concentration derived from multiple sample points along the barn length is preferred to using single points. The placement of these sampling points should be carefully chosen to represent the spatial variability of target gases concentrations and this depends on the barn layout.

3.2.2. *Vertical sampling strategy*

Gas concentrations were recorded both along the central axis ($H = 3$ m) and near the ridge of the barn. Depending on the sampling location, CO_2 concentrations were measured using NDIR sensors, OP laser or PAS (Table 1). Vertical effects, under restricted ventilation conditions, were studied by comparing VR ratios based on the available types of concentration measurements that encompassed the total barn length, hence in case of multiple measurement points (in the central axis) the averaged concentrations of all 5 individual measurement points were used.

Along the central axis of the barn, the mean VR ratio based on NDIR measurements for CO_2 concentration was lower (0.70 ± 0.03) than that when the OP laser was used (0.90 ± 0.05 see Table 5). From the higher VR values measured here by this type of NDIR sensors, both in comparison to the OP laser and to the PAS analyser (Mendes, Ogink et al., 2015), it can be inferred that the NDIR sensors overestimate CO_2 concentrations. In the ridge, using the PAS for CO_2 concentration measurements, the VR ratio of 0.89 ± 0.05 was very similar to that determined at the central axis using the OP laser. In both cases, ratios were close to 1, yet they were statistically different ($P = 0.05$ and 0.04 respectively using OP laser and PAS). Along the central axis of the barn, the coefficient of variation was however greater than that at the ridge (central axis with OP laser: CV = 35%, minimum ratio = 0.40, maximum ratio = 1.81; ridge with PAS: CV = 16%, minimum ratio = 0.74, maximum ratio = 1.19). This lower variability of ratios in the ridge indicates that measuring at this location could result in more precise estimated values for ventilation rate. This result is not consistent with the optimal position for concentration measurements defined by Shen et al. (2012) using response surface methodology. The major difference between their study and ours is that the ridge did not act as an outlet in the study of Shen et al. (2012). When the ridge functions as a permanent outlet, it may yield more precise estimates of the VR ratios because concentrations of both CO_2 and SF_6 are more stable and are similar to the conditions that occur near the outlets of mechanically ventilated livestock barns. However, measurements made at the central axis of the barn took place at $H = 3.0$ m which is relatively close to the AOZ. The AOZ is known as a region of relatively high turbulence, where the naturally produced, or artificially injected gases, are likely to be mixed with fresh air, causing the concentration measurements to be more variable. The increased variability of gaseous concentrations of CO_2 and SF_6 as the sampling location approaches to the AOZ ($H = 4$ to 1 m) in this dairy cattle barn was also observed by Mendes, Edouard, et al.

Table 5 – Ratios of ventilation rates calculated using CO_2 or SF_6 as a tracer gas (VR_{CO_2}/VR_{SF_6}, dimensionless); days of measurement (N), mean, standard error of the mean (SEM), minimum, maximum and coefficient of variation (CV, %) for each sampling site, each equipment used for the measurement of CO_2 concentrations (average of the barn length) and for restricted or open side screens.

Sampling site	Equipment for CO_2 measurement[a]	Side screens	N[b]	VR_{CO_2}/VR_{SF_6} (dimensionless)					P value[d]
				Mean[c]	SEM	Minimum	Maximum	CV (%)	
Central axis	NDIR sensors	Restricted	38	0.70^{***}	0.03	0.37	1.04	25	0.06
		Open	19	0.61^{***}	0.03	0.37	0.80	20	
	OP Laser	Restricted	43	0.90^{*}	0.05	0.40	1.81	35	
Ridge	PAS	Restricted	10	0.89^{*}	0.05	0.74	1.19	16	0.92
		Open	8	0.88	0.10	0.51	1.37	32	

[a] $[SF_6]$ was always measured using the gas chromatograph.

[b] Different numbers of N result from missing data for some gas measurement devices at some days.

[c] Mean significantly different from 1 (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; t-test).

[d] Refers to the p value from the ANOVA comparing restricted and open situations intra-equipment for CO_2 concentration measurement.

(2015). For restricted ventilation situations, when it is technically feasible, measurements in the ridge should be favoured since concentrations are less likely to be influenced by turbulence and more representative of the barn average. When the placement of sampling points in the ridge is not technically feasible, concentration measurements along the central axis of the barn might be realised (using several sampling points or an average of the barn length) provided that the researcher accepts a larger variability due to the spatial variability of concentrations. These recommendations should generally apply for the typical livestock barns in North and West Europe. In case of a different barn layout, the positioning of sampling lines and points should always be considered and be adapted accordingly.

3.3. *Conventional versus very open ventilation situations*

To analyse the impact of opening the barn side screens, which results in air leaving the building both by the ridge and through the sides of the barn, the ratios found in conventional and very open ventilation situations were compared using available CO_2 and SF_6 measurement options that represented the total barn length. VR ratios were plotted against either VR_{CO_2} or VR_{SF_6} in both ventilation situations to illustrate both the trends and dispersion in the data (Fig. 4).

Along the central axis of the barn, the mean VR ratio was lower for very open situations compared with conventional ones (0.61 *vs.* 0.70 using NDIR sensors, $P = 0.06$; Table 5). When the side screens were open, both VR_{CO_2} and VR_{SF_6} were, on average, higher than when side screens were restricted. Wind speeds and directions were very similar for open and restricted situations and therefore unlikely to explain the difference (Table 3). Outside temperatures differed slightly, being on the average 3.3 °C lower for the restricted situation with a mean difference between inside and outside temperatures of almost 6 °C (Table 3). As reported in the literature, this can lead to lower ventilation rates and could partly explain the differences observed in the present study (e.g. Kiwan et al., 2013; Ngwabie et al., 2011; Wang et al., 2016). However, in most of these studies, variations in temperature are difficult to dissociate from variations in side screen opening rates which complicates the interpretation. For example, in Wang et al. (2016) a lower VR was recorded for a lower outdoor temperature with fully closed curtains compared to higher temperature with fully open curtains. In our study, turbulence might also have affected the measurement of concentrations at 3–4 m above the floor with very open situations preventing proper mixing of air. Also, cows can introduce resistance in the AOZ leading to difficulties to analyse air flow patterns (Wu et al., 2012). Cross ventilation in very open situations can also affect gas mixing behaviour (Demmers et al., 1998). However, in the ridge the mean VR ratios for open and conventional ventilations were very similar (0.88 *vs.* 0.89, $P = 0.92$; Table 5). In this case, the variability of the ratios doubled when the side screens were open compared with conventional ventilation ($CV = 32\%$ *vs.* 16%).

Regardless of the location or type of instrument used to measure CO_2 concentration, average VR_{CO_2} were always lower than VR_{SF_6} (i.e. mean ratios < 1). This result is quite normal in the literature but it is very difficult to conclude whether one method overestimates or the other underestimates ventilation rates (Kiwan et al., 2013; Muller et al., 2007; Zhang et al., 2005). Arguments exist for both hypotheses and these are discussed in the following sections.

3.3.1. *Hypothesis: the CO_2 mass-balance underestimates VR_{CO_2}*

As emphasised by Calvet et al. (2013), the methodology based on CO_2 production by the animals needs to be verified with several aspects in order to adapt to the changing animal breeds and management practices. Among these aspects, the contribution of manure to total CO_2 production at the barn level might indeed be under-estimated using the CIGR equations (Pedersen & Sällvik, 2002; Pedersen et al., 2008) when applied to the dairy barn considered in this paper. The calculated amount of CO_2 produced in $m^3\ h^{-1}\ hpu^{-1}$ at the house level is supposed to account for the contribution from manure by using a constant production of $0.20\ m^3\ h^{-1}\ hpu^{-1}$ at the house level instead of 0.18 at the animal level, that is to say considering a contribution from manure of 10% of the total CO_2 production at the house level. However, it should be mentioned that for animal houses where manure is stored indoors for more than 3 weeks and/or for houses including a

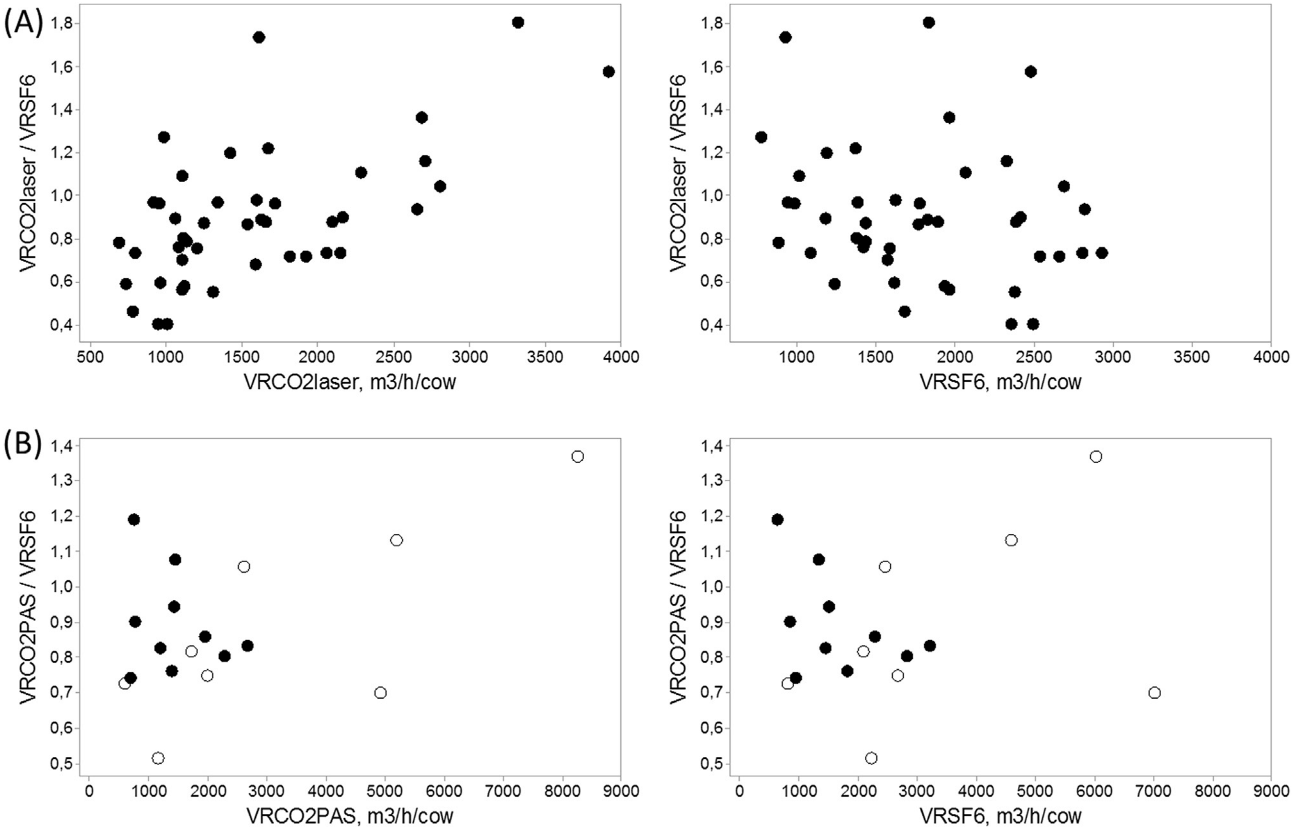

Fig. 4 – Plots of VR_{CO_2}/VR_{SF_6} ratios against VR_{CO_2} (with CO_2 concentrations measured either using PAS or laser) and VR_{SF_6} measured along the central axis of the barn (A) and in the ridge (B) for "restricted" ventilation situations (full symbols) and "open" ventilation situations (open symbols).

deep litter, the contribution of manure to the total CO_2 production at the house level might be higher (Pedersen et al., 2008). Liquid manure stored in the pit beneath the slatted floor has been reported to contribute up to 37.5% of the total CO_2 release from a fattening pig house (Ni, Vinckier, Hendriks, & Coenegrachts, 1999). This value might appear to be extreme; however, it suggests that the quantity of CO_2 release from manure could be seriously underestimated in the CIGR equations. Similarly, Edouard et al. (2012) showed that the CO_2 production from dairy cattle bedding (i.e. deep litter) was close (80%) to that from the animals themselves. In the barn considered in the present study, the pit below the slats was only emptied a few times a year (even not emptied at all between 15th of August and 31st of January following national rules on manure field application) and the building included a small area of deep litter for calving. When performing calculations for PCO_2 by progressively increasing the percentage of manure contribution, i.e. by increasing the coefficient from 0.20 to 0.22 or 0.24 $m^3\ h^{-1}\ hpu^{-1}$ respectively by considering a contribution from manure of 18 or 25% of the total CO_2 production, the resulting VR_{CO_2} increased by 10% or 20% respectively compared to the use of the 0.20 coefficient. This is far from being negligible. More empirical research is needed to better refine estimates of the contribution of manure to total barn CO_2 concentration. Its ease of use in cattle barns however lead many authors to favour this method, especially in experiments to determine emission factors where random errors in single daily measurement values play a minor role in the overall accuracy of the emission factor (Ogink et al., 2013). Looking at the positive linear trends between ratios and VR_{CO_2} (Fig. 4), it can be hypothesised that VR_{CO_2} values are more sensitive to changes in VR than are VR_{SF_6}.

3.3.2. *Hypothesis: the SF_6 mass balance overestimates VR_{SF_6}*

The use of tracer gas for the estimation of ventilation rates assumes complete mixing of the tracer with air inside the building. However, the air inside naturally ventilated livestock buildings is known to be far from completely mixed (Demmers et al., 1998). It has been shown here that in very open situations, both VR_{CO_2} and VR_{SF_6} were on the average higher than under conventional ventilation conditions and their ratio more variable. Examining the greater dispersion of the data with VR_{SF_6} (Fig. 4), it seems that the SF_6-based method had poorer precision when used to estimated ventilation rates compared to the CO_2-based method. In open situations, ventilation rates estimates based on tracer techniques are subject to large variations depending on climatic conditions, especially wind speed and direction. The accuracy of the tracer method was indeed shown to be lowest at high wind speed compared to calm days (Demmers et al., 1998). This incomplete mixing of ventilated air and ingoing air may lead to lower tracer gas concentration at the sample location, resulting in an overestimation of the ventilation rate (Ogink et al., 2013). Although large numbers of injection points for

SF_6 were used, its release might not be that well integrated with air close to the emitting surface of pollutant gas as CO_2 released from animals. The possibility that SF_6 was not injected at the same and constant rate at all the injection points during the whole measurement period (e.g. because of outlets blocked with dust), leading to a heterogeneous distribution of SF_6 concentrations in the barn cannot be excluded. Particularly in the case of strong cross ventilation, insufficient mixing of the SF_6 molecules in the entire barn, with a high molecular weight, might create conditions where the SF_6 molecules do not reach the heights of the measurement points when passing the side outlets. Missing a small fraction of the SF_6 injected in the barn might have resulted in higher VR_{SF_6}. This technical reason, and the costs of SF_6 equipment, can be seen as constraints for the use of this method in large scale experiments for the determination of emission factors.

4. Conclusion

- Measuring the average tracer concentration over a full barn length leads to more accurate ventilation rates than using one single point, even if it is placed in the middle of the barn.
- For conventional ventilation situations, when technically feasible, measurements in the ridge should be favoured. Measured concentrations are likely to be less influenced by turbulence and more representative of the barn average. Concentration measurements along the central axis of the barn may provide suitable results although larger variability due to spatial variations in concentration may occur. This may be a helpful sampling strategy provided other gas and/or dust measurements are made at the same locations.
- In very open situations, both VR_{CO_2} and VR_{SF_6} were on average higher than in conventional ventilation. Higher variability of VR ratios indicated that cross ventilation might lead to disturbed air flows and affect gas mixing behaviour.
- Regardless of the sampling location, and the equipment used for CO_2 concentration measurements, VR_{CO_2} were, on average, lower than VR_{SF_6} (ratios < 1). This can be related to a systematic overestimation of CO_2 concentration through an indication of bias in NDIR sensors, an underestimation of CO_2 produced by the manure at the barn level, and/or overestimation of VR_{SF_6} due to incomplete mixing of air.
- The NDIR method led to lower average VR ratios as compared to the other two methods for the measurement of CO_2 concentrations, suggesting a systematic overestimation of CO_2 concentrations. However, it also yielded to the lowest values for CVs (both in conventional and very open conditions). It is recommended that these sensors are used with great care with CO_2 concentrations corrected with background measurements using the same type of sensors.
- Excluding the use of NDIR sensors, this study showed that both independent methods for the estimation of ventilation rates, gave very similar results with a small systematic difference, being 10–12% lower in the CO_2 mass balance method compared to SF_6 based measurements. This difference might be attributed to potential bias in both methods.

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