Calvet Sanz, S.; Gates, RS.; Zhang, G.; Estellés, F.; Ogink, NWM.; Pedersen, S.; Berckmans, D. (2013). Measuring gas emissions from livestock buildings: A review on uncertainty analysis and error sources. Biosystems Engineering. 116:221-231. doi:10.1016/j.biosystemseng.2012.11.004.

Measuring gas emissions from livestock buildings: a review on uncertainty analysis and error sources

S. Calvet[a], R.S. Gates[b], G. Zhang[c], F. Estellés[a], Ogink, N.W.M.[d], Pedersen, S.[c], Berckmans, D.[f]

[a] Institute of Animal Science and Technology, Universitat Politècnica de València. Camino de Vera s.n. 46022 Valencia, Spain

[b] Agricultural and Biological Engineering Department, University of Illinois at Urbana-Champaign, Urbana IL 61801 USA

[c] Department of Biosystems Engineering, Aarhus University, Blichers Allé 20, Postboks 50, DK-8830 Tjele, Denmark

[d] Wageningen UR Livestock Research. P.O. Box 135, 6700 AC Wageningen, Netherlands

[f] Division Measure, Model & Manage Bioresponses (M3-BIORES), Katholike Universiteit Leuven, Kasteelpark Arenberg 30, B-3001 Leuven, Belgium

Abstract

Measuring gaseous and particulate emissions from livestock houses has been the subject of intensive research over the past two decades. Currently, there is general agreement regarding appropriate methods to measure emissions from mechanically ventilated buildings. However, measuring emissions from naturally ventilated buildings remains an elusive target primarily because there is no reference method for measuring building ventilation rate. Ventilation rates and thus building emissions estimates for naturally ventilated buildings are likely to contain greater errors compared with those from mechanically ventilated buildings. This work reviews the origin and magnitude of errors associated with emissions from naturally ventilated buildings as compared to those typically found in mechanical ventilation. Firstly, some general concepts of error analysis are detailed. Then, typical errors found in the literature for each measurement technique are reviewed, and potential sources of relevant systematic and random errors are identified. The emission standard uncertainty in mechanical ventilation is at best 10% or more of the measured value, whereas in natural ventilation it may be considerably higher and there may also be significant unquantifiable biases. A reference method is necessary to obtain accurate emissions estimates, and for naturally ventilated structures this suggests the need for a new means of ventilation measurement. The results obtained from the analysis of information in this review will be helpful to establish research priorities, and to optimize research efforts in terms of quality of emission measurements.

Keywords: error analysis, gas emissions, livestock housing, random error, systematic error, uncertainty

1. Introduction

When the result of a measurement is reported, the quality of that result should also be reported to provide an idea of its reliability. This is crucial for two reasons: on the one hand, scientists and engineers can understand and make better use of the results of a study; on the other hand, policy makers must understand the credibility of the data in order to make sound policy decisions. For example, reporting uncertainty is a key aspect in the methodology for the elaboration of greenhouse gas emissions inventories established by the Intergovernmental Panel on Climate Change (IPCC, 2001).

Measuring gaseous and particulate emissions from livestock buildings, particularly under commercial conditions, is a challenging task which is subjected to different uncertainty sources. This lack of certainty about emission estimates may be attributed to three main causes (EPA, 1996). The first cause is the inherent spatial and temporal variability in the processes which produce the emissions. These are influenced by environmental conditions in a complex way, resulting in a form of sampling uncertainty. Secondly, the measurement instruments themselves have an associated uncertainty in their results. Finally, if simplifications and assumptions are made, these may have associated uncertainties (e.g. assuming a steady state condition inside the building involves neglecting the accumulation or deposition process inside the building).

In general terms, to calculate an emission rate from a livestock building it is necessary to establish a mass balance in which ventilation rates and the difference between inlet and outlet concentrations are key measurements (Phillips et al., 1998). This process implies the occurrence of potentially significant errors of different origins, particularly in naturally ventilated buildings. These buildings are widely used in housing species such as cattle as well as housing other species in regions where they can provide effective ventilation with low energy consumption, or where electricity supply is unreliable or costly. In many cases, these buildings are completely open and some basic assumptions of the mass balance are not fulfilled (e.g. complete mixing of gases); further, determining the boundary conditions becomes unpractical. For example, openings can be both inlets and outlets, or change from inlet to outlet with shifting wind patterns and local topography. In these situations, the accuracy and precision of commonly used measurement methods is expected to be low, and therefore it is difficult to compare emissions from different housing or mitigation systems in such cases.

In the literature, there is a wide heterogeneity of methodologies and terms used to refer to errors in research on livestock building emissions. For this reason, it becomes very complicated to analyse much of the information on errors reported in literature to date. To establish future measurement strategies and priorities it is necessary to review what is known about the nature and magnitude of these uncertainties and to identify which are the main sources of errors. Therefore, the main objective of this paper is to critically review the state-of-the-art of uncertainty analysis and assess future needs in this area. Firstly, general and uniform definitions on uncertainty analysis are introduced from the appropriate literature. Secondly, error analyses provided in published works are reviewed and discussed. Finally, research priorities to calculate and reduce uncertainties in livestock building emission measurements are analysed.

2. Definitions

To analyse the nature and magnitude of errors in a comprehensive way, it is necessary to define and unify concepts for common use in emissions measurements. Although the term “measurement error” is usually used to define discrepancies between what is being measured and the real value, this and other terms must be properly and consistently used. These concepts are defined by the International Organization for Standardization (ISO, 1995), and are discussed here.

Uncertainty of measurement is a parameter that is associated with the result of that measurement. It characterizes the dispersion of the values that could reasonably be attributed to the quantity measured and thus has an inherent statistical basis. The parameter can be a standard deviation (*standard uncertainty*), or a confidence interval which is expected to encompass a certain fraction of the distribution of values (*expanded uncertainty*). Uncertainty can be obtained either directly by statistical analysis of a series of observations (*Type A uncertainty*) or by other means (*Type B* *uncertainty*) which can include expert judgement and calculated uncertainty using the law of propagation of uncertainty (*combined standard uncertainty*).

Uncertainty and error are related concepts which must not be confused. An error is defined as the difference between an individual measurement result and the real (true) value which is being measured. Since the true value is an idealized concept, errors cannot be exactly known. According to their nature, three types of errors can be identified in a measurement (Ellison, Rosslein, & Williams, 2000). First, random errors arise from unpredictable variations of a quantity measured, and the statistical distribution of these errors determines the uncertainty value which is the precision with which the measurement is made. Second, systematic errors are defined as the difference between the averages obtained from a large number of replicated measurements of a given measurand and its (unknown) true value (ISO, 1995). These errors determine the accuracy of the measurement system and where possible should be corrected, as far as they are identified and quantified (e.g. via calibration). The third type includes spurious errors, which normally invalidate a measurement and typically arise through instrument malfunction or human failure.

An error is an idealized concept related to a single measurement whereas uncertainty is a quantitative value that characterizes all the errors of a whole measurement system. Therefore, a measurement system may have a large numerical or percentage uncertainty, yet a particular measurement with that system may have a small error due to random chance. The expression “error analysis” can be used to describe studies to characterize the nature and magnitude of errors for a certain measurement, and to establish error apportionment among different error sources in order to improve the quality of measurements.

Uncertainty is a statistical concept based on one or more error sources, and therefore an uncertainty analysis is useful to determine the magnitude and relevance of these sources (Ellison et al., 2000; JCGM, 2008). In this analysis all systematic errors must be identified and corrected, if possible, whereas random errors are identified, quantified and then propagated to obtain the emission uncertainty (Estellés, Calvet, Melse & Ogink, 2011; Gates, Casey, Xin, & Burns, 2009). Additionally, a sensitivity analysis provides a means to determine the relevance of different error sources in the overall error, and is thus a powerful tool for identifying the crucial aspects to reduce overall uncertainty and/or measurement costs (Calvet, Estellés, Cambra-López, & Torres, 2010; Gates et al., 2009; Zhang, Pedersen, & Kai, 2010).

Another aspect to be considered in the analysis of the nature and magnitude of measurement errors is the definition of the output variable that is investigated. The errors involved in an emission measurement over a short time basis on a specific livestock operation will be very different from errors connected to variables that include a much longer time basis and greater spatial variation. For example, when determining the mean yearly ammonia (NH_3) emission of pig housing systems, Ogink, Mosquera & Melse (2008) showed that the main error sources arise from temporal and spatial sampling variation (i.e. seasonal effects and variation among the livestock operations studied due to different management regimes). Instrument errors of underlying single measurements in such measurement schemes may be of lesser importance if they can be substantiated by sufficient independent replications, and if they are not subject to systematic instrument errors. Both time and space bases have to be specified when discussing errors related to emission measurements. In the following section, the time and space basis of errors is, unless otherwise indicated, restricted to the smallest possible time and space variation, i.e. typically measuring emissions in a time interval of a few minutes in a representative outlet section. Furthermore in discussing the needs for improvement of measurement methods it is relevant to include definitions of required output variables and related designs of measurement schemes.

3. Uncertainty in airborne emission measurements

3.1. General overview

Emissions of atmospheric pollutants from livestock buildings cannot be measured directly, thus to obtain the uncertainty of this output variable it is necessary to firstly assess the influence of the main involved parameters, which are gas concentrations and measurements used to determine ventilation flows (Gates, Casey, Xin, Wheeler, & Simmons, 2004; Gates et al., 2009; Calvet, Estellés et al., 2010). The product of these two parameters effectively determines the emission rate (neglecting adjustments for temperature and pressure). Therefore, according to the law of propagation of uncertainty for emission observations (ISO, 1995), the parameter with the higher associated uncertainty expressed in relative terms will be the one with greater impact on the combined standard uncertainty (relative).

It is crucial to determine significant sources of random and systematic errors in order to identify potential research priorities. The identification of these sources is presented in Figure 1 for building measurements and in Figure 2 for chamber emission measurements. The distinction between random and systematic error sources is crucial, because those types of errors have different implications. Whereas random errors are identified by statistical means and can be reduced by replicated measurements, systematic errors can only be identified by comparing to a reference measurement (ISO, 1995). This has critical implications for the measurement system since systematic errors lead to biased results independently from the number of replications.

Methods for determining ventilation rates may differ considerably between naturally and mechanically ventilated buildings. Normally, errors of measured ventilation rates tend to be higher in naturally ventilated buildings, which may lead to higher errors of measured emissions (Phillips, Scholtens, Lee, Garland & Sneath, 2000). Additionally, simplifications and assumptions used when calculating the emissions may lead to additional errors. This simplification uncertainty can arise, for example, from defining a steady state balance for a dynamically changing situation of concentrations and ventilation rates, which may be of particular relevance in naturally ventilated buildings. Therefore, errors in these two types of housing systems have been reported separately. Errors from wind tunnel or flux chamber methods will be also reported in a separate section.

3.2. Error sources in measured concentrations

Techniques to measure NH_3 concentration are well characterized in terms of precision (Table 1), but the variability of gas concentrations in buildings has been demonstrated (Moura, Carvalho, Souza, Naas & Souza, 2010; Miles, Rowe & Owens, 2008), and the incorrect selection of sampling positions may lead to errors in measured gas concentration from -50% to over 200% of the measured value (Lefcourt, 2002). The best position to determine gas concentrations for mass balances are the air outlets of the building. However, in naturally ventilated buildings inlet and outlet positions are critically dependent on meteorological conditions and local topography, and therefore the proper selection of inlets and outlets is not trivial. This is one of the reasons why measuring representative gas concentrations in very open naturally ventilated buildings is a real challenge for researchers.

Even in mechanically ventilated buildings with many fans, gas concentrations and emission fluxes can be irregularly distributed. In these cases, sampling concentration errors should be specifically considered, because they can be comparable in relative terms to measured ventilation errors of measured forced ventilation rates (Calvet, Estellés et al., 2010; Moody et al., 2008).

The gas sample transport to the analyser may also involve a systematic error considering the absorption of gases such as NH_3 in different materials when long sampling lines and certain measuring devices are used (Shah, Grabow, & Westerman, 2006; Rom & Zhang, 2010). Mukhtar et al. (2003) reported about 1 ppm reduction due to absorption in Teflon tubing, regardless of the magnitude of inlet concentration, temperature or length of tubing. This effect, however, can be minimized by selecting a proper sampling strategy and by establishing an adequate stabilization period before recording the concentration value (Gates, Xin, Casey, Liang & Wheeler, 2005; Moody et al., 2008).

3.3. Error sources of mechanical ventilation measurements

In mechanically ventilated buildings, errors associated with measuring ventilation rate are probably the most relevant error source of emission measurements. A summary of findings in recent research is discussed here. From the wide variety of measurement protocols (Table 2), perhaps the most accurate is the use of measuring fans (Berckmans, Vandenbroeck, & Goedseels, 1991; Demmers et al., 1999; Casey et al., 2002; Gates et al., 2004), which have standard uncertainty lower than 5%. A large number of commercial fans (about 800) were tested in Denmark in the years 1978 -2005. The measurements were carried out using a common test procedure between Germany, The Netherlands and Denmark, (DLG/IMAG-DLO/SjF, 1993; Pedersen & Strom, 1995). A cross-check of the accuracy was carried out in 1991 between the German test institution DLG, the Dutch IMAG-DLO and Research Centre Bygholm. A four-pole axial fan was circulated and performance tested in the range 0-40 Pa of negative pressure. The difference among measurements was about 2 %. Measuring error under laboratory conditions can be negligible compared to other uncertainties. However, the ventilation flow in practice is exposed to a variable pressure drop and undetermined dust accumulation, which can lead to relevant underestimations (Casey et al, 2008) if exposed measuring fans are not calibrated again after measurement campaigns.

A similar measurement system allows measuring large, sidewall exhaust fans. It is based on first obtaining the *in situ* fan performance as a function of the pressure drop and then computing ventilation from measured building static pressure and the time of operation of each fan. This method also provides accurate results in farms with several single-speed fans. An example of this is the FANS-Fan Assessment Numeration System (Gates, Casey, Xin, Wheeler, & Simmons, 2004), which has been used extensively in the United States. This method provides a satisfactory calibration of fans, with a 3% standard uncertainty and less than 2% underestimation for disturbance of the measurement device (Casey, Ford, McClure, Zhang, & Gates, 2007). Apart from fan calibration, random error in this technique may arise from the determination of fan operational status (Moody et al., 2008) or flow profile changes induced during in-situ calibration of a given ventilation fan (Morello, 2011; Lopes, 2012). Ideally, determination of ventilation fan status should be more frequent than the minimum expected fan operation cycle, which may be as frequent as 30 s (Darr, Zhao, Ni, & Gecik, 2008). However, emissions tend to be greater when ventilation is higher (e.g. the second half of the cycle in broilers), and therefore less frequent measurements of fan status would not significantly increase the ventilation rate uncertainty (Calvet, Cambra-López, Blanes-Vidal, Estellés & Torres, 2010; Gates, Casey, Wheeler, Xin & Pescatore, 2008).

Systematic error sources are well identified in this measurement technique and therefore they may be avoided by proper measurement protocols and fan maintenance (except perhaps for systems with sidewall fan performance degradation during long term studies). These biases arise from the flow reduction due to dust accumulation and ageing of mechanisms in the fan (Casey et al., 2008). This will undoubtedly lead to overestimation of measurement if manufacturer curves are used (by as much as 40%), and on-farm calibration of fans is therefore needed before and during the measurements.

3.4. Error sources of natural ventilation measurements

Measuring natural ventilation in livestock buildings is a challenging task, particularly in very open buildings. Therefore, several options have been developed to determine ventilation or emission rates in these types of buildings (Table 2), but until now there is no operational reference or standard technique. Thus, systematic errors are difficult to identify unless there is a reference to compare with. For this reason, it is often necessary to use mechanical ventilation as a reference to determine the reliability of these methods (Xin et al. 2009; Liang et al., 2006; Li et al., 2005). However, in most situations it is not possible to use mechanically ventilation as a reference for natural ventilated buildings. A crucial issue of all techniques currently used in these buildings is therefore that no reference method is available to validate the measured emissions and their uncertainties, and the fundamental knowledge is still scarce to develop such a reference method.

Among the available techniques to measure ventilation in naturally ventilated buildings, the use of tracer gas is widely used, with gases of both natural origin (Xin et al., 2009; Pedersen et al., 1998; Blanes & Pedersen, 2005; Li et al, 2004; Liang et al., 2005)) and artificial origin (Demmers et al., 1999; Schrade, Keck, Zeyer, Emmenegger, & Hartung, 2010). In both cases, thorough mixing of tracers with the air inside the building is important to improve the sampling accuracy. Although these techniques perform satisfactorily under well-controlled conditions, the assumption of complete mixing of tracers may be questionable in very open buildings. Under field conditions, the identification of inlets and outlets is crucial, because they may change according to meteorological conditions (Ikeguchi & Moriyama, 2010; Schrade et al., 2010).

The uncertainty level of the tracer gas method is highly dependent on the distribution of the tracer gas, the number of measurement positions, the sampling locations for the measurements and the method used to handle the data for analysis. Different sampling locations for sensors may result in as much as 40% difference in the determination of the tracer concentration (Zhang et al., 2010), and therefore the proper selection of these locations is crucial. Furthermore, due to changing wind conditions, air outlets and inlets may change in short time periods.

The release rate of the tracer can be an important error source. For artificial tracer gases, the use of critical orifices may result in very accurate release rates (Schrade et al., 2010). However, the release rates of natural tracers (carbon dioxide, water vapour and heat) are calculated according to biophysical production models which are subjected to diverse random and/or systematic error sources. Among these tracers, the most widely used given its reliability is the carbon dioxide (CO_2) balance.

A prerequisite of this method is that CO_2 concentration in barns can be distinguished with sufficient accuracy from background CO_2 concentration in inlet air. In practice, this means a difference in CO_2 concentration of at least 200 ppm between the inside and outside air (Van Ouwerkerk & Pedersen, 1994). A sensitivity analysis conducted by Blanes & Pedersen (2005) demonstrated that 150 ppm difference corresponds to about 10% error of estimated ventilation rate. However, in many open buildings this conditions and the proper mixing of CO_2 are not fulfilled. Thus methodological improvements are still necessary to evaluate smaller concentration differences together with incomplete mixing of CO_2. Although there is a widely accepted methodology to perform these balances (CIGR, 2002) it is necessary to update the balance parameters in order to adapt to the changing animal genetics and management practices. To achieve these goals, many efforts can be found in the literature, providing heat and moisture relations for livestock and poultry species (Blanes & Pedersen, 2005; Chepete & Xin, 2004; Chepete, Xin, Puma, & Gates, 2004; Brown-Brandl et al., 2004; Gates, Overhults, & Zhang, 1993; Li et al., 2005; Xin et al., 2009).

Carbon dioxide balances are based on the estimation of animal heat production, which is normally determined in respiration chambers. However, the heat produced by animals is affected by a number of parameters such as feed intake, animal sex, growth and activity. The physiology and location variations of the animals during different operations (such as feeding and milking in ruminants) are also important factors to be considered in the CO_2 production distribution. Although Zhang et al. (2010) estimated a 10% uncertainty in heat production by animals, some authors have detected that the currently accepted heat production relations are underestimated in farm conditions (>20%) due to the continuously changing genetics with increased growth rates (Xin, et al., 2001; Calvet, Estellés, Cambra-López, Torres, & Van den Weghe, 2011). These potential changes must be revised and, if necessary, included in the heat production model.

In CO_2 balances, two more aspects are crucial for controlling biased emission results. The first one is the relationship between animal heat and CO_2 production and the diurnal variation of animal heat production. This depends on the species, body mass and feeding level. This parameter varies between 0.16 and 0.21 m^3/h per heat production unit (hpu) (Table 3), and is directly affected by the respiratory quotient (Pedersen et al., 2008).The standard uncertainty of this parameter is typically 10%, but there is also 20% standard uncertainty in determining the diurnal variation of CO_2 per hpu (Zhang et al., 2010). The second aspect is the contribution of manure to total CO_2 production. This contribution has been quantified by several authors and no uniform results have been found, likely because it varies with manure handling systems, stocking density, weather, and other uncontrolled factors. Pedersen et al. (2008) proposed a correction factor of +10% in houses where the manure is not stored for more than 3 weeks. However, in many situations manure is stored indoors over a longer time period, resulting in higher CO_2 contribution from the manure. In broilers, a 20% contribution was identified at the end of a 35-day cycle (Calvet et al., 2011), whereas Ni, Vinckier, Hendriks and Coenegrachts (1999) found as much as a 35% contribution from manure in pig production facilities. The proportion of CO_2 produced by manure can even reach an amount comparable to animal respiration in deep-litter systems (Jeppsson, 2000).

Alternative techniques to determine ventilation flows such as computational fluid dynamic (CFD) models (Bartzanas, Kittas, Sapounas, & Nikita-Martzopoulou, 2007; Blanes-Vidal, Guijarro, Balasch, & Torres, 2007; Yan, Barker, Sun, Zhang, & Gates, 2010), or the pressure difference method (Demmers et al., 2001) tend to be less accurate than tracers. For these methods there is very limited literature available and more investigations are required to quantify their uncertainty level. In general terms, the uncertainties associated with these techniques probably exceed 50% due to the great influence of aerodynamic parameters. Modelling using CFD, however, may be very useful to determine proper measurement locations if it is combined with proper field-scale validation, which is very difficult to accomplish under farm conditions.

3.5. Wind tunnels and flux chambers

Flux chambers constitute a promising alternative method for determining gaseous emissions, particularly in those housing systems where mass balances and tracer techniques become unreliable (Ogink, Mosquera, Calvet and Zhang, 2012). Some authors have tested chambers to determine emission rates at a building scale (Van Dooren & Mosquera, 2010; Wheeler et al., 2010). These chambers enclose a small surface inside the farms and the emission from this surface is then evaluated.

A critical drawback of the flux chamber method is that it is very difficult to reproduce inside the chamber the environmental conditions of the building, particularly air velocity over the emitting source (Hudson & Ayoko, 2009; Parker et al., 2010). Therefore, chambers may be used for comparison purposes, but particular care must be taken when comparing different studies. Short measuring intervals are necessary so as to not disturb the emission source (Van Dooren & Mosquera, 2010; Wheeler et al., 2010). If no air movement is created, chambers tend to underestimate NH_3 emissions (Van Dooren & Mosquera 2010; Wheeler et al., 2010), leading to unacceptable biases in the measured emission flow. However, it is a physical law that mass diffusion from an emitting surface is a function of air velocity, and so in chambers the selection of appropriate air velocity and chamber dimensions is problematic. Recent attempts have been made to standardize measurements (Parker et al., 2012). These authors obtained a correction factor based on water evaporative flux ratio that provided more accurate estimates than uncorrected flux measurements. They also recommend that all research results should include details on the chamber design and operating conditions during measurement.

A second drawback of this technique is its practical use in real farm conditions, since it may affect the normal operation of the farm and may not be used over some kinds of surfaces (e.g. on slatted floors) (Ni, Vinckier, Coenegrachts & Hendriks, 1999). Finally, the emissions may vary among different surfaces inside the farm which must be accounted for. For all these reasons, a reference is always necessary to validate the use of chambers for measuring emissions.

4. Current knowledge gaps and research needs

Specific research on emissions uncertainty has focused on mechanically ventilated buildings (Gates et al., 2009; Calvet, Estellés et al., 2010). These studies have a double perspective: firstly, they aim to quantify the uncertainty of measured emissions; secondly, they also try to optimize measurement efforts for a desired quality of measurements. In mechanically ventilated buildings, and under very controlled circumstances, the emission standard uncertainty has been reported to be in the range from 5 to 10% (Calvet, Estellés et al., 2010; Gates et al., 2009). Sensitivity analysis has provided information on the contribution of different error sources (Figure 3). However, according to the authors' experiences it seems realistic to accept that in many studies the uncertainty for short time basis building emissions lies within the range 10-20% or even greater.

The emission uncertainty in naturally ventilated buildings is poorly characterized. With the current knowledge it is not possible to establish the typical uncertainties of different measurement strategies. However, considering the high uncertainties in ventilation rates (Van Buggenhout et al., 2009; Zhang et al., 2010), the authors doubt that less than 20% standard uncertainty can be achieved with any measurement system, and probably in many measurements it may be much more than 50%. Therefore, further efforts to characterize errors of these estimates and to improve measurement methods for naturally ventilated buildings are critically needed improve our emission inventory models and means of assessing mitigation technologies.

In general terms, simplifications and assumptions made when designing protocols for measuring emissions may lead to optimization of costs, but their influence on measurement uncertainty must also be determined. An example of this kind of analysis was developed by Estellés, Calvet and Ogink (2010) and can be applicable for both mechanical and natural ventilation. Wet chemistry (NH_3 trapping in a wet acidic solution) is commonly used in Europe to determine NH_3 emissions, since it is a robust and precise method. However, this measurement system integrates the concentration measurement (typically over 24h), thus losing any information of temporal variation in concentration throughout the sampling period. As discussed by these authors, when measuring average 24-h gas concentrations an average daily ventilation rate can be used without affecting the emission uncertainty. This approach may also be useful when using natural tracers such as CO_2 balances (Xin et al., 2008; Liang, Xin, Li, Gates, Wheeler, & Casey, 2006; Li et al, 2005), since the correction for animal activity, which follows a daily pattern, is not necessary (Pedersen et al., 2008). The study by Estellés, et al. (2010) utilized a database of approximately 7,000 measurement days of continuous measurements in different conditions (animal species and climatic conditions) in Denmark, The Netherlands and Spain. They concluded that this simplification leads to less than 2% systematic error (the emission rate was systematically overestimated), and approximately 3% additional random error. This sort of information is extremely valuable in practice: only if researchers have complete knowledge about uncertainties of different measurement alternatives, they will be able to effectively decide the most suitable option.

As indicated previously, for mechanically ventilated buildings there are strategies to quantify the emission uncertainty and in general terms researchers tend to agree on the degree of confidence of measured emissions. However, specific research should be conducted towards optimizing measurement protocols under the constraint of maintaining an acceptable degree of confidence. In mechanical ventilation, it is suggested that further studies be developed and conducted to answer the following questions:

- What range in uncertainty does each gas and particulate concentration measurement system exhibit under real farm conditions?
- What is a realistic range in uncertainty for different means of determining ventilation flow rate?
- What effect do assumptions and simplifications on the measured systems have on the degree of confidence in the measured results?
- How can measurement strategies be optimized in terms of sufficient replicate measurements and adequate sampling of different temporal and spatial variation sources?

Answering these questions would undoubtedly lead to more efficient and reliable measurements. In addition it is recommended that future research publications adopt a common strategy to analyse and report the emissions uncertainty.

When compared with mechanical ventilation, the degree of uncertainty in naturally ventilated buildings is considerably higher, and in most cases unknown due to a lack of specific knowledge of the error sources. Therefore, there is an urgent need for improved methods of characterizing and quantifying error sources of measured emissions, particularly in buildings which are very open in structure.

Clearly, the main indicator of this greater uncertainty arises from the inability to quantify errors in measured ventilation rate in naturally ventilated buildings. A first step in addressing this critical omission is to find a reliable, robust (and preferably simple) means of testing measured values of ventilation rate against a reference standard. However, while developing a reliable reference or standard system would be an effective way for assessing the uncertainty of the different measurement protocols used nowadays, it remains an elusive goal. Comparisons with a reference standard for natural ventilation measurement would provide essential information on random and systematic errors of the measurement techniques commonly used under real farm conditions (tracer balances, chambers and others). Some promising approaches might include:

- Physical scale models with defined boundary conditions.
- Computational models with defined boundary values and constraints.
- Full scale barns with artificial NH_3 sources and known release of NH_3 to the air and artificial heat and CO_2 producing virtual livestock.
- Developing low-cost sensor networks for better determining gas concentration and airflow distribution patterns.

4. Conclusions

The main differences between emission measurements from naturally and mechanically ventilated buildings are the magnitude of random errors and the significance of bias. In mechanically ventilated buildings potential biases have been identified and can be avoided, whereas random error may be reduced to acceptable levels (i.e. 10-20%). However, in naturally ventilated buildings bias is difficult to identify and correct and random error is likely substantially greater than in mechanically ventilated buildings.

Special care should be taken when establishing measurement protocols, in order to identify and avoid biases, and to reduce the most influencing error sources. Also, the inclusion of uncertainty when reporting emissions is necessary. In some types of naturally ventilated buildings, particularly in those which are very open in structure, reducing these errors will require the use of more precise equipment and sampling in a great number of locations. Comparison between different measurement methods can be useful to reduce errors, but in general terms a reference standard method is required to accurately assess and compare the emissions of naturally ventilated buildings. However, no reference standard method is currently available to validate the estimated emissions and their uncertainties in naturally ventilated buildings. To develop such a reference standard method, more efforts to understand the fundamental aspects of natural ventilation will be necessary.

5. References

Bartzanas, T., Kittas, C., Sapounas, A. A., Nikita-Martzopoulou, Ch. (2007). Analysis of airflow through experimental rural buildings: sensitivity to turbulence models. *Biosystems Engineering, 97,* 229-239.

Berckmans, D., Vandenbroeck, PH., & Goedseels, V. (1991). Sensor for continuous measurement of the ventilation rate in livestock buildings. *Indoor air,* 1, 323-336.

Blanes, V., & Pedersen, S. (2005). Ventilation flow in pig houses measured and calculated by carbon dioxide, moisture and heat balance equations. *Biosystems Engineering, 92,* 483-493.

Blanes-Vidal, V., Guijarro, E., Balasch, S., & Torres, A. G. (2008). Application of computational fluid dynamics to the prediction of airflow in a mechanically ventilated commercial poultry building. *Biosystems Engineering, 100,* 105-116.

Brown-Brandl, T., J. A. Nienaber, H. Xin, and R.S. Gates. 2004. A literature review of swine heat production. *Transactions of the ASAE* 47(1):259-270.

Calvet, S., Cambra-López, M., Blanes-Vidal, V., Estellés, F., & Torres, A.G. (2010). Ventilation rates in mechanically-ventilated commercial poultry buildings in Southern

Europe: Measurement system development and uncertainty analysis. *Biosystems Engineering, 106,* 423-432.

Calvet, S., Estellés, F., Cambra-López, M., & Torres, A.G. (2010). Estimation of Emission Uncertainty from a Broiler Building Using Numerical Methods. *ASABE 2010 Annual International Meeting*. ASABE Paper No. 1008955. St. Joseph, Mich.: ASABE.

Calvet, S., Estellés, F., Cambra-López, M., Torres, A.G., & Van den Weghe, H.F.A. (2011). The influence of broiler activity, growth rate and litter on carbon dioxide balances for the determination of ventilation flow rates in broiler production. *Poultry Science, 90, 2449-2458*.

Casey, K. D., Ford, S. E., McClure, J. W., Zhang, Y., & Gates, R. S. (2007). Determining fan performance using fans: An investigation of performance impacts. *Applied Engineering in Agriculture, 23,* 333-338.

Casey,K.D., Gates,R.S., Wheeler,E.F., Xin,H., Liang,Y., Pescatore,A.J., & Ford,M.J. (2008). On-farm ventilation fan performance evaluations and implications. *Journal of Applied Poultry Research, 17,* 283-295.

Casey, K. D., Wheeler, E. F., Gates, R. S., Xin, H., Topper, P. A., Zajaczkowsky, J. S., Liang, Y., Heber, A. J., Jacobson, L. D. (2002). Quality assured measurements of livestock building emissions: Part 4: Building ventilation rate. *Air and Waste Management Association Conference*. December, 2002 San Francisco CA.

Chepete, H. J., & Xin, H. (2004). Heat and moisture production of poultry and their housing systems: Molting layers. Transactions of the ASHRAE 110(2): 274-285.

Chepete, H. J., Xin, H., Puma, M. C., & Gates, R.S. (2004). Heat and moisture production of poultry and their housing systems: Pullets and layers. Transactions of the ASHRAE 110(2): 286-299.

CIGR (2002). *Climatization of animal houses. Heat and moisture production at animal and house levels*. Pedersen, S. & Sälvik, K. (eds.). Danish Institute of Agricultural Sciences, 46 p. Horsens, Denmark.

Darr, M. J., Zhao, L., Ni, J. Q., & Gecik, C. (2008). A robust sensor for monitoring the operational status of agricultural ventilation fans. *Transactions of the ASABE, 50,* 1019-1027.

Demmers, T. G. M., Burgess, L. R., Short, J. L., Philips, V. R., Clark, J. A., & Wathes, C. M. (1999). Ammonia emissions from two mechanically ventilated UK livestock buildings. *Atmospheric Environment, 33,* 217-227.

Demmers, T. G. M., Phillips, V. R., Short, L. S., Burgess, L. R., Hoxey, R. P., & Wathes, C. M. (2001). 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.

DLG/IMAG-DLO/SjF (1993). Gebrauchswertprüfung von Stallventilatoren sovie von Zuluft- und Ablufteinheiten mit eingebauten Ventilatoren. Editors: Niethammer F., Vries R.L. and Pedersen S., DLG D/81.

Ellison, S. L. R., Rosslein, M., & Williams, A. (2000). *Quantifying Uncertainty in Analytical Measurement*. (2nd ed.). EURACHEM / CITAC Guide No. 4.

EPA. 1996. Evaluating the Uncertainty of Emission Estimates. Chapter 4 in: *Emission Inventory Improvement Program*. Technical Report series Volume VI: Quality Assurance Procedures and DARS Software. Research Triangle Park, North Carolina.

Estellés, F., Calvet, S., & Ogink, N.W.M. (2010). Effects of diurnal emission patterns and sampling frequency on precision of measurement methods for daily ammonia emissions from animal houses. *Biosystems Engineering, 107,* 16-24.

Estellés, F., Calvet, S., Melse, R.W. & Ogink, N.W.M. (2011). Uncertainty modelling to evaluate nitrogen balances as a tool to determine N_2 and N_2O formation in ammonia bioscrubbers. *Environmental Engineering Science,* in press.

Gates, R. S., Casey, K. D., Xin, H., & Burns, R. T. (2009). Building emissions uncertainty estimates. *Transactions of the ASABE, 52,* 1345-1351.

Gates, R.S., K.D. Casey, E.F. Wheeler, H. Xin, and A.J. Pescatore. 2008. U.S. broiler ammonia emissions inventory model. *Atmospheric Environment* 42(14):3342-3350.

Gates, R.S., H. Xin, K.D. Casey, Y. Liang and E.F. Wheeler. 2005. Method for measuring ammonia emissions from poultry houses. *Journal of Applied Poultry Research* 14(3):622-634

Gates, R. S., Casey, K. D., Xin, H., Wheeler, E. F., & Simmons, J. D. (2004). Fan assessment numeration system (FANS) design and calibration specifications. *Transactions of the ASAE, 47,* 1709-1715.

Gates, R. S., Overhults, D. G., & Zhang S. H.. 1993. Heat and moisture production for modern broilers. Proceedings, Livestock Environment IV. Fourth International Symposium, University of Warwick, Coventry England. E. Collins and C. Boon, editors. ASAE: St. Joseph, MI.

Hinz, T., & Linke, S. (1998). A comprehensive experimental study of aerial pollutants in and emissions from livestock buildings. Part 1: Methods. *Journal of Agricultural Engineering Research, 70,* 119-129.

Hudson, N, Ayoko, G.A. (2009). Comparison of emission rate values for odour and odorous chemicals derived from two sampling devices. *Atmospheric Environment,* 43, 3175-3181.

Ikeguchi, A., & Moriyama, H. (2010). Measurement method of ventilation rate with tracer gas method in open type livestock houses. *Proceedings of the CIGR XVIIth World Congress* – Québec City, Canada. Paper No. 101061.

IPCC (2001). *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. IPCC/OCDE/IEA.

ISO (1995). *Guide to the expression of uncertainty in measurement*. (1st ed.). Genève (Switzerland): International Organization for Standardization.

JCGM (2008). *Evaluation of measurement data - Supplement 1 to the "Guide to the expression of uncertainty in measurement" - Propagation of distributions using a Monte Carlo method*. Joint Committee for Guides in Metrology. Sèvres Cedex, France.

Jeppsson, K.-H. (2000). Carbon dioxide emission and water evaporation from deep-litter systems. *Journal of Agricultural Engineering Research, 77,* 429-440.

Krause, K. H., & Janssen, J. (1990). Measuring and simulation of the distribution of ammonia in animal houses. *Second International Conference on Air Distribution in Rooms – ROOMVENT*, 12 p.

Lefcourt, A. M. (2002). Some potential problems for measuring ammonia emissions form farm structures. *Transactions of the ASABE, 45,* 1585-1591.

Li, H., Xin, H., Liang, Y., Gates, R. S., Wheeler, E. F., & Heber A. J. (2005). Comparison of direct vs. indirect ventilation rate determinations in layer barns using manure belts. Transactions of the ASAE 48(1): 367-372.

Liang, Y., H. Xin, H. Li, R.S. Gates, E.F. Wheeler, & K.D. Casey. (2006). Effect of measurement interval on estimation of ammonia emission rates for layer houses. Transactions of the ASAE 49(1): 183-186.

Lopes, G. 2012. Evaluation of Transitions for Testing Agricultural Ventilation Fans with the Fan Assessment Numeration System (FANS). M.S. thesis, Biosystems and Agricultural Engineering Department, University of Kentucky, Lexington KY 40546-0276.

Miles, D. M., Rowe, D. E., & Owens, P. R. (2008). Winter broiler litter gases and nitrogen compounds: Temporal and spatial trends. *Atmospheric Environment, 42,* 3351-3363.

Moody, L.B., H. Li, R.T. Burns, H. Xin, R. S. Gates, S.J. Hoff and D.G. Overhults. 2008. Southeastern Broiler Gaseous and Particulate matter Emissions Monitoring Quality Assurance Project Plan. Published as *Special ASABE peer reviewed publication*. 289 pages. ASABE. St. Joseph, MI. http://asae.frymulti.com/aqap_handbook.asp?confid=aqap2008

Morello, G. 2011. Influence of Fan Operation on Fan Assessment Numeration System (FANS) Test Results. M.S. thesis, Biosystems and Agricultural Engineering Department, University of Kentucky, Lexington KY 40546-0276.

Moura, D.J., Carvalho, T.M.R., Souza, Z.M. Nääs, I.A., Souza, G.S. (2010). Broiler gas spatial variability on different minimum ventilation systems. *Proceedings of the CIGR XVIIth World Congress* – Québec City, Canada. Paper No. 100659.

Mukhtar, S., Rose, A., Capareda, S., Boriack, C., Lacey, R., Shaw, B., Parnell Jr, C. (2003). Assessment of ammonia adsorption onto Teflon and LDPE tubing used in pollutant stream conveyance. *Agricultural Engineering International: the CIGR Journal of Scientific Research and Development*. Manuscript BC 03 012. Vol. V.

Ni, J., Vinckier, C., Coenegrachts, J., & Hendriks, J. (1999). Effect of manure on ammonia emission from a fattening pig house with partly slatted floor. *Livestock Production Science*, *59,* 25-31

Ni, J. Q., Vinckier, C., Hendriks, J., & Coenegrachts, J. (1999). Production of carbon dioxide in a fattening pig house under field conditions. II. Release from the manure. *Atmospheric Environment, 33,* 3697–3703.

Ogink, N.W.M., Mosquera, J., Calvet, S., Zhang, G. (2012). Methods for measuring gas emissions from naturally ventilated livestock buildings: developments over the last decade and perspectives for improvement. *Biosystems Engineering,* submitted.

Ogink, N.W.M., Mosquera, J. & R.W. Melse (2008). Standardized testing procedures for assessing ammonia and odor emissions from animal housing systems in The Netherlands. Proceedings from the National Conference on Mitigating Air Emissions from Animal Feeding Operations Exploring the advantages, limitations, and economics of mitigation technologies, May 19 - 21, 2008, Des Moines, Iowa (IA), USA.

Parker, D.B., Caraway, E.A., Rhoades, M.B., Cole, N.A., Todd, R.W., & Casey K.D. (2010). Effect of wind tunnel air velocity on voc flux from standard solutions and cafo manure/wastewater. *Transactions of the ASABE,* 53, 831-845.

Parker, D., Ham, J., Woodbury, B., Cai, L., Spiehs, M., Rhoades, M., Traube, S., Casey, K., Todd, R., & Cole, A. (2012). Standardization of flux chamber and wind tunnel flux measurements for quantifying volatile organic compound and ammonia emissions from area sources at animal feeding operations. *Atmospheric Environment, in press*.

Pedersen, S., Blanes-Vidal, V., Jorgensen, H., Chwalibog, A., Haeussermann, A., Heetkamp, M. J., & Aarnink, A. J. A. (2008). Carbon Dioxide Production in Animal

Houses: A Literature Review. *Agricultural Engineering International: CIGR Ejournal*. Manuscript BC 08 008, Vol. X. December, 2008.

Pedersen, S. & Strøm, J.S. (1995). Performance Testing of Complete Ventilation Units. *Applied Engineering in Agriculture, 11,* 131-136.

Pedersen, S., Takai, H., Johnsen, J. O., Metz, J. H. M., Koerkamp, P. W. G. G., Uenk, G. H., Phillips, V. R., Holden, M. R., Sneath, R. W., Short, J. L., White, R. P., Hartung, J., Seedorf, J., Schroder, M., Linkert, K. H., & Wathes, C. M. (1998). A comparison of three balance methods for calculating ventilation rates in livestock buildings. *Journal of Agricultural Engineering Research, 70,* 25-37.

Phillips, V.R., Scholtens, R., Lee, D.S., Garland, J.A., & Sneath, R.W. (2000). A review of methods for measuring emission rates of ammonia from livestock buildings and slurry or manure stores, Part 1: Assessment of basic approaches. *Journal of Agricultural Engineering Research*, 77, 355-364.

Phillips, V. R., Holden, M. R., Sneath, R. W., Short, J. L., White, R. P., Hartung, J., Seedorf, J., Schroder, M., Linkert, K. H., Pedersen, S., Takai, H., Johnsen, J. O., Koerkamp, P. W. G. G., Uenk, G. H., Scholtens, R., Metz, J. H. M., & Wathes, C. M. (1998). The development of robust methods for measuring concentrations and emission rates of gaseous and particulate air pollutants in livestock buildings. *Journal of Agricultural Engineering Research, 70,* 11-24.

Rabaud, N. E., James, T. A., Ashbaugh, L.,L., & Flocchini, R.G. (2001). A passive sampler for the determination of airborne ammonia concentrations near large-scale animal facilities. *Environmental Science & Technology, 35,* 1190-1196.

Redwine, J. S., Lacey, R. E., Mukhtar, S., & Carey, J. B. (2002). Concentration and emissions of ammonia and particulate matter in tunnel-ventilated broiler houses under summer conditions in Texas. *Transactions of the ASAE, 45*, 1101-1109.

Rom, H. B., & Zhang, G.Q. (2010). Time delay for aerial ammonia concentration measurements in livestock buildings. *Sensors, 10,* 4634-4642.

Roadman, M. J., Scudlark, J. R., Meisinger, J. J., & Ullman, W. J. (2003). Validation of Ogawa passive samplers for the determination of gaseous ammonia concentrations in agricultural settings. *Atmospheric Environment, 37,* 2317-2325.

Scholtens, R., & Van't Ooster, C. (1994). Application of the carbon dioxide mass balance method to evaluate ventilation rates in livestock buildings. *Proceedings of the XII World Congress on Agricultural Engineering,* Milano, Italy.

Schrade, S., Keck, M., Zeyer, K., Emmenegger, L., & Hartung, E., (2010). Measuring concept for determining ammonia emission from naturally ventilated dairy housing with an outdoor exercise area. *Proceedings of the CIGR XVIIth World Congress* – Québec City, Canada. Paper No. 101131.

Shah, S.B., Grabow, G.L., & Westerman, P.W. (2006). Ammonia adsorption in five types of tubing materials. *Applied Engineering in Agriculture, 22,* 919-923.

Simmons, J. D., & Lott, B. D. (1997). Reduction of poultry ventilation fan output due to shutters. *Applied Engineering in Agriculture, 13,* 671-673.

Van Buggenhout, S., Van Brecht, A., Eren Özcan, S., 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.

Van Dooren, H.J.C., & Mosquera, J. (2010). Measurement of ammonia emissions from three ammonia emission reduction systems for dairy cattle using a dynamic flux chamber. *Proceedings of the CIGR XVIIth World Congress* – Québec City, Canada. Paper No. 101322.

Van Ouwerkerk, E. N. J., & Pedersen, S. (1994). Application of the carbon dioxide mass balance method to evaluate ventilation rates in livestock buildings. *Proceedings of the XII World Congress on Agricultural Engineering,* Milano, Italy.

Vranken, E., Gevers, R., Aerts, J. M., and Berckmans, D. (2005). Performance of model-based predictive control of the ventilation rate with axial fans. *Biosystems Engineering, 91,* 87-98.

Wheeler, E.F., Topper, P.A., Adviento-Borbe, M.A.A., Brandt, R.C., Topper, D.A., & Elliott, H.A. (2010). Flux chamber validation for ammonia measurements versus whole room emission. *Proceedings of the CIGR XVIIth World Congress* – Québec City, Canada. Paper No. 100656.

Xin, H., Li, H., Burns, R.T., Gates, R.S., Overhults, D.G., & Earnest, J.W. (2009). Use of CO_2 concentration or CO_2 balance to assess ventilation rate of commercial broiler houses. Transactions of the ASABE 52(4): 1353-1361.

Xin, H., Berry, I.L., Tabler, G.T., & Costello, T.A. (2001). Heat and moisture production of poultry and their housing systems: broilers. *Transactions of the ASAE, 44,* 1851-1857.

Yan, W., Barker, D., Sun, Y., Zhang, Y., & Gates. R. S. (2010). Performance simulation of high volume low speed fans in a free stall barn. XVIIth World Congress of the International Commission of Agricultural Engineering (CIGR), 13-17 June, Quebec City, Canada

Zhang, G., Pedersen, S., & Kai, P. (2010). Uncertainty analysis of using CO_2 production models by cows to determine ventilation rate in naturally ventilated buildings.

Proceedings of the CIGR XVIIth World Congress – Québec City, Canada. Paper No. 100542.

Table 1: Precision of techniques to measure ammonia concentration. Typical values are provided although precision may vary for different concentration ranges.

Measurement technique	Magnitude	Reference
Chemiluminiscence	2% - 5%	Ni, Vinckier, Coenegrachts and Hendriks (1999)
Passive flux samplers	5% - 10%	Rabaud, James, Ashbaugh and Flocchini (2001); Roadman, Scudlark, Meisinger and Ullman (2003)
Wet chemistry	<5%	Roadman et al. (2003)
Photo acoustic	2.5%	Hinz and Linke (1998)
Electrochemical	8%	Redwine, Lacey, Mucktar and Carey (2002)

Table 2: Overview of ventilation rate measurement techniques for mechanically and naturally ventilated buildings. An estimation of the standard uncertainty typically corresponding to each technique is also included (adapted from Van Buggenhout et al., 2009).

Measurement technique	Type	Magnitude	Potential biases	Reference
Manufacturer curves	Mechanical	20%	Effects of shutters, dirtiness and ageing (up to 50% reduction)	Casey et al. (2002, 2008); Simmons and Lott (1997)
Measuring fans	Mechanical	< 5%	-	Berckmans et al. (1991); Demmers et al. (1999)
FANS	Mechanical	3%	Fan disturbance Dirtiness and ageing	Gates et al. (2004); Casey et al. (2007); Pedersen & Strom (1995).
Hot wire anemometer	Mechanical	10%	Dirtiness and ageing	Calvet, Cambra-López et al. (2010)
Tracer gases	Natural	10-15	Gas sampling location Identification of inlets and outlets	Demmers et al. (2001)
CO_2 balance	Natural	15-40	Gas sampling location CO_2 produced by animals CO_2 produced by litter	Pedersen et al. (1998); Blanes and Pedersen (2005); Pedersen et al. (2008); Xin et al. (2001)
Moisture balance	Natural	5-40	Latent heat of animals and manure	Pedersen et al. (1998); Blanes and Pedersen (2005)
Heat balance	Natural	30-100	Sensible heat of animals	Pedersen et al. (1998); Blanes and Pedersen (2005)
Hot wire anemometer	Natural	25	Identification of inlets and outlets	Krause and Janssen (1990); Scholtens and Van't Ooster (1994)
CFD calculations	Natural	15-65	Model parameters	Blanes-Vidal et al. (2007); Bartzanas et al. (2007)
Pressure difference method	Natural	> 50%	Model parameters (tend to overestimate)	Demmers et al. (2001);
Free impelling turbine	Natural	5-25	Identification of inlets and outlets	Van Ouwerkerk and Pedersen (1994); Vranken, Gevers, Aerts and Berckmans (2005)

Table 3: Provisional values of CO_2 production (m^3 h^{-1} hpu^{-1}) in different animal houses, at animal and house level (Pedersen et al., 2008)

	Animal level	House level*
Cows		
Calves	0.155	0.170
Dairy cows	0.180	0.200
Pigs		
Weaners	0.170	0.185
Growing pigs	0.185	0.200
Sows	0.165	0.180
Poultry		
Broilers < 0.5 kg	0.165	0.180
Broilers > 0.5 kg	0.170	0.185
Layers	0.165	0.180
Sheep	0.160	0.175

* Including CO_2 production from manure, except for deep litter and indoor manure storage over a time period longer than 3 weeks

Figure 1. Uncertainty diagram when determining gas emissions from livestock buildings. Potential sources of random errors (precision) and systematic errors (bias) are also indicated

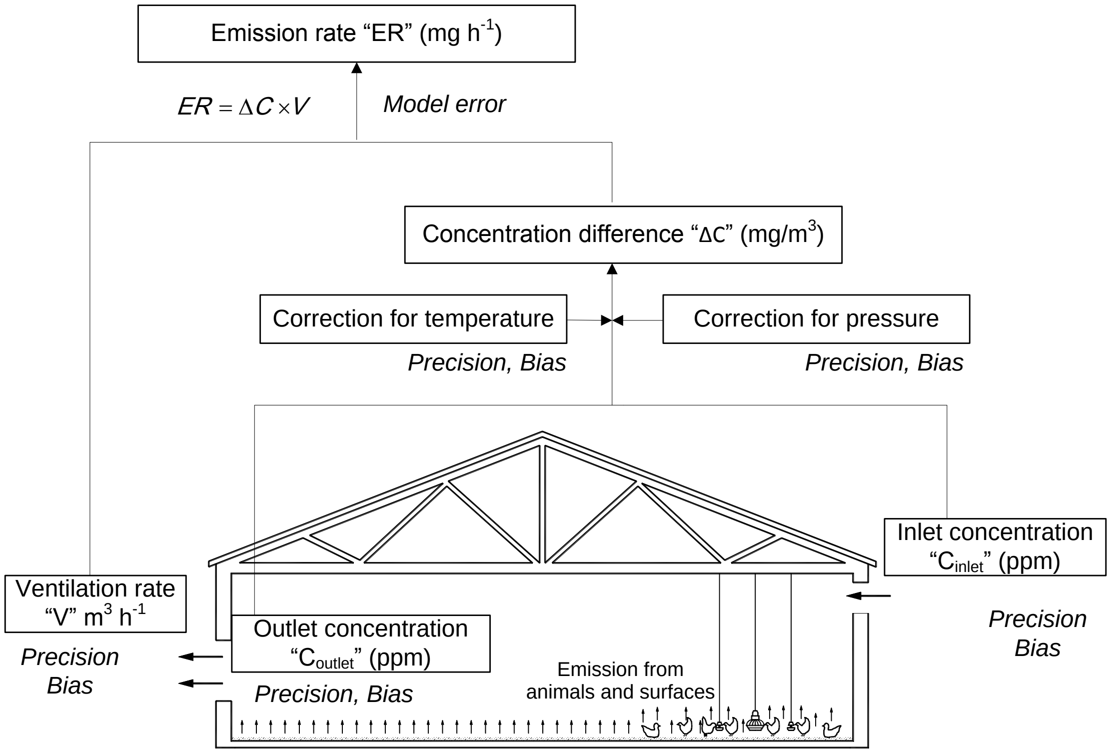
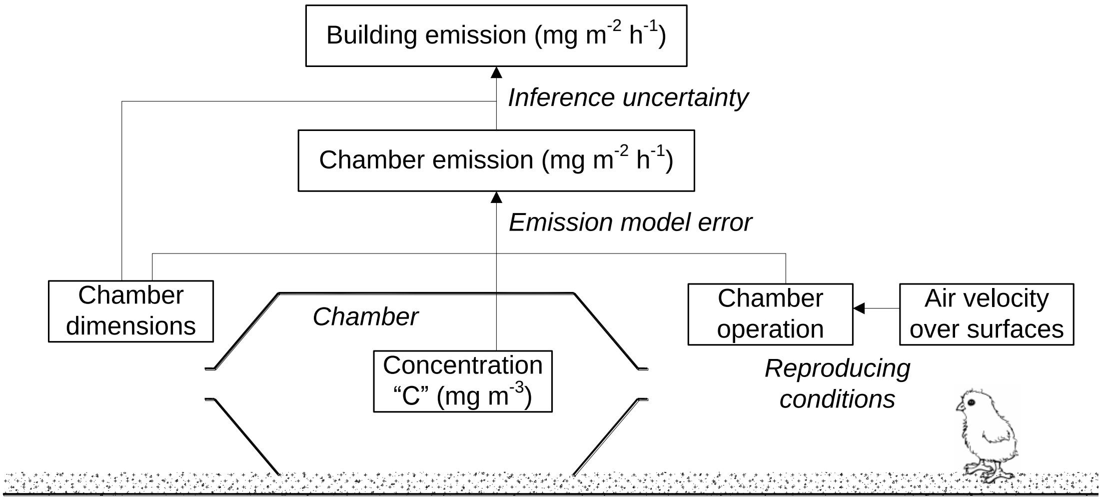


Figure 2. Uncertainty sources when determining gas emissions using the flux chamber method.



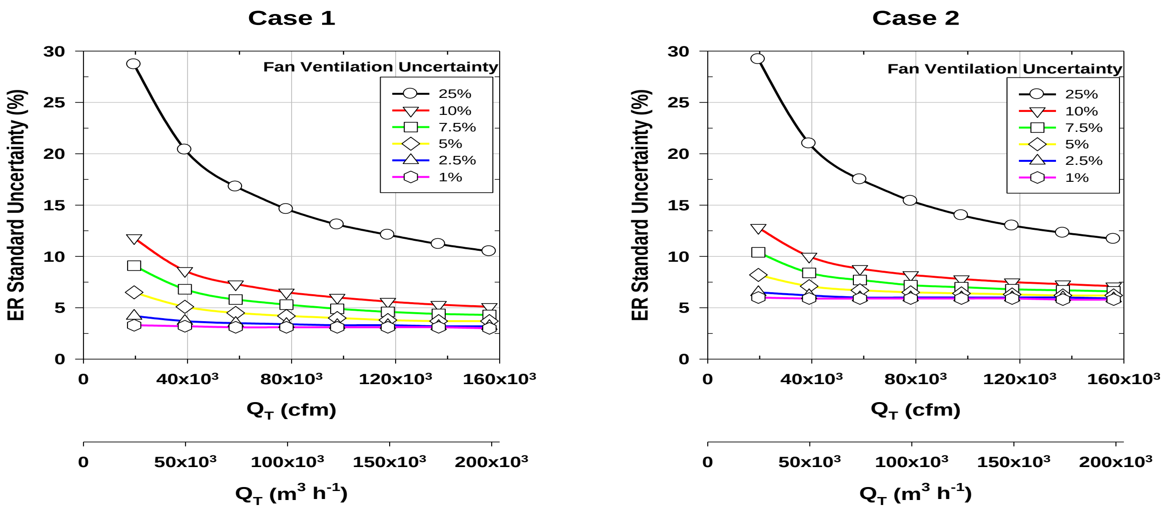


Figure 3. Combined standard uncertainty estimates for ER as a function of building ventilation rate (Q_T) and ventilation uncertainty (ΔQ_T) expressed as % of Q_T. Note that each point along a curve represents one more fan with the same uncertainty being added. Case 1 uncertainties on inputs include 3% for calibration gas and 0.5% instrument standard uncertainty; whereas Case 2 uncertainties on inputs include 3% for calibration gas and 5% for instrument standard uncertainty. (Source: Gates et al., 2009).