INTRODUCTION

Greater interest in documenting and decreasing the environmental footprint of food production translates into a need to identify methods to quantify greenhouse gas (GHG) contributions from various sources within a farm and understand the implications of using different quantification methods between and within studies. Carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) make up the primary GHG emissions from animal feeding operations. Direct and indirect sources of CO₂, CH₄, and N₂O emissions in...
animal production systems includes the animals, feed storage areas, manure deposition and storage areas, and feed and forage production fields (Fig. 1). Each of the 3 primary GHG may be more or less prominent from each emitting source. Similarly, the livestock species dictates the importance of enteric CH$_4$ emissions.

Because a variety of quantification methods are available, method selection is important. Each method identified has its own benefits and challenges for use in the stated application. Studies have conducted method comparisons (Pacholski et al., 2006; Parker et al., 2013), but although some methods have greater accuracy or precision compared with other methods, not all methods are feasible for every situation due to resource constraints or other reasons. In the absence of a perfect method for all situations, full knowledge of the advantages and disadvantages of each method is extremely important during the development of the experimental design and interpretation of results (Table 1). Considerations for method selection include intended goal, compatibility with production system, equipment investment and maintenance, frequency and duration of sampling needed to achieve desired representativeness of emissions fluxes over time, accuracy and precision of the method, and environmental influences on the method response accuracy and precision.

The objective of this paper is to review both the principles behind measuring gas flux from different sources in animal production and the selection of methods available for quantifying gaseous flux, including GHG flux, from the various sources on the farm. Although citations reference work that quantifies emissions from gases of interest other than GHG, the underlying principles and methodologies are applicable to GHG.

**PRINCIPLES OF MEASURING FLUX**

Air emissions represent the amount of gas or other airborne pollutant that moves per unit time. Often, emissions are reported per minute (Wang-Li et al., 2013) or on a daily basis (Todd et al., 2008). In the case of the former, the reported measure often reflects mean observations for a sampling period. Daily means often reflect one or more measurement periods within a day that are summed and multiplied by a factor to reflect total emissions during a 24-h period based on the assumption that the measured time period or periods are representative of and reflect what has occurred throughout the day. Therefore, when comparing data between studies,
### Table 1. Summary of methods for measuring greenhouse gas emissions and flux from animal production systems

<table>
<thead>
<tr>
<th>Method</th>
<th>Application</th>
<th>Underlying principles</th>
<th>Benefits</th>
<th>Drawbacks</th>
<th>Example citations</th>
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<tbody>
<tr>
<td>In vitro techniques</td>
<td>Mimic rumen environment and screening tool for dietary treatments</td>
<td>Direct measurement of gas produced during an incubation period (hour, day, or week)</td>
<td>Inexpensive, quick, basic laboratory equipment and a gas chromatograph needed</td>
<td>Provides estimate of rumen gas production and access to fistulated animals necessary</td>
<td>Pell and Schofield (1993) and Meale et al. (2012)</td>
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<td>Chamber techniques (static and passive), including flux hoods</td>
<td>Study emissions from individual or small groups of animals, with or without manure accumulation, and measure emissions from surfaces (fields, piles, lots, and manure storage surfaces)</td>
<td>Direct measurement of gases built up in a chamber over time (static) or emitted from a chamber with measured flow rate (passive or flux hood)</td>
<td>Considered the “gold standard” for measuring animal emissions; field chambers (static, dynamic, or flux hoods) inexpensive to construct and function with manual or automated sampling system</td>
<td>Artificial environment for the animal; infrastructure and operating costs are high for animal chambers; chamber placement or large numbers of chambers critical for representative of lot, field, pile, or surface; and surface emissions represent emissions only from the surface and not from animals if present (lots, corral, and pastures)</td>
<td>Ellis et al. (2001), Misselbrook et al. (2001), Boadi et al. (2004), Sommer et al. (2004), Grainger et al. (2007), Misselbrook et al. (2006), Rochette et al. (2011), Kahrmark and Millar (2014), and Li et al. (2015)</td>
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<td>Head boxes (mobile or stationary, with or without animal restraint)</td>
<td>Measure enteric emissions or respired gases (energetics studies)</td>
<td>Gas concentrations are measured in real time coupled with direct flow measures or flow rate determined using a tracer gas approach</td>
<td>Real-time measures and good application to pastured or free-stall environments if animals not restrained</td>
<td>Artificial environment for the animal when restrained, observations may not represent daily pattern of emissions when animals not restrained, and investment cost</td>
<td>Place et al. (2011), Utsunomi et al. (2011), Hristov et al. (2015), and Huhtanen et al. (2015)</td>
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<td>Tracer gas methods, including CO₂ mass balance</td>
<td>Estimate ventilation flow rate (naturally ventilated buildings) and couple with concentration measures to determine emissions from ruminants (enteric emissions), lots, corrals, or buildings</td>
<td>Mass released of a stable gas is determined and used as an indicator of mass of gas of interest emitted, similar to the use of marker methods in nutrition studies</td>
<td>Often cheaper than direct methods of measurement and high accuracy of mass measurement</td>
<td>Diurnal or diel effects not discernible and samples are collected for future analyses</td>
<td>Johnson et al. (1994), Kahrarabat et al. (2000), McGinn et al. (2006a), Xin et al. (2009), Samer et al. (2012), Samer and Abuara (2014), and Chiavegato et al. (2015a)</td>
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<tr>
<td>Emissions measurement</td>
<td>Often ventilated buildings but applicable to any source</td>
<td>Direct measurement of flow or ventilation rate coupled with concentration measures (same principle as chamber methods)</td>
<td>Real-time measurements, multiple gases measured simultaneously, ability to isolate emission source, and continuous measures provide representativeness of conditions present over sampling period</td>
<td>Extensive set up time and calibration expense necessary for continuous measurement</td>
<td>Lin et al. (2012) and Joo et al. (2015)</td>
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<td>Dispersion modeling</td>
<td>Model emissions across large areas including corrals, lots, pastures, and manure storage structures</td>
<td>Measure concentration at a downwind location and use backward dispersion modeling method to estimate source emission rate</td>
<td>Measurement across large surface area possible, ease of equipment setup relative to other methods, and ability to isolate emission sources</td>
<td>Turbulence due to surface variation creates uncertainty in model assumptions and model output accuracy dependent on data input and model itself</td>
<td>McGinn et al. (2006b), Pacholski et al. (2006), and Flesch et al. (2007)</td>
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<td>Micrometeorological methods</td>
<td>Most applicable to feedlot, corrals, and some pastures where large, relatively uniform surface areas are present</td>
<td>Emissions gradient for any gas of interest is determined at multiple heights above source and flux across the source is determined</td>
<td>Addresses surface variation and the resulting influence of turbulence, well suited for large surface area sources, and lack of uniform surfaces can be addressed through the use of eddy covariance adjustments</td>
<td>Assumes steady-state conditions over emitting surface unless adjustments made and requires multiple towers and repeated sampling for time period representation of emissions</td>
<td>Hutchinson et al. (1982), Harper et al. (1999), Baek et al. (2006), Shah et al. (2006), Todd et al. (2007), and Park et al. (2006)</td>
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it is important to understand when and how often measures were actually made. Data that report flux values typically include emissions with the added dimension of area included in the calculation or quantity per unit time and unit area. Reporting emissions on a flux basis can be useful when calculating emission factors, making comparisons between studies, or considering comparative importance of emission sources within a farm.

Regardless of the method used to measure emissions or flux, concentration and flow measures are central to the calculation. The chemistry underlying measurement of concentration varies between methods and analytes of interest. A number of chemical methods are available to quantify concentration of GHG and other gases of interest including gas chromatography (GC), infrared spectroscopy, open path Fourier transform infrared spectroscopy (OP-FTIR) technologies, photoacoustic spectroscopy, mass spectroscopy, tunable diode laser absorption spectroscopy technology, and solid-state electrochemical technology. Measures may be made on-site (real time) or samples may be collected for later analyses in a laboratory. Advantages of spectroscopic instruments include linear responses over a wide range of concentrations, accuracy, and stability. Many of the instrumental methods offer rapid response times and are portable; however, instruments tend to be expensive (e.g., tunable diode lasers and OP-FTIR; Borhan et al., 2012). The tradeoff is that less expensive options are comparatively unstable and require frequent calibration (i.e., solid-state electrochemical sensors; Borhan et al., 2012), have short life spans for the sensors, or require that samples be transported back to a laboratory (i.e., GC), thus giving up real-time analyses.

Approaches to measuring flow vary; methods may use either a direct measurement of flow or indirect methods to estimate flow. Direct flow measurements are often made using mass flow meters or sonic anemometers whereas indirect methods of determining flow often use a marker approach coupled with appropriate analytical techniques to relate marker and target analyte concentrations. An example of a marker method for determining flow is provided by Xin et al. (2009).

**QUANTIFYING ENTERIC EMISSIONS**

Options to measure respired GHG from ruminant animals include direct measurement methods such as respiration chambers (Grainger et al., 2007), head boxes (Utsumi et al., 2011; Huhtanen et al., 2015), or tracer gas methods (Johnson et al., 1994). Estimates of in vivo performance also can be obtained using in vitro gas production techniques. Each approach has its advantages and disadvantages.

Respiration chambers, often considered “the gold standard,” measure concentration of emitted gases in real time and measure flux using direct methods such as mass flow meters or differential pressure transducers (Bhatta et al., 2007). Concentration measures are made using GC, photoacoustic spectroscopy, OP-FTIR, or nondispersive infrared spectroscopy. Respiration chambers require a large capital investment followed by high operating costs but do allow measurements to be made for the whole animal with or without excreta present. Respiration chambers do allow for measurements beyond enteric CH₄ if appropriate instrumentation is available. Criticisms of the use of respiration chambers includes reduced feed intake when animals are isolated in the chambers (McGinn et al., 2004) although data from grouped animals demonstrate performance, including feed intake, that is comparable to large group and commercial production settings (Li et al., 2015). Animals are removed from their native environment but most adjust well to the chamber environment although group behaviors are not exhibited (Chiavegato et al., 2015a). However, respiration chambers are unsuitable for mimicking pasture settings due to the need to confine animals within the chamber, thus preventing the forage selection aspect of grazing behavior.

Head boxes include strategies that lock the animal in place (Place et al., 2011) or allow the animal to come and go into the head box (Hristov et al., 2015). Gas concentrations are measured in real time using instrumentation that parallels that used in respiration chambers. Because response time needs to be rapid, infrared spectroscopy techniques such as OP-FTIR or nondispersive infrared spectroscopy are best suited for head box approaches. Flow measures may be made via direct measurement (Maia et al., 2015) or by using a tracer gas approach (Hristov et al., 2015). An increasing number of off-the-shelf products are available with varying costs. In addition to commercially available equipment, head boxes have been constructed by researchers (Place et al., 2011). Notable limitations with this approach include stress on the animal when the animal is locked in place or removed from its customary environment. Animals can be locked in place only if feed is provided; other models that allow an animal to come and go are best suited to pastured animals. However, when animals are free to enter the head box as they wish (for milking or feeding), fewer observations over the course of the day may be captured and the small number of observations may not represent the variation that occurs throughout the day.

Similar to a head box is the use of a tracer gas method (Johnson et al., 1994; McGinn et al., 2006a) that combines a halter, a harness, and a canister that can travel with the animal or remain stationary above a stalled animal. This system collects a portion of each respired
Measuring greenhouse gases from animal production

FLUX MEASURES FROM ANIMAL HOUSING

The prominent methods for measuring GHG emissions from housing include tracer gas ratio techniques as a means of determining ventilation or flow rate or direct ventilation measures. Both approaches require concentration measures of gases of interest using methods previously identified (see “Principles of Measuring Flux”).

Like tracer gas techniques used to determine enteric \( \text{CH}_4 \) emissions, tracer gas methods have been successfully used to determine \( \text{CH}_4 \) and other gaseous emissions from animal housing, including buildings and lots (Kaharabata et al., 2000; Samer et al., 2012). Tracer gas ratio methods require that a tracer gas be emitted at a known rate near the \( \text{CH}_4 \) source (or other gas of interest) and that the concentrations of \( \text{CH}_4 \) and the tracer gas be measured downwind. However, the accuracy of the method heavily relies on the assumption that the tracer emissions are representative of the \( \text{CH}_4 \) emissions and similarly move across the landscape (Kaharabata et al., 2000).

Modeling techniques coupled with downwind concentration measures have been extensively used to determine flux and emissions. Flesch et al. (2007) and McGinn et al. (2006b, 2007) both studied feedlot emissions and applied an inverse dispersion technique where a single, line-averaged concentration was measured at a downwind distance and a backward Lagrangian stochastic dispersion model was used to infer the emission rate of the source. As with any modeling exercise, the accuracy of the emissions estimate depends on accuracy of the model, data available to develop the model, and accuracy of data input into the model. Turbulence across landscapes, in particular, creates uncertainty with respect to model assumptions. Uncertainty and model accuracy are heavily influenced by wind speed, air stability, and lack of a constant emission rate from the source. Regardless, when the goal is to quantify emissions from large surface areas, this approach is favored. Flesch et al. (2005) used a backward dispersion model approach on a simulated feedlot with known \( \text{CH}_4 \) emissions and predicted emissions within 2% of that measured in a field experiment, depending on where the concentration was measured and whether ambient or in-plot wind statistics were used.

A method that takes into account variation in surface characteristics and the resulting influence on turbulence effects measurements is the use of micrometeorological methods (Shah et al., 2006). In some cases, these methods use flux measures across an undisturbed surface area and average aerial measures. Feedlot or corral studies, in particular, have used micrometeorological gradient methods that consider measurements at different heights (Hutchinson et al., 1982; Harper et al., 1999; Baek et al., 2006; Todd et al., 2007). A drawback of gradient methods is the assumption that steady-state conditions exist over a surface area that is uniform in sources of, and sinks for, emissions (Prueger and Kustas, 2005). When these assumptions are clearly not able to be met, single-height flux measurements such as eddy covariance may be the best approach. Regardless of approach, the underlying assumption that animals are stationary in pastures, corrals, or feed yards poses a challenge and brings error into collected measures.

MEASURING GREENHOUSE GAS FLUX FROM MANURE DEPOSITION AND STORAGE AREAS

Emissions from manure deposited inside animal housing areas are captured when housing emissions are measured. Methods for measuring those emissions were previously discussed. Methods for collecting and measuring GHG emissions from manure storage and/or production lots include the use of downwind concentration measures combined with modeling techniques (Koehn et al., 2013), the use of micrometeorological methods
Flux Measures from Fields

Methods similar to those used for manure deposition and storage areas can be deployed for determining GHG emissions from fields, including methods that use a combination of concentration measurement and modeling techniques with micrometeorological techniques (Harper et al., 1999) or chamber techniques (Pacholski et al., 2006; Millar et al., 2013; Kahmark and Millar, 2014; Chiavegato et al., 2015b). Because animals are not present in crop fields, the assumption that surface emissions reflect total area emissions is correct, thereby improving accuracy of micrometeorological method estimates from fields compared with estimates from corrals, lots, or pastures. Static or dynamic chamber methods are also suitable for quantifying flux from fields although accurate emissions representation from large areas becomes a challenge due to the number of chambers that must be placed to obtain adequate representation of the variation within the area for surface conditions and soil influences on emissions (nutrient composition, texture, and moisture content).

SUMMARY AND CONCLUSIONS

In the absence of a perfect method for quantifying GHG flux from livestock farms, researchers must be aware of the options available, the underlying principles beyond flux measures and methods, and the attributes of the various options. The basis for the selected method should align with the objective of the study...
recognizing that compromises often are necessary to accommodate resource restrictions (labor, equipment availability, and financial resources). These compromises influence the accuracy of measurements and ability to compare data across studies, which is important to consider when only a small proportion of farms are measured and those measurements are desired to be applicable to the industry as a whole.

**LITERATURE CITED**


Kalmar, K., and N. Millar. 2014. Stainless steel chamber construction method. W.K. Kellogg Biological Station, Michigan State University, Hickory Corners, MI.


