Animal (2013), **7:s2**, pp 386–393 © Her Majesty the Queen in Right of Canada, as represented by the Minister of Agriculture and Agri-Food Canada 2013.
doi:10.1017/S1751731113000657

animal

Developments in micrometeorological methods for methane measurements

S. M. McGinn†

Agriculture and Agri-Food Canada, 5403 – 1 Avenue South, PO Box 3000, Lethbridge, Alberta, Canada T1J 4B1

(Received 26 November 2012; Accepted 17 March 2013)

Micrometeorological techniques can be applied to estimate methane (CH_4) emissions from ruminants and livestock manure using CH_4 concentration measured within the internal surface boundary layer. The main advantage of these techniques is that they are non-intrusive, thereby eliminating the impact of the measurement set-up on the calculated CH_4 emission. This review focuses on four micrometeorological techniques, namely, the integrated horizontal flux (IHF), flux gradient (FG), eddy covariance (EC) and the dispersion modelling using the backward Lagrangian stochastic method (BLS). Each technique has unique advantages and limitations when used for estimating enteric (ruminant) and manure CH_4 emissions. The IHF technique may be theoretically simpler then the FG, EC or BLS techniques, but all require high-resolution instruments to measure concentration. The EC and BLS techniques also require a measurement of the wind statistics. This review discusses the appropriate use of these four micrometeorological techniques for estimating CH_4 emissions in animal agriculture and the recent advances in measurement technology.

Keywords: methane, micrometeorology, technique, livestock, manure

Implications

Accurate measurements of methane (CH_4) emissions are essential to understand the importance of livestock's contribution to the greenhouse gas issue, and to develop mitigation strategies to improve the environmental sustainability of animal agriculture. These goals will become even more important as animal production escalates to meet global population demands. A clear understanding of the limitations and accuracy of measurement techniques presented in this review is needed to advance our understanding of CH_4 emissions from animal agriculture.

Introduction

Animal agriculture production is estimated to account for 8% to 10.8% of the global emissions of greenhouse gases (O'Mara, 2011). Methane (CH_4) is a large component of these emissions where globally the annual emission of ruminant enteric CH_4 is 91.9 million tonnes, and CH_4 from livestock manure is 11.2 million tonnes (O'Mara, 2011). The enteric CH_4 from ruminants alone is estimated to account for 25% to 40% of the anthropogenic release of CH_4 (Clark, 2013). It follows that accurate measurement of CH_4 emissions from ruminants and livestock manure is necessary to develop best management practices to reduce these CH_4 emissions and to ultimately improve the environmental sustainability of the livestock industry. These goals will become even more relevant with the expected expansion of the livestock industry because of increased demand for meat and milk by an escalating human population estimated to reach nine billion by 2050 (Smith *et al.*, 2007). Fundamental to accurate measurement is the need for techniques that give direct measurements of CH_4 emissions under a variety of management and environmental conditions.

A variety of CH_4 emission techniques for intensive livestock systems have been reviewed in the literature, for example, National Research Council (2003) and McGinn (2006). The review edited by Makkar and Vercoe (2007) outlined in a series of chapters *in vitro* and *in vivo* techniques, where the latter included the enteric tracer technique (i.e., using an enteric permeation tube containing sulphur hexafluoride (SF_6)) as well as the tunnel and chamber methods, but did not cover micrometeorological techniques. Denmead (2008) discussed the use of chambers (surface) and micrometeorological techniques for CH_4 and nitrous oxide sources. A focused review by Harper *et al.* (2011) also described a few non-micrometeorological techniques (animal chambers, enteric tracer, external tracer and mass balance) and provided an in-depth description of micrometeorological

† E-mail: sean.mcginn@agr.gc.ca

https://doi.org/10.1017/S1751731113000657 Published online by Cambridge University Press

techniques used to estimate CH_4 emissions from livestock. A more recent review of techniques for measuring CH_4 emissions from livestock was presented by Storm *et al.* (2012), mostly covering the use of animal chambers, enteric tracer, *in vitro* and modelling; other techniques are very briefly mentioned including some micrometeorological techniques. This review provides an overview of the micrometeorological techniques, whereas the appropriate reviews mentioned above can provide the details.

The objective of the current review is to build on the previous reviews by focusing on the limitations of specific micrometeorological techniques and their practical application to animal agriculture CH_4 emissions. Insights into the accuracy are also investigated by reporting on studies where emissions using different techniques are compared. Finally, a discussion follows on the recent developments in micrometeorological techniques to estimate CH_4 emissions from livestock and livestock manure.

General application of micrometeorological techniques

There exists an assortment of micrometeorological techniques for calculating the emission of enteric CH_4 from ruminants (Harper *et al.*, 2011) or CH_4 directly from livestock manure. These include the flux gradient (FG), eddy covariance (EC), relaxed eddy accumulation (REA), integrated horizontal flux (IHF) and boundary-layer budgeting (BLB). More recent application of dispersion modelling (e.g., backward Lagrangian stochastic model, BLS) has also been used to estimate emissions from ruminants and livestock manure. A widely used BLS technique is the WindTrax model (Thunder Beach Scientific, Nova Scotia, Canada).

All these micrometeorological techniques share the advantage of being non-intrusive, as well as providing near-continuous emissions data. As micrometeorological techniques generally have a large measurement footprint, they can also result in a spatial average of the source strength. However, not all micrometeorological techniques are conducive to measurement situations in animal agriculture, where the source area is small such as manure storage facilities and small pens containing animals.

Some micrometeorological techniques such as the FG and EC techniques are best suited to operate within the fully adjusted internal boundary layer (IBL), where the properties of the air stream, at the measurement height, is in equilibrium with the surface, that is, the vertical flux at the measurement height equals the emission rate from the underlying surface. A simple 'rule-of-thumb' is that the fully adjusted IBL roughly increases in height by 1 m for every 100 m distance from the upwind leading edge of the source area (Vesala *et al.*, 2008). Other more detailed relationships exist in defining this boundary layer, for example, as a function of the surface roughness and distance from the leading edge (Munro and Oke, 1975). CH_4 concentrations measured by sensors positioned above the fully adjusted IBL do not correspond with the surface emissions. Where the CH_4 source area is small such that the sensor height is above the fully adjusted IBL, it is necessary to calculate a 'footprint' of the sensor (the upwind area that influences the sensor's measurements) to determine how much of the source area is seen by the sensor (e.g., as reported by Schuepp *et al.* 1990).

Typically, micrometeorological techniques also assume that the source strength is evenly distributed (spatially homogeneous). Exceptions to this are the modified IHF (modified mass difference (MMD); Harper *et al.*, 2011) technique or when using the BLS (WindTrax) technique where the source location is known and treated as a point source. The need for spatially uniform source strength is more achievable for manure storage facilities such as open pits than for non-confined grazing ruminants. When the enteric CH_4 from grazing ruminants is the targeted source, one option is to place global positioning system (GPS) units on the animals and then treat them as point sources (McGinn *et al.*, 2011).

It is possible to reduce the impact of assuming even distribution of the source strength when using the BLS technique (Flesch *et al.*, 2005). As the distance between the source and location of concentration detection increases, the sensitivity of the calculated emissions to the source distribution decreases. This implies a benefit to having the detection distance away from the source. This principle was demonstrated by McGinn *et al.* (2006) who showed that treating point sources as an area source resulted in smaller error with increased distance between the source and site of CH_4 detection. Where a combined emission is from two or more distinct sources (e.g., two barns on a farm), Flesch *et al.* (2005) reported that positioning the concentration sensor twice the source separation distance downwind gave errors in emissions of $<10\%$. In practice, there is a limitation to the downwind distance, where the concentration dilutes with distance from the source. As a result, while it may be advantageous to have the detector some distance downwind from the source, the source must also be close enough to measure a significant concentration difference from the background concentration. There is also a disadvantage with long distances between the source and sensor in that the operational wind direction 'window' narrows with increasing distance.

IHF

The IHF technique is based on the accounting of CH_4 entering and leaving a small source (e.g., manure storage pond) via the open air, where the difference is equated to the amount of CH_4 emitted by the source. This technique imposes no restriction on the source strength distribution. In this technique, the CH_4 emission (Q; g/m^2 per s) is calculated as the sum of mean horizontal fluxes accumulated above the source height (z_1; m):

$$Q = \frac{1}{x}\sum_{z_1}^{z_2} \left[\bar{u}\left(\bar{C}_d - \bar{C}_u\right)\right] \Delta z \qquad (1)$$

where u is wind speed (m/s), C the concentration (g/m^3) and subscripts d and u denote the downwind and upwind

https://doi.org/10.1017/S1751731113000657 Published online by Cambridge University Press

locations, respectively[1]. The maximum height (z_2) is where the horizontal flux declines to zero (the lowest height where the incoming and outgoing CH_4 concentrations become equal), and x is the path distance across the source that the wind follows. With a uniform landscape, it is assumed that the magnitude of the incoming and outgoing u is equal at any given height in equation (1).

The application of the IHF technique is best suited to horizontally uniform surfaces such as a manure storage pond that ensures a smooth C_d and u profile. When the IHF technique is applied to source that is not horizontally homogenous, for example, a manure pile or a raised manure storage pond, care must be taken to ensure that the C and u profiles are characterized accurately. This typically requires using at least five sampling heights. Where the height of zero horizontal flux is beyond the highest measurement height, it is possible to account for this by extrapolation. This has been done by regressing C and u against the natural log of the height ($\ln z$) and expressing Q as a function of the regression coefficients (Ryden and McNeill, 1984). The IHF-modified version MMD with its more elaborate field requirement does not require that the source strength be spatially evenly distributed. To be independent of wind direction, the MMD requires a horizontal line averaged of concentration along each source perimeter, at several heights on all perimeters (i.e., the face), thereby enclosing the entire source.

Laubach *et al.* (2008) used the IHF technique to determine the enteric emissions from cattle grazing ryegrass in small paddocks. They reported an average enteric CH_4 emission of 161 g/animal per day. The IHF technique has also been used to calculate CH_4 emissions from open-top tanks containing dairy liquid manure, ranging between 11 (after emptying) and 153 $\mu g/m^2$ per s (Vanderzaag *et al.*, 2011).

In using equation (1), two assumptions are made as outlined by Gao *et al.* (2009). First, it is reasonable to assume that fluctuations in u at one point are the same as fluctuations in wind speed along the entire perimeter when C is a line-average concentration (e.g., using an open-path laser) and u is point measurement along a perimeter. Second, the product of the time-averaged wind speed ($\bar{u}$) and time-averaged concentration ($\bar{C}$) in equation (1) is a simplification, which should actually be written as the time-averaged product of u and C ($\overline{uC}$). This time-averaging error is often unavoidable owing to instrumentation restrictions (e.g., cup anemometers fail to measure short-term fluctuations). Gao *et al.* (2009) state that this error causes an overestimate (in the MMD technique) of 5% to 20%.

FG

Emissions using the FG technique are calculated as the product of the turbulent (or eddy) diffusivity (K; m^2/s) and the vertical concentration gradient ($\Delta C/\Delta z$; g/m^3 per m). The turbulent diffusivity for different properties (e.g., momentum and heat) is assumed to be related, such that it can be determined by combining atmospheric properties. The Schmidt number (Sc), for example, is the ratio of turbulent diffusivity of momentum to mass ($Sc = K_m/K_c$). Therefore, determining K_m provides an estimate of K_c when the value of Sc is known[2]. The value of K_m is calculated (Monteith, 1973) using:

$$K_m = \frac{ku^*z}{\phi_m} \quad (2)$$

where von Karman's constant (k) relates the size of eddies to height above ground, friction velocity (u^*; m/s) is derived from wind statistics measured using a three-dimensional sonic anemometer, z (m) is the measurement height above the surface and ϕ_m a non-dimensional correction for the effect of thermal stability on the wind profile. This stability correction is calculated as a function of the atmospheric stability as reflected in the Monin–Obukhov parameter (L; m). The FG emission (Q in g/m^2 per s) is then given as:

$$Q = \frac{(-kz\,u^*)}{\phi_m\,Sc}\left[\frac{\Delta C}{\Delta z}\right] \quad (3)$$

The FG technique was first applied to livestock where enteric CH_4 from grazing sheep was measured by Judd *et al.* (1999). Since then, this technique has also been applied to grazing cattle (Laubach *et al.*, 2008). Like other micrometeorological techniques, FG is best suited to operate in the fully adjusted IBL; else a footprint model (Vesala *et al.*, 2008) must be used to gauge the influence of the source configuration on the calculated emission (see the discussion below).

EC

The EC technique is based on monitoring the vertical flux of a gas at a point above the source area. For a horizontally extensive source, the surface emission Q (g/m^2 per s) is taken as equal to the vertical flux at the measurement point, and is determined as the product of the instantaneous deviation from the mean vertical wind speed (w'; m/s) and the instantaneous deviation from the mean CH_4 concentration (C'; g/m^3):

$$Q = \overline{w'\,C'} \quad (4)$$

where the overbar indicates that the cross product is averaged, usually over a 10 to 30 min interval. This technique requires sensors with very fast response times to measure w and C, in the order of 10 times a second (10 Hz). A three-dimensional sonic anemometer is generally used to measure w. Post-measurement corrections (coordinate rotations) are needed to ensure the mean w is zero.

When applying the EC technique, consideration must be made for the characteristics of the upwind source area. Where the upwind source is extensive and homogeneous,

[1] Equation (1) is a simplified expression that neglects the turbulent flux component (Gao *et al.*, 2009).

[2] Most FG studies assume equality of diffusivities; however, Flesch *et al.* (2002) reported $Sc = 0.63$.

https://doi.org/10.1017/S1751731113000657 Published online by Cambridge University Press

the location of the EC detectors should be at a height within the fully adjusted IBL (reflective of the surface emission). Where the source is not extensive (finite) and/or not evenly distributed, it is necessary to understand what the influence of the source at upwind distances has on the measured emission at a particular height, the so-called footprint of the source (Vesala *et al.*, 2008). The footprint is dependent on the measurement height, wind speed and direction, atmospheric stability and surface roughness. Vesala *et al.* (2008) outlines a few approaches to estimating the footprint, using Lagrangian stochastic trajectory, large eddy simulation and closure models. Another approach was used by Baum *et al.* (2008) at a beef cattle feedlot that uses a simplified (parameterized) footprint model, developed by Hsieh *et al.* (2000).

The concentration of CH_4 is measured with either an open- or closed-path analyser. When the latter is used, air is drawn from near the sonic anemometer and is pumped through the closed-path analyser. The offset in sampling times between the wind speed measurement and the concentration is used to align the two measurements. Detto *et al.* (2011) summarized the limitations and advantages of both open- and closed-path detection of CH_4 concentration. A major disadvantage of the closed-cell approach is the greater power demand because of the high-flow pump. This approach therefore is not as flexible regarding siting or would require a higher level of maintenance (battery replacement). Peltola *et al.* (2012) compared three closed-path and one open-path CH_4 analyser used in EC, and concluded that the open-path system, although not the most accurate, is a good choice where power is a concern.

An unavoidable error found in closed-cell sampling is the underestimate of the emission due to high-frequency losses in the sampled concentration fluctuations (Nordbo and Katul, 2013). This error can be as high as 20% but can be corrected. The error is more common as the height of the sample decreases (note that the frequency of the turbulent fluctuations increases closer to the ground), and for closed-cell analysers, as the length of the inlet tube increases.

Recent advancements in technology has produced an open-path CH_4 sensor (e.g., LI-7700; LI-COR Biosciences, Lincoln, NE, USA) that was used by Dengel *et al.* (2011) to measure CH_4 emission (on a per sheep basis) from grazing sheep. Such an application requires considerable caution, as the source strength is not spatially homogeneous and as the measurement footprint contains animals moving in and out throughout the day. Not knowing the exact stocking rate at any time also causes error in converting the area source (g/m^2 per day) to an animal source (g/animal per day) when using an average stocking rate of the herd. They acknowledge a bias for half hour emissions because of roaming sheep, but argue that the EC technique in this situation is more accurate over a long averaging time. This assumes that the animals move about randomly.

BLS

The BLS technique is used in the WindTrax dispersion model. The dispersion model is used to relate the concentration $(C)_{SIM}$ within the dispersion plume to the simulated source emission $(Q)_{SIM}$. The C measured either as a line or point detection is then divided by the simulated ratio.

$$Q = \frac{C_{\underset{256}{\text{MEASURED}}}}{(C/Q)_{\underset{257}{\text{SIM}}}} \quad (5)$$

WindTrax requires several parameters that are typically derived using data collected from a three-dimensional sonic anemometer. These are the surface roughness (z_o), u^*, L and wind direction.

The WindTrax model was used recently for estimating enteric CH_4 emissions at dairies (Bjorneberg *et al.*, 2009; Gao *et al.*, 2011; McGinn and Beauchemin, 2012), paddocks containing grazing beef cattle (McGinn *et al.*, 2011), cattle feedlots (van Haarlem *et al.*, 2008) and for livestock manure (Todd *et al.*, 2011). There are several limitations of the BLS technique. It requires that the area source of emission be well defined or that location of point source(s) be known as well; there is a need to accurately measure background concentration. There are atmospheric conditions when the BLS technique is expected to fail in estimating emission data. These conditions may differ depending on the experimental set up, but roughly correspond to the following criteria given by Flesch *et al.* (2009): (a) at low wind speeds when $u^* \leqslant 0.15$ m/s, (b) at times of strong stable or unstable atmospheric stratification when $|L| < 10$ m, and (c) when the wind profile is unrealistic as denoted by $z_o \geqslant 1$ m. More recently, Flesch *et al.* (2013) reported refinements to the filtering criteria that increased the amount of useable data. Another limitation when using WindTrax occurs when the wind direction is such that only part of the source (edge) is used to determine the source emission. This situation leads to errors in part because with small shifts in wind direction (especially under light wind speeds) over the averaging period, there can be times when there is no upwind coverage of the source. To avoid this complication, Flesch *et al.* (2009) used periods when WindTrax used at least 50% coverage of the source area.

Accuracy of micrometeorological techniques

A key question often raised is whether or not micrometeorological techniques have the accuracy and precision to investigate mitigation strategies such as dietary treatments. In a study where comparisons are being made between treatments, the precision of the measurements (e.g., concentration) must be high enough not to mask the differences because of treatments.

Insights into the accuracy of micrometeorological techniques are gained by comparing emissions from simultaneous measurements, that is, side-by-side within a study using the same source. As not one technique is completely error-free, accuracy of micrometeorological techniques is more difficult to gauge than understanding the practical limitation of a technique (as discussed above). Some value may exist in comparing emission between studies; however, in general

https://doi.org/10.1017/S1751731113000657 Published online by Cambridge University Press

such comparisons are confounded by differences in experimental design, between- and within-animal variability, and diet factors. For example, Broadi *et al.* (2004) reported on CH_4 emissions from dairy cows over several studies using different techniques, ranging from 286 to 433 g/cow per day. It follows that only studies that use side-by-side measurements may provide the needed evidence to understand the accuracy of micrometeorological techniques.

There have been some comparisons of micrometeorological techniques against non-micrometeorological techniques within a study. Park *et al.* (2010) compared CH_4 emissions from liquid swine manure using IHF (MMD) and small surface chambers for liquid manure. Significant differences existed that they attributed to source strength heterogeneity, where the chamber emissions were more influenced by location than the spatially average MMD technique. It follows that comparisons between techniques is more useful when the temporal and spatial scales are equal, for example, comparisons between micrometeorological techniques. Griffith *et al.* (2008) showed that an external tracer technique agreed within 10% of CH_4 emissions made using the IHF technique. McGinn *et al.* (2009) reported a 7% difference in CH_4 emissions between the BLS and enteric tracer techniques where penned cattle were the CH_4 source. In this study, each animal was treated as a point source using the WindTrax model, where cattle positions were given by GPS units mounted on each animal. They reported that the BLS technique was sufficiently precise to allow evaluation of the differences in CH_4 emission from cattle under different dietary treatments. Tomkins *et al.* (2011) compared BLS (WindTrax) to whole-animal chambers (conducted sequentially) and reported enteric CH_4 emissions (corrected for dry matter intake (DMI)) of 29.7 and 30.1 g CH_4/kg DMI, respectively. The correction for DMI is needed as intake decreased 15% when the cattle were placed in the chamber, and DMI affects CH_4 emission.

A few studies report the comparison of different micrometeorological techniques within a study. Laubach *et al.* (2008) reported a good fit of CH_4 emissions from cattle in small paddocks when using the BLS, FG and IHF techniques (plus an enteric tracer technique) simultaneously, provided that a minimum separation between the paddock and sensor location exists when using the FG and IHF techniques. In their study, using 22 m separation, the BLS emissions were correlated with IHF ($R^2 = 0.85$) and FG ($R^2 = 0.75$); however, the BLS emissions were 20% higher than the two techniques. Laubach and Kelliher (2005) reported the comparison of CH_4 emissions for grazing dairy cows measured using the BLS technique against that of the FG and the IHF techniques. They concluded for their experimental design that the BLS (statistical errors of 15% to 20% when using point detection of concentration) and IHF (statistical errors of 10%) were preferred techniques over that of the FG technique. The FG technique was deemed to have higher uncertainty as a result of the need to use a footprint model when applying this technique to a finite area source; suitability is low (Table 1). Laubach and Kelliher (2005) acknowledge that the BLS error may improve if line-averaged concentration measurements are used instead of point concentrations.

Table 1 *Summary of micrometeorological techniques regarding their application of methane emissions for animal agriculture*

	Suitability of application			
	Scale			
	Paddock or lagoon		Pasture or farm	
Technique	Enteric	Manure	Enteric	Manure
IHF	***	***	*	*
FG	*	*	**[1]	***
EC	*	*	**[1]	***
BLS	***	***	***	***

IHF = integrated horizontal flux; FG = flux gradient; EC = eddy covariance; BLS = backward Lagrangian stochastic.
[1]Requires evaluation of the footprint area and livestock density.
*Not recommended, **potential, ***most relevant.

Another way of determining accuracy of a micrometeorological technique is to release a tracer gas at a known flow rate and to use the technique to calculate a recovery rate. Ideally, the gas flow from a cylinder of gas is regulated by a mass flow controller during the release/recovery period, and the total gas released over the period is checked by weighing the cylinder before and after the release. The BLS technique has been tested by Ro *et al.* (2011) who report a recovery of 98%, and McBain and Desjardins (2005) who recovered 106%. Gao *et al.* (2009) found a recovery of 101% for the IHF technique and 103% for the BLS technique. Harper *et al.* (2009) reported (for ammonia) that the BLS technique estimated 100.1% recovery rates from known true release rates. McGinn *et al.* (2006) used BLS (WindTrax point source releases at a dairy) and reported recoveries of 86% and 100% for trace releases of CH_4 and SF_6, respectively. The low 86% recovery of CH_4 was attributed to the presence of cattle (area source) confounding CH_4 point source release. Previous release and recovery work by Flesch *et al.* (2004), using an open-path laser, found that the BLS recovered 102% of the controlled release. Harper *et al.* (2010) looked at a number of release/recovery BLS studies and concluded the BLS accuracy was $100 \pm 10\%$.

A related accuracy challenge when comparing enteric CH_4 emissions from different treatments (e.g., dietary) is the need to normalize the emissions by dividing by the DMI. This procedure removes the effect of the amount of intake (Grainger *et al.*, 2007), allowing a focus on more relevant factors. Inaccuracy in measuring DMI, especially for grazing animals, contributes to inaccuracy of emission studies. For production systems where the feed is highly regulated, measuring DMI is more direct than that from grazing animals. Other indices reported is the CH_4 emission per kg digestible DMI, per MJ (gross energy) of the feed or per production amount (kg milk or meat), where inaccuracies add to the overall error in the CH_4 emission factor.

https://doi.org/10.1017/S1751731113000657 Published online by Cambridge University Press

CH_4 concentration detection and wind statistics

Fundamental to all micrometeorological techniques is the requirement for accurate and precise measurement of concentration, at a resolution high enough to detect differences between the background and the elevated source concentration associated with the source or between treatment concentrations. A number of detectors exist, such as those outlined by Neftel *et al.* (2006) including three commonly used approaches, that is, laser and Fourier transform infrared (FTIR) spectroscopy, and infrared gas analysers.

Open-path CH_4 lasers (e.g., Boreal Lasers Inc., model GasFinder, Edmonton, AB, Canada) have been used in the BLS technique for some time to detect the line concentration of CH_4 (Flesch *et al.*, 2009; Gao *et al.*, 2009; McGinn and Beauchemin, 2012). Where the CH_4 concentration associated with the source is close to the background concentration, the error in calculating the difference is large, and the emission value is uncertain.

Recently, the open-path laser and FTIR have been used in conjunction with a digitized stepping motor (scanner) to allow multi-path CH_4 concentrations measurements using one laser or FTIR unit, thus avoiding the problem of between-sensor differences (e.g., drifting and offsets). The elimination of the between-sensor differences increases the resolution of the horizontal concentration gradient that can be measured (downwind–upwind concentration). This is especially significant when the source strength is weak, that is, in the case of low stocking rates (animals per ha) of grazing ruminants. The scanner when used with an open-path laser can also be programmed to optimize light-return levels, which can otherwise drift when the laser beam misaligns with its reflector that is more common over longer paths.

The recent development of the fast-response CH_4 open-path sensor proved sensitive to the presence of grazing cattle (Baldocchi *et al.*, 2012) and was used to measure enteric CH_4 emissions from grazing sheep (Dengel *et al.*, 2011) when supported by footprint analysis.

The EC and BLS techniques require information on atmospheric turbulence that is quantified using a three-dimensional sonic anemometer. Typically, this sensor is mounted (leveled) over the source area at a height of 2 to 3 m. The high-frequency outputs of the sensor are the vertical (w) and two horizontal (u and v) wind speeds, plus their cross products (uu, vv, ww, uv, uw, vw). These data are averaged over 10 to 30 min intervals generally, and a two-stage rotation (Kaimal and Finnigan, 1994) is carried out to set the mean w and v to zero. The algorithms to extract the turbulence data (e.g., EddyPro software; LI-COR Biosciences; WindTrax) has become more user-friendly, allowing the non-micrometeorologist access to EC and BLS techniques.

Summary

Considerable expertise is needed to successfully apply micrometeorological techniques to measure CH_4 emissions from livestock and livestock manure. This is especially the case where these techniques are deployed to measure small differences between treatments as part of a mitigation investigation.

The ease of application depends on many factors, including the scale of the emission. The IHF (MMD) technique is perhaps most straightforward, but still requires some assumptions regarding the time averaging of measurements. No assumptions are needed regarding the characteristics of the source distribution or strength, but a minimum separation distance between source and concentration detection is required. Practical limitations exist, such as the small paddock size that limits the measurement period of grazing ruminants (pending the stocking rate and forage available), and the number of concentration and wind speed measurements that are needed. The FG and the EC techniques are theoretically more demanding and are intended for large area and uniform CH_4 sources. Neither of these techniques are recommended for measuring enteric CH_4 from grazing cattle on pasture unless a footprint is known and the movement of the cattle is monitored (e.g., using camera or GPS). The BLS technique is a promising approach that has application for all scales (Table 1) including grazing ruminants that are confined in a paddock.

Recent developments in micrometeorological techniques have focused on better detection and greater understanding of the limitations and determining the accuracy of these techniques. For example, in the BLS technique when using WindTrax, more precise data filtering criteria has improved the quantity of useable emission data. In addition, advancements in the instrumentation (e.g., open-path lasers) used in micrometeorological techniques have improved the resolution of the CH_4 concentration and increased the accuracy/precision of the techniques. The availability of a fast response detector for CH_4 concentration now allows EC applications. Improvements in the field configuration, where one sensor (e.g., open-path laser) mounted on a scanner can replace the need for multiple sensors eliminate the between-sensor error.

Some micrometeorological techniques are best suited to evaluate herd scale (small paddocks of livestock) and manure storage facilities CH_4 emissions, and offer the opportunity to investigate mitigation strategies. A greater challenge exists when using these techniques for large-scale (pastoral) grazing livestock where the source strength is weak. It is expected that further instrumentation developments in the measurement of concentration, and increased understanding of the constraints to estimating emissions, will continue to advance the application of micrometeorological techniques.

Acknowledgements

This paper was published as part of a supplement to *animal*, publication of which was supported by the Greenhouse Gases & Animal Agriculture Conference 2013. The papers included in this supplement were invited by the Guest Editors and have undergone the standard journal formal review process. They may be cited. The Guest Editors appointed to this supplement

https://doi.org/10.1017/S1751731113000657 Published online by Cambridge University Press

are R. J. Dewhurst, D. R. Chadwick, E. Charmley, N. M. Holden, D. A. Kenny, G. Lanigan, D. Moran, C. J. Newbold, P. O'Kiely, and T. Yan. The Guest Editors declare no conflict of interest.

References

Baldocchi D, Detto M, Sonnentag O, Verfaillie J, Teh YA, Silver W and Kelly NM 2012. The challenges of measuring methane fluxes and concentrations over a peatland pasture. Agricultural and Forest Meteorology 153, 177–187.

Baum KA, Ham JM, Brunsell NA and Coyne PI 2008. Surface boundary layer of cattle feedlots: implications for air emissions measurement. Agricultural and Forest Meteorology 148, 1882–1893.

Bjorneberg DL, Leytem AB, Westermann DT, Griffiths PR, Shao L and Pollard MJ 2009. Measurements of atmospheric ammonia, methane, and nitrous oxide at a concentrated dairy production facility in southern Idaho using open-path FTIR spectrometry. Transactions of the ASABE 52, 1749–1756.

Broadi DA, Benchaar C, Chiquette J and Massé D 2004. Mitigation strategies to reduce enteric methane emissions from dairy cows: update review. Canadian Journal of Animal Science 84, 319–335.

Clark H 2013. Nutritional and host effects on methanogenesis in the grazing ruminant. Animal 7 (suppl. 1), 41–48.

Dengel S, Levy PE, Grace J, Jones SK and Skiba UM 2011. Methane emissions from sheep pasture, measured with an open-path eddy covariance system. Global Change Biology 17, 3524–3533.

Denmead OT 2008. Approaches to measuring fluxes of methane and nitrous oxide between landscapes and the atmosphere. Plant Soil 309, 5–24.

Detto M, Verfaillie J, Anderson F, Xu L and Baldocchi D 2011. Comparing laser-based open- and closed-path gas analyzers to measure methane fluxes using the eddy covariance method. Agriculture and Forest Meteorology 151, 1312–1324.

Flesch TK, Prueger JH and Hatfield JL 2002. Turbulent Schmidt number from a tracer experiment. Agricultural and Forest Meteorology 111, 299–307.

Flesch TK, Wilson JD, Harper LA and Crenna BP 2005. Estimating gas emissions from a farm with an inverse-dispersion technique. Atmospheric Environment 39, 4863–4874.

Flesch TK, Harper LA, Powell JM and Wilson JD 2009. Inverse-dispersion calculation of ammonia emission from Wisconsin dairy farms. Transactions of the ASABE 52, 253–265.

Flesch TK, Wilson JD, Harper LA, Crenna BP and Sharpe RR 2004. Deducing ground-air emissions from observed trace gas concentrations: a field trial. Journal of Applied Meteorology 43, 487–502.

Flesch TK, McGinn SM, Chen D, Wilson JD and Desjardins RL 2013. Data filtering for BLS calculation of emissions rates: improvements to increase data retention. Advances in Animal Biosciences, Proceedings of the Greenhouse Gases and Animal Agriculture Conference, Dublin, Ireland.

Gao Z, Desjardins RL and Flesch TK 2009. Comparison of a simplified micrometeorological mass difference technique and an inverse dispersion technique for estimating methane emissions from small area sources. Agricultural and Forest Meteorology 149, 891–898.

Gao Z, Yuan H, Ma W, Liu XJ and Desjardins RL 2011. Methane emissions from a dairy feedlot during the fall and winter seasons in northern China. Environmental Pollution 159, 1183–1189.

Grainger C, Clarke T, McGinn SM, Auldist MJ, Beauchemin KA, Hannah MC, Waghorn GC, Clark H and Eckard RJ 2007. Methane emissions from dairy cows measured using the sulfur hexafluoride (SF_6) tracer and chamber techniques. Journal of Dairy Science 90, 2755–2766.

Griffith D, Bryant GR, Hsu D and Reisinger AR 2008. Methane emissions from free-ranging cattle: Comparison of tracer and integrated horizontal flux techniques. Journal of Environmental Quality 37, 582–591.

Harper LA, Denmead OT and Flesch TK 2011. Micrometeorological techniques for measurement of enteric greenhouse gas emissions. Animal Feed Science and Technology 166–167, 227–239.

Harper LA, Flesch TK, Weaver KH and Wilson JD 2010. The effect of biofuel production on swine farm methane and ammonia emissions. Journal of Environmental Quality 39, 1984–1992.

Harper LA, Flesch TK, Powell JM, Coblentz WK, Jokela WE and Martin NP 2009. Ammonia emissions from dairy production in Wisconsin. Journal of Dairy Science 92, 2326–2337.

Hsieh C, Katul G and Chi T 2000. An approximate analytical model for footprint estimation of scalar fluxes in thermally stratified atmospheric flows. Advances in Water Resources 23, 765–772.

Judd MJ, Kelliher FM, Ulyatt MJ, Lassey KR, Tate KR, Shelton ID, Harvey MJ and Walker CF 1999. Net methane emissions from grazing sheep. Global Change Biology 5, 647–657.

Kaimal JC and Finnigan JJ 1994. Atmosphere boundary layer flows: their structure and measurements, pp 234–240. Oxford University Press, New York, USA.

Laubach J and Kelliher FM 2005. Measuring methane emission rates of a dairy cow herd (II): results from a backward-Lagrangian stochastic model. Agricultural and Forest Meteorology 129, 137–150.

Laubach J, Kelliher FM, Knight TW, Clark H, Molano G and Cavanagh A 2008. Methane emissions from beef cattle – acomparison of paddock- and animal-scale measurements. Australian Journal Experimental Agriculture 48, 132–137.

Makkar HPS and Vercoe PE 2007. Measuring methane production from ruminants. Springer, Dordrecht, The Netherlands.

McBain MC and Desjardins RL 2005. The evaluation of a backward Lagranfian stochastic (BLS) model to estimate greenhouse gas emissions from agriculture sources using a synthetic tracer source. Agricultural anf Forest Meteorology 135, 61–72.

McGinn SM 2006. Measuring greenhouse gas emissions from point sources in agriculture. Canadian Journal of Soil Science 86, 355–371.

McGinn SM and Beauchemin KA 2012. Dairy farm methane emissions using a dispersion model. Journal of Environmental Quality 41, 73–79.

McGinn SM, Flesch TK, Harper LA and Beauchemin KA 2006. An approach for measuring methane emissions from whole farms. Journal of Environmental Quality 35, 14–20.

McGinn SM, Beauchemin KA, Flesch TK and Coates T 2009. Performance of a dispersion model to estimate methane loss from cattle in pens. Journal of Environmental Quality 38, 1796–1802.

McGinn SM, Turner D, Tomkins N, Charmley E, Bishop-Hurley G and Chen D 2011. Methane emissions from grazing cattle using point-source dispersion. Journal of Environmental Quality 40, 22–27.

Monteith JL 1973. Principles of environmental physics. William Clowes and Sons Limited, London.

Munro DS and Oke TR 1975. Aerodynamic boundary-layer adustment over a crop in neutral stability. Boundary Layer Meteorology 9, 53–61.

National Research Council 2003. Air emissions from animal feeding operations: current knowledge, future needs. The National Academies Press, Washington, DC.

Neftel A, Fischer C and Flechard C 2006. Measurements of greenhouse gas fluxes from agriculture. In Greenhouse gases and animal agriculture: an update (ed. CR Soliva, J Takahashi and M Kreuzer), pp. 3–12. Elsevier, Amsterdam.

Nordbo A and Katul G 2013. A wavelet-based correction method for eddy-covariance high-frequency losses in scalar concentration measurements. Boundary Layer Meteorology 146, 81–102.

O'Mara FP 2011. The significance of livestock as a contributor to global greenhouse gas emissions today and in the near future. Animal Feed Science and Technology 166–167, 7–15.

Park K-H, Wagner-Riddle C and Gordon RJ 2010. Comparing methane fluxes from stored liquid manure using micrometeorological mass balance and floating chamber methods. Agricultural and Forest Meteorology 150, 175–181.

Peltola O, Mammarella I, Haapanala S, Burba G and Vesala T 2012. Field intercomparison of four methane gas analysers suitable for eddy covariance flux measurements. Biogeosciences Discussions 9, 17651–17706.

Ro KS, Johnson MH, Hunt PG and Flesch TK 2011. Measuring trace gas emission from multi-distributed sources using vertical radial plume mapping (VRPM) and backward Lagrangian stochastic (BLS) techniques. Atmosphere 2, 553–566.

Ryden JC and McNeill JE 1984. Application of the micrometorological mass balance method to the determination of ammonia loss from a grazed sward. Journal of the Science of Food and Agriculture 35, 1297–1310.

Schuepp PH, Leclerc MY, MacPhereson JI and Desjardins RL 1990. Fooprint prediction of scalar fluxes from analytical solutions of the diffusion equation. Boundary Layer Meteorology 50, 355–373.

Smith P, Matino D, Cai Z, Gwary D, Janzen H, Kumar P, McCarl B, Ogle S, O'Mara F, Rice C, Scholes B, Sirotenko O, Howden M, McAllister T, Pan G, Romanenkov V, Schneidere U and Towprayoon S 2007. Policy and technological constraints to implementation of greenhouse gas mitigation options in agriculture. Agriculture, Ecosystems and Environment 118, 6–28.

https://doi.org/10.1017/S1751731113000657 Published online by Cambridge University Press

Storm IMLD, Hellwing ALF, Nielsen NI and Madsen J 2012. Methods for measuring and estimating methane emission from ruminants. Animals 2, 160–183.

Todd RW, Cole NA, Casey KD, Hagevoort R and Auvermann BW 2011. Methane emissions from southern high plains dairy wastewater lagoons in the summer. Animal Feed Science and Technology 166–167, 575–580.

Tomkins NW, McGinn SM, Turner DA and Charmley E 2011. Comparison of open-circuit respiration chambers with a micrometeorological method for determining methane emissions from beef cattle grazing a tropical pasture. Animal Feed Science and Technology 166–167, 240–247.

van Haarlem RP, Desjardins RL, Gao Z, Flesch TK and Li X 2008. Methane and ammonia emissions from a beef feedlot in western Canada for a twelve-day period in the fall. Canadian Journal of Animal Science 88, 641–649.

VanderZaag AC, Wagner-Riddle C, Park K-H and Gordon RJ 2011. Methane emissions from stored liquid dairy manure in a cold climate. Animal Feed Science and Technology 166–167, 581–589.

Vesala T, Kljun N, Rannik U, Rinne J, Sogachev A, Markkanen T, Sabelfelt K, Foken Th and Leclerc MY 2008. Flux and concentration footprint modelling: state of the art. Environmental Pollution 152, 653–666.

https://doi.org/10.1017/S1751731113000657 Published online by Cambridge University Press