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On-farm beef cattle methane emissions measured with tracer-ratio and inverse-dispersion modelling techniques

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Abstract. The development and validation of management practices to mitigate greenhouse gas (GHG) emissions from livestock requires accurate emission measurements. This study assessed the accuracy of a practical inverse dispersion (IDM) micrometeorological technique to quantify methane (CH_4) emitted from a small cattle herd (16 animals) confined to a 63 x 60 m pen. The IDM technique calculates emissions from the increase in CH_4 concentration measured downwind of the animals. Two types of open-path (OP) gas sensors were used to measure concentration in the IDM calculation: a Fourier transform infrared spectrometer (IDM-FTIR) or a CH_4 Laser (IDM-Laser). The actual cattle emission rate was given by a tracer-ratio technique using nitrous oxide as the tracer gas. We found very good agreement between the two IDM emission estimates (316 and 322 g CH_4 head^{-1} d^{-1} for the IDM-FTIR and IDM-Laser, respectively) and the tracer-ratio measurements (315 g CH_4 head^{-1} d^{-1}). This study shows that a practical IDM measurement approach can provide an accurate method of estimating cattle emissions.

Keywords: micrometeorological techniques, GHG emissions, grazing cattle, spectroscopy, OP-FTIR

1 Introduction

Enteric methane (CH_4) from livestock is a major contributor to agricultural greenhouse gas (GHG) emissions. A significant effort is being made to mitigate these emissions through diet modification, feed supplements, and breeding (Vyas et al., 2018). Increasingly there is a requirement for mitigation claims to be validated when these practices are applied on-farm (DoE, 2014), and simple and accurate methods for on-farm emission measurements are required.

On-farm enteric emissions have been measured by portable respiration hoods for tethered and non-tethered animals (Garnsworthy et al., 2012; Zimmerman and Zimmerman, 2012); by use of internal or external tracer-gas releases from the animal (Johnson et al., 1994); and by micrometeorological techniques based on the enhanced gas concentrations measured downwind of animals (Harper et al., 2011). The objective of this study was to examine the accuracy of a practical inverse dispersion modelling (IDM) technique for measuring CH_4 emissions from a herd of confined animals. The IDM technique offers the possibility of a relatively simple emission

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measurement, without the need for animal handling or modifying animal behavior. In this study the IDM technique is used to measure emissions from a small herd of cattle, and these measurements are tested against a robust tracer-ratio based measurement.

2 Materials and Methods

2.1 Experimental design

The study took place at the Chiswick pastoral research laboratory (30° 37’ S, 151° 33’ E) in Armidale, New South Wales, Australia in February 2013. Methane emissions were measured from 16 Angus steers placed in a temporary 63 × 60 m pen (Fig. 1) located in a flat and open field. There were no other cattle nearby, and the nearest trees (30 m height) were at least 300 m from the site. Vegetation in the field was removed prior to the study and no pasture was available to graze.

The study cattle had an average body weight of 373 kg (standard deviation = 59 kg). The animals were fed a blended oaten/lucerne chaff ration (90.2% of dry matter, 15.1 % crude protein) dispensed from automated feeders (Bindon, 2001) that recorded the individual animal intakes. The feeders were cleaned daily and any remaining feed was weighed to check that the total consumed amount matched the sum of the individual animal intakes. Feed and water were offered *ad libitum*. This feeding regime began four weeks prior to the emission measurements. During the seven-day emission measurement period, the average dry matter intake (DMI) was 11.9 kg head^{-1} d^{-1}. Approximately two weeks before the measurements, each animal was fitted with a backpack (glued to their back) to hold a small nitrous oxide (N_2O) gas canister used for the emission measurements.

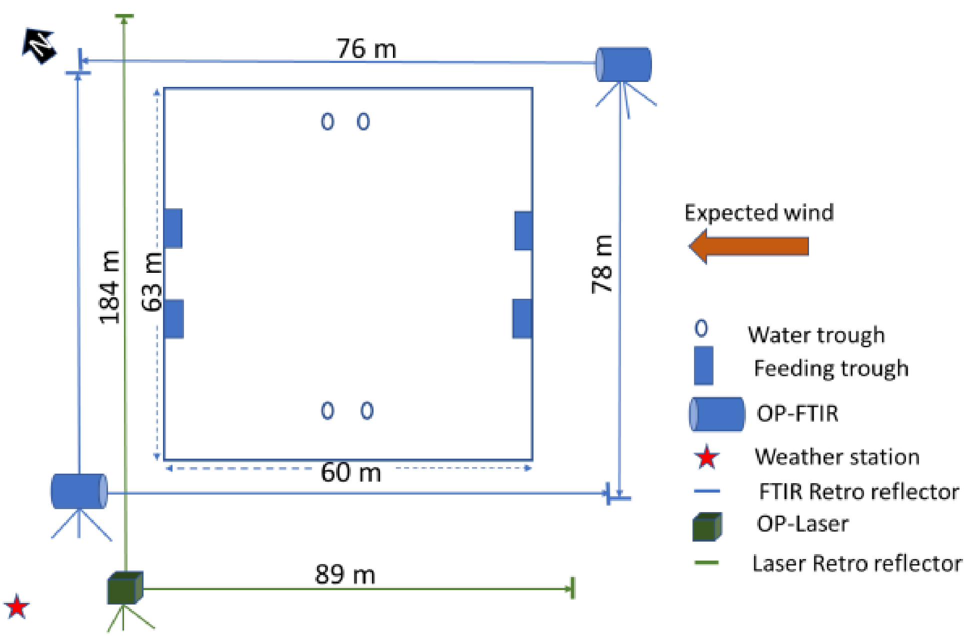

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Figure 1: Schematic layout of the experimental site, showing the OP-FTIR and the laser paths. The figure is not to scale.

During the emission measurement period (14−21 February 2013) each study animal carried an N_2O canister in their backpack, from which gas was released at a controlled rate as part of the tracer-ratio measurement technique. At 9:00 each morning during the measurement period the 16 study animals were walked from the cattle pen to the adjacent yards (80 m north), and the N_2O gas canister in the backpack was replaced with a fully filled canister. Cattle were absent from the study pen for approximately 30 min while this occurred. Other than during the canister replacement period, the animals moved and ate freely in the pen while emissions were measured.

2.2 Methodologies

A tracer-ratio technique was used to measure CH_4 emissions from the study animals. This is a conceptually simple and defensible method for measuring emissions, and we will consider this technique as giving the "true" CH_4 emission rate from the animals. Two different implementations of the IDM technique were compared with the tracer ratio measurements.

2.2.1 Tracer-ratio technique (N_2O Tracer)

The tracer-ratio measurements followed the procedure described in Bai (2010), Griffith et al. (2008), and Jones et al. (2011) with the herd emission rate of CH_4 calculated following Eq. (1):

$$Q_{CH4} = Q_{N2O} * (\Delta CH_4/\Delta N_2O) \quad (1)$$

Where Q_{N2O} is the known N_2O release rate from the canisters in the animal backpacks, and ΔCH_4 and ΔN_2O are the CH_4 and N_2O concentration enhancements (above the local background level) measured downwind of the animal pen.

The N_2O tracer was released from pressurized canisters (Catalina Cylinders) located in insulated backpacks on each animal. Each canister was fitted with a head encompassing capillary tube (0.025 mm inner diameter, SGE Analytical Science Pty Ltd, Australia) to control the N_2O flow rate. The canister was filled with approximately 300 g of N_2O to provide an average flow rate of 10 g h^{-1} over a 24 h period. The temperature of the canisters was recorded every 6 minutes (Thermochron Temperature model TCS, OnSolutions, Australia). The canisters and temperature sensors were exchanged every 24 h at a nearby yard. Following the procedure in Bai (2010), the canister flow rate was calibrated with a gas temperature dependent factor determined from the measured canister temperature. Canisters were also weighed at the start and end of each 24 h period to get the actual daily N_2O release rate.

Atmospheric concentrations of CH_4 and N_2O were measured upwind and downwind of the cattle pen using two open-path Fourier transform infrared (OP-FTIR) spectrometers. The details of the OP-FTIR system can be found in Bai (2010). The OP-FTIR spectrometers were mounted on a motorized aiming system (custom made at the University of Wollongong) to allow the spectrometer to be aimed at different retro reflectors. The two OP-FTIR units were positioned on opposite corners outside the cattle pen, and each unit was alternatively aimed at

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two reflectors so that gas concentration was measured along the four sides of the pen (Fig. 1). This configuration allowed the downwind CH_4 and N_2O enhancements to be measured for any wind direction. The OP-FTIR measurement-paths fell approximately 7 m outside the fence line. The distance between the OP-FTIR sensor and retro reflector was either 76 or 78 m, and the measurement path was 1.4 m above the ground. The OP-FTIR measurement sequence was repeated automatically so that every 5-min the line-average gas concentration on each path was measured. The collected OP-FTIR spectra were analyzed using the MALT (Multiple Atmospheric Layer Transmission) analysis program to derive the line-average concentrations of CH_4 and N_2O (Griffith, 1996). Ambient temperature and pressure were measured and used in the MALT analysis. The average gas concentrations on each of the four paths were averaged over a series of 15-min intervals, from which we calculated a timeseries of CH_4 emissions.

During the study we collected a number of air samples using volumetric flasks (600 mL). Samples were spaced along each measurement path and taken when animals were absent from the pen. These samples were later analyzed in the laboratory using a closed-path FTIR spectrometer and the CH_4 and N_2O values were used to cross-calibrate the two OP-FTIR sensors, with retroactive correction factors applied to all OP-FTIR data.

Tracer-ratio emission measurements were excluded for periods when the canisters outlets were blocked or had dropped off the animals, when there was optical misalignment of the OP-FTIRs, or when the enhancement of CH_4 and N_2O concentration was less than 50 and 10 ppb, respectively.

2.2.2 Inverse Dispersion Modelling technique

Herd CH_4 emissions were calculated using the IDM technique (Flesch et al., 2004), based on the downwind enhancement of CH_4, wind information, and a map of the pens and gas sensor locations. The WindTrax software is used for these calculations (www.thunderbeachscientific.com).

The upwind and downwind CH_4 concentration was measured using either the OP-FTIR system previously described (designated IDM-FTIR) or by an open-path CH_4 laser system (designated IDM-Laser). The laser system used a single laser unit (GasFinder2, Boreal Laser Inc., Edmonton, AB, Canada) located outside the animal pen, mounted on a pan-tilt scanning motor (PTU D300, FLIR Motion Control Systems, Burlingame, CA, USA). The scanning motor was programmed to sequentially measure CH_4 concentration on two paths. The paths ran along two sides of the pen, and their location was chosen to provide upwind and downwind concentrations during the prevailing southeasterly winds (Fig. 1). The two-paths were 89 and 184 m in length. The laser alternated between the two paths with a dwell time of 1-min on each path. Line-average CH_4 concentration was recorded approximately once a second, and the path average concentrations were averaged into 15-min intervals. Air samples collected during the study (described earlier) were used to cross-calibrate the laser and the OP-FTIR sensors (applying a retroactive correction multiplier to the laser concentrations).

A weather station southwest of the cattle pen (Fig. 1) included a 3-dimensional sonic anemometer (CSAT-3, Campbell Scientific Inc, Logan Utah, USA) mounted 2.45 m above the ground. The anemometer provided the wind information needed for the IDM calculation, including the friction velocity (u_*), Obukhov stability length

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(L), average windspeed and wind direction, and the standard deviation of the velocity fluctuations in the three directional components ($\sigma_{u,v,w}$). The surface roughness length (z_0) was calculated from these variables. The wind variables were averaged into 15-min intervals matched to the gas concentration dataset.

The CH_4 emissions were calculated in 15-min intervals using the WindTrax software. In the calculations we defined the CH_4 as coming from an elevated area source 0.8 m above ground, which overlaid the pen area. In the IDM analysis we followed the procedure of Flesch et al. (2005) to remove error-prone intervals when either $u_* <$ 0.15 m s^{-1}, $|L|<$ 5 m, $z_0 <$ 0.9 m, or when the fraction of WindTrax trajectory touchdowns inside the pen source covered < 10% of the pen area. Intervals were also removed when the concentrations measured by the OP-FTIR or the laser corresponded to low signal levels: i.e., spec.max was < 0.25 in the spectral region of 2200 cm^{-1} for the OP-FTIR, or the light level reported by the laser fell outside the 2000−13000 range, or the laser quality parameter $R^2 < 0.97$.

2.2.3 Calculating Average Emissions

The tracer-ratio and IDM measurements are a discontinuous time series of 15-min average emission rates lasting for seven-days. In order to create a properly weighted daily average emission rate, these discontinuous data were used to create an ensemble 24-h diel emission "curve" for each technique. Each emission observation was binned into one of the 96 15-min periods making up the ensemble day. Any 15-min interval with no observations was assigned an emission rate estimated by interpolation from the surrounding intervals. The average daily emission rate was calculated by summing the 15-min emission intervals over the 24 h day.

3 Results

3.1 Climate condition

During the 7-d emission measurement period the total rainfall was 0.4 mm, the wind speeds (at 2.45 m above ground) varied from 2 to 8 m s^{-1}, and the wind direction was predominately from the east. This period had excellent conditions for the micrometeorological measurements due to the lack of precipitation, the absence of light wind periods, and the steady easterly winds.

3.2 Methane emission measurements

3.2.1 Tracer-ratio measurements

The OP-FTIR system measured downwind CH_4 enhancements between 50 and 150 ppb, and N_2O enhancements between 12 and 30 ppb over the study. These enhancements are well above the minimum sensitivity of the OP-FTIR given by Bai (2010): 2 ppb for CH_4 and < 0.3 ppb for N_2O). Over the seven study days, emissions were measured during 90% of the ensemble 24 h day (i.e., 86 of the 96 possible 15-min periods). The calculated average daily emissions (± standard error) from the tracer-ratio technique was 315.1 (± 4.3) g CH_4 $head^{-1}$ d^{-1} (Table 1).

Table 1. Methane emission rates from the three micrometeorological measurements (tracer-ratio, IDM-FTIR, IDM-Laser) and an emission estimate based on the dry matter intake of the animals (using an IPCC recommended calculation§). Methane yield is also shown.

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	Emission Rate ($g\ CH_4\ head^{-1}\ d^{-1}$)	Yield ($g\ CH_4\ kg^{-1}$ DMI)
Tracer-Ratio	315	27.0
IDM-FTIR	316	27.0
IDM-Laser	322	27.1
IPCC[§]	254[§]	21.3
Charmley et al. (2016)[‡]	246	20.7

[§]IPCC (2006) calculation based on DMI (Eq. 10.21). Assumes CH_4 energy content = 55.65 MJ (kg CH_4)$^{-1}$, DMI energy content = 18.45 MJ (kg DMI)$^{-1}$, and CH_4 conversion factor Y_m = 6.5%.
[‡] Methane production (g/day) = 20.7 (±0.28) ×DMI (kg d^{-1})

3.2.2 The inverse-dispersion modelling (IDM) emissions

Over the seven-day study, 90% of the ensemble day was represented with the IDM-FTIR measurements, and 79% was represented by the IDM-Laser measurements. The majority of missing periods resulted from instrumental issues (e.g., low signals caused by condensation on mirrors, power failure), and to a lesser extent by inappropriate meteorological conditions (e.g., low wind speed). The 24-h diel CH_4 flux over the measurement period is shown in Figure 2. There are differences between the three ensemble emission relationships in Fig. 2. We assume the tracer-FTIR data is most accurate data set. Differences between the tracer and IDM approaches is due to a combination of a less-sensitive laser sensor (compared to the OP-FTIR) and the incorrect assumption that animals were spread evenly over the pen (which effects the FTIR and laser estimates differently due to different measurement locations). Both IDM-FTIR and Tracer-Ratio measurement show a similar emission pattern: emission rates at a minimum at 9:00 local time, and at a maximum during the early evening. This emission peak pattern reflected the time when animals were fed, or the pellets were topped up. However, IDM-Laser shows a late minimum emission at 12:00 local time, likely due to a solar related alignment of retro reflector. From the 24-h ensemble diel emission curve we calculate average daily emission rates of 316.4 (± 12.1) and 321.6 (± 26.9) g CH_4 head^{-1} d^{-1} for the IDM-FTIR and IDM-Laser measurements, respectively (Table 1). These results are not statistically different from each other ($p < 0.05$). Both IDM estimates were not statistical different from the tracer-ratio results ($p < 0.05$).

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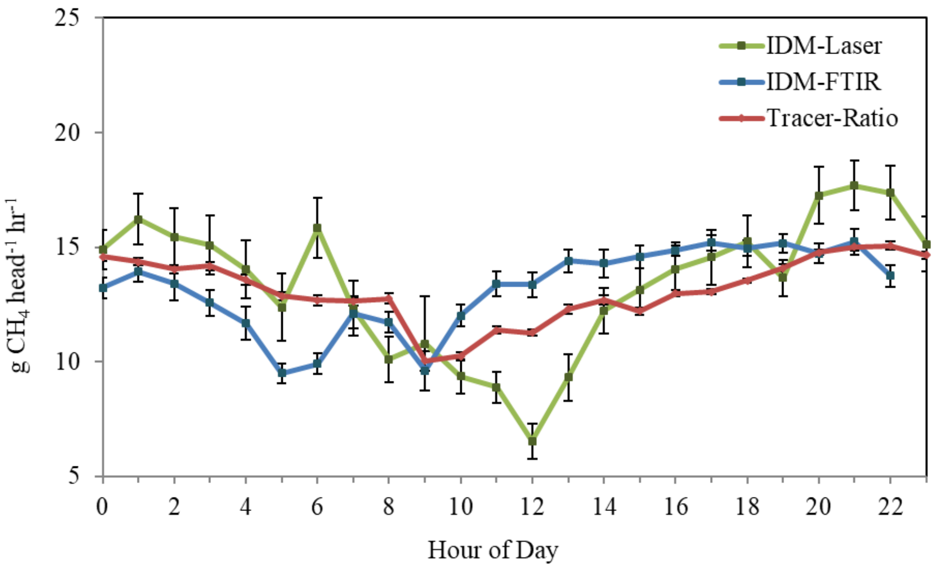

Figure 2: Ensemble 24-h diel CH_4 emission pattern measured by IDM-Laser, IDM-FTIR, and Tracer-Ratio method (hourly values based on 7-d of measurements). Error bars denote the standard error of mean.

4 Discussion

There was excellent agreement between the tracer-ratio and the IDM measurements of cattle CH_4 emissions (there were no statistical differences between the different techniques). For potential users of the IDM technique, these results are an important finding. When previously applied to cattle environments, some recent IDM studies have monitored animal positions assuming this information is critical to getting accurate calculations (e.g., McGinn et al. (2011)). Alternatively, other studies constrained animal locations by fencing to minimize the errors when animal positions were not monitored (Flesch et al., 2016). However, our IDM calculations assuming cattle were evenly distributed across the paddock were nearly identical to the tracer-ratio results that implicitly include the impact of animal positions. This indicates that IDM studies like ours can use the much simpler approach where the whole paddock is treated as a gas source, and animal positions need not be monitored. This seems to confirm a similar finding from McGinn et al. (2015). The effect of this simplification on measurement accuracy is likely to depend on animal density and the size of the paddock. For example, the measurement of a small number of animals in a large paddock is likely to be very sensitive to the exact animal positions. But in the modest sized paddock studied here (and in McGinn et al., (2015)) this is not the case.

It is interesting to compare our measured CH_4 emission rates with estimates made using the IPCC (2006) suggested relationships based on DMI. Using the IPCC recommendations that CH_4 emissions represent 6.5 % of the gross energy intake of the cattle (Y_m) and with our DMI = 11.9 kg d^{-1}, we calculate (Eq. 10.21) an emission rate of 254 g CH_4 $head^{-1}$ d^{-1}. Using the equation from Charmley et al. (2016) and with the yield of 20.7 g CH_4 kg^{-1} DMI, the estimated CH_4 emissions rate is 246 g CH_4 $head^{-1}$ d^{-1}. The DMI based CH_4 estimates were lower than the tracer-ratio measurement of 321 g CH_4 $head^{-1}$ d^{-1}. What might explain this difference?

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- Weather conditions during our study were nearly ideal for the micrometeorological calculations, resulting in a large and representative set of emission calculations over the study, and a good estimate of the 24-h ensemble daily emission rate. A time-of-day sampling bias in the tracer-ratio measurements is unlikely to cause the difference.
- Differences between the tracer-ratio and IPCC estimated rates would occur if there were significant manure or rectal emissions that are measured by the micrometeorological techniques, but not reflected in the IPCC estimates. However, the general view is that these emissions are small in comparison to enteric emissions (Flessa et al., 1996; Kebreab et al., 2006; McGinn et al., 2019). In addition, when animals were absent from the pen, we did not observe enhanced CH_4 levels downwind of the pen, indicating low emission rates from the pen manure.
- Based on the tracer-ratio measurements, the Y_m in this study is higher than the IPCC suggested value: our measured Y_m of 8.3 % is outside the 6.5 ± 1 % range suggested by IPCC (2006). But the IPCC suggestion is a rough estimate, and several grazing studies have found Y_m values higher than our 8.3 % (e.g., Tompkins and Charmley (2015); McGinn et al. (2011); Ominski et al. (2006)).

5 Conclusions

We are very confident in the tracer-ratio measurements given the conceptual simplicity of the approach (where each animal is a tracer gas source), given that the OP-FTIR is a very sensitive gas sensor, and given the agreement between the associated IDM measurements. We thus view the relatively high emission rates we observed to be representative of the conditions of the study.

The (external) tracer ratio technique is a "gold standard" for measuring cattle emissions in an ambient outdoor environment. However, this technique is difficult to use given the need to outfit the animals with tracer sources, and to monitor tracer gas concentrations downwind. Encouragingly, our results indicate that a logistically simple IDM technique can provide an accurate tool for measuring emissions from cattle, with far greater practicality than the tracer-ratio technique. It is worth noting that micrometeorological methods like IDM represent one of the major approaches for measuring cattle emissions (in addition to internal SF_6 tracer technique and respiration chambers). Our results should give users added confidence that a practical micrometeorological technique can provide an accurate method of estimating emissions.

6 Data availability

The raw data are not available to the public. For any inquiry about the data, please contact the corresponding author (mei.bai@unimelb.edu.au).

7 Author contributions

All authors contributed to the conceptualization, methodology, and draft writing-original draft preparation. TC, TF, FP, MB, and NT contributed to writing-reviewing and editing. TF, TC, FP, and MB contributed to formal analysis. DC, RH, NT, JH, DM contributed to funding acquisition and investigation.

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9 Declaration of interests

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

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