

1 Beef cattle methane emissions measured with tracer-ratio and 2 inverse dispersion modelling techniques

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14 **Abstract.** The development and validation of management practices to mitigate greenhouse gas (GHG) emissions
15 from livestock requires accurate emission measurements. This study assessed the accuracy of a practical inverse
16 dispersion [modelling](#) (IDM-[micrometeorological](#)) technique to quantify methane (CH₄) emitted from a small cattle
17 herd (16 animals) confined to a 63 x 60 m experimental pen. The IDM technique calculates emissions from the
18 increase in CH₄ concentration measured downwind of the animals. The measurements were conducted for 7 days.
19 Two types of open-path (OP) gas sensors were used to measure concentration in the IDM calculation: a Fourier
20 transform infrared spectrometer (IDM-FTIR) or a CH₄ [Laser](#)[laser](#) (IDM-Laser). The actual cattle emission rate
21 was measured with a tracer-ratio technique using nitrous oxide as the tracer gas. We found very good agreement
22 between the two IDM emission estimates (308.1 ± 2.1 (mean ± s.e) and 304.4 ± 8.0 g CH₄ head⁻¹ d⁻¹ for the IDM-
23 FTIR and IDM-Laser, respectively) and the tracer-ratio measurements (301.9 ± 1.5 g CH₄ head⁻¹ d⁻¹). This study
24 [shows](#)[suggests](#) that a practical IDM measurement approach can provide an accurate method of estimating cattle
25 emissions.

26 **Keywords:** micrometeorological techniques, GHG emissions, beef cattle, spectroscopy, open-path gas sensors

27 1 Introduction

28 Agriculture is the main source of anthropogenic methane (CH₄) emitted to the atmosphere, which includes
29 emissions from ruminants, rice agriculture, waste treatment, and biomass burning (Solomon et al., 2007). Methane
30 is an important greenhouse gas (GHG) with a global warming potential that is 28 times that of carbon dioxide
31 (CO₂) in a 100 year time [frame](#) (Myhre et al., 2013). Enteric CH₄ from livestock is a major source of GHG
32 emissions. A significant effort is being made to mitigate these emissions through diet modification, feed
33 supplements, farm management, grazing strategies, and animal breeding (Min et al., 2020; Vyas et al., 2018); with
34 ruminant nutritional management strategies seen as the most direct impact mitigation option ([Cottle et al.,
35 2011](#))[\(Cottle et al., 2011\)](#). Increasingly there is a requirement for mitigation claims to be validated when these
36 practices are applied on-farm (DoE, 2014), and simple and accurate methods for on-farm emission measurements
37 are [required](#)[needed](#).

38

39 On-farm entericCH₄ emissions from beef cattle have been measured using three main techniques. 1) Portable
40 respiration hoods for tethered and non-tethered animals (Garnsworthy et al., 2012; Zimmerman and Zimmerman,
41 2012) directly measure the gas concentration of incoming and exhaust air from individual animals. However, this
42 technique limits the animal's movements, requires intensive training for animals and labor, and it does not account
43 for emissions from the animalanimal's rectum. 2) Tracer-ratio gas releases from the animal (Johnson et al., 1994),
44 such as SF₆ (Grainger et al., 2007), assumes the tracer gas and the emitted CH₄ have similar transport paths, so
45 that a tracer measurement can establish the CH₄ emission rate. This is a simple technique, but there are challenges
46 with logistics and handling animals that are similar to the respiration hood technique. 3) Micrometeorological
47 techniques are typically considered a herd-scale measurement, where the emission rate is calculated from the
48 measurement of enhanced gas concentrations downwind of an animal herd (Harper et al., 2011), and these include
49 the mass balance technique ([Laubach et al., 2008; Lockyer and Jarvis, 1995](#))[\(Laubach et al., 2008; Lockyer and](#)
50 [Jarvis, 1995\)](#), eddy covariance (Dengel et al., 2011; Felber et al., 2015), and inverse dispersion techniques (Flesch
51 et al., 2005; Todd et al., 2014). The main advantage of micrometeorological techniques is that they do not interfere
52 with the animals or the environment.

53 The objective of this study was to examine the accuracy of a practical inverse dispersion modelling (IDM)
54 technique for measuring CH₄ emissions from beef cattle. The IDM technique offers the possibility of relatively
55 simple emission measurements, without the need for animal handling or modifying animal behavior. In this study
56 two IDM techniques are used to measure emissions from a small herd of confined cattle, and the results tested
57 against a robust tracer-ratio based measurement.

59 **2 Materials and Methods**

60 **2.1 Experimental design**

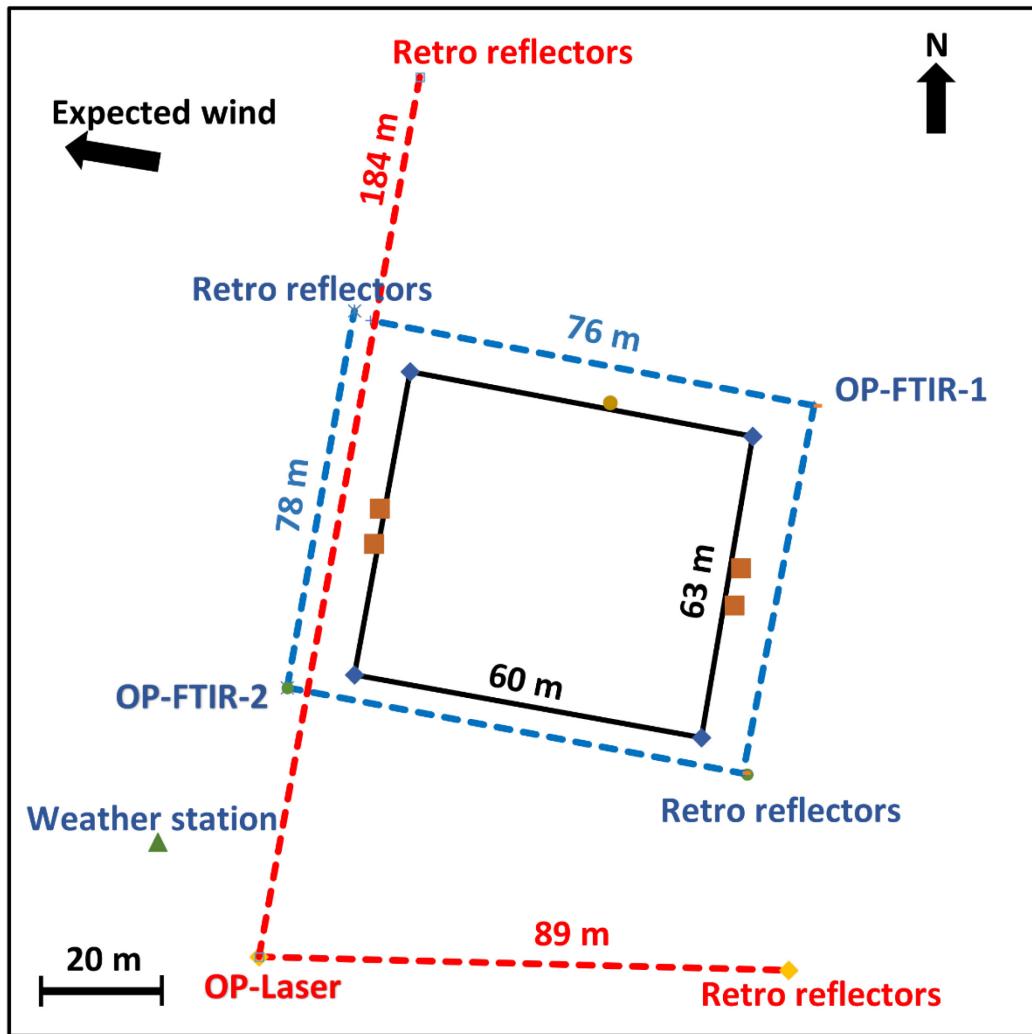
61 The study took place at the Chiswick pastoral research laboratory (30° 37' S, 151° 33' E) in Armidale, New South
62 Wales, Australia in February 2013. Methane emissions were measured from 16 Angus steers placed in a temporary
63 63 × 60 m pen (Fig. 1) located in a flat and open field. There were no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

66
67 The study cattle had an average body weight of 373 kg (standard deviation = 59 kg). The animals were fed a
68 blended oaten/lucerne chaff ration (90.2% of dry matter, 15.1% crude protein) dispensed from automated feeders
69 (Bindon, 2001) that recorded the individual animal intakes. The feedersfeedingtroughs were cleaned daily, and
70 any remaining feed was weighed to check that the total consumed amount matched the sum of the individual
71 animal intake. Feed and water were offered *ad libitum*. This feeding regime began four weeks prior to the emission
72 measurements. During the seven-day emission measurement period, the average dry matter intake (DMI) was
73 11.9 kg head⁻¹ d⁻¹. Cattle manure was not removed during the measurement period. Approximately two weeks
74 before the measurements, each animal was fitted with a backpack (glued to their back) to hold a small nitrous
75 oxide (N₂O) gas canister used for the tracer-ratio emission measurements (Jones et al., 2011).

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81 Figure 1: Schematic layout of the experimental site, showing an animal pen in the center, two OP-FTIR systems (blue
82 dashed lines) and the OP-Laser system (red dashed lines). Two feeding troughs (brown squares) were on both sides of
83 the pen, and one water trough (brown circle) was on the north of the pen. A weather station (green triangle) was 50 m
84 away from the SW corner of the animal pen.

85

86 During the emission measurement period (14 to 21 February 2013) each study animal carried a N₂O canister in a
87 backpack, and controlled rates of N₂O were released as part of the tracer-ratio measurement technique. At 9:00
88 daily during the measurement period, the 16 study animals were walked from the cattle pen to the adjacent yards
89 (80 m north), and the N₂O gas canister in the backpack was replaced with a fully filled canister. Cattle were absent
90 from the study pen for approximately 15 to 30 min while this occurred. Other than during the canister replacement
91 period, the animals moved and ate freely in the pen while emissions were measured.

92

93 2.2 Concentration sensors

94 2.2.1. OP-FTIR

Atmospheric concentrations of CH₄ and N₂O were measured upwind and downwind of the cattle pen using two open-path Fourier transform infrared (OP-FTIR) spectrometers. OP-FTIR can quantify a wide range of real-time gas concentrations simultaneously with high resolution (Smith et al., 2011). The details of the OP-FTIR system used in this study can be found in Bai (2010) and Paton-Walsh et al. (2014). Briefly, the modulated infrared (IR) beam from the Bruker IRcube spectrometer (Matrix-M IRcube, Bruker Optics, Ettlingen, Germany) is transferred through the optics to a modified Meade Schmidt-Cassegrain telescope (25.4 cm diameter, Model LX200R, Meade Instrument Corp., Irvine, California, USA) and a secondary mirror, and diverged to 250 mm parallel beam and extended to a distant retro reflector (up to 500 m from the spectrometer) (PLX Industries, Deer Park, New York, USA). The parallel beam is then reflected by the retro reflector and returned to a Mercury Cadmium Telluride (MCT) detector (Infrared Associates Inc., Stuart, Florida, USA) where temperature is controlled by a Stirling cycle mechanical refrigerator cooling system (-196 °C) (Ricor K508, Salem, New Hampshire, USA), as described further in (Bai, 2010). A Zener-diode thermometer (type LM335) and a barometer (PTB110, Vaisala, Helsinki, Finland) provide real-time ambient temperature and pressure data (at the same height of the measurement path) for the analysis of the measured spectra. The spectrometer is operated at 1 cm⁻¹ resolution, and one spectrometer scan takes approximately 4 secs (13 scans min⁻¹). For acceptable signal to noise ratios, a minimum measurement period of 1 min is required. The measured spectra are quantitatively analyzed using the MALT analysis program and a nonlinear least squares fitting procedure described in Griffith (1996), based on the reference spectra from the molecule absorption databases (HITRAN) (Rothman et al., 2009). The best fitted spectrum is used to retrieve the line-average gas concentrations of CH₄ and N₂O over the measurement path. The sensitivity of the OP-FTIR units for CH₄ and N₂O is 1 part per billion (ppb), corresponding to 2 and 0.4 ppb for a 100 m path, respectively. To achieve good spectra, parameters including instrument field-of-view (FOV), spectral signal intensity (spec. max), and the residual spectrum between the measured and modelled spectra (RMSresid) are examined. A software “Spectronous” (Ecotech, Knoxfield, Victoria Australia) automatically controls spectrometer, sample collecting, spectrum analysis, data logging and display of the calculated concentrations in real time, together with ambient pressure and temperature.

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 two reflectors so that gas concentration was measured along the four sides of the pen (Fig. 1). This configuration allowed the downwind CH₄ and N₂O enhancements to be measured for any wind direction. The OP-FTIR measurement sequence was repeated automatically so that every 5-min the line-average gas concentration on each path was measured. 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 CH₄ emissions. 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.

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132 2.2.2. OP-Laser

133 The open-path laser ([OP-Laser](#)) system used a single laser unit (GasFinder2, Boreal Laser Inc., Edmonton, AB, 134 Canada) located outside the animal pen, mounted on a pan-tilt scanning motor (PTU D300, FLIR Motion Control

135 Systems, Burlingame, CA, USA). The OP laser contains a transceiver that houses the laser diode, drive electronics,
136 detector module and micro-computer subsystems. Collimated light emitted from the transceiver traverses the open
137 measurement path to a distant retro reflector (up to 500 m) and back. A portion of the beam passes through an
138 internal reference cell. The ratio of measured external and reference signals is used to determine the gas
139 concentration from the open path. The retro reflector mounted on a tripod consists of an array of six gold-coated
140 6 cm corner cubes with effective diameters of approximately 20 cm. The scanning motor was programmed to
141 sequentially measure CH₄ concentration on two paths. The paths ran along two sides of the pen, and their location
142 was chosen to provide upwind and downwind concentrations during the prevailing easterly winds (Fig. 1). The
143 two-paths were 89 and 184 m in length, and the laser measurement path was approximately 5 m outside the fence
144 line. The laser alternated between the two paths with a dwell time of 1-min on each path. Line-average CH₄
145 concentration was recorded approximately once a second, and the path average concentrations were averaged into
146 15-min intervals. The sensitivity of the laser units is 1 part per million-meter (ppm-m), corresponding to 10 ppb
147 for a 100-m path.

148

149 2.3 Methodologies

150 A tracer-ratio technique was used to measure CH₄ emissions from the study animals. This is a conceptually simple
151 and defensible method for measuring emissions, and we will consider this technique as giving the “true” CH₄
152 emission rate from the animals. Two different implementations of the IDM technique were compared with the
153 tracer-ratio measurements.

154 2.3.1 Tracer-ratioRatio technique ([N₂O-Tracer](#))

155 The tracer-ratio measurements followed the procedure described in Bai (2010), Griffith et al. (2008), and Jones et
156 al. (2011), with N₂O used as the tracer gas and released through a canister at a controlled release rate. The N₂O
157 release point was closed to cattle mouth and nose where the majority of CH₄ was emitted. The N₂O tracer gas
158 followed the emitted CH₄ downwind of the animal pen, and both concentrations of N₂O and CH₄ were measured
159 simultaneously by an OP-FTIR (Fig. 1).

160 The N₂O tracer (> 99%, BOC Instrument grade, Australia) was released from pressurized canisters (Catalina
161 Cylinders) located in insulated backpacks on each animal. Each canister was fitted with a head encompassing
162 capillary tube (0.025 mm inner diameter, SGE Analytical Science Pty Ltd, Australia) to control the N₂O flow rate.
163 The canister was filled with approximately 300 g of N₂O to provide an average flow rate of 10 g h⁻¹ over a 24 h
164 period. The temperature of the canisters was recorded every 5 minutes (Thermochron Temperature model TCS,
165 OnSolutions, Australia). The canisters and temperature sensors were exchanged every 24 h at a nearby yard.
166 Following the procedure in Bai (2010), the canister flow rate was calibrated with a gas temperature dependent
167 factor determined from the measured canister temperature. Canisters were also weighed at the start and end of
168 each 24 h period to get the actual daily N₂O release rate.

169

170 The calculation for each pressurized canister N₂O flow rate follows three steps:

171

172 1) The N₂O flow rate of each canister was calculated following Bai (2010) (Eq.1):

173 $Q_{N2O}(t) = Q_0 + \alpha T(t)$ (1)

174 Where $Q_{N2O}(t)$ is the individual canister flow rate ($g\ h^{-1}$) at temperature T ($^{\circ}C$), t = time, T = temperature $^{\circ}C$ at
175 time (t), Q_0 is a constant canister flow rate at temperature $0^{\circ}C$, $g\ h^{-1}$, α is the N_2O flow rate temperature
176 dependent factor, $g\ h^{-1}\ ^{\circ}C^{-1}$. The temperature was measured at 5-min intervals.

177

178 2) The integrated N_2O flow rate over the total release time (RT, $\sim 24h$) equals the mass loss of N_2O gas (Δm_{N2O} ,
179 g) (Eq.2):

180 $Q_0 = (\Delta m_{N2O} / RT) - (\sum (\alpha T(t))) / RT$ (2)

181 Where $\Delta m_{N2O} = WN_{2O_{start}} - WN_{2O_{end}}$

182 The mass loss of N_2O was determined by the initial and the end weight of the canister (g), $WN_{2O_{start}}$, $WN_{2O_{end}}$,
183 respectively. The integrated N_2O flow rate of each canister was then interpolated to a 15-min interval flow rate
184 using linear interpolation function (Igor 6.3.7.2). The total N_2O flow rate of the 16 canisters (Q_{N2O}) was used for
185 the CH_4 emission rate calculation.

186

187 3) Following the procedure described in Bai (2010), Griffith et al. (2008), and Jones et al. (2011), the herd emission
188 rate of CH_4 was calculated (Eq.3):

189 $Q_{CH_4} = Q_{N2O} * (\Delta CH_4 / \Delta N_2O) * (M_{CH_4} / M_{N2O}) / N_{animal}$ (3)

190 Where Q_{CH_4} is the CH_4 emission rate, $g\ head^{-1}\ h^{-1}$, Q_{N2O} is the integrated N_2O flow rate of total canisters in the
191 animal backpacks, determined by mass loss of N_2O at canister temperature T and release time t , $g\ h^{-1}$, is multiplied
192 by 24 to calculated $g\ head^{-1}\ d^{-1}$. The ΔCH_4 and ΔN_2O parameters are the CH_4 and N_2O concentration enhancements
193 (above the local background level) measured downwind of the animal pen using the OP-FTIR spectrometers,
194 M_{CH_4} is the molecular mass of CH_4 , $16\ g\ mol^{-1}$, M_{N2O} is the molecular mass of N_2O , $44\ g\ mol^{-1}$, N_{animal} is [animal](#) the
195 number [of animals](#), 16.

196

197 During the study we collected a number of air samples using volumetric flasks (600 mL). Samples were spaced
198 along each measurement path and taken when animals were absent from the pen. These samples were later
199 analyzed in the laboratory using a closed-path FTIR spectrometer (Griffith, 1996) and the CH_4 and N_2O values
200 were used to cross-calibrate the two OP-FTIR sensors.

201

202 Tracer-ratio emission measurements were excluded for periods when the canisters outlets were blocked-[off](#), had
203 dropped off the animals, when there was optical misalignment of the OP-FTIRs, or when the enhanced CH_4 and
204 N_2O concentration was less than 50 and 10 ppb, respectively.

205 2.3.2 Inverse Dispersion Modelling technique

206 Herd CH_4 emissions were calculated using the IDM technique (Flesch et al., 2004). This micrometeorological
207 technique estimates emissions based on the enhancement of CH_4 measured downwind of the animal pen. The link
208 between the concentration enhancement and the pen emission rate is calculated using an atmospheric dispersion
209 model. The freely available software WindTrax (www.thunderbeachscientific.com) is used for that calculation.
210 WindTrax combines a backward Lagrangian stochastic dispersion model with mapping software and takes as
211 input: the upwind and downwind CH_4 concentration measurements, wind information from a sonic anemometer,

212 and a map of the pen and gas sensor locations. General information on WindTrax applications is given in Flesch
213 and Wilson (2005).

214
215 The upwind and downwind CH₄ concentration was measured using either the OP-FTIR system previously
216 described (designated IDM-FTIR) or by an open-path CH₄ laser system (designated IDM-Laser).

217 Air samples collected during the study were used to cross-calibrate the laser and the OP-FTIR sensors (applying
218 a retroactive correction multiplier to the laser concentrations). Air samples were collected at 2-min intervals to
219 get 15-min average concentrations for the period from 9:15 to 9:30 when the cattle were not in the paddock. The
220 samples were analyzed using a by gas chromatographchromatography (Agilent 7890) at the University of
221 Melbourne laboratory. Three positions were sampled: 1) directly west of the paddock along the laser/FTIR line,
222 2) near the laser, southwest of the paddock, and 3) far south of the paddock along the southerly laser line. Winds
223 were from light and from the east. We assumed the CH₄ and N₂O concentrations at these positions would be
224 similar (as cattle were absent) and would provide the basis for calibration of the lasers and FTIRs.

225
226 A weather station southwest of the cattle pen (Fig. 1) included a 3-dimensional sonic anemometer (CSAT-3,
227 Campbell Scientific Inc, Logan Utah, USA) mounted 2.45 m above the ground. The anemometer provided the
228 wind information needed for the IDM calculation, including the friction velocity (u_*), Obukhov stability length
229 (L), average windspeed and wind direction, and the standard deviation of the velocity fluctuations in the three
230 directional components ($\sigma_{u,v,w}$). The surface roughness length (z_0) was calculated from these variables (Garratt,
231 1992). The wind variables were averaged into 15-min intervals matched to the gas concentration dataset.

232 233 2.3.3 Data filtering criteria

234 The CH₄ emissions were calculated in 15-min intervals using the WindTrax software. We defined the CH₄ as
235 coming from an elevated area source 0.8 m above ground, which overlaid the pen area. In the IDM analysis we
236 followed the procedure of Flesch et al. (2005) to remove error-prone intervals when either $u_* < 0.15 \text{ m s}^{-1}$, $|L| < 5$
237 m, $z_0 < 0.9 \text{ m}$, or when the fraction of WindTrax trajectory touchdowns inside the pen source covered < 10% of
238 the pen area. Intervals were also removed when the concentrations measured by the OP-FTIR or the laser
239 corresponded to low signal levels: i.e., FOV < 35, RMSresid < 0.2%, spec.max was < 0.25 in the spectral region
240 of 2200 cm⁻¹ for the OP-FTIR, or the light level reported by the laser fell outside the 2000 to 13000 range, or the
241 laser quality parameter R² < 0.97.

242 2.3.4 Calculating Average Emissions

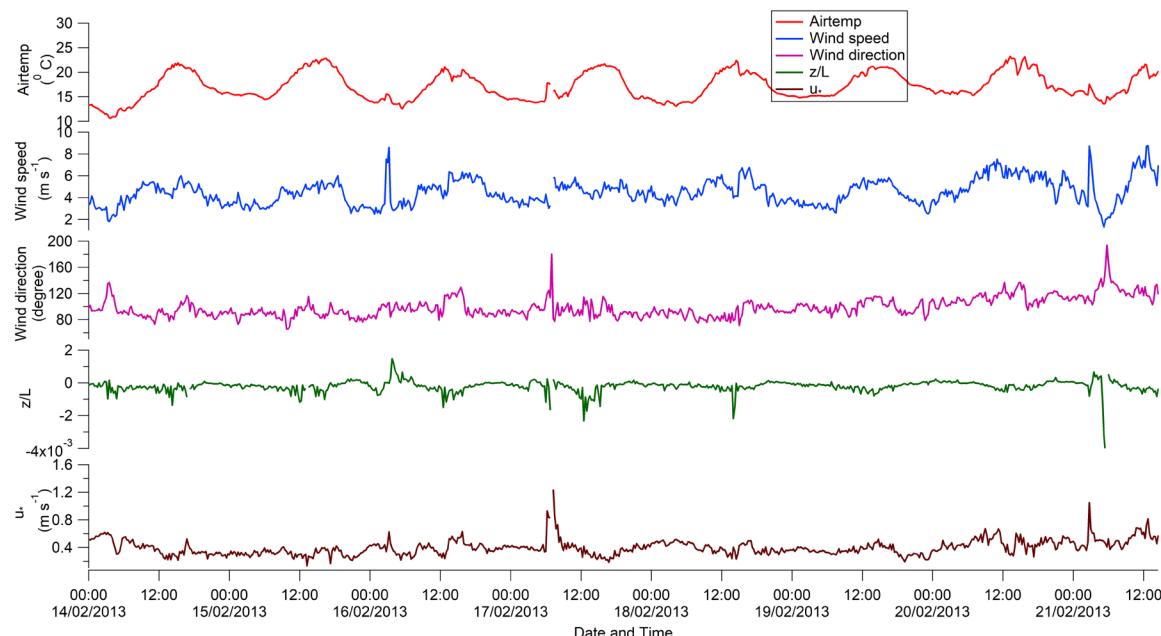
243 The tracer-ratio and IDM measurements are a discontinuous time series of 15-min average emission rates lasting
244 for seven days. In order to create a properly weighted daily average emission rate, these discontinuous data were
245 used to create an ensemble 24-h diel emission “curve” for each technique. Each emission observation was binned
246 into one of the 96 15-min periods making up the ensemble day. We used Generalized Additive Models (GAM)
247 fitted to the time series of gas emission to impute missing measurements (Bai et al., 2020). The time series of gas
248 emission and associated GAM fit for each measurement method are shown in Appendices (Fig. A1). The average
249 daily emission rate was calculated by summing the 15-min emission intervals over the 24 h day.

251 Following IPCC (2006) ~~recommendations~~, CH₄ ~~emission using emissions~~ were also calculated
252 based on DMI (Eq. 10.21). This assumes CH₄ energy content = 55.65 MJ (kg CH₄)⁻¹, DMI energy content = 18.45
253 MJ (kg DMI)⁻¹, and CH₄ conversion factor Y_m = 6.5%.

254 **3 Results**

255 **3.1 Climate condition**

256 During the seven-day emission measurement period the total rainfall was 0.4 mm, the average minimum and
257 maximum ambient temperature was 12.9 and 22.4 °C, respectively. The wind speeds (at 2.45 m above ground)
258 varied from 2 to 8 m s⁻¹, and the wind direction was predominately from the east (Fig. 2). This period had excellent
259 conditions for the micrometeorological measurements due to the lack of precipitation, the absence of light wind
260 periods, and the steady easterly winds.



261
262 **Figure 2** Ambient temperature (Airtemp), wind speed, wind direction ~~was~~ measured during the study. Atmospheric
263 stability parameter (z/L) and wind friction velocity (u*) are also plotted.

264

265 **3.2 Methane emission measurements**

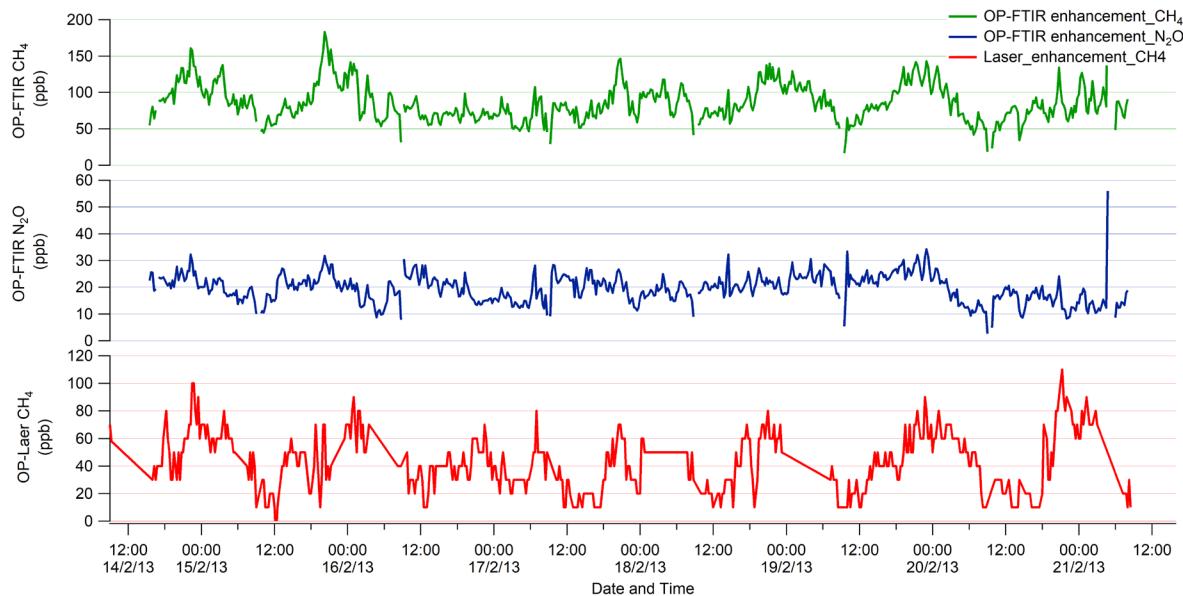
266 **3.2.1 Tracer-ratioRatio measurements**

267 The OP-FTIR system measured downwind CH₄ enhancements between 50 and 150 ppb, and N₂O enhancements
268 between 12 and 30 ppb over the study (Fig. 3). These enhancements are well above the minimum sensitivity of
269 the OP-FTIR given by Bai (2010) of 2 ppb for CH₄ and < 0.4 ppb for N₂O. Over the seven study days, emissions
270 were measured during 90% of the ensemble 24 h day (i.e., 86 of the 96 possible 15-min periods). The average
271 daily emission rate (\pm standard error) from the tracer-ratio technique was 301.9 (\pm 1.5) g CH₄ head⁻¹ d⁻¹ (Table 1).

272

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275

276 **Figure 3. The concentration enhancement of N_2O and CH_4 from OP-FTIR and CH_4 from OP-Laser over the**
 277 **measurement period of 14–21 February 2013.**

278

279

280

281 **Table 1. Methane emission rates from the three micrometeorological measurements (Tracer-Ratio, IDM-FTIR, IDM-**
 282 **Laser) and an emission estimate based on the dry matter intake of the animals (using an IPCC recommended**
calculation[§]). Methane yield ($\text{g CH}_4 \text{ kg}^{-1}$ DMI) is also shown.

	Emission Rate	Methane Yield
	($\text{g CH}_4 \text{ head}^{-1} \text{ d}^{-1}$)	($\text{g CH}_4 \text{ kg}^{-1}$ DMI)
Tracer-Ratio	301.9 (1.5)	27.0
IDM-FTIR	308.1 (2.1)	27.0
IDM-Laser	304.4 (8.0)	27.1
IPCC [§]	254 [§]	21.3

[§]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%.

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3.2.2 The inverse-dispersion-modelling (IDM) emissions3.2.2 Inverse Dispersion Modelling measurements

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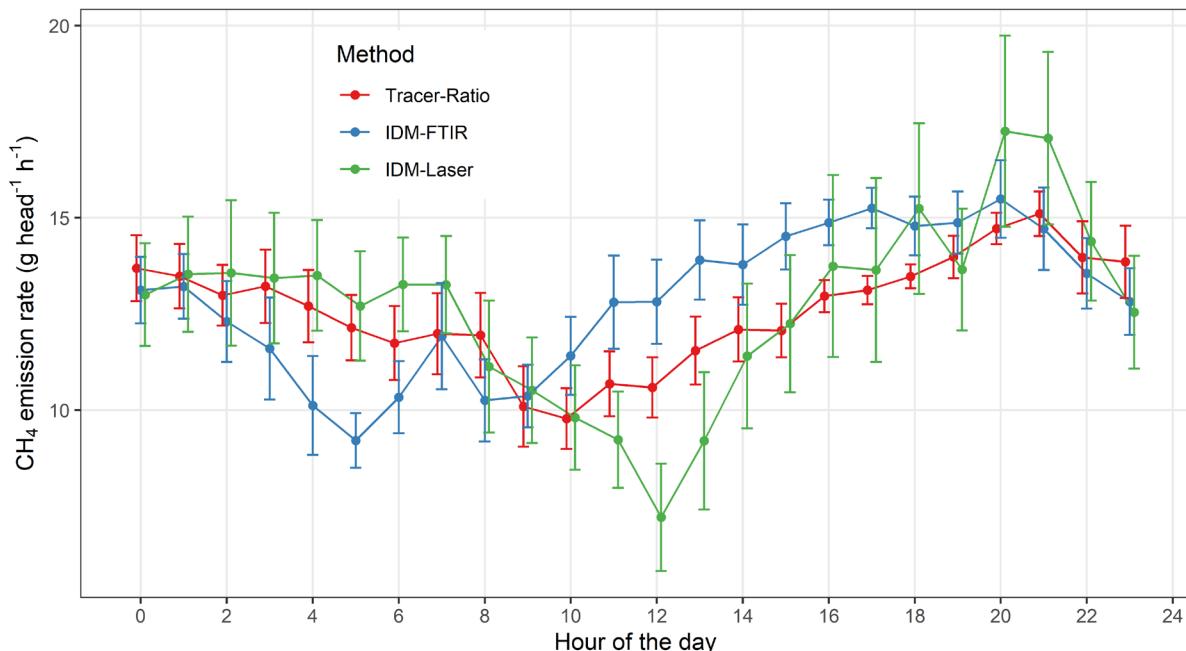
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293

Over the seven-day study, 90% of the ensemble 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, $u_* < 0.15 \text{ m s}^{-1}$). The 24-h diel CH_4 flux over the measurement period is shown in Figure 4. There are differences between the three ensemble emission relationships in Figure 4. We assume the tracer-FTIR data is most accurate data set. Differences between the tracer and IDM approaches are 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 of the IDM-FTIR and tracer-ratio measurements show a similar emission pattern: emission rates at a minimum around 9:00 local time, and at a maximum during the early evening. This

294 emission peak pattern reflected the time when animals were fed, or the pellets were topped up. However, IDM-
295 Laser shows a late minimum emission at 12:00 local time, likely due to a solar related alignment of the retro
296 reflector. We calculated average daily emission rates of $308.1 (\pm 2.1)$ and $304.4 (\pm 8.0)$ g CH₄ head⁻¹ d⁻¹ for the
297 IDM-FTIR and IDM-Laser measurements, respectively (Table 1). These results are not statistically different from
298 each other. Both IDM estimates were not statistical different from the tracer-ratio results.

299



300
301 **Figure 4: Ensemble 24-h diel CH₄ emission pattern measured by IDM-Laser, IDM-FTIR, and Tracer-Ratio method**
302 **(hourly values based on 7-d of measurements). Error bars denote the standard error of mean.**

303

304 **4 Discussion**

305 There was excellent agreement between the tracer-ratio and the IDM measurements of cattle CH₄ emissions (there
306 were no statistical differences between the different techniques). For potential users of the IDM technique, these
307 results are an important finding. When previously applied to cattle environments, some recent IDM studies have
308 monitored animal positions assuming this information is critical to getting accurate calculations (e.g., McGinn et
309 al., (2011)). Alternatively, other studies constrained animal locations by fencing to minimize the errors when
310 animal positions were not monitored (Flesch et al., 2016). However, our IDM calculations assuming cattle were
311 evenly distributed across the paddock were nearly identical to the tracer-ratio results that implicitly include the
312 impact of animal positions. This indicates that IDM studies like ours can use the much simpler approach where
313 the whole paddock is treated as a gas source, and animal positions need not be monitored. This seems to confirm
314 a similar finding from McGinn et al. (2015). The effect of this simplification on measurement accuracy is likely
315 to depend on animal density and the size of the paddock. For example, the measurement of a small number of
316 animals in a large paddock is likely to be very sensitive to the exact animal positions. But in the modest sized
317 paddock studied here (and in McGinn et al., (2015)) this is not the case.

318

319 It is interesting to compare our measured CH₄ emission rates with estimates made using the IPCC (2006) suggested
320 relationships based on DMI. Using the IPCC recommendations that CH₄ emissions represent 6.5 % of the gross
321 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
322 g CH₄ head⁻¹ d⁻¹. Using the equation from Charmley et al. (2016) ~~and~~ with the yield of 20.7 g CH₄ kg⁻¹ DMI, the
323 estimated CH₄ ~~emission~~emission rate is 246 g CH₄ head⁻¹ d⁻¹. The DMI based CH₄ estimates were lower than the
324 tracer-ratio measurement of 321 g CH₄ head⁻¹ d⁻¹. What might explain this difference?

- 325 • Weather conditions during our study were nearly ideal for the micrometeorological calculations,
326 resulting in a large and representative set of emission calculations over the study, and a good estimate of
327 the 24-h ensemble daily emission rate. A time-of-day sampling bias in the tracer-ratio measurements is
328 unlikely to cause the difference.
- 329 • Differences between the tracer-ratio and IPCC estimated rates would occur if there were significant
330 manure or rectal emissions that are measured by the micrometeorological techniques, but not reflected
331 in the IPCC estimates. However, the general view is that these emissions are small in comparison to
332 enteric emissions (Flessa et al., 1996; Kebreab et al., 2006; McGinn et al., 2019). In addition, when
333 animals were absent from the pen, we did not observe enhanced CH₄ levels downwind of the pen,
334 indicating low emission rates from the pen manure. There were no manure stockpiles nearby during the
335 study. This suggests that IPCC estimates may have larger uncertainties.
- 336 • Based on the tracer-ratio measurements, the CH₄ conversion factor Y_m in this study is higher than the
337 IPCC suggested value, that is: our measured Y_m of 8.3 % is outside the 6.5 ± 1 % range suggested by
338 IPCC (2006). However, the IPCC suggestion is a rough estimate, and several grazing studies have found
339 Y_m values higher than our 8.3 % (e.g., Tompkins and Charmley (2015); McGinn et al. (2011); Ominski
340 et al. (2006)).

341 5 Conclusions

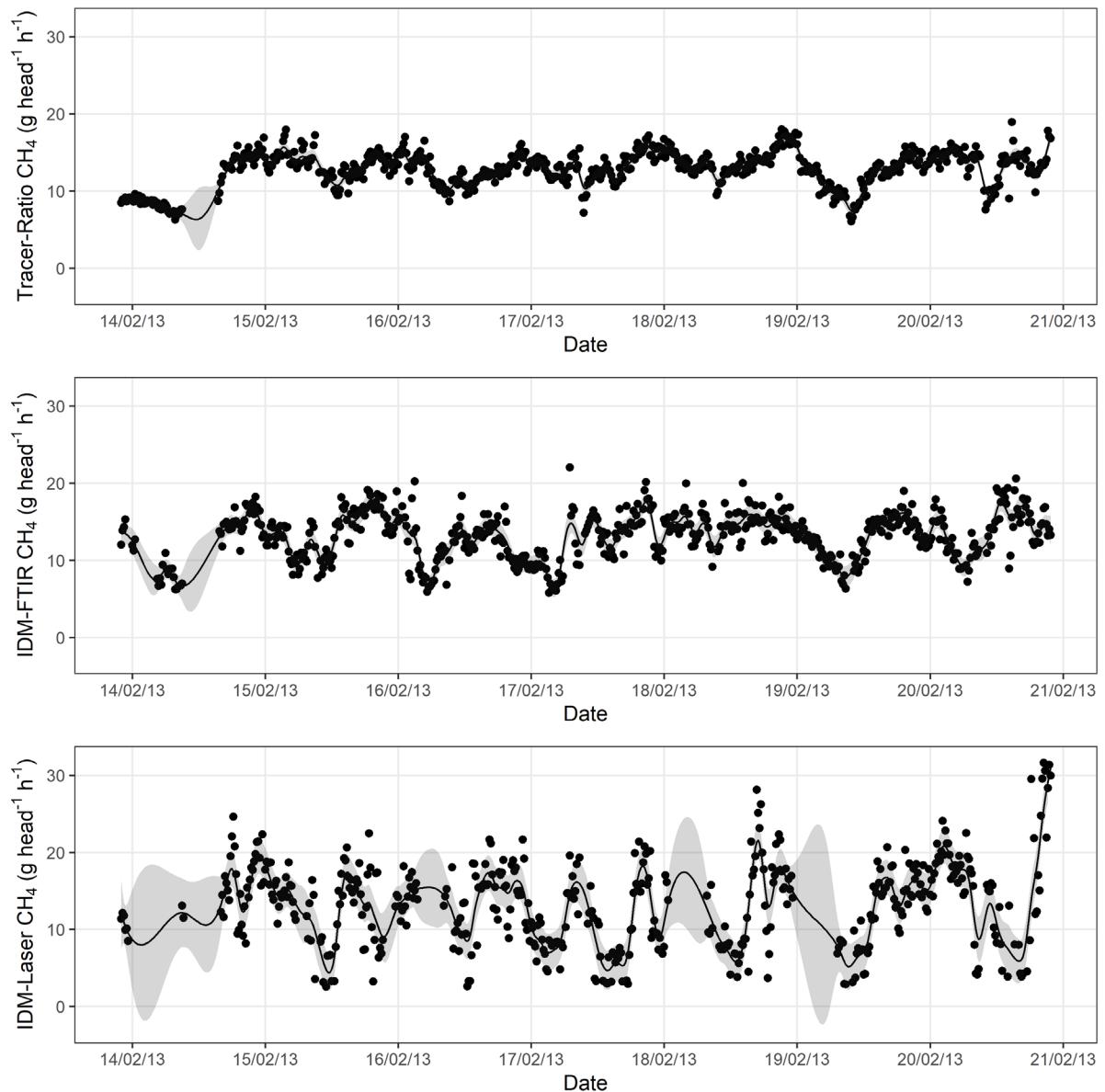
342 We are very confident in the tracer-ratio measurements given the conceptual simplicity of the approach (where
343 each animal is a tracer gas source), given that the OP-FTIR is a very sensitive gas sensor, and given the agreement
344 between the associated IDM measurements. We thus view the relatively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

346

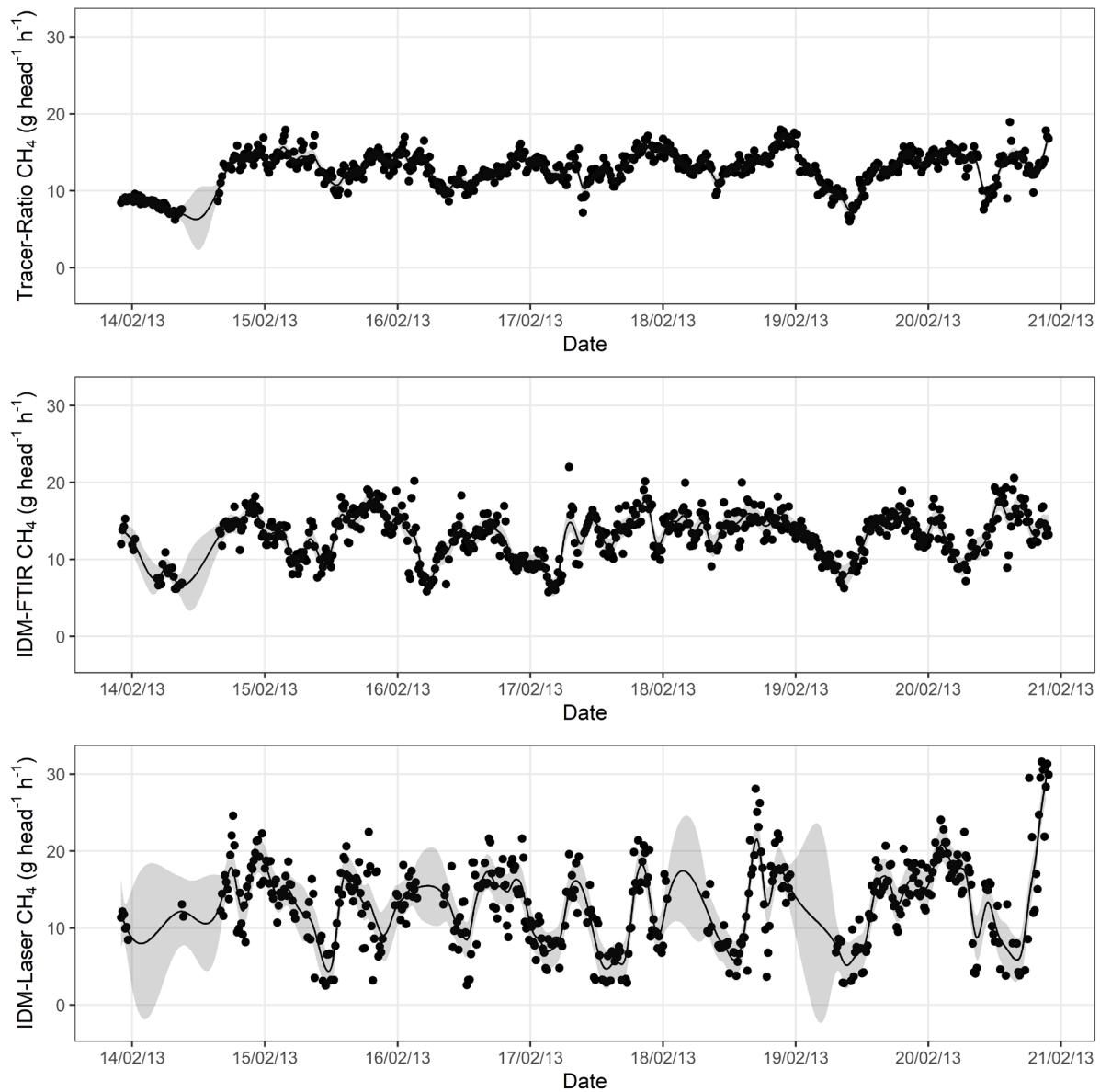
347 The (external) tracer ratio technique is a “gold standard” for measuring cattle emissions in an ambient outdoor
348 environment. However, this technique is difficult to use given the need to outfit the animals with tracer sources,
349 and to monitor tracer gas concentrations downwind. Encouragingly, our results indicate that a logically simple
350 IDM technique can provide an accurate tool for measuring emissions from cattle, with far greater practicality than
351 the tracer-ratio technique. It is worth noting that micrometeorological methods like IDM represent one of the
352 major approaches for measuring cattle emissions (in addition to internal SF₆ tracer technique and respiration
353 chambers). Our results should give users added confidence that a practical micrometeorological technique can
354 provide an accurate method of estimating CH₄ emissions at farm scales.

355 6 Appendices

356 Appendix A



358



359
 360 **Figure A1:** Time series of CH_4 emissions measured using the Tracer-Ratio, IDM-FTIR, and IDM-Laser methods. Black
 361 dots show the 15 minutes measurements. The solid black line shows the mean value of gas emission estimated from a
 362 GAM fit to the measurement data. The shaded area represents the 95% credible intervals of the mean gas emission
 363 from the GAM fit (i.e., it contains 95% of the potential mean values of gas emission at a given time).
 364

365 **7 Data availability**

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

368 **8 Author contributions**

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

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378 **10 Declaration of interests**

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

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