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Prepared by: Dr Frances Phillips
University of Wollongong

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Executive summary

Methane is a powerful greenhouse gas, with over 60% of Australia's methane emissions come from agricultural sources. Ruminant livestock are the single biggest contributors to methane emissions in Australia today. Methane is also a highly concentrated form of energy and a loss of methane represents lost production. Current knowledge shows that methane production from cattle can be influenced by feed intake, feed source, feed processing, addition of rumen modifiers or general changes in rumen micro flora and genetics (Johnson and Johnson, 1995; Hegarty *et al*, 2007). Pasture quality and type have been clearly demonstrated to influence the level CH_4 emissions from grazing ruminants.

To refine the emissions estimates from livestock, assess the impact of emission mitigation strategies and verify practice change as a carbon Farming Initiative (CFI) requires CH_4 emission measurement techniques suitable for use with a range of animal production systems, and with the precision to measure the anticipated changes in CH_4 emissions. However options to determine methane emissions from grazing ruminants are limited. The Open-path FTIR plus tracer gas technique is a novel technique to estimate emissions of methane from ruminants in their normal, undisturbed free-grazing environment. The technique releases a tracer-gas at a known, controlled rate close to the mouth of the animal with both the tracer-gas and the emitted CH_4 measured simultaneously by OP-FTIR spectroscopy downwind from the gas source. The technique has been demonstrated to have increased precision in estimating emissions compared with other micrometeorological techniques (Bai *et. al.* 2009) and is of particular interest for measuring CO_2 and CH_4 emissions from smaller groups of grazing animals where the emissions from the source area are not uniform. The technique is less intrusive for the animals and provides a herd averaged emissions and, with a (typically) 3-minute temporal resolution, provides information on the distribution of emission over the day highlighting changes in emissions with animal behaviour.

This project aimed to demonstrate the operation, advantages and limitations of open-path FTIR spectroscopy to measure CH_4 emissions from livestock in a grazing environment with the objective of developing the capability within the research community in measuring greenhouse gas emissions using the technology. As livestock production systems in Australia are highly varied, this project measured methane emissions from four production systems: dairy cows in high rainfall region in Victoria, beef steers in north Queensland, representing the northern Australian rangelands; sheep grazing pasture of differing quality on the Tablelands of NSW; and sheep grazing two pasture systems in the sheep-wheat region of WA. By working with the staff from the University of Wollongong staff at each research institute gained an understanding of the advantages and limitations of the technique and the requirements to obtain quality emissions data and allowed researchers to assess if the technique can be of an advantage within their research programs.

In association with measuring emissions from the livestock systems, the University of Wollongong staff demonstrated the open path FTIR technology at four Field days. The demonstrations generated considerable interest with primary producers, giving producers an understanding of the technologies available to help them manage emissions from their production system.

The OP-FTIR tracer gas technique has been shown to have a precision of 5-10% under favourable conditions, and can provide an emission estimate each 3 minutes over 24 hours. This highlights the relationship between CH_4 production and animal behaviour. Emission measurements from sheep showed emissions were typically highest in the mid-morning decreasing in the afternoon, with a second but lower maximum in the early evening, and with lowest production at night, correlating with animal grazing patterns. In contrast emissions from the dairy cows increased dramatically from around 300 g CH_4 animal^{-1}day^{-1} before leaving the paddock, to 600 g CH_4 animal^{-1}day^{-1} on returning from the dairy where they received supplementary feed. Emissions from sheep on the New England Tablelands increased dramatically when introduced to the pasture after being constrained at the yards with limited available feed, with emissions reducing to normal levels over the following 12 hours. Emissions from steers in northern Queensland were greatest when leaving the pasture to access water, decreasing from ~ 200 down to ~ 150 g CH_4 animal^{-1}day^{-1} over the following 5 hours.

The project has provided baseline data for CH_4 emissions from the four animal production systems across Australia. Comparison of emissions from sheep for the systems studied showed that emissions per animal were greatest for sheep grazing pasture typical of the region in WA (29.7±0.6 g CH_4 animal^{-1}day$^{-1)}$, while sheep grazing the high quality pasture on high fertility soils on the New England Tablelands showed the lowest emissions (15.5±1.0 g CH_4 animal^{-1}day^{-1}), and emissions from sheep in the other systems were comparable (19.5±1.0 to 21.1±0.6 g CH_4 animal^{-1}day^{-1}). However until this data is compared with measures of production, animal live weight gain or feed intake, the difference in emission intensity cannot be confirmed.

The use of a tracer gas relies on placing a gas canister on or near an animal, which is not always feasible. An alternate method of retrieving an emission estimate from the measured methane concentration is to model the dispersion of the gas plume using a backward Lagrangian stochastic model, commonly in the software program WindTrax. However with WindTrax the error for individual emission estimates is reported to be up to 40%, limiting the usefulness of the technique. A comparison of the retrieved emission estimates for both the emitted CH_4 and the tracer gas in this work has shown that it is possible to constrain the WindTrax bLs model using the controlled release of a tracer-gas in the area of the animals, offering a technique to measure emissions from remote animals with greater precision.

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Abstract

Not only is methane is a powerful greenhouse gas, it is also a highly concentrated form of energy and loss of methane from the rumen represents lost production, and the reduction in methane emissions is of increasing importance in animal production systems. Livestock production systems in Australia are highly varied and any strategies to reduce methane emissions will be targeted to particular systems. To refine the emissions estimates from livestock and assess the impact of emission mitigation strategies requires techniques to measure CH_4 emissions from ruminants in a range of production systems and with the precision to detect the anticipated changes in emissions. This project demonstrated the use of open path FTIR spectroscopy to measure methane emissions from a range of animals systems and has developed within the research community the capability and infrastructure for measuring greenhouse gas emissions using the technique. The project has ensured primary producers are equipped with the knowledge, tools and strategies to manage emissions from their production systems. In addition the project has provided baseline data for CH_4 emissions from a range of production systems including dairy, beef and sheep industries throughout Australia, while developing the protocols for measuring emissions from those systems.

1. Introduction

Methane is a powerful greenhouse gas, and over 60% of Australia's methane emissions come from agricultural sources. Ruminant livestock are the single biggest contributors to methane emissions in Australia today. Large quantities of methane are produced during fermentation in the rumen and released by burping or breathing. Methane is a highly concentrated form of energy and a loss of methane represents lost production. Current knowledge shows that methane production from cattle can be influenced by feed intake, feed source, feed processing, addition of rumen modifiers or general changes in rumen micro flora and genetics (Johnson and Johnson, 1995; Hegarty *et al*, 2007). Pasture quality and type have been clearly demonstrated to influence the level CH_4 emissions from grazing ruminants. Increasing pasture digestibility, decreasing fibre or utilising feed species that are high in compounds such as tannins or oils are a few of the examples that have been shown to decrease CH_4 production in the rumen. Management options, including the feeding of supplements, herd management or the use of irrigation to improve pasture quality are also available to reduce CH_4 emissions (Eckard *et al*, 2010).Energy lost as methane and total nitrogen (N) are two of the most significant inefficiencies in ruminant production systems (Eckard *et al*, 2010). In an increasingly carbon constrained economy, agriculture will be required to demonstrate a reduction in emissions and quantifying the amount of methane lost by cattle is thus important to implementing sustainable farming practices.

To refine the emissions estimates from livestock, assess the impact of emission mitigation strategies and verify practice change as a carbon Farming Initiative (CFI) requires CH_4 emission measurement techniques suitable for use with a range of animal production systems, and with the precision to measure the anticipated changes in CH_4 emissions . However options to determine methane emissions from grazing ruminants are limited. Chamber measurements typically place 1 to 2 animals in a box type structure to measure CH_4 emissions (Blaxter and Clapperton, 1965; Moe and Tyrrell, 1979). The technique provides very detailed information on emissions from a limited number of animals over a limited time and in a non-natural environment. The sulphur hexafluoride (SF_6) tracer technique places a permeation tube in the rumen of the animal where it emits SF_6 at a known rate with the animals breath encompassing both the CH_4 and SF_6 being sampled into evacuated canisters on a collar mounted on the animal (Johnson et al., 1994; Lassey et al., 1997). In the standard configuration, the estimate only includes emissions from the mouth/nostrils. The technique returns a time averaged CH_4 emission rate for individual animals. The technique is readily used with free-grazing animals with the canister apparatus having minimum impact on animal behaviour.

Several micrometeorological techniques have been used to measure herd averaged emissions from grazing animals, including mass balance, eddy covariance and backward Lagrangian stochastic (bLs) methods (Denmead, 2004; Flesh et al., 2004, 2005; Laubach, 2010; Laubach and Kelliher, 2004; 2005, 2005a). However the uncertainties and limitations of the micrometeorological techniques can limit the application of the technique in distinguishing the effectiveness of mitigation strategies.

Open-path FTIR and open-path lasers have also been used to determine CH_4 emissions strengths from livestock. The measured concentrations are combined with wind statistical data to calculate emission strengths from an unknown source using a backward

Lagrangian stochastic (bLs) model implemented in WindTrax software (Thunder Beach Scientific, University of Alberta, Edmonton, Alberta, Canada). The assumptions in the Lagrangian stochastic model include that the source of the gas is uniformly distributed over an area, the gas is emitted from ground level, and the wind turbulence has not been disturbed by obstacles such as tree lines, hedge rows, fences and structures, which can limit the application of the model in animal systems. However the method has been successfully employed to determine emissions from dairy cows (Laubach and Kelliher, 2004, 2005, 2005a), small groups of corralled beef steers (Bai *et al* 2008), and feedlots (Loh et al., 2008), where animal density is high and evenly distributed over an area.

The Open-path FTIR plus tracer gas technique is a novel technique to estimate emissions of methane from ruminants in their normal, undisturbed free-grazing environment and has been demonstrated to have increased precision in estimating those emissions compared with other micrometeorological techniques (Bai *et. al.* 2009). The technique is of particular interest for measuring CO_2 and CH_4 emissions from smaller groups of grazing animals where the emissions from the source area are not uniform. The tracer is released at a known, controlled rate close to the mouth of the animal, with both the tracer and the CH_4 measured simultaneously by OP-FTIR spectroscopy downwind from the gas source. Generally N_2O is used as the tracer gas as it is safe and non-toxic, can be readily released in sufficient quantities for enhancements above background to dominate natural fluctuations, and can be measured simultaneously with CH_4 and CO_2 by FTIR spectroscopy. The technique is less intrusive for the animals and provides a herd averaged emissions and with a (typically) 3-minute temporal resolution provides information on the distribution of emission highlighting changes in emissions with animal behaviour. Similar to bLs techniques, the technique relies on wind to transport the animal produced methane and tracer gas to the open path instruments, and is subject to loss of data under non favourable wind conditions. This can lead to discrimination to daytime data. However with the tracer-OPFTIR technique minimum wind criteria can be less restrictive.

This project aimed to demonstrate the operation, advantages and limitations of open-path FTIR spectroscopy to measure CH_4 emissions from livestock in a grazing environment. Livestock production systems in Australia are highly varied, and to achieve this methane emissions were measured from four production systems: dairy cows in high rainfall region in Victoria, beef steers in north Queensland, representing the northern Australian rangelands; sheep grazing pasture of differing quality on the Tablelands of NSW; and in the sheep-wheat region of WA, sheep grazing pasture typical for the region compared with pasture anticipated to reduce CH_4 production in the rumen. The project objective was to develop the capability within the research community in the measurement of greenhouse gas emissions using open-path spectroscopy, and ensure primary producers are equipped with the knowledge, tools and strategies to manage emissions from their production system by demonstrating to producers the technology available to measure GHG emissions from their systems. As part of this, the project has provided baseline data for CH_4 emissions from a range of production systems while developing and testing the protocols for measuring emissions from those systems.

2. Instrumentation

2.1 OP-FTIR Spectrometer

The OP-FTIR instrument consists of an FTIR spectrometer, (Matrix IR-Cube, Bruker Optik GmbH, Ettlingen, Germany) equipped with a mechanically cooled (-196°C, RicorK508) MCT detector (Infrared Associates Inc., Florida, USA, or Judson Industries, Montgomeryville, PA, USA) coupled to a 250 mm Schmidt-Cassegrain telescope (LX 200ACF, Meade Instruments Corporation, Irvine California, USA). The telescope has been modified to function as a parallel beam expander, expanding the beam from 25 to 250 mm diameter and reducing beam divergence by a factor of ten to 2 mradians. The system is mounted onto a heavy duty tripod (Gibralter model 4-60450-OA, Quickset International Inc., Illinois, USA) with, currently, a manually adjustable head (model 4-62926-7) to allow alignment of the beam between spectrometer and retro-reflector. The spectrometer scans continuously and, in typical operation, records a time-averaged (nominally every 3-minutes) infrared absorption spectrum of the open atmospheric path between spectrometer and retro-reflector located 100 to 130m from the instrument. Each spectrum is analysed immediately after collection using the MALT analysis program to provide path-averaged concentrations of NH_3, N_2O, CO_2, CH_4, CO and water vapour (Griffith, 1996). Operation of the system is fully automated under the control of a laptop computer running a program written at the University of Wollongong (OSCAR, G. Kettlewell).

2.2 Tracer-gas

The tracer-gas canisters are 240 x 60 mm diameter aluminium canisters commonly used as “paint ball” canisters fitted with a head encompassing a capillary tube (PEEKsil HPLC capillary tubing, 0.025mm inner diameter, SGE Analytical Science Pty Ltd, Ringwood, Vic. Australia) to limit the flow-rate of tracer gas to around 10 gh^{-1}. Laboratory tests showed an increase in flow rate with the canister in a horizontal position, as on the sheep’s back, compared to vertical as attached to cattle, and the length of the capillary was increased from 25 to 35 mm to ensure a flow rate of ~10 gh^{-1}. Each canister is filled with approximately 300 g of N_2O (liquid nitrous oxide, engine boost grade, product code 624, BOC Australia, Sydney, NSW, Australia) as the tracer gas, with canisters replaced after 24 hours. Animals are typically moved into nearby yard to facilitate the change over of canisters.

When measuring emissions from cattle the canister is protected by a PVC tube lined with insulation to limit temperature extremes with the canister usually attached to the animals using a pony harness (Figure 1). Canisters are mounted on the sheep’s back using a purpose built canvas backpack designed by staff at DPI Victoria, and attached via Velcro strips glued onto the back (Figure2). Again a layer of insulation provides protection from solar radiation. The wool on the back of sheep should be clipped to limit movement of the canister. A full gas canister weighs between 900 and 1100 g, and once the animal is trained to the canister, appears to have minimal detrimental effect on animal behaviour. Typically measurements are made from between 20 and 60 animals with canisters attached to up to 20 animals.

Figure 1: Tracer gas canister attached to cow

Figure 2: Tracer gas canister attached to sheep

The average tracer-gas flow-rate for each canister is determined from the weight loss of gas and the release time. However, as the instantaneous flow-rate of the gas varies with temperature the canister temperature is monitored using temperature logging buttons (logging interval 3 or 6 minutes; Thermocron eTemperature model TCS, OnSolutions, Baulkham Hills, NSW, Australia) attached to each canister.

The time (t, hours) and temperature (T, °C) dependent flow rate of the N_2O from a canister, F(t), (gh^{-1}) can be calculated from the relationship:

$$F(t) = F_0 + \frac{dF}{dT}\left(T(t) - T_0\right) \qquad \text{Eq. 1}$$

Where $\frac{dF}{dT}$ is the temperature dependence of the flow rate, determined in the laboratory by monitoring the flow rate at a range of temperatures as 0.184 ±0.036g $h^{-1}°C^{-1}$, F_0 is the canister flow rate (gh^{-1}) at T_0=0°C.

As the integrated flow rate over the release time, t_r, is equal to the mass of gas lost Δm (g),

$$\int_0^{t_r} F(t)dt = \Delta m \qquad \text{Eq. 2}$$

F_0 can be calculated from Eq. 1 and 2 such that:

$$F_0 = \frac{\Delta m}{t_{t_r}} - \frac{dF}{dT}\int_0^{t_r}\left(T(t) - T_0\right)dt \qquad \text{Eq. 3}$$

F_0 is calculated for each canister from Eq. 3, allowing F(t) to be calculated at temperature T and time t from Equation 1. The time-temperature dependent N_2O emission rate is the sum of the flow from the total number of canisters, n

$$Q_{N_2O(t)} = \sum_{i=1}^{n} F_i(t) \qquad \text{Eq. 4}$$

$Q_{N2O(t)}$ is interpolated from the time resolution of the temperature buttons to that of the CH_4 and N_2O volume mixing ratio data.

The CH_4 emission, Q_{CH4}, at time t is calculated from the relationship:

$$Q_{CH_4} = \frac{\Delta[CH_4]}{\Delta[N_2O]} Q_{N_2O} * \frac{MWt_{CH_4}}{MWt_{N_2O}} * \frac{24}{n_{animals}} \qquad \text{Eq. 5}$$

where: Q_{CH_4} = flux CH_4 at time t (g animal^{-1} day^{-1}), Q_{N_2O} = time-temperature emission of the tracer gas, N_2O at time t as calculated above (gh^{-1}), $\Delta[CH_4]$ = enhancement in CH_4 mixing ratio over local background mixing ratio (ppbv) and $\Delta[N_2O]$ = enhancement in N_2O mixing ratio over local background mixing ratio (ppbv) both at time t, MWt_{CH4} and MWt_{N2O} are the molecular weights of CH_4 (16.0 gmol^{-1}) and N_2O (44.0 gmol^{-1}), $n_{animals}$ is the number of animals, and 24 (hday^{-1}) converts the flux from per hour to per day.

2.3 Weather Station and Meteorological Criteria

A weather station installed close to the animals' enclosures provides 3-dimensional wind speed and wind direction data at 10 Hz resolution and averaged to 15 minutes (sonic anemometer, CSAT3, Campbell Scientific Inc, Logan Utah, USA). A wind sentry and cup anemometer (03001 RM Young Wind Sentry set, Campbell Scientific Inc, Logan Utah, USA) provide additional wind direction and speed in conjunction with air temperature (T107, Campbell Scientific Inc, Logan Utah, USA) and humidity (HMP55C, Campbell Scientific Inc, Logan Utah, USA) measured each minute and averaged to (typically) 5 minutes. All data are recorded to a data logger (CR5000, Campbell Scientific Inc, Logan Utah, USA) and downloaded daily.

Emission data quality from the technique is influenced by the weather conditions. To ensure efficient mixing of the CH_4 and tracer gas, and to limit influence of upwind CH_4 sources, data are rejected when wind speed < 1-2.0 ms^{-1}, dependent on the geometry of the site and the strength of nearby CH_4 sources. Rain and fog decrease the signal strength at the detector, decreasing the precision of the data. The loss in precision accelerates when signal strength decreases to less then half the maximum signal strength, when data are rejected. Data collected when the wind direction is within 10 to 20° (dependent on site geometry) of the measurement path are rejected as the area of the paddock sampled may not be representative of the animals.

3. Methodology

Typically two OP-FTIR instruments were setup with parallel paths, on either side of the paddock in which the animals were grazing, and perpendicular to the predominant wind direction (Figure 3). The CH_4 emitted from the animals and the N_2O from the canisters is carried by the same wind turbulence to Instrument 1 (I1), downwind from the animals. However, as any CH_4 or N_2O sources upwind from the experimental paddock will also contribute to the concentration at Instrument 1, Instrument 2 (I2) monitors the gas concentration entering the paddock, with the concentration due to the experimental animals assumed to be the difference in concentration entering and leaving the paddock (I1-I2). A third instrument provides increased flexibility in the experimental design.

CH_4 emission measurements were made from four livestock systems, with a field day held in conjunction with field campaigns at which attendees were able to observe the OP-FTIR system in operation and have questions answered by the University of Wollongong staff.

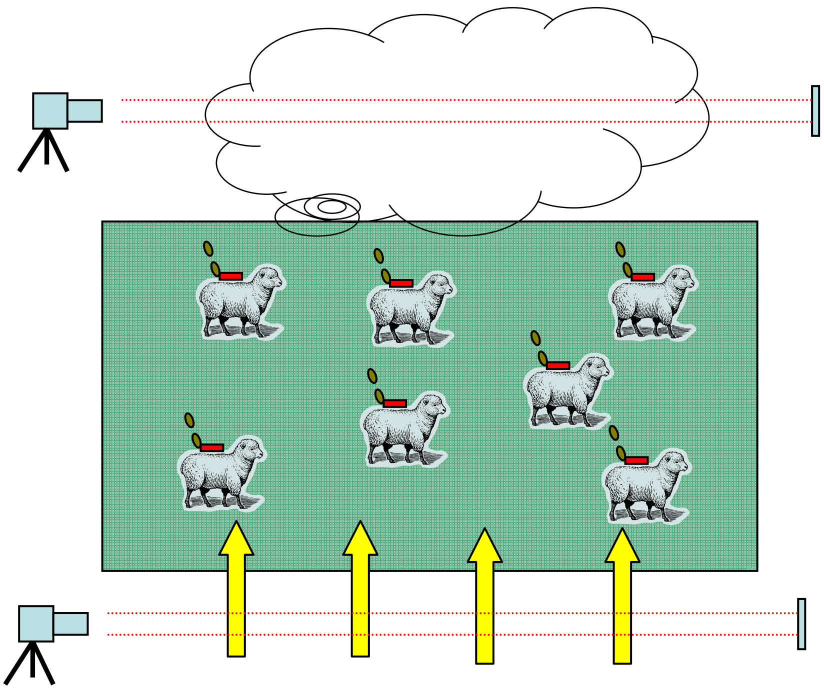


Figure 3: Schematic showing placement of instruments I1 and I2 in relation to experimental enclosure for animals and the predominant wind direction; tracer gas canisters located on animals.

3.1. BCCH 1034: Methane emission measurements from Dairy cows in conjunction with DPI Victoria

In conjunction with BCCH1034, measurements of emissions from 54 dairy cows were conducted using OP-FTIR over 3 weeks. OP-Lasers were operated in parallel to the OP-FTIR systems (D Turner University of Melbourne), with three OP-FTIRs and 2 CH_4 OP-lasers used. Measurements were made at DemoDairy, Terang, a demonstration dairy farm in south western Victoria. Methane emissions were measured from a subset of the herd with the animals separated from the main herd at the start of the experiment and remained separate for the duration of the experiment.

The DemoDairy site presented particular challenges due to the proximity of the dairy and other animal trials taking place in close proximity to the site. The paddocks on the south-western side of the property were selected for the measurements with the dairy to north-east and other farm animals in the north-east to east sector. Measurements were only made when the wind was from the south-eastern to north-western sector, the expected prevailing wind direction, with the experimental animals removed to comparable pasture when conditions were predicted to be unsuitable. The region has a high rainfall with Terang having a long term average annual rainfall of about 780 mm (2011 year mean), adding to the complexity of making the emission measurements.

A series of 10 paddock were established with each providing grazing for 1 milking period defined as time between morning and afternoon milking events (around 8:00 to 15:00 and 16:00 to 7:00). Feed intake was estimated from the difference between feed on offer pre and post grazing (Dr Graeme Ward DPI Vic.). The Farm maintains records of milk production and supplementary feed intake. The paddock sizes were 0.2-0.4Ha, except for paddock 1 and 2 which were 0.1Ha and provided insufficient feed for the animals. Three OP-FTIR instruments were employed to increase the flexibility of the site design and reduce downtime with relocating instruments.

Due to the limitations with the animals access to feed bins, tracer-gas canisters were not mounted on the animals and were instead mounted on posts on the paddock boundaries at around 1.2 m height. The weight loss of gas was measured several times over the measurement period for comparison with $Q_{N_2O(t)}$ calculated by the relationship in Equation 4.

The measured CH_4 concentration was interpreted to an emission rate by:

1. Assuming the transport of tracer-gas released at the corral fence modelled the transport of CH_4 from the animals and using the relationship in Equation 5,

2. Modelling the dispersion of CH_4 between the animals and the IR path using a backward Lagrangian model (bLs) (WindTrax).

3. In addition the emission rate of the N_2O tracer-gas was retrieved using WindTrax and compared with the calculated time-temperature dependent flow rate, with the possibility of using the comparison to constrain the bLs model to retrieve the CH_4 emission strength.

3.2. BCCH1033: CH_4 emission measurements from sheep in conjunction with Roger Hegarty and Malcolm McPhee, I&I and UNE NSW, Armidale NSW.

In association with Drs. Roger Hegarty and Malcolm McPhee methane emissions were compared from sheep grazing low productive pastures on the hills and high productive pastures on the river flats. The measurement site was part of the “Sheep Production Demonstration Site, On-farm methane management Strategies“ project. The trial consisted of 2 treatments, low productive pastures on the hills and high productive pasture on the river flats. Each treatment included 3 replicate groups of sheep, with (initially) 16 ewes + 16 lambs in each group on the low productive treatment and 32 ewes + 32 lambs on the high productive treatment. Measurements were made from 2 replicates from each treatment in March-April 2011. Three OP-FTIR instruments were used for the measurements, including the MLA funded instrument. Tracer-gas canisters were attached to 15 to 20 animals for each group, varying with the animal groups.

The CH_4 mixing ratio measured by the OP-FTIR are interpreted to emission strengths based on the relationship in Equation 5.

3.3. BCCH 1032: Methane emissions from steers in collaboration with CSIRO at Lansdowne, QLD

Emissions measurements were made at the CSIRO Lansdown Research Station in May/June 2011, with emissions measured from a small herd (29) of Belmont Red steers. The animals grazed freely in a large nearby paddock until around 8:00 am when they were bought into an enclosed pen, simulating the animals coming to a water hole. The CH_4 emissions from the animals were measured using both the OP-FTIR and OP-lasers with the animals in the pen for up to 5 hours after which the animals were released to again free graze. Two OP-FTIR systems were used with one placed upwind and the second downwind from the animals. Tracer-gas canisters (20), releasing N_2O at a rate of ~ 10 gh^{-1}, were attached to the posts of the pen. CSIRO staff (Drs Nigel Tomkins and Mei Bai) also measured the cattle CH4 emissions using a scanning open path laser. Animal intake measurements were not undertaken, due to the difficulty in sampling the paddock used for grazing.

The calculated time-temperature dependent N_2O flow rate was compared with the cumulative weight loss of N_2O gas by weighing the canisters approximately midway through the release period.

As the area available to the animals was restricted the source area of the corral could be considered to be uniform, and the source of the tracer-gas, although not attached to the animals, approximated the animal location. The CH_4 mixing ratios measured by the OP-FTIR are interpreted to emission strengths by:

1. Assuming the transport of tracer-gas released at the corral fence modelled the transport of CH_4 from the animals, and using the relationship in Equation 5.

2. Modelling the dispersion of CH_4 between the animals and the IR path using a bLs model in WindTrax.

3. In addition the emission rate of the N_2O tracer-gas was retrieved using WindTrax and compared with the calculated time-temperature dependent flow rate, with the possibility of using the comparison to constrain the bLs model in the retrieval of CH_4 emission strength.

3.4. BCCH 1031: CH_4 emission measurements from sheep at Ridgefield Farm, Pingelly WA, in conjunction with Assoc Prof Phil Verco, UWA.

Emissions were measured from 2 groups of sheep at UWA Ridgefield Farm near Pingelly WA in association with Assoc Prof Phil Vercoe in November 2011. Emissions were measured from 60 sheep grazing pasture typical of the farm and the local region. The sheep were contained in two paddocks, each with an area of approx. 0.6Ha (120 by 50m), with sheep grazing each paddock for 5 days. Canisters were mounted on 20 sheep. In addition emission measurements were made from 30 sheep grazing a Bisserulla pasture as part of a related research program led by Dr Andrew Thompson (DAFWA). In addition CH4 emissions were also measured using a "butter-box" and from blood samples at the end of the grazing period as part of the second project. Feed intake estimates were made by DAFWA staff, and the animals weighed pre and post the experiment. Measurement time on the Bisserulla was limited by pasture availability. The original paddock was divided into 4 sub paddocks, each providing 1 to 2 days grazing with the sheep moved once pasture mass could limit intake, with emissions measured for 7 days.

4. Field Days

At each measurement site a field day was held coinciding with the OP-FTIR methane emission measurements.

4.1 BCCH 1034: Field Day in conjunction with DPI Victoria

The University of Wollongong OP-FTIR team participated in the “Farming into the Future - Increasing productivity and reducing emissions” Field day organised by Graeme Ward at the DPI Victoria Hamilton Research farm in November 2010. The day was attended by Agribusiness and Key extension agents as well as producers, with close to 100 attendees. The OP-FTIR demonstration incorporated CH_4 emission measurements from sheep grazing a range of pastures, as part of BCCH 1009. The demonstration generated substantial interest from attendees, as well as features in articles in the Weekly Times (10 November 1010) and Hamilton Spectator (20 November 1010) plus an interview with Laura Poole, ABC Rural Reporter, Victoria, was broadcast on Bush Telegraph “Sheep backpacks measuring methane” on 12 December 2010. An interview with Steve Hynes generated an article in the Warrnambool Standard, “South-West tackles methane emissions, Tackling a gassy question” published on 16 December 2010.

As part of the measurement campaign, staff from DPI Victoria (James Hollier and Andy Phelan) and University of Melbourne (Debra Turner) were trained on the OP-FTIR system. Graeme Ward (DPI Victoria) gained extensive experience in the requirements of a measurement campaign and in the operation of OP-FTIR systems, while Kym Mathew (Manager Demo Dairy) became familiar with the farm requirements to estimate CH_4 emissions.

4.2 BCCH1033. Field Day in conjunction with Roger Hegarty and Malcolm McPhee, I&I and UNE NSW, Armidale NSW.

The OP-FTIR was demonstrated at the Trevenna Field day held on 30th March at the UNE-I&I Trevenna site, Armidale, NSW. The field day was successful with approximately 60 attendees and positive feedback, with considerable interest in the changes in CH_4 emissions from the animals over the day and changing animal activity, as demonstrated by the OP-FTIR system.

4.3 BCCH 1032. Field Day in conjunction with CSIRO Lansdowne, QLD

The UoW team featured at the Field Day at the Lansdown farm, hosted by CSIRO, on the 27-May-2011 demonstrating the OP-FTIR technique for measuring CH_4 emissions from livestock. The OP-FTIR instruments were setup adjacent to the OP-Laser with a comparison of the two techniques explained to the attendees by Dr Nigel Tomkins and Dr Frances Phillips. The open-path presentations received considerable attention with many people remaining at the instruments to continue asking questions.

4.4 BCCH 1031. Field Day in conjunction UWA at Ridgefield Farm, Pingelly WA

As part of the measurement of CH_4 emissions from sheep, the University of Wollongong participated in the 'Whole-farm Carbon Emission" Field Day at Ridgefield Farm on Tuesday 18th October 2011, showcasing the OP-FTIR system in operation. The field day was well attended with 150 registered participants with 55 producers and agriculture consultants or educators and the media. The OP-FTIR presentation was very well received, receiving a score of 4.2 out of 5, the highest score for the presentations on the survey, with many participants unwilling to move onto the next station and remaining at the OP-FTIR station to continue asking questions.

5. Results

5.1. Comparison of Tracer-Gas Release Rates.

The time-temperature dependent N_2O release rate as calculated in Equation 4 was compared with the loss of N_2O by intermittently weighing canisters during the release period during CH_4 emissions measurements, when measuring emissions from steers at Lansdown, Qld and dairy cows at Terang, Victoria (Figures 4 and 5 respectively). The weight loss of N_2O from the canisters was measured typically three times during the release time at Terang and once, close to mid-release time during the measurement of emissions from Belmont Red steers at Lansdown.

During emissions measurements from steers at the Lansdown Station the canisters were weighed midway through the release time to determine the loss of N_2O by weight. While the average of the absolute difference in the loss of N_2O (calculated from the time-temperature dependence (Equation 4) and measured mass loss of N_2O) for individual canisters was 4.3±3.3%, the difference in the total flow rate for the day ($Q_{N_2O(t)} = \sum_{i=1}^{n} F_i(t)$ t= time canister weighed) was between 0.5 and 3.5%.

At Terang a large number of canisters were deployed over an extended area and the time required to weigh all canisters was up to an hour. The difference in the average loss N_2O for all the canisters and at time t was greater at Terang, particularly in the first two hour of release (Figure 5), however the uncertainty in difference in the two flow rates is dominated by the uncertain in the t when the canisters were weighed. The average difference in cumulative loss of N_2O by weight and calculated by the relationship in Equation 4 was 5.9±3.4% if data when release period was < 2h was not included.

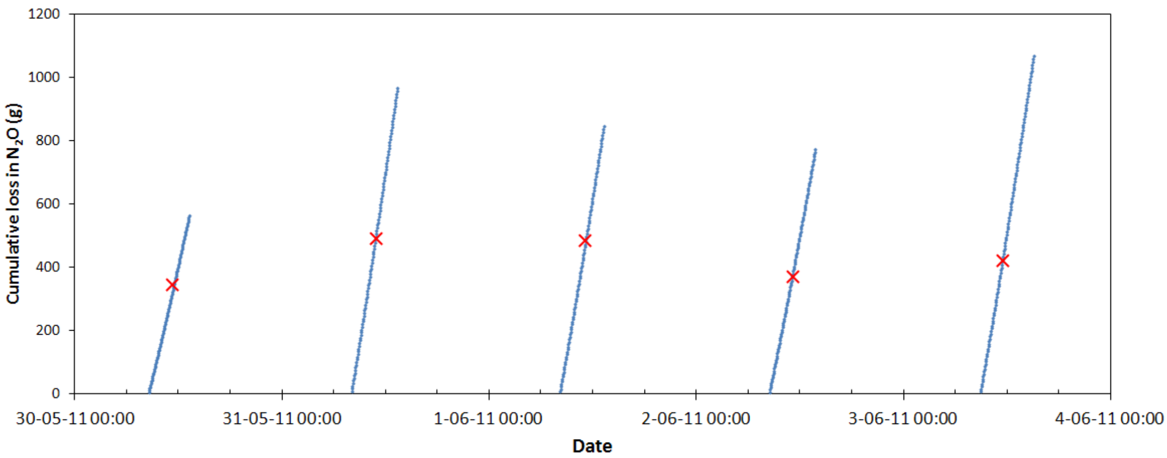


Figure 4: A comparison of the cumulative loss of N_2O calculated by Equation 4 ( ) and by weight (x) from the controlled release of N_2O as a tracer-gas during measurements of CH_4 emissions from steers at Lansdown Station Qld. The difference in the cumulative loss of N_2O from individual canisters was 4.3±3.3%, while the difference flow rate for the day ($Q_{N_2O(t)}$ t= time canister weighed) ranged from 0.5 and 3.5%

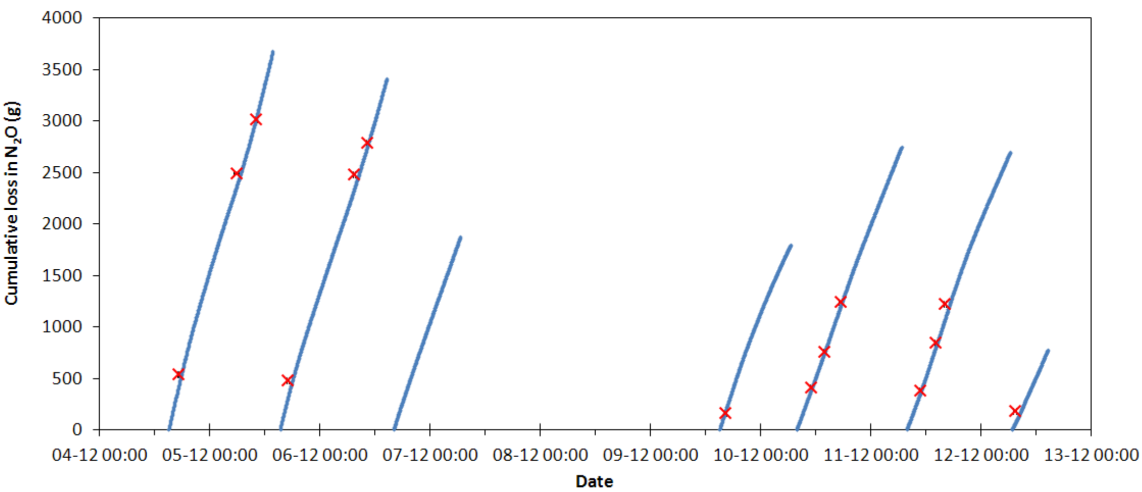


Figure 5: A comparison of the cumulative loss of N_2O calculated by Equation 4 ( ) and by weight (x) from the controlled release of N_2O as a tracer-gas during measurements of CH_4 emissions from steers at DemoDairy, Terang, Victoria. The difference in flow rate for the day ($Q_{N_2O(t)}$ t= time canister weighed) and loss by weight 5.9±3.4% if data when t < 2h was not included. However the differences when t< 2h were up to 20%, with the uncertainty in the difference in cumulative loss of N_2O dominated by the uncertainty t due to the extended time required to weigh all canisters.

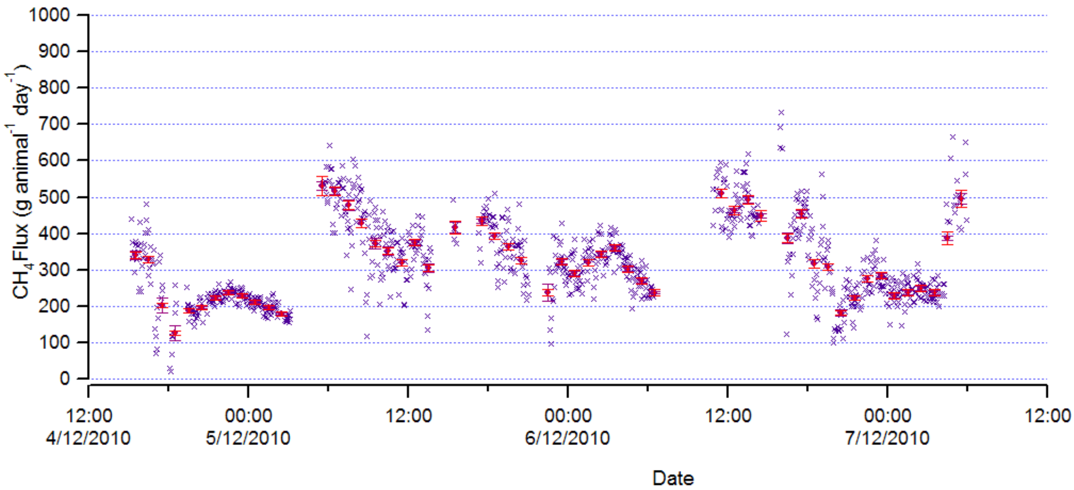
5.2. Methane Emission Estimates

5.2.1 BCCH 1034: Methane emission measurements from Dairy cows in conjunction with DPI Victoria

Measurements of Methane emissions from 54 dairy cows were made between the 4th and 12th December 2010. Measurements were not made on the 7th, 8th and morning of the 9th

due to unfavourable wind conditions and anticipated heavy rain. During this time the animals were moved to comparable pasture. Data was lost for 1 to 1.5 hours in the morning and evenings when the animals left the paddock to be milked. The time of milking varied between 4:00 and 7:30 in the morning and 14:00 to 15:30 in the evening. The animals received supplements while at the dairy and were moved to new pasture following each milking. The initial grazing area was insufficient for the animals and was increased for the 3rd grazing event on the evening 5th December.

Emissions were markedly higher immediately following cows returning from the dairy in the morning when emisisons increased up to 600 g CH_4 animal^{-1} day^{-1} (Figure 6). This may be associated with the animals receiving supplements at the dairy (DMI 3.33 kg cow^{-1} at each milking). The DMI from pasture ranged from 1.76 to 5.45 kg cow^{-1}, and was lowest for the initial paddock when pasture was limited. An average daily emissions was calculated on 3 days, from afternoon milking to afternoon milking the next day, 15:30 to 15:30) as 307±9 (day1, 4th-5th), 298±11 (day4 10th-11th) and 381±7 (day 5 11th – 12th) g animal^{-1} day^{-1}. The averaged daily emission from all data collected was 350±4 g CH_4 animal^{-1} day^{-1}. The distribution of emissions over the day varied with time of milking, with highest emissions soon after cows returned from the dairy, low pre-milking and lowest through the night (Figure 7).



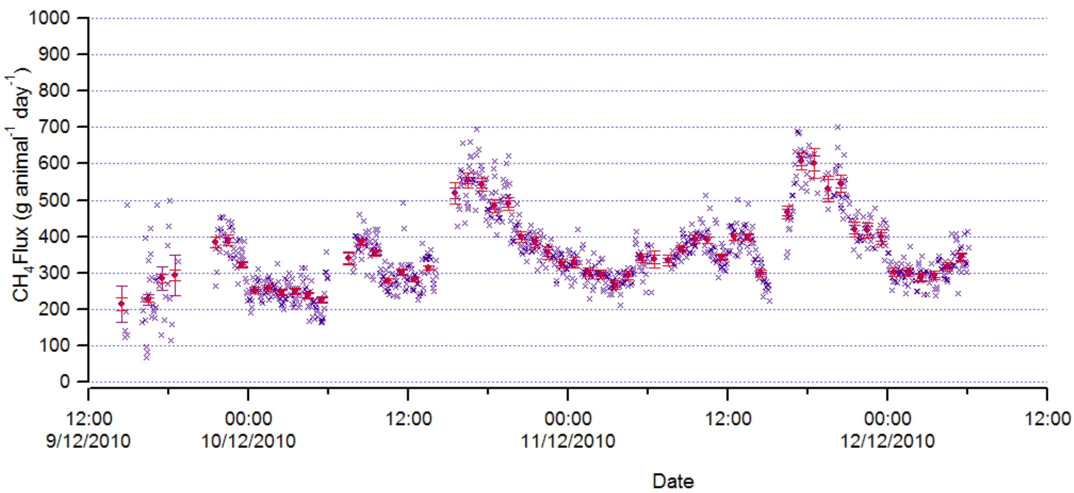


Figure 6: CH_4 emission estimate measured with OP-FTIR in conjunction with a tracer-gas, N_2O released from canisters located at the paddock boundary, showing the individual emission

estimates (x) and the average of the estimates for the hour. There is rapid increase in emissions evident after the cows have returned from the dairy and receiving feed supplements. The cows were away from the paddock at the dairy for around an hour each milking. The time of milking varied from 4:00 to 8:00 in the morning and 14:00 to 15:30 in the evening.

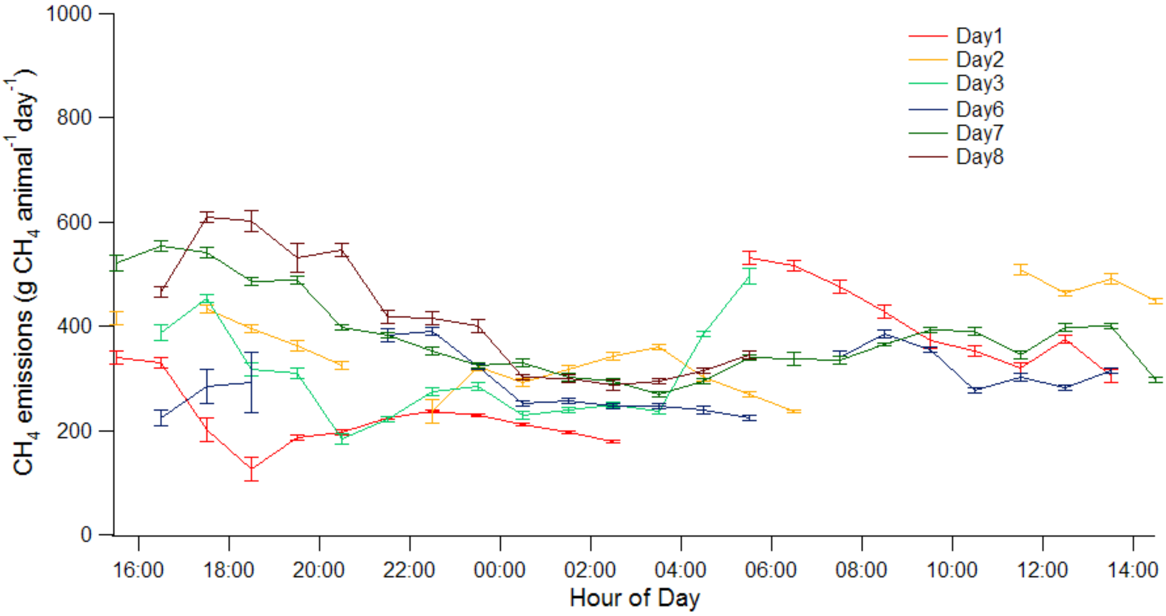


Figure 7: CH_4 emissions were lowest during the night, and increased rapidly after the cows returned from the dairy were they were supplied with feed supplements, and decreased to the next milking. The time of increase in emissions is offset due to the varying times when the animals left the paddock to be milked.

5.2.2 BCCH1033 Measurement Campaign: CH_4 emission measurements from sheep grazed on 2 pastures of different qualities, in conjunction with Roger Hegarty and Malcolm McPhee, I&I and UNE NSW, Armidale NSW.

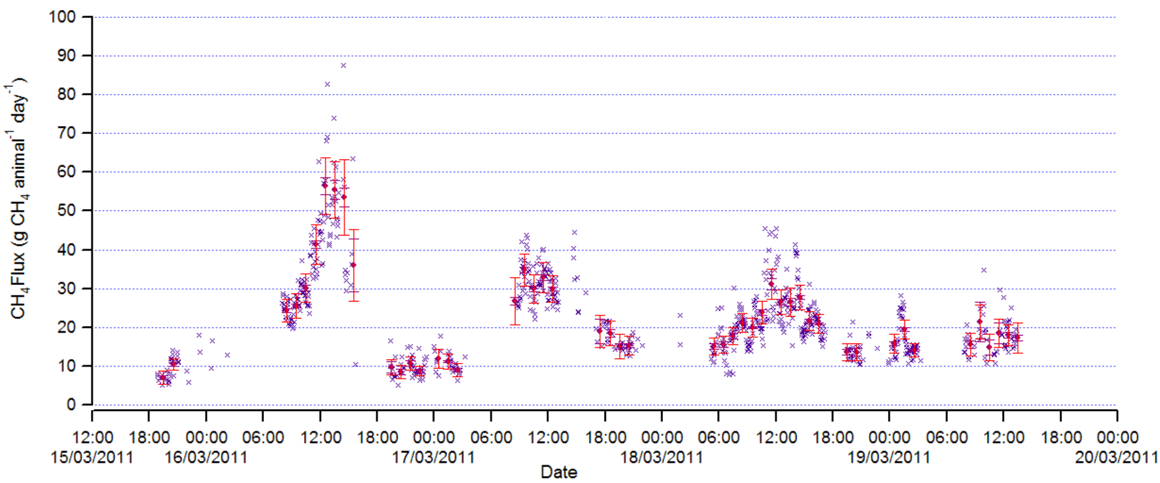
Emissions were measured from sheep grazing pasture on low fertility soils between 15th and 23rd March 2011. Sheep comprised two of three replicates from an ongoing trial, with 16 ewes and 16 lambs in group1 and 15 ewes and 14 lambs in group 2 (Figure 8). Between 25 March and 2nd April emissions were measured from a second two mobs of sheep grazing pasture on high fertility soils on the river flats, with 32 ewes and 31 lambs in replicate 1 and 32 ewes and 32 lambs in replicate two (Figure 9). The area for grazing was the same for both treatments and replicates with each replicate grazing a separate paddock. Tracer-gas canisters were attached only to the ewes. Initially the wool of the sheep was not clipped prior to attaching the canister. However this resulted in the canister moving as the sheep moved, irritating the animal. Once the wool was clipped and the canister secure on the back of the sheep the animals quickly became accustomed to the backpack and canister.

The variability in emission estimates was greater for the low fertility treatment, reflecting the lower numbers of sheep, and the lower enhancement in atmospheric CH_4 concentration above local background. On the 16th between 12:00 and 16:00 the scatter in the emissions data increased considerably, with emission estimates substantially greater compared with other data. The wind direction was changing from perpendicular to parallel with the measurement path, and with the limited number of sheep in a relatively large area, the number of sheep being sampled, with and without tracer-gas canisters, may have not been representative of the mob.

On the first day of measurement of Replicate 1, sheep grazing pasture on high fertility soil, emissions were unusually high (approx 70 g CH_4 animal^{-1}day^{-1}) and decreasing over 12 hours to around 20 g CH_4 animal^{-1}day^{-1}. The sheep had been located at the yards prior to being moved to the paddock and from observation it was noted the animals appeared hungry when they arrived at the paddock. This data was omitted for the purpose of calculating a daily distribution of emissions.

The average daily CH_4 emissions were estimated to be 19.5±0.45 g CH_4 animal^{-1}day^{-1} (Replicate 1 19.6±0.58 g CH_4 animal^{-1}day^{-1}; Replicate 2 21.1±0.65 g CH_4 animal^{-1}day^{-1}). The estimated daily average emissions from Replicate 1 grazing pastures on the high fertility soils were substantially higher compared to the measured emissions from Replicate 2 with 15.5±0.99 g CH_4 animal^{-1}day^{-1} and 19.5±0.98 g CH_4 animal^{-1}day^{-1} respectively, with a combined daily average 17.9±0.41 g CH_4 animal^{-1}day^{-1} .

With four groups of animals, emission measurements were made for each group for only 4 days. With data lost due to unfavourable wind conditions this is insufficient to fully characterise the emissions. The distribution in emissions with time of day shows higher emissions in morning, lower emissions in the early afternoon increasing again slightly in the evening and lowest over night (Figure 10).



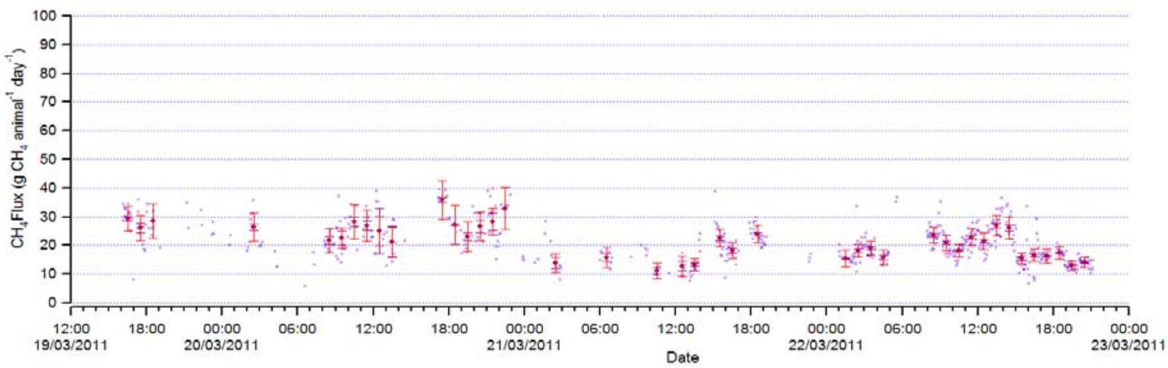
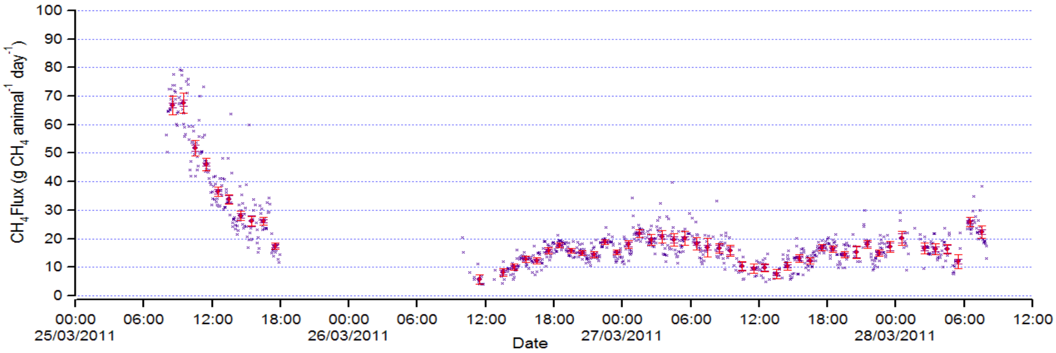


Figure 8: CH_4 emission estimates from sheep grazing pasture on low fertility soils (Treatment 1) measured with OP-FTIR in conjunction with a tracer-gas, N_2O released from canisters located on sheep's back, showing the individual emission estimates (x) and the average of the estimates for the hour. Upper Panel. Replicate 1: the data with very high variability on the 16th may be due to the animals not being representative sampled due to the low stocking rate Lower Panel: Replicate 2.



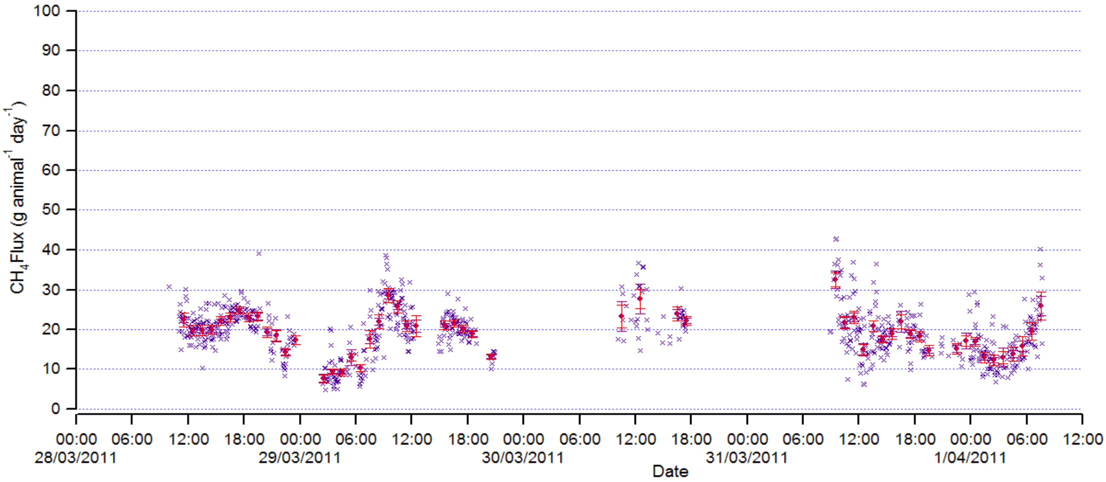


Figure 9: CH_4 emission estimates from sheep grazing pasture on high fertility soils (Treatment 2) measured with OP-FTIR in conjunction with a tracer-gas, N_2O released from canisters located on sheep's back, showing the individual emission estimates (x) and the average of the estimates for the hour. Upper Panel Replicates 1: High emissions in the first 12 hours may be due to the sheep being kept at the yards for extended period prior to entering the paddock and having a high initial feed intake. Lower Panel: Replicate 2.

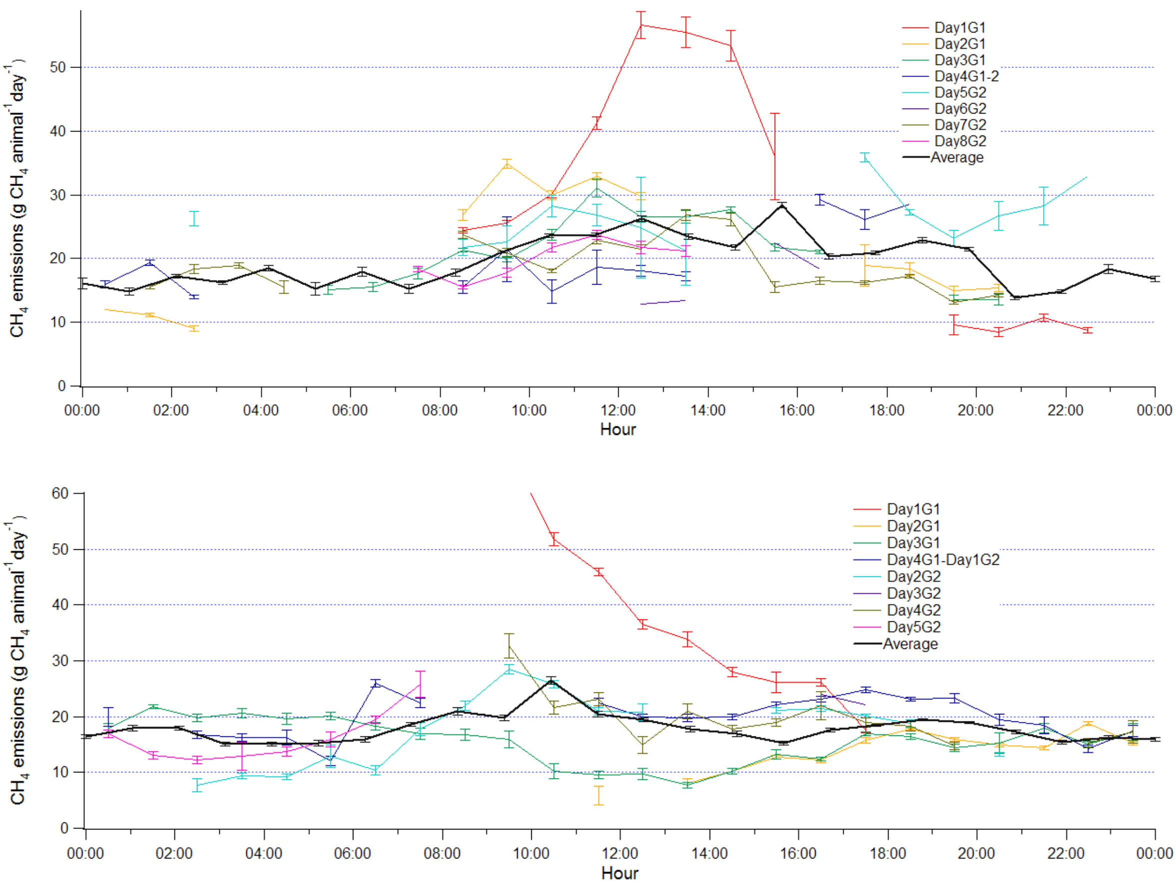


Figure 10: Hour Averaged data comparing emission profiles for each day of measurement for Upper Panel: Treatment 1, and Lower Panel Treatment 2 showing the distribution of emissions over the day with high emission mid morning decreasing mid-afternoon, an increase in the early evening and lowest emission during the night. The data are the average of the all data available for each hour for the day. The Average emissions is the average of all data available for each hour for all days.

5.2.3 BCCH 1032: Methane emissions from steers in collaboration with CSIRO at Lansdowne, QLD

Methane emissions were measured from 29 Belmont Red steers between 25 May and 4 June 2011, with tracer-gas canisters deployed from the 30th May. Emission data was not collected on 28th and 29th, (Saturday and Sunday) due to staffing issues for moving the animals, with N_2O tracer-gas and CH_4 emissions data collected over 5 days from 30th May to 3rd June. Measurements were made from around 8:00, when the animals were bought to the corral until approximately 13:00. However the wind velocity was often very low until 9:00 or later. The criteria for minimum wind speed was reduced to 1 ms^{-1} as other sources of CH_4 in the immediate area were limited. CSIRO staff, Mai Bai and Nigel Tomkins operated a scanning OP-Laser in parallel to the OP-FTIR measurements.

Emission estimates for CH_4 were calculated from the CH_4 and N_2O mixing ratio data based on the relationship in Equation 5. Emissions were high at around 200 g CH_4 animal^{-1}day^{-1} when animals were first entered the corral decreasing over the morning to around 130 g CH_4 animal^{-1}day^{-1} (Figure 11). From the data available the average emissions between 9:00 and

14:00 (times when data was available each day) the average emissions were 176±5, 152±4, 179±4 and 194±11 g CH_4 animal^{-1}day^{-1} for days 2 to 5 respectively. Hourly averaged data was calculated by averaging all data available for each hour. The averaged emission calculated from hourly averaged data (9:00 to 15:00, 292 emission estimates) was 160±3 g CH_4 animal^{-1}day^{-1}.

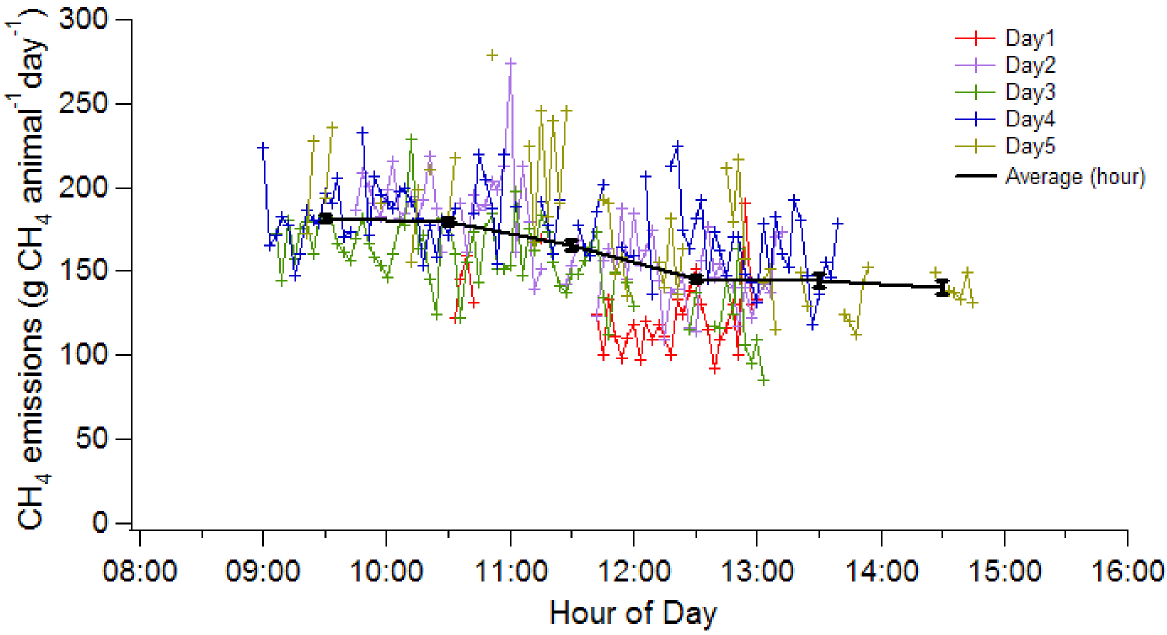


Figure 11: The CH_4 emissions from 29 Belmont Red steers were measured at Lansdown Station between 30th May and 3rd June. The + indicates an emission estimate calculated from the 3-minute average CH_4 and N_2O mixing ratios. The average emission estimate is the average of all individual emissions for that hour. The hourly average emission was calculated by averaging all available data for each hour. The average emission between 9:00 and 15:00 was 160±3 g CH_4 animal^{-1}day^{-1}.

5.2.4 BCCH 1031: CH_4 emission measurements from sheep at Ridgefield Farm, Pingelly WA, in conjunction with Assoc Prof Phil Verco, UWA.

Methane emissions were measured from 60 sheep grazing pasture typical for the Ridgefield farm and the local Pingelly region between 9 and 20 October 2011. Wind conditions were generally favourable, predominantly from the east or west with wind speed up to 8 ms^{-1}. However, around midnight wind-speeds regularly decreased to less then 2 ms^{-1}. Local sources of CH_4 were limited with few animals located upwind from the measurement site and other mobs of sheep generally located several hundred meters away, allowing the minimum wind speed criteria to be reduced to 1 ms^{-1}. Due to the width of the paddock (50 m) a wind direction criteria of > ±20° from the bearing of the instrument path was maintained to ensure the animals were representatively sampled.

The daily averaged CH_4 emissions with the sheep grazing the regional pasture was calculated from 1506 individual 3 minute emissions estimates to be 29.7±0.6 g CH_4 animal^{-1}day^{-1}. Data availability throughout the day was limited, and emission estimates for individual days could not be calculated, however from Figure 12, variability in emission from day to day is evident. A pattern in the distribution in the emission over the day is not as evident as in other data, but decreased emissions in the evening and higher in the morning are evident (Figure 13).

Emissions from sheep grazing the Bisserulla pasture were made between 21st and 29th October (Figure 14). A daily emission was calculated for days 3, 4 and 7 as 20.6±0.6, 18.8±0.6 and 16.3±0.7 g CH_4 animal^{-1}day^{-1}, while an averaged daily emissions calculated for all data for all days (2047 3-minute emissions estimates) was 20.0±0.3 g CH_4 animal^{-1}day^{-1}. The distribution of emissions over the day (Figure 15), again shows higher emissions during the morning and lower at night and variation in emissions from day to day.

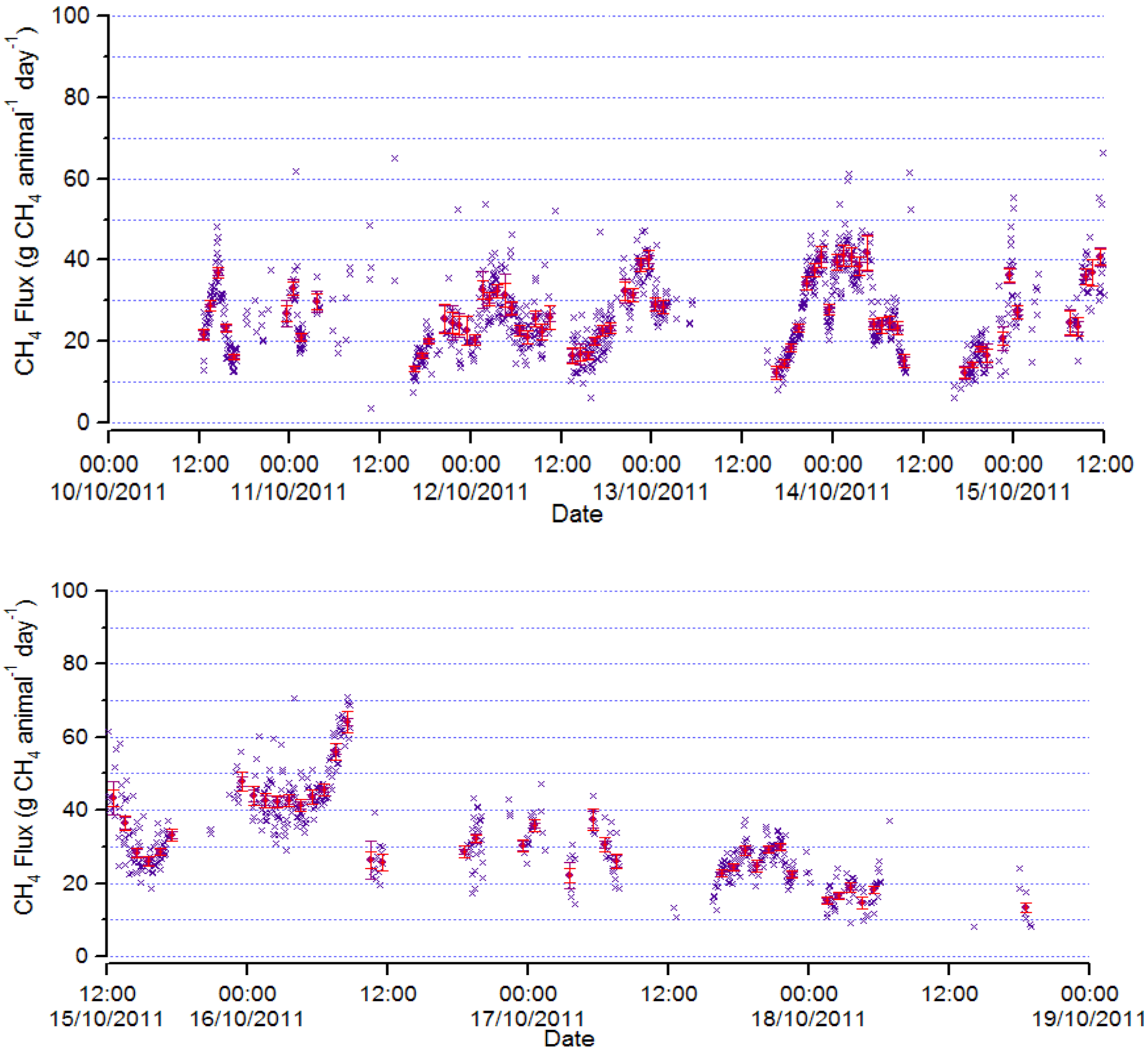


Figure 12: CH_4 emission estimates from sheep grazing regional pasture measured with OP-FTIR in conjunction with a tracer-gas, N_2O released from canisters located on the sheep, showing the individual emission estimates (x) and the average of the estimates for the hour. Upper Panel. Days 1-5, Lower Panel: Days 5-9.

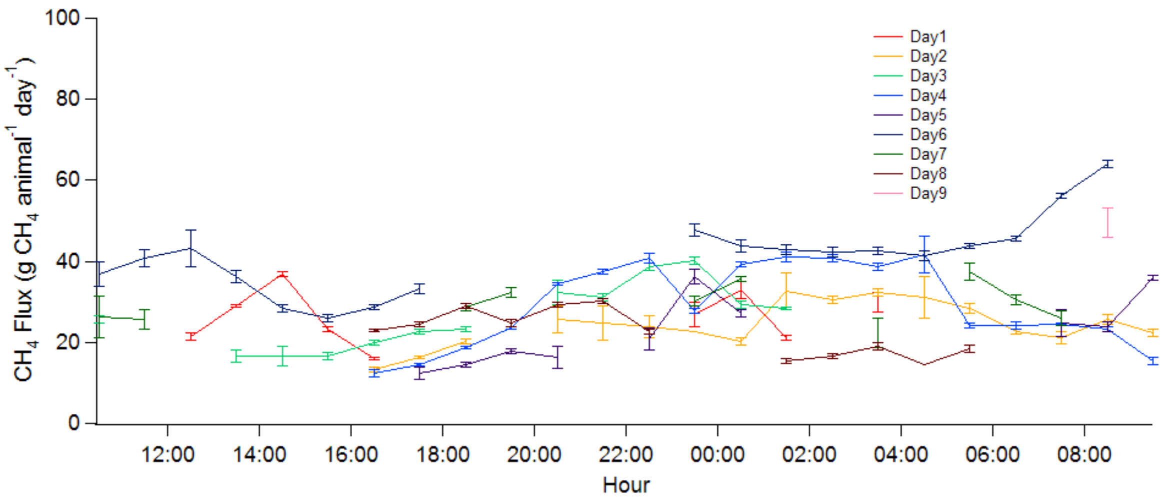


Figure 13: Hour Averaged data for each day of measurement from typical regional pasture highlighting a decrease of emissions in the evenings and an increase of emissions in the morning.

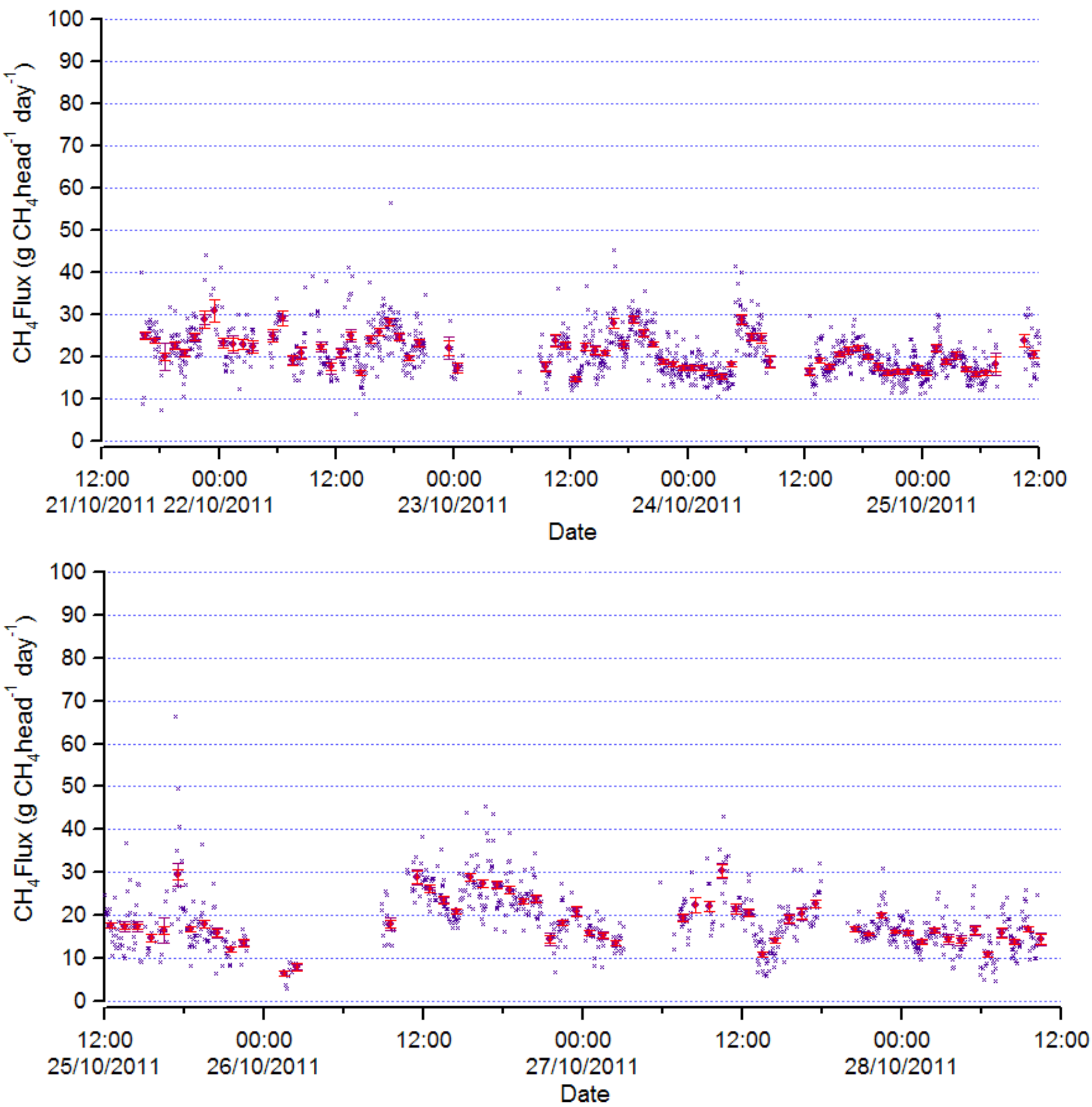


Figure 14: CH_4 emission estimates from sheep grazing Bisserulla pasture measured with OP-FTIR in conjunction with a tracer-gas, N_2O released from canisters located on the sheep, showing the individual emission estimates (x) and the average of the estimates for the hour. Upper Panel. Days 1-3, Lower Panel: Days 4-7.

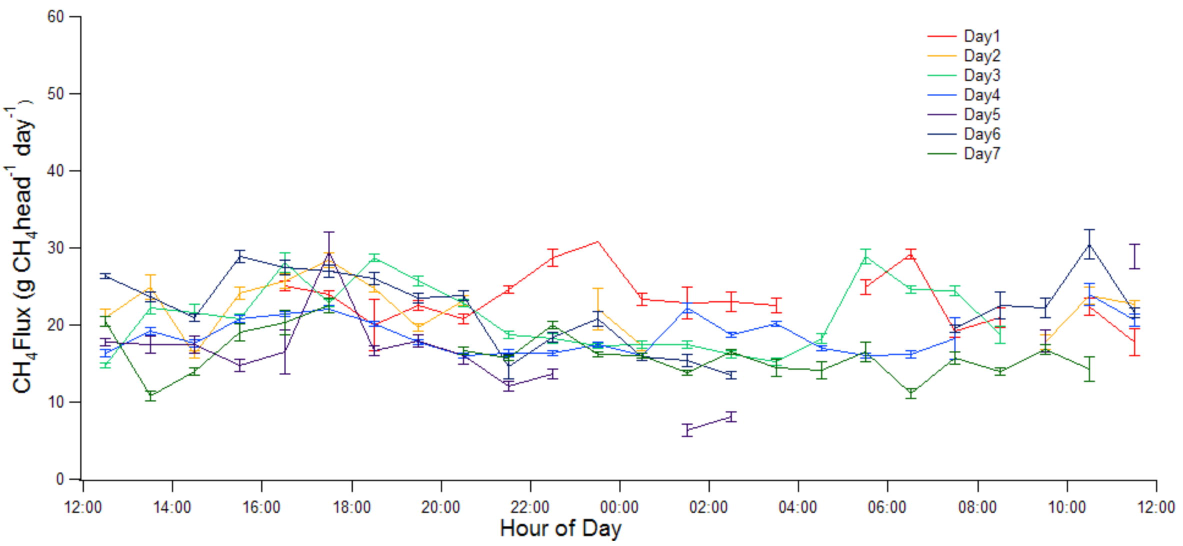


Figure 15: Hour Averaged data for each day of measurement from Bisserulla pasture showing no obvious pattern to emissions, but highlighting a decrease of emissions in the evenings and an increase of emissions in the morning.

5.3 Comparison of CH_4 Estimates using a Tracer-Gas and WindTrax bLs Model

Data collected at DemoDairy, Terang, VIC as part of BCCH 1034 was analysed with 2 alternate methods, using a Tracer-gas (OP Tracer Gas) and bLs modelling (WindTrax).

While a similar pattern is evident in the emissions of CH_4 and N_2O from each method, generally WindTrax over estimates compared to the OP Tracer gas method (Figures 16 & 17). Also the scatter in the WindTrax data set is much greater than that in the OP Tracer Gas data set, which in turn leads to a greater uncertainty in the WindTrax retrieved emission rates (Tables 1 & 2).

Figure 18 highlights the differences between the OP Tracer Gas and WindTrax simulations a bit more clearly. The figure shows 15 minute emission rates for CH_4 and N_2O from each method. The most obvious feature evident is, when WindTrax does over estimate the source strength it is a significant over estimation. However there are periods where both the OP Tracer Gas and WindTrax agree quite well.

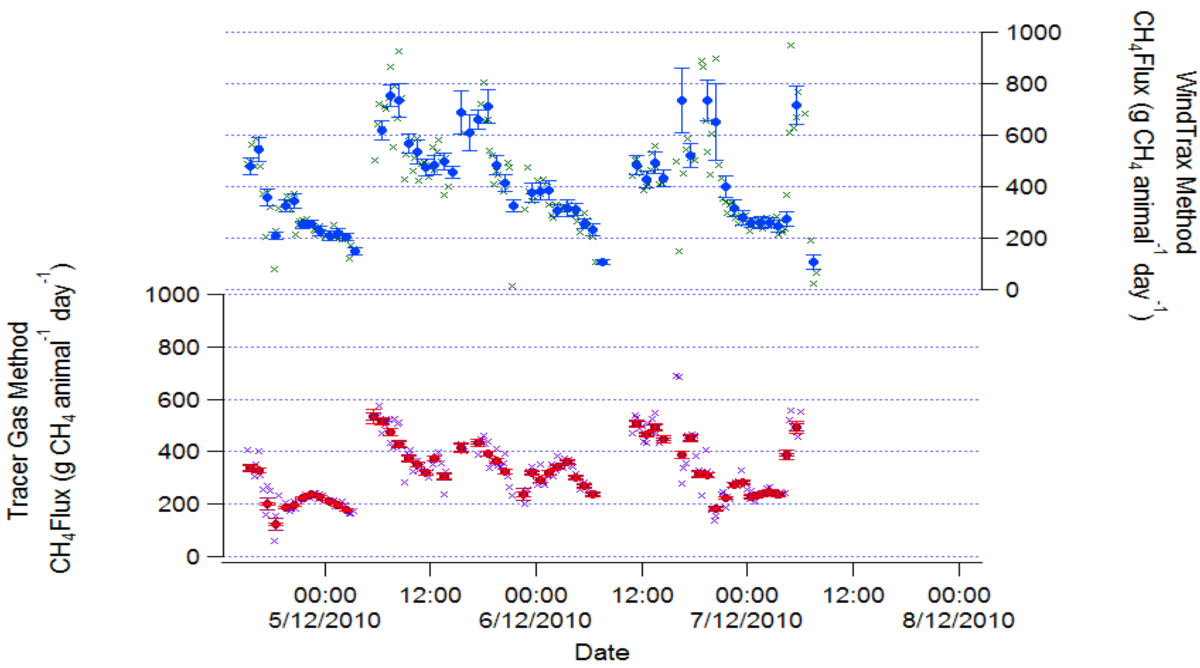
The daily diurnal cycle graphs of the emission rates of CH_4 and N_2O from each method also highlight the greater scatter and uncertainty retrieved from WindTrax (Figures 19-22). Given the 2 methods show a similar pattern to the emission estimates it is feasible that the OP Tracer Gas method could be used to constrain the WindTrax model simulations leading into the future.

Table 1: Daily emission rates for CH_4 & N_2O from OP Tracer Gas and WindTrax. Day 1,6 & 7 were the only days with full data sets to determine these averages. It is quite clear that WindTrax tends to over estimate the emission rates and has greater uncertainty.

	Day 1	Day6	Day7
Tracer CH_4 (g animal^{-1} day^{-1})	307.0 ± 9.0	298.0 ± 11.0	381.0 ± 7.0
WindTrax CH_4 (g animal^{-1} day^{-1})	387.5 ± 27.5	433.6 ± 48.5	422.8 ± 35.8
Tracer N_2O (g hr^{-1})	163.9 ± 0.1	117.0 ±0.1	120.7 ± 0.1
WindTrax N_2O (g hr^{-1})	209.4 ± 15.1	179.3 ± 20.8	137.2 ± 11.6

Table 2: Total Daily emission rates from the OP Tracer Gas and WindTrax. Data from Days 1, 6 & 7 were used in the calculation as these were the only days with full daily hourly averages.

	OP Tracer Gas	WindTrax
CH_4 (g animal^{-1} day^{-1})	350.0 ± 4.0	414.7 ± 37.2
N_2O (g hr^{-1})	133.9 ± 0.1	175.3 ± 15.8



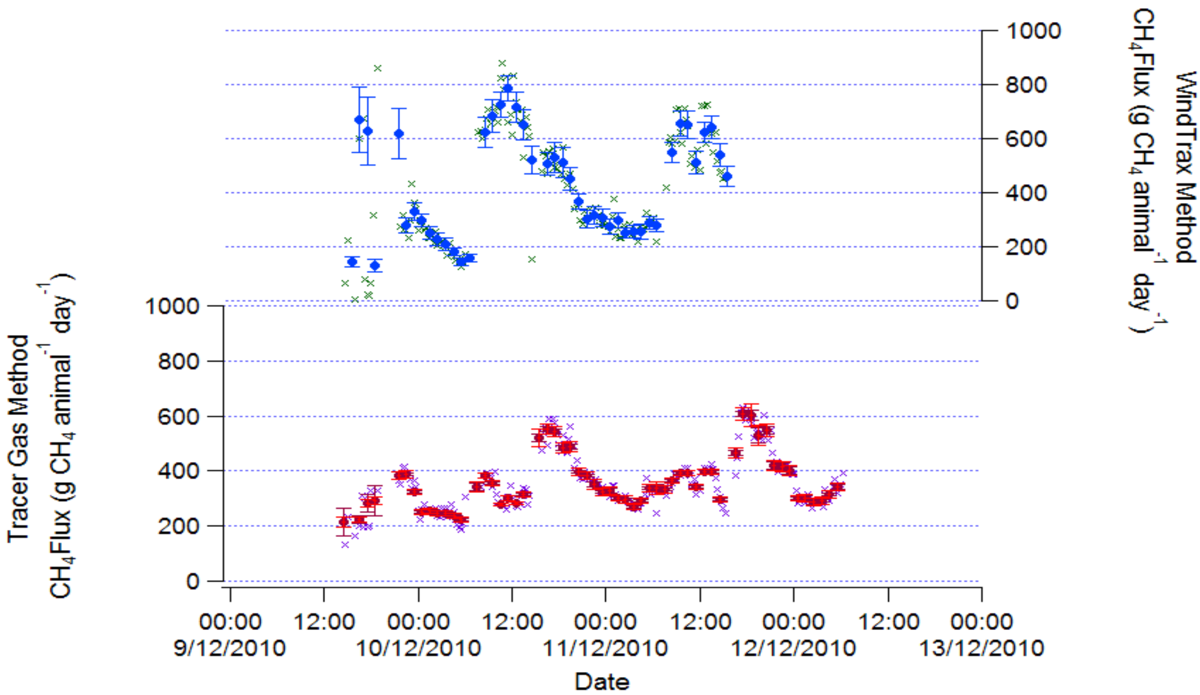


Figure 16: Hourly averaged and 15 minute CH_4 emission calculated from the measured CH_4 and N_2O mixing ratios as for Equation 5 compared with the emissions calculated using a bLs model (WindTrax). While the pattern of emissions is similar the emission estimates and uncertainty are generally greater in the data from WindTrax. Upper Panel: Days 1-3, Lower Panel: Days 4-6

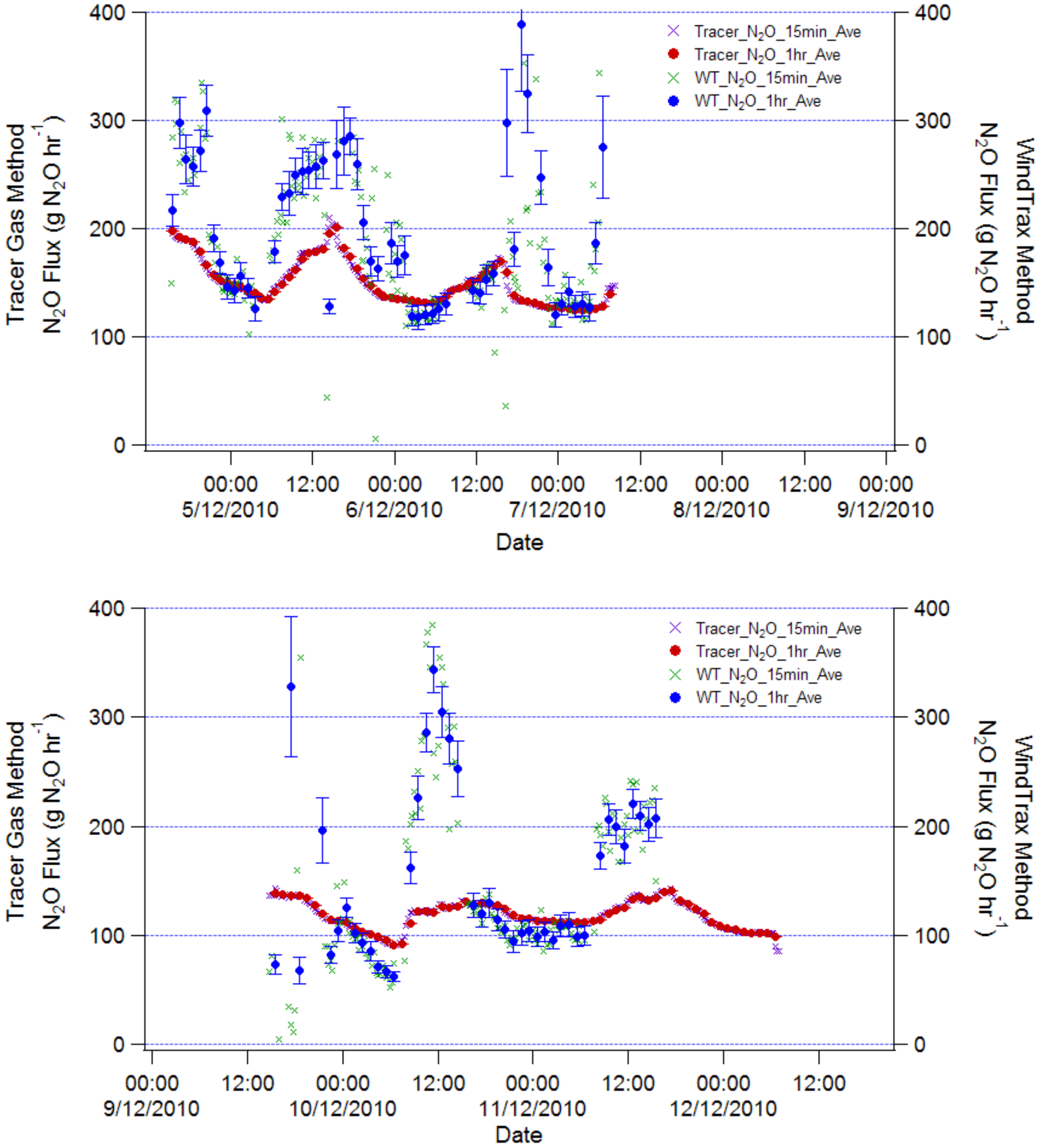


Figure 17: Comparison of the 15 minute and hourly averaged N_2O emission rates determined using Equation 4 for the OP Tracer Gas and WindTrax simulation shows that while the distribution of emissions is similar, the emissions and uncertainty are generally greater in data retrieved using the WindTrax bLs model. Upper Panel: Days 1-3, Lower Panel: Days 4-6

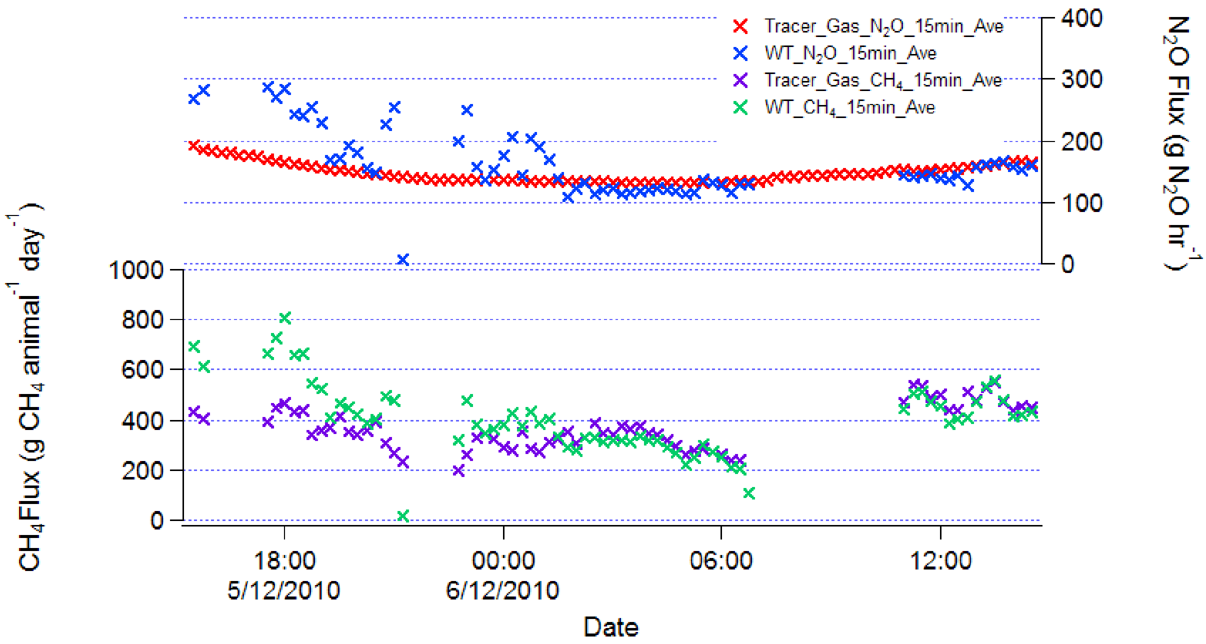


Figure 18: Expanded Day 2 15min averaged emission rate comparison for CH_4 and N_2O from OP Tracer Gas and bLs Wintrax. Emissions retrieved using WindTrax and that with a tracer-gas can be quite comparable, but at other times WindTrax can significantly over estimate in its emission rate calculation.

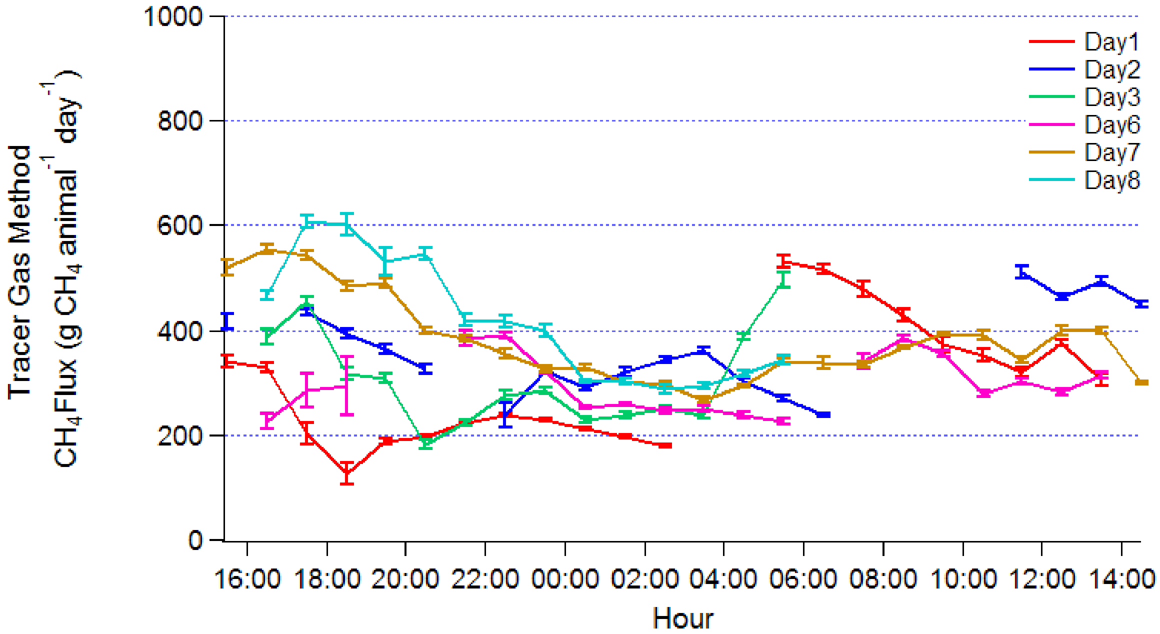


Figure 19: The data are the average of emissions from each hour. The distribution of CH_4 emissions over the day retrieved using the OP Tracer Gas show less variability and smaller uncertainty compared with emissions retrieved using WindTrax (Figure 20).

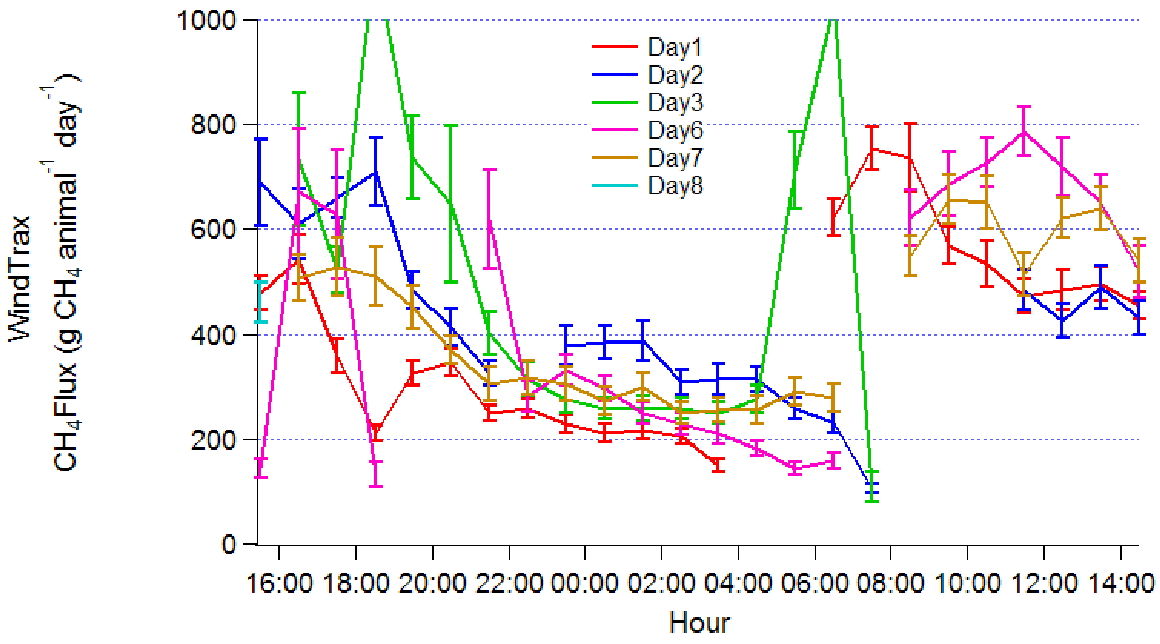


Figure 20: The data are the average of emissions from each hour. The distribution of CH_4 emissions over the day retrieved using the WindTrax model show greater variability and higher uncertainty compared with emissions retrieved using a tracer-gas (Figure 19).

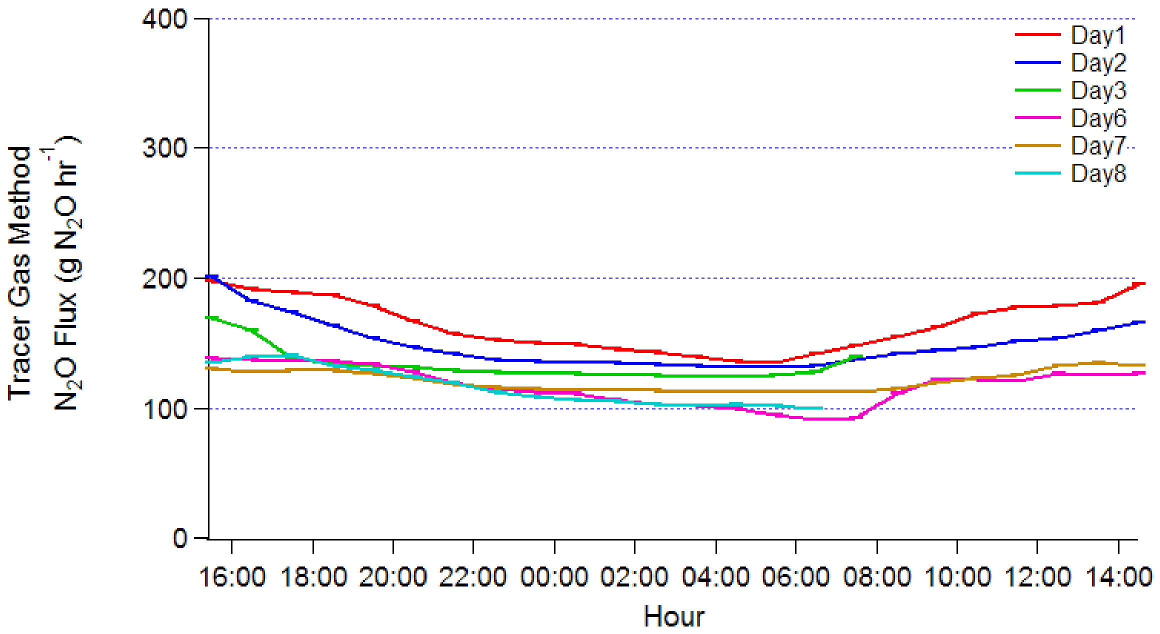


Figure 21: The data are the average of emissions from each hour. The distribution of N_2O emissions over the day calculated using Equation 4 for the OP Tracer Gas show less variability and much smaller uncertainty compared with emissions retrieved using WindTrax (Figure 22).

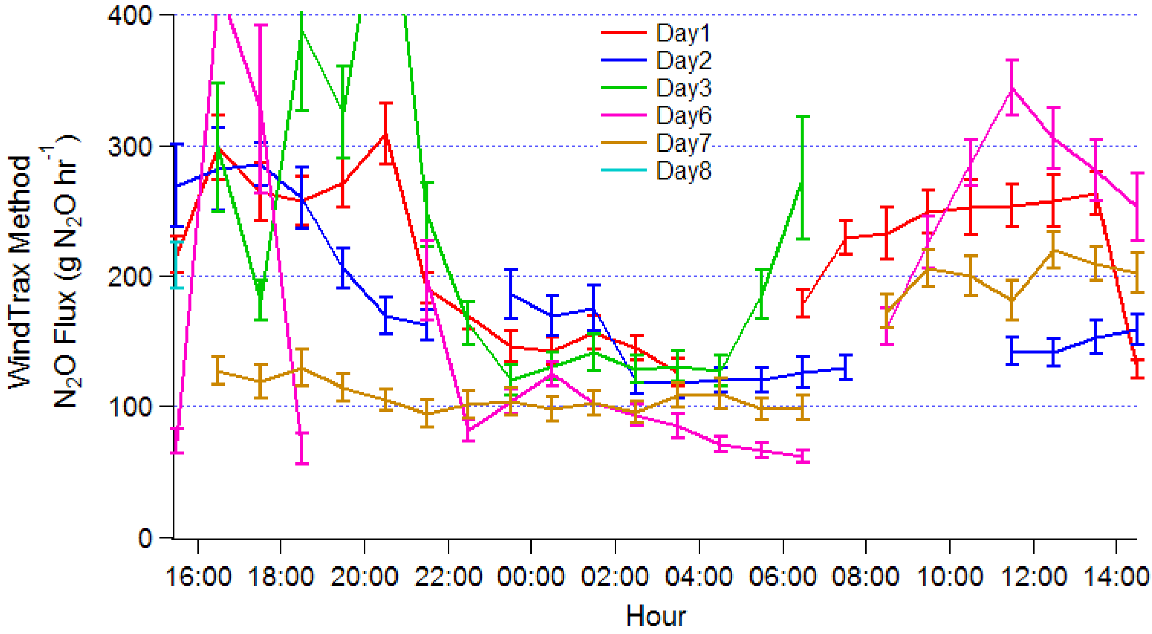


Figure 22: The data are the average of emissions from each hour. The distribution of N_2O emissions over the day retrieved using the WindTrax model show greater variability and higher uncertainty compared with emissions retrieved using a tracer-gas (Figure 21).

6. Discussion and Conclusion.

An objective of this project was to demonstrate the OP-FTIR technology to the research community. The available technologies to measure emissions from livestock in a grazing environment are limited and this project provided researchers with an understanding of the advantages and limitations of the technique and the requirements to obtain quality emissions data and allowed researchers to assess if the technique can be of an advantage within their research programs. This has been achieved with staff from four research institutes working alongside University of Wollongong staff during and with several staff trained in the operation of the equipment. An additional staff member has also been added to the UoW team and is now trained the operation of the system, increasing the expertise available to the research community.

University of Wollongong staff has demonstrated the operation of the technology at four Field days, one at each site, where the technology has generated considerably interest from primary producers and agri-business agents, and has featured in multiple articles in regional newspapers and producer journals. The University of Wollongong with the OP-FTIR measurement technique have also featured in the ABC program Landline, in association with DPI Victoria and an associated project.

Methane emissions have been measured from four animals systems using OP-FTIR technology including 2 sheep systems, beef cattle and dairy cattle providing directly comparable emission estimates (Table 3). With sheep, emissions from sheep grazing pasture typical of the sheep-wheat area of WA had the greatest emissions per animals while sheep grazing the high quality pasture on high fertility soils on the New England Tablelands showed the lowest emissions (Replicate 2). Emissions from sheep in the other systems were comparable. However until this data is compared with measures of production, live weight gain or feed intake, the differences cannot be confirmed as significant.

The accuracy of the flow rate of the N_2O tracer-gas is critical in deriving CH_4 emissions from the CH_4 and N_2O measured mixing ratios. The comparison of the loss of N_2O gas, as determined by weight and the loss calculated from the time-temperature dependent flow rate during measurements at Lansdown showed a difference of 0.5 to 3.5% in the emission rate. The canisters were weighed approximately mid way through the release period, when as the calculated flow rate is constrained at t=0 and t=final, the error is anticipated to be greatest. The comparison of the cumulative loss of gas during measurements at Terang was 5.9±3.4% for t>2h, however when the elapsed time was less then 2 hours the difference increased considerably. The comparison was compromised by the time required to weigh all canisters, with the error in t dominated the uncertainty and a more extensive comparison of individual canisters is warranted and will be completed.

Under favourable wind conditions and site geometry the variability in the individual emission estimates (3-minute time resolution) was typically < 10%, and highlighted the relationship between CH_4 production and animal behaviour. Typically emissions were highest in the mid morning decreasing in the afternoon, with a second but lower maximum in the early evening, with lowest production in the evenings, correlating with animal grazing patterns. In contrast emissions from the dairy cows increased dramatically from around 300 g CH_4 animal^{-1}day^{-1} before leaving the paddock, increasing to 600 g CH_4 animal^{-1}day^{-1} on returning from the dairy where they received supplementary feed. Emissions from sheep on the New England Tablelands increased dramatically when introduced to the pasture after being constrained at the yards with limited available feed, with emissions reducing to normal levels over the following 12 hours. Emissions from steers in northern Queensland were greatest when leaving the pasture to access water, decreasing over the following 5 hours from up to 200 to ~ 150 g CH_4 animal^{-1}day^{-1}.

Comparison of CH_4 emissions retrieved using the WindTrax bLs model with emissions retrieved using a tracer-gas indicates the bLs model over estimates the emissions. This is supported by the comparison of the N_2O emission retrieved using the bLs model and the calculated flow rate, with similar difference in the retrieved emissions for the two gases. The cause of this difference is to be investigated further however it is anticipated to be due to the bLs model incorrectly assuming the source of emissions is uniform over the paddock (or source) area. It has been shown that the distribution of animals close to the line sensor has greater impact on the retrieved emissions compared to the far side of the source area, and will result in an over or under estimate of the emissions with higher or lower animal density (Bai 2010). The similarity in the differences in N_2O and CH_4 emissions retrieved from the two methods offers an opportunity to constrain the WindTrax bLs model using the controlled release of a tracer-gas in the area of the animals.

6.1 Recommendations

The OP-FTIR system has been demonstrated to be a valuable technique to measure CH_4 emissions from grazing livestock with the precision required to quantify changes in emissions ~ 10% anticipated with many proposed mitigation strategies. However, as with all micrometeorological techniques, favourable wind conditions are essential, although the criteria are less restrictive as the wind statistical data do not have to be modelled. To achieve this sufficient measurement time must be allowed for non-favourable conditions. This was highlighted with the experiment to measure emissions from sheep on the New England Tablelands.

The project increased the number of OP-FTIR instruments available to UoW to three and 5 in Australia. The additional instrument increased the flexibility of the site design and reduced downtime. In comparing emissions from multiple groups of animals an additional instrument would allow for measurements in parallel, reducing time required in the field and therefore expense, but more importantly would allow comparison of emission under the same environmental conditions without compromising measurement time.

The project has also highlighted the importance of the geometry of the site in producing quality data, with longer instrument path lengths and narrower paddock width giving higher quality data for the same grazing area. Similarly it may be preferred to reduce the number of animals, reducing the grazing area required and the width of the paddock.

The University of Wollongong has commission the building of a scanning head for the OP-FTIR instrument, and is currently testing and refining the prototype design.

Table 3: CH_4 emission rate summary from all measurement sites

Location	**Animal**	**Treatment**	**CH_4 Emission Rate (g animal^{-1} day^{-1})**
Demo Dairy, Terang, VIC	Dairy Cows	Regional pasture + silage (Tracer Method)	350 ± 4
	Dairy Cows	Regional Pasture + Silage (WindTrax Method)	414 ±37
CSIRO Lansdown Research Farm, Townsville, QLD	Belmont Red Steers	Regional pasture	160 ± 3
UNE-I&I Trevenna Site, Armidale, NSW	Merino Ewes/ Cross Bred Lambs	Low Fertility Soils – Replicate 1	19.6 ± 0.6
	Merino Ewes/ Cross Bred Lambs	Low Fertility Soils – Replicate 2	21.1 ± 0.6
	Merino Ewes/ Cross Bred Lambs	High Fertility Soils – Replicate 1	15.5 ± 1.0
	Merino Ewes/ Cross Bred Lambs	High Fertility Soils – Replicate 2	19.5 ± 1.0
UWA Ridgefield Research Farm, Pingelly, WA	Merino Wethers	Regional Pasture	29.7 ± 0.6
	Merino Wethers	Bisserulla	20.0 ± 0.3

7. Bibliography

Bai M. 2010 Greenhouse Gas Emissions from Agriculture. *In* School Chemistry, Faculty of Science. pp 293. University of Wollongong.

Blaxter K. L.Clapperton J. L., 1965. Prediction of the amount of methane produced by ruminants. British Journal of Nutrition 19, 511-522.

Denmead O. T., 2004. Atmospheric dispersion of gases and odours from animal production systems. J. of Ag. Met. 60, 163-171.

Flesch T. K., Wilson J. D.Harper L. A., 2005. Deducing ground-to-air emissions from observed trace gas concentrations: A field trial with wind disturbance. J. Applied Met. 44, 475-484.

Johnson K., Huyler M., Westberg H., Lamb B.Zimmerman P., 1994. Measurement of methane emissions from ruminant livestock using a sulfur hexafluoride tracer technique. Env. Sci. & Tech. 28, 359-362.

Johnson K. A.Johnson D. E., 1995. Methane emissions from cattle. J. Anim. Sci. 73, 2483-2492.

Laubach J., 2010. Testing a Lagrangian model of dispersion in the surface layer with cattle methane emissions. Agr. For.Met. 150, 1428-1442.

Laubach J., Kelliher F. M., 2005a. Measuring methane emission rates of a dairy cow herd (II): results from a backward-Lagrangian stochastic model. Agr. For. Met. 129, 137-150.

Laubach J., Kelliher F. M., 2004. Measuring methane emission rates of a dairy cow herd by two micrometeorological techniques. Agri. For. Met. 125, 279-303.

Laubach J., Kelliher F. M., 2005b. Methane emissions from dairy cows: Comparing open-path laser measurements to profile-based techniques. Agri. For. Met. 135, 340-345.

Loh Z., Chen D., Bai M., Naylor T., Griffith D., Hill J., Denmead T., McGinn S., Edis R., 2008. Measurement of greenhouse gas emissions from Australian feedlot beef production using open-path spectroscopy and atmospheric dispersion modelling. Aust. J. Exp. Ag. 48, 244-247.

Moe P. W., Tyrrell H. F., 1979. Methane Production in Dairy Cows. J. Dairy Sci. 62, 1583-1586.