MEAT & LIVESTOCK AUSTRALIA

finalreport

Project code: FLOT.331

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Date published: November 2009

ISBN: 9781741918090

PUBLISHED BY

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NORTH SYDNEY NSW 2059

Greenhouse gas emissions from Australian beef cattle feedlots

Meat & Livestock Australia acknowledges the matching funds provided by the Australian Government to support the research and development detailed in this publication.

Abstract

The project was the first Australian study to measure greenhouse gas emissions from beef cattle feedlots using open-path spectroscopy and atmospheric dispersion modelling. The average methane (CH_4) emission was 113 g head^{-1} d^{-1}, about 40% lower than estimates using the standard Moe and Tyrrell model, but close to average estimates using the IPCC Tier II model. Thus, results support the use of IPCC Tier II for modelling CH_4 emissions in beef cattle feedlots. Average ammonia (NH_3) emission was 176 g head^{-1} d^{-1} (nearly three times IPCC Tier II modelled estimates), while average nitrous oxide (N_2O) emission was 3.3 g head^{-1} d^{-1} (half that of IPCC-modelled emissions). This suggests that the greater-than-expected volatilisation of NH_3 may have resulted in less-than-expected nitrogen remaining available for N_2O production via nitrification-denitrification. Indirect N_2O emissions from land-deposited NH_3 and NO_x may be substantial (an additional 75% of the direct N_2O emissions). Thus the total greenhouse contribution of N_2O emissions (in CO_2-e) was estimated at 60% of the feedlot CH_4 emission. Average carbon dioxide (CO_2) emission was 12.9 kg head^{-1} d^{-1}. This is somewhat higher than modelled estimates, although livestock-respired CO_2 is not considered a net anthropogenic greenhouse gas emission.

Executive Summary

The project objectives were:

1. To provide measures of greenhouse gases, methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2), as well as ammonia (NH_3), from two beef cattle feedlots, representative of Australian production systems, which can then be used to update the current livestock emission accounting system.

2. To demonstrate the link between various intensive livestock management practices and their influence on greenhouse gas emissions, thereby improving our understanding of the potential for management of total greenhouse gas emissions from the feedlot production system.

3. To develop enhanced Australian capability in quantification of greenhouse gas emissions from agricultural production systems.

The project employed a combination of open-path (OP) spectroscopy and micrometeorology, in a backward Lagrangian Stochastic (bLS) dispersion model, to calculate emissions of CH_4, NH_3, N_2O and CO_2, from two beef cattle feedlots, over two-week measurement periods, during two summer and two winter seasons. Gas concentration measurements were made with an OP Fourier-transform infrared (FTIR) spectrometer (all four gases), and four Boreal OP lasers (CH_4 and NH_3). Micrometeorological measurements were made with a CSAT three-dimensional sonic anemometer. The bLS dispersion model was facilitated by use of the WindTrax program. Supplementary, long-term measurements of NH_3 and oxides of nitrogen (NO_x), using a self-contained system of rack-mounted trace gas analysers (EcoTech), were carried out subsequent to the campaigns. Emissions measured by the OP methodology were compared with currently-used biophysical animal models.

Average CH_4 emission was 113 g head^{-1} d^{-1}, considerably less (about 40%) than estimates by the Moe and Tyrrell model, currently used in Australia for beef cattle methane emissions. The measured average was much closer to the average estimate by the IPCC Tier II model, at 104 g head^{-1} d^{-1}. These results support the use of the IPCC Tier II model in preference to Moe and Tyrrell for estimation of methane emissions in beef cattle feedlots in Australia. The diurnal pattern of methane emission was characterised by higher emissions in the evening and immediately following feeding times, probably associated with increased animal eructation.

A strong interaction between main effects demonstrated that site and season alone were not sufficient to describe the variation of methane emission. Results suggest differences in emissions of CH_4 between sites and seasons were indirectly related to ration type and environmental conditions.

Methane emission from effluent ponds was 9 kg ha^{-1} d^{-1} to 22 kg ha^{-1} d^{-1} from a limited sample. Emissions from empty cattle pens and manure piles were not quantified separately. For future studies, additional gas analysers (sensors), operating simultaneously across the feedlot, would assist in the relative quantification of different CH_4 sources.

Average NH_3 emission was 176 g head^{-1} d^{-1}. This was almost three times greater than estimates by the IPCC Tier II model (63 g head^{-1} d^{-1}). Measured emissions of N_2O averaged 3.3 g head^{-1} d^{-1}, about half that of the IPCC Tier II modelled estimate of 6.5 g head^{-1} d^{-1}. Thus, greater-than-expected

volatilisation of NH_3 may have resulted in less-than-expected formation of N_2O, because less-than-expected ammonified nitrogen remained in the soil/manure for subsequent nitrification-denitrification to N_2O. High NH_3 volatilisation and NO_x emissions suggested that indirect N_2O emissions from beef cattle feedlots may be substantial (about 75% of the direct N_2O emissions). Therefore, total (direct and indirect) N_2O emissions from the feedlot amount to about 5.8 g $head^{-1}$ d^{-1}, or a greenhouse contribution equivalent to 60% of feedlot CH_4 emissions (in terms of CO_2-e).

Diurnal variation in both NH_3 and N_2O emissions were characterised by a maximum in the middle of the day, probably associated with generally higher temperatures (increased vapour pressure), and greater wind-speed (increased rate of diffusion).

The strong interaction between site and season for both NH_3 and N_2O was not clarified by closer examination of animal live-weight and diet, as was the case with methane. Results suggest that the current inventory method for predicting nitrogenous gas emissions is unable to accurately estimate emissions. Environmental and manure pad conditions probably have a greater influence on emissions of N_2O and NH_3 than ration types and animal characteristics.

NH_3 emission from effluent ponds was estimated at 13 to 33 kg ha^{-1} d^{-1}. As for methane, emissions from empty pens and manure piles could not be quantified separately, but it seems likely that episodic emissions of NH_3 from empty pens contributed to high emission peaks, particularly during summer 2008 at Feedlot B.

Carbon dioxide (CO_2) emissions averaged 12.9 kg $head^{-1}$ d^{-1}, somewhat higher than estimated emissions by the IPCC Tier II model, and also higher than other measurements in the literature. While livestock-respired CO_2 is not considered a net anthropogenic greenhouse gas emission, because it is recycled carbon, the relative balance between CO_2 and CH_4 is of interest.

The study compared measured values with modelled estimates of greenhouse gas and NH_3 emissions from beef cattle feedlots in Australia. The current Australian methodology (Moe and Tyrrell, 1979) resulted in an overestimation of enteric CH_4 emissions, while IPCC Tier II methodology provided a closer estimate of emissions for Australian feedlot systems. Measured ammonia emissions were considerably greater than modelled estimates, while measured N_2O emissions were much less. Site and season alone were not very informative factors for model estimates of these two gases, and more information on fine-scale environmental and biological processes may improve prediction of NH_3 and N_2O emissions from beef cattle feedlots.

Open-path spectroscopy and bLS modelling proved to be a useful approach for determining gas emissions from Australian beef cattle feedlots. The assumption of homogeneity of the source area, implicit in the WindTrax model, remains a potential source of error, particularly at low stocking, where many of the pens have no cattle. The ability of the WindTrax model to resolve emissions from multiple different sources simultaneously was limited by the number of instruments (sensors) deployed across the feedlot at different times. More instruments, running for longer periods would improve the discrimination between different emission sources within a large feedlot.

Long-term monitoring of NH_3 and NO_x emissions, using a trace gas station (TGS), proved an effective method of capturing seasonal variation of emissions of NH_3 in particular. Properly maintained and centrally located, the TGS will be a valuable tool for year-round studies of NH_3 emission, and its subsequent dispersion and deposition.

Contents

1 Background

In Australia, beef cattle account for an estimated 58% of livestock greenhouse gas (GHG) emissions (ALFA, 2008), 40% of agricultural sector emissions and 7% of total national emissions (DCC, 2009). Lot-fed beef cattle spend their last 75 to 250 days in the feedlot, prior to market (DCC, 2009). Therefore, of a national beef cattle population of about 28.8 million, some 680 000 animals are on a feedlot at any one time (ALFA, 2008). Grain-fed beef cattle have lower enteric methane (CH_4) emissions than grass-fed beef cattle on a per kg weight-gain basis (ALFA, 2008) and yet, because of the much higher absolute weight-gain associated with feedlot finishing diets, greater emissions on a per head per day basis (DCC, 2009). Thus, beef cattle feedlots account for an estimated 3.5% of livestock GHG emissions (ALFA, 2008), 2.4% of agricultural emissions or 0.4% of total national emissions, and are a minor, but significant source of GHG emissions within the agricultural sector.

Feedlots are a highly managed system where dietary mitigation strategies can be implemented without a great change in management. In addition cattle-pad and manure management sources of CH_4 and nitrous oxide (N_2O), while minor compared with enteric CH_4 emissions, are much more intensive and quantifiable in the feedlot compared with broad-acre grazing (DCC, 2009).

In Australia, emissions of enteric CH_4 are generally estimated using the Blaxter and Clapperton (1965) model for free range cattle, and the Moe and Tyrrell (1979) model for feedlot cattle (DCC, 2009). Emissions of CH_4 and N_2O associated with manure management are generally estimated with IPCC Tier II methods (IPCC 2006).

This was the first Australian study to use open-path spectroscopy and micrometeorology to quantify GHG emissions from beef cattle feedlots, and to compare the field measurements with estimates derived from the commonly used models, Blaxter and Clapperton (1965), Moe and Tyrrell (1979) and IPCC Tier II (2006).

2 Project Objectives

The project objectives were:

1. To provide measures of greenhouse gases, methane (CH_4) and nitrous oxide (N_2O), as well as ammonia (NH_3), from two feedlots, representative of Australian production systems, which can then be used to update the current livestock emission accounting system.

2. To demonstrate the link between various intensive livestock management practices and their influence on greenhouse gas emissions, thereby improving our understanding of the potential for management of total greenhouse gas emissions from the feedlot production system.

3. To develop enhanced Australian capability in quantification of greenhouse gas emissions from agricultural production systems.

3 Methodology

The project used a micrometeorological approach based on measurements of gas concentrations with open and closed path gas analysis and a backward Lagrangian Stochastic (bLS) dispersion model to calculate CH_4, NH_3, N_2O and CO_2 emissions from beef cattle feedlots. This methodology has been successfully used to measure greenhouse gas emissions from beef cattle feedlots elsewhere in the world (Flesch et al., 2005, 2007; Laubach and Kelliher, 2005; McGinn et al., 2006), but this was the first such Australian study.

3.1 Field sites

Two feedlots, representative of Australian beef cattle feedlots, were selected for the study. Feedlot A was a southern site located near Charlton, Victoria (36°21'41" S, 143°24'5" E), while Feedlot B was a northern site located near Dalby, Queensland (27°8'14" S, 151°26'3" E). Data were collected during eight 2-week field campaigns at the two sites, in summer and winter, of two consecutive years (Table 1). Feedlot A has a maximum capacity of 20 000 head, but was operating at between 13 000 and 18 000 head at the time of the four field campaigns. Feedlot B has a maximum capacity of about 17 000 head, but was operating between maximum capacity (16 800) and as low as one third of capacity (6 200) over the four field campaigns.

Table 1: Sampling period, number of head and proportion of cattle pens occupied during eight field campaigns at two beef cattle feedlots, Feedlot B and Feedlot A, during winter 2006, summer 2007, winter 2007 and summer 2008.

Campaign			start	end	# head	pen area (ha)		
						occupied	empty	total
2006	winter	Feedlot B	24-Aug	31-Aug	16817	25.2	0.4	25.6
		Feedlot A	1-Aug	10-Aug	18092	22.0	1.7	23.7
2007	summer	Feedlot B	29-Jan	8-Feb	13583	25.1	0.4	25.6
		Feedlot A	19-Feb	1-Mar	16713	22.7	1.0	23.7
2007	winter	Feedlot B	3-Sep	8-Sep	10681	18.6	7.0	25.6
		Feedlot A	1-Aug	10-Aug	13074	21.8	1.9	23.7
2008	summer	Feedlot B	31-Jan	7-Feb	6192	13.7	11.9	25.6
		Feedlot A	25-Feb	5-Mar	12926	20.8	2.9	23.7

During each campaign four different source areas were distinguished, occupied cattle pens, empty cattle pens, manure stockpiles and effluent ponds (Figure 1).

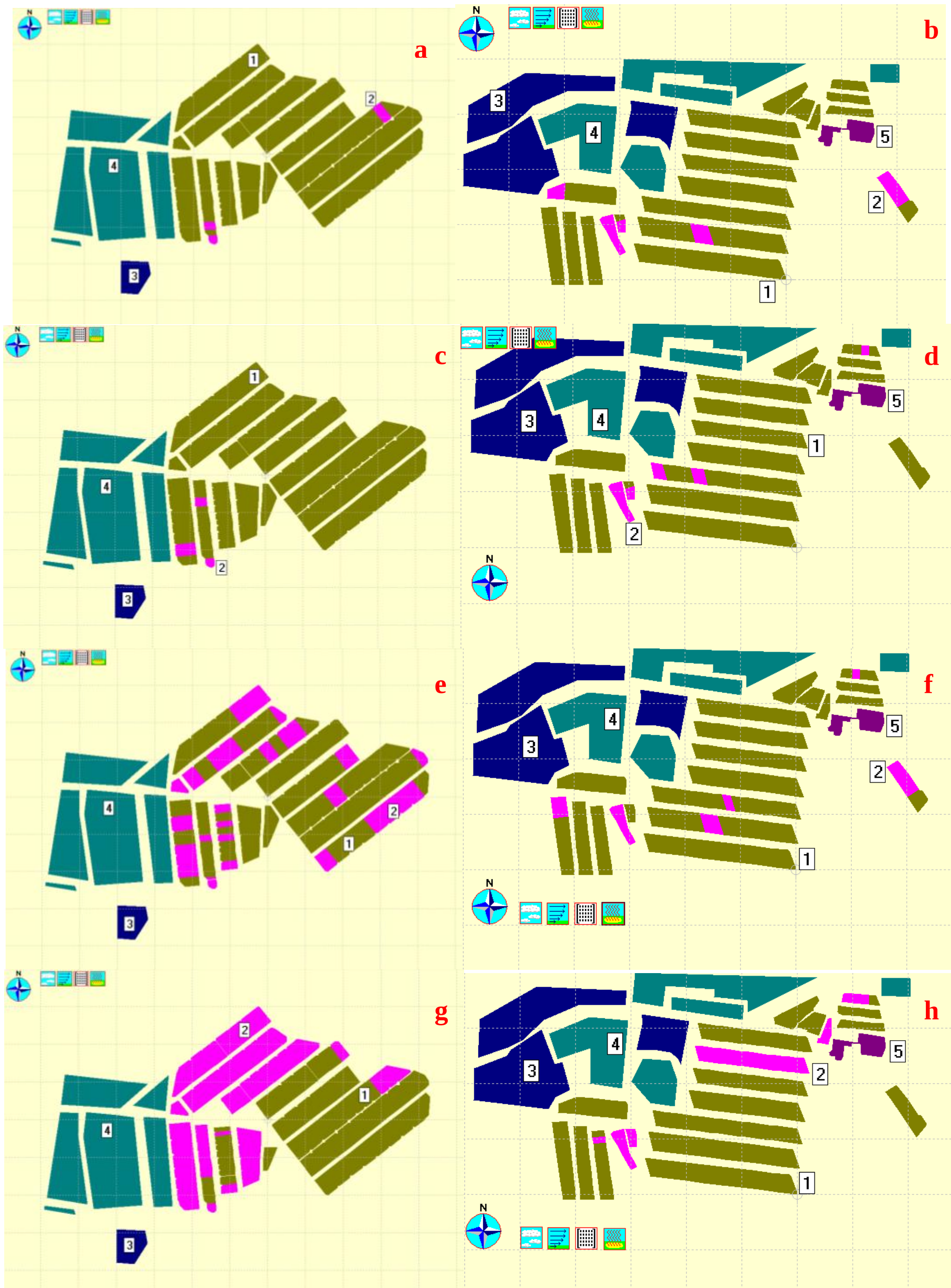

Figure 1: WindTrax projects of eight field campaigns: (a) Feedlot B winter 2006, (b) Feedlot A winter 2006, (c) Feedlot B summer 2007, (d) Feedlot A summer 2007, (e) Feedlot B winter 2007, (f) Feedlot A winter 2007, (g) Feedlot B summer 2008 and (h) Feedlot A summer 2008. Source areas are colour-coded depicting (1) occupied cattle pens - olive source area, (2) empty cattle pens - pink source area, (3) manure piles - blue source area, (4) effluent ponds - teal source area, and (5) a feed processing plant - purple source area (Feedlot A only).

3.2 Open-path spectroscopy

An open-path mid-infrared Fourier Transform Infrared (OP-FTIR) spectrometer constructed by the University of Wollongong measured CH_4, CO_2, N_2O and NH_3 simultaneously (Plate 1). Two open-path (OP) methane lasers and two OP ammonia lasers (GasFinder2.0, Boreal Laser Inc, Edmonton, Alberta, Canada) measured CH_4 and NH_3 (Plate 2).

Plate 1: Open-path Fourier Transform Infrared (OP-FTIR), including Bomem spectrometer, in the field at Feedlot A.

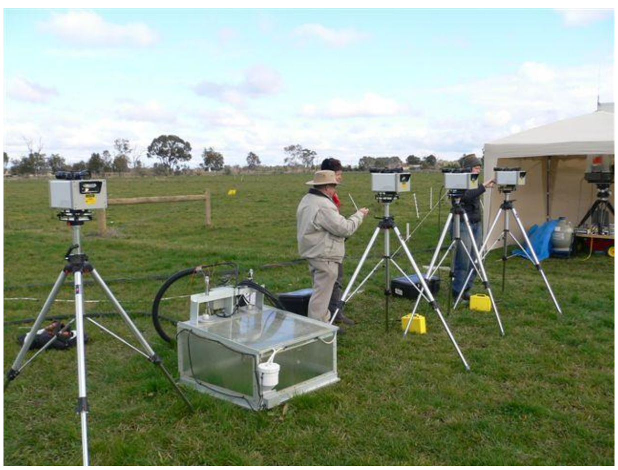

Plate 2: Open-path lasers in the field at Feedlot A.

In the initial days of each campaign, a period of calibration was carried out, when OP lasers were arranged side by side with the OP-FTIR (Plate 3), measuring the same gas over the same path length (Figure 2b). Thus, cross-calibration enabled all gas concentrations to be expressed on the same scale using the OP-FTIR spectrometer as the standard, reducing between-instrument variation. Following initial side-by-side calibration, OP spectroscopic instruments were placed strategically across the feedlot during each 2-week campaign, to measure line-averaged gas concentrations at a range of locations (Figure 2c - e). Line-averaged concentrations for each gas by each instrument were averaged over 15-minute periods throughout each campaign.

Plate 3: Side by side calibration of OP lasers and OP-FTIR, including Bruker spectrometer, in the field at Feedlot A.

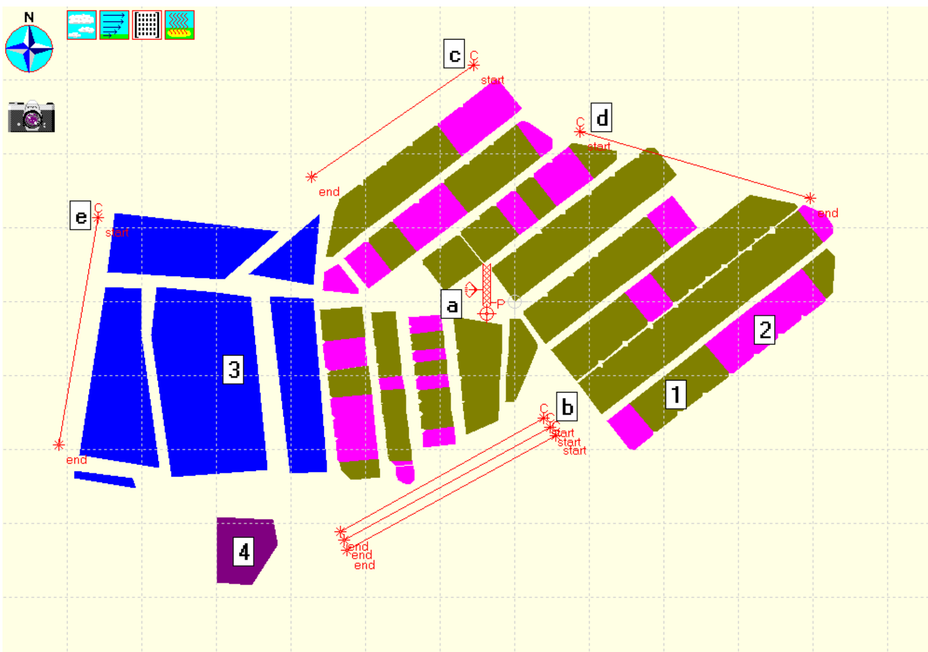

Figure 2: An example WindTrax project screen depicting the Feedlot B (1) occupied cattle pens - olive source area, (2) empty cattle pens - pink source area, (3) effluent ponds - blue source area, (4) manure piles - purple source area, (a) central location of micrometeorological station with 3D sonic anemometer, (b) initial arrangement of OP-FTIR side-by-side with OP lasers for preliminary calibration, (c,d) subsequent location of OP lasers to measure cattle-pen gas-flux from different vantage points, (e) subsequent location of OP lasers to measure effluent pond gas-flux.

3.3 Micrometeorology

A micrometeorological station (Plate 4), including a CSAT three-dimensional sonic anemometer, (Plate 5), an OP gas analyser (Licor 7200) and a data logger (CR5000, Campbell Scientific, Logan, UT, USA); recorded wind speed, wind direction, and surface heat flux, at a central location on the feedlot (Figure 2a). From these data, turbulence statistics including Monin-Obhukov length (L), friction velocity (u*) and surface roughness (z_0), were calculated to characterise atmospheric dispersion and turbulence across the feedlot. These data were averaged over 15-minute time intervals, to coincide with the line-averaged gas concentration data from the sensors.

Plate 4: Micrometeorological station in the field at Feedlot A.

Plate 5: Detail of three-dimensional sonic anemometer and infrared gas analyser on micrometeorological station.

3.4 Atmospheric dispersion modelling

Atmospheric dispersion modelling was carried out using the bLS model as described by Flesch et al. (2004). Its application was facilitated by the use of WindTrax software package (Thunder Beach Scientific, Nanaimo, BC, Canada). Four source areas were identified and located in the feedlots, including occupied cattle pens, empty cattle pens, effluent ponds, and manure piles. Source areas and OP gas analysers (sensors), were geospatially referenced in the WindTrax model (Figure 2). Using a backward Lagrangian Stochastic (bLS) method (Flesch et al., 2004), WindTrax estimated CH_4, NH_3, N_2O and CO_2 fluxes from source areas, modelling back from the line-averaged gas concentrations at the sensors, via atmospheric dispersion and turbulence patterns defined by the micrometeorological data, to flux estimates from the source areas. Backward-modelled touchdowns define the source area from which emissions came, resulting in the measured concentrations at each sensor, during each 15-minute interval (Figure 3). The modelling process was repeated for all instruments and gases, over all time intervals, in all campaigns. In addition, for CH_4 and NH_3, average gas fluxes were determined from a combination of instruments (two OP lasers and the OP-FTIR), when multiple flux measurements from multiple instruments were available in each 15-minute interval.

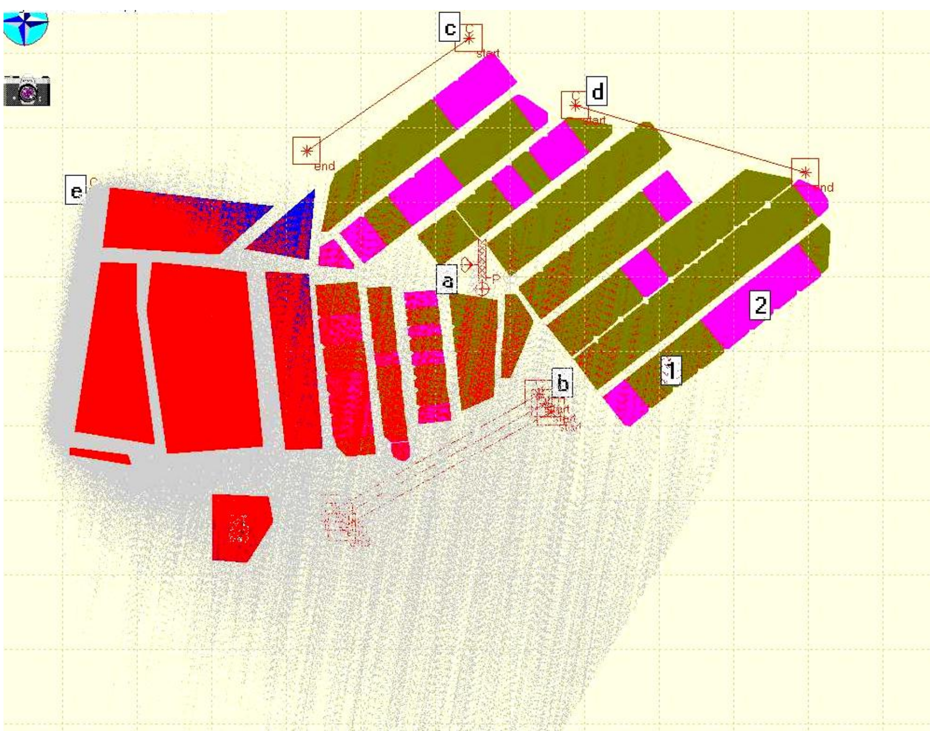

Figure 3: An example of a WindTrax project screen depicting backward Lagrangian Stochastic (bLS) modelling of gas flux from a single sensor, during a single 15-minute period. Gas-flux is estimated as the rate of gas emission ($\mu g_{GAS}.m^{-2}.s^{-1}$) from the contributing source area (the footprint of red touchdowns) that would have resulted in the measured gas concentration at the sensor (e), given the prevailing wind speed, wind direction and turbulence measured by the micrometeorological station (a).

Filtering criteria were applied to remove unreliable data, following Flesch et al. (2007). Data for removal included Boreal laser data where the light signal intensities were less than 1800 or greater than 13000, or where the coefficient of variation (r^2) was less than 0.50. Meteorological data for removal included the following; absolute Monin-Obukov Length (|L|) < 10 (i.e., -10>L<10); surface roughness (z_0) < 0 m or z_0 > 0.9 m; friction velocity (u*) < 0.15. WindTrax flux estimates that had a footprint of less than 10% of the source area were removed.

3.5 Statistical analysis

Analysis of variance (ANOVA) of emissions due to campaign (year, season and site) and diurnal variation (hour within campaign) were tested using general linear models in SAS (v9.1.3, SAS Institute Inc., NC, USA) by the ordinary least-squares method. Prior to ANOVA, data were transformed by natural log, to meet the assumption of homoscedasticity. Transformed data with a residual (actual-predicted) value, more than 3 standard deviations greater than, or less than, the mean were removed as outliers, to meet the assumption of standard normal distribution.

3.6 Long-term monitoring with trace gas station

In order to extend the emissions database to define more clearly the daily and seasonal cycles, a trace gas station (TGS) was employed for monitoring trace gas concentrations, which can run with minimal attention for long periods. An account of the TGS and its operation has been given by Denmead et al. (2008). Combined with the micrometeorological station, the TGS provides a means of extending emission measurements for indefinite periods. In 2008, it was employed at the Feedlot A to measure fluxes of NH_3 and the oxides of nitrogen (NO_x) over a period of 187 days, covering autumn and winter. Although not included in the original plans for the project, the use of the TGS more than doubled the database of NH_3 and NO_x emissions.

The TGS, manufactured by Australian firm Ecotech, comprises a CH_4/non-CH_4 hydrocarbon analyser, a chemiluminescence NH_3 analyser, a trace-level chemiluminescence NO-NO_2-NO_x analyser, and trace-level UV fluorescence SO_2 and H_2S analysers, rack-mounted in an air-conditioned cabinet which, in turn, is mounted on a trailer for transport (Plate 6). Only the NH_3 and NO_x analysers were employed in the present study. Ancillary equipment includes chemical scrubbers and converters, pumps and plumbing to service all the analysers simultaneously, a switching system to allow measurement on air samples from different points in the atmosphere, a computer for data logging and storage, and an automatic calibration system. In our operation, the system provides 1-min averaged concentrations and switches air streams at pre-determined intervals. Unlike the open-path instruments employed in campaign mode, the TGS analysers are closed-path, providing concentration measurements at a point in space rather than line-averaged concentrations. Thus the air samples they analyse have been subject to emissions from a smaller part of the feedlot than those analysed by the open-path instruments whose paths of measurement are hundreds of m long. For the TGS, air is drawn from intakes at heights of 1.5 m and 3.2 m above the ground at a location within or beside the feedlot and the two air streams are switched at 7½-min intervals. The station is mains-powered, which is a limitation on its use in remote locations.

The only available power outlet at Feedlot A was on the feedlot perimeter in the south east sector. This limited the data available for analysis since the winds often blew from the east, south-east and south. However, winds blowing from these directions provided opportunities to measure the background atmospheric gas concentrations of NH_3 and NO_x, which were required for data analysis. The background concentration for NH_3 was set consequently at 5 ppb and that of NO_x at 1 ppb. Some 18,016 15-min runs were made, but with down time due to problems with the power supply and unfavourable wind directions, the number of runs available for analysis was reduced to 5,633. In these runs, NH_3 concentrations typically exceeded 1000 ppb and NO_x 10 ppb. Emission rates were calculated by application of the bLS technique using the software package WindTrax as described elsewhere in the report. The available data were filtered for wind directions between 0° and 190°; the number of touchdowns in the feedlot in the footprint of the TGS, using alternative cut-off coverages of 1% and 2% of the feedlot area (smaller than the requirement of ≥ 10% coverage for our open-path measurements); low turbulence levels, with a cut-off for the friction velocity of 0.1m s^{-1}; and periods of intense atmospheric stability and instability affecting the turbulence, with cut-offs for Monin-Obukhov stability lengths (L) between 10 and -10 m. Filtering for a coverage ≥ 2% or more of the feedlot area reduced the number of available runs to 4549 which was still some 30 times the number of runs available in a typical summer or winter campaign.

Plate 6: Rack-mounted gas analysers in the air-conditioned TGS cabinet.

3.7 Biophysical emission models

A number of mathematical models attempt to predict enteric CH_4 output, as well as emissions of CH_4, N_2O and NH_3 from manure. The models used here are primary empirical, and attempt to associate gaseous emissions with dietary factors. The biophysical model utilises 3 equations for the prediction of enteric methane emissions, Blaxter and Clapperton (B&C; 1965), Moe and Tyrrell

(M&T; 1979) and IPCC Tier II. The IPCC Tier II is used for beef cattle in the United States; however the Australian methodology uses M&T for feedlot cattle.

The equation of Blaxter and Clapperton (1965) utilises the ration digestibility and intake of the animal to calculate a proportion of the gross energy contained in the diet which is converted to methane. Similarly the IPCC Tier II methodology uses a set value to represent the proportion of gross energy which is emitted as methane. For feedlot cattle, this value is 3%. The equation of Moe and Tyrell (1979), in contrast, uses the proportions of different carbohydrate fractions in the ration and calculates the methane output of each fraction. M&T may be more adaptable for high grain diets and therefore thought to representative of feedlot diets. However, it was originally developed from work on dairy cows offered moderate to high levels of grain in rations based on conserved forages (soluble reside range from 180 to 540 g/kg DM). B&C (derived in sheep) is used in a number of national inventories, and for dairy and grazing beef cattle in the Australian methodology.

Methane emissions from manure are estimated using IPCC methods for prediction from volatile solids with country specific emissions adjustments (warm vs. temperate region) made. These models also estimate emissions of N_2O and NH_3 based on partitioning of nitrogen within the animal, nitrogen excretion and proportion of excreted nitrogen as N_2O and NH_3.Standard SCA models are used to predict nitrogen balance in the animal based on intake of nitrogen (as crude protein) and growth (increase in animal nitrogen content in the form of protein).

Each of these equations requires specific inputs, primarily the ration composition, but also animal intakes, live weights and growth rates. The biophysical model used here was designed to use data collected from feedlot operations in the form of lot or bunk sheets to calculate gaseous emissions. This part of the study was designed to evaluate the effectiveness of the different models in predicting emissions and also compares the usefulness of the model in Northern Hemisphere studies to the current study.

4 Results and Discussion

Temperatures were generally higher at Feedlot B than Feedlot A, in both winter and summer (Table 2). Feedlot A was a generally windier site than Feedlot B (with stronger gusts). Feedlot A received less rainfall than Feedlot B, and predominantly winter rainfall, compared with more (predominantly summer) rainfall at Feedlot B.

Table 2: Prevailing weather conditions (average minimum daily temperature, average maximum daily temperature, total rainfall, average daily wind speed, average daily wind gust speed, average minimum daily relative humidity, average maximum daily relative humidity), during eight field campaigns at two beef cattle feedlots, Feedlot B (Queensland) and Feedlot A (Victoria), during winter 2006, summer 2007, winter 2007 and summer 2008.

Campaign		start	end	average daily temperature (°C)		total rainfall (mm)	average daily windspeed (km/h)		average daily relative humidity (%)	
				min	max		mean	gust	min	max
2006 winter	Feedlot B	24-Aug	31-Aug	12.3	25.3	4.4	8.1	18.0	31.8	70.4
	Feedlot A	1-Aug	10-Aug	3.3	15.2	2.0	6.7	29.6	49.3	89.8
2007 summer	Feedlot B	29-Jan	8-Feb	19.1	34.4	7.4	9.2	19.9	23.5	71.8
	Feedlot A	19-Feb	1-Mar	17.9	31.8	0.0	12.6	45.5	24.6	77.6
2007 winter	Feedlot B	3-Sep	8-Sep	10.4	18.9	23.6	7.4	17.3	48.5	83.7
	Feedlot A	1-Aug	10-Aug	4.7	19.7	4.4	4.2	32.7	63.1	90.5
2008 summer	Feedlot B	31-Jan	7-Feb	19.0	29.7	61.4	11.8	32.5	48.1	71.3
	Feedlot A	25-Feb	5-Mar	12.0	26.7	0.2	10.8	37.0	17.7	68.2

Emissions of CH_4, NH_3, N_2O and CO_2, during each campaign, are presented in g head^{-1} d^{-1} (Table 3), and kg ha^{-1} d^{-1} (Table 4). Emissions of all gases are presented in both per head and area-based units for purposes of comparison with each other and with the literature. However, as NH_3 and N_2O are not direct animal emissions, but occur via soil/pad processes following excretion, per head emissions of these gases (Table 3) are not a direct measure of efficiency of N utilisation in the animals. Emissions from different sources (occupied pens, unoccupied pens, effluent ponds and manure stockpiles) were not distinguishable due to a limited number of sensors. Therefore the results presented are “whole feedlot” emissions, attributed to the cattle (g head^{-1} d^{-1}, Table 3) or occupied pens (kg ha^{-1} d^{-1}, Table 4), but are derived from all potential sources.

Table 3: Means and standard errors of per-head emissions (g head^{-1} d^{-1}) of CH_4, NH_3, N_2O and CO_2 during eight field campaigns, measured by different instruments. Field campaigns were carried out at two beef cattle feedlots, Feedlot B (Queensland) and Feedlot A (Victoria), during winter 2006, summer 2007, winter 2007 and summer 2008. Measurements of CH_4 and NH_3 were made by three separate instruments (two open-path lasers and an open-path FTIR) as well as by all three instruments in concert (multi). CO_2 and N_2O measurements were made by the open-path FTIR only.

Campaign			Gas	CH_4				NH_3				N_2O	CO_2
			Instrument	laser 12	laser 13	FTIR	multi CH_4	laser 15	laser 16	FTIR	multi NH_3	FTIR	FTIR
2006	winter	Feedlot B	mean	**187.5**	**163.0**	**159.2**	**131.5**	**214.7**	**197.2**	**179.2**	**143.1**	**1.6**	**12889**
			std error	4.8	5.8	7.9	4.7	9.0	10.1	10.4	7.6	0.1	538
		Feedlot A	mean	**104.7**	**92.5**	**93.8**	**98.9**	**168.3**	**142.9**	**135.1**	**151.4**	**5.3**	**13298**
			std error	4.2	5.1	4.0	2.8	11.9	7.9	7.8	5.6	0.6	579
2007	summer	Feedlot B	mean	**72.8**	**158.2**	**105.2**	**127.4**	**112.5**	**140.3**	**136.0**	**133.2**	**3.6**	**22055**
			std error	2.6	7.3	3.7	3.0	4.7	2.7	4.9	2.8	0.2	894
		Feedlot A	mean	**139.1**	**118.9**	**118.1**	**127.8**	**144.3**	**160.9**	**138.4**	**153.0**	**2.5**	**10529**
			std error	5.8	4.4	4.6	3.2	7.1	6.6	5.4	4.3	0.2	344
2007	winter	Feedlot B	mean	**147.3**	**134.4**	**131.2**	**138.3**	**93.5**	**91.6**	**89.4**	**94.0**	**5.7**	**13447**
			std error	4.9	3.6	3.8	3.7	3.7	2.8	3.1	2.8	0.2	339
		Feedlot A	mean	**78.3**	**116.4**	**126.0**	**122.8**	**309.3**	**278.9**	**271.1**	**305.1**	**0.1**	**5072**
			std error	1.7	1.3	2.2	1.6	5.2	4.5	5.3	5.0	0.0	214
2008	summer	Feedlot B	mean	**79.4**	**137.7**	**117.1**	**63.8**	**384.9**	**395.2**	**381.1**	**324.4**	**4.8**	**16746**
			std error	16.3	79.0	58.6	14.8	66.1	69.1	211.7	34.7	4.6	9265
		Feedlot A	mean	**121.4**	**101.4**	**83.9**	**91.0**	**124.6**	**119.5**	**105.3**	**102.0**	**2.5**	**8844**
			std error	2.1	1.9	1.6	1.5	6.3	3.9	3.7	3.1	0.2	154
All Campaigns			average	**116.3**	**127.8**	**116.8**	**112.7**	**194.0**	**190.8**	**179.4**	**175.8**	**3.3**	**12860**

Table 4: Means and standard errors of area-based emissions (kg ha^{-1} d^{-1}) of CH_4, NH_3, N_2O and CO_2 during eight field campaigns, measured by different instruments. Field campaigns were carried out at two beef cattle feedlots, Feedlot B (Queensland) and Feedlot A (Victoria), during winter 2006, summer 2007, winter 2007 and summer 2008. Measurements of CH_4 and NH_3 were made by three separate instruments (two open-path lasers and an open-path FTIR) as well as by all three instruments in concert (multi). CO_2 and N_2O measurements were made by the open-path FTIR only.

Campaign			Gas	CH_4				NH_3				N_2O	CO_2
			Instrument	laser 12	laser 13	FTIR	multi CH_4	laser 15	laser 16	FTIR	multi NH_3	FTIR	FTIR
2006	winter	Feedlot B	mean	**125.1**	**108.8**	**106.3**	**87.8**	**143.3**	**131.6**	**119.6**	**95.5**	**1.1**	**8601**
			std error	3.2	3.9	5.3	3.1	6.0	6.7	7.0	5.1	0.1	359
		Feedlot A	mean	**85.9**	**75.9**	**77.0**	**81.2**	**138.2**	**117.3**	**110.9**	**124.2**	**4.4**	**10913**
			std error	3.4	4.2	3.3	2.3	9.8	6.5	6.4	4.6	0.5	475
2007	summer	Feedlot B	mean	**39.3**	**85.5**	**56.8**	**68.9**	**60.8**	**75.8**	**73.5**	**72.0**	**2.0**	**11916**
			std error	1.4	3.9	2.0	1.6	2.6	1.5	2.6	1.5	0.1	483
		Feedlot A	mean	**102.5**	**87.6**	**87.0**	**94.2**	**106.3**	**118.5**	**102.0**	**112.8**	**1.9**	**7758**
			std error	4.3	3.2	3.4	2.3	5.2	4.8	4.0	3.2	0.2	253
2007	winter	Feedlot B	mean	**84.6**	**77.2**	**75.4**	**79.5**	**53.7**	**52.6**	**51.4**	**54.0**	**3.3**	**7726**
			std error	2.8	2.1	2.2	2.1	2.2	1.6	1.8	1.6	0.1	195
		Feedlot A	mean	**46.9**	**69.7**	**75.4**	**73.5**	**185.2**	**167.0**	**162.3**	**182.7**	**0.1**	**3037**
			std error	1.0	0.7	1.3	0.9	3.1	2.7	3.2	3.0	0.0	128
2008	summer	Feedlot B	mean	**36.0**	**62.4**	**53.0**	**28.9**	**174.3**	**178.9**	**172.5**	**146.9**	**2.2**	**7581**
			std error	7.4	35.8	26.5	6.7	29.9	31.3	95.8	15.7	2.1	4194
		Feedlot A	mean	**75.6**	**63.1**	**52.2**	**56.7**	**77.6**	**74.4**	**65.6**	**63.5**	**1.6**	**5507**
			std error	1.3	1.2	1.0	0.9	3.9	2.4	2.3	1.9	0.1	96
All Campaigns			average	**74.5**	**78.8**	**72.9**	**71.3**	**117.4**	**114.5**	**107.2**	**106.5**	**2.0**	**7880**

4.1 Methane (CH_4)

Average per head CH_4 emission was 113 g head^{-1} d^{-1} over all eight campaigns (Table 3). This is about 40% lower than predicted by the current Australian methodology (Moe and Tyrrell, 1979) and closer to IPCC Tier II model (see section 4.6 below). McGinn et al. (2008) measured substantially higher CH_4 emissions from beef cattle feedlots in Alberta, Canada, at 214 g head^{-1} d^{-1}. They reported lower CH_4 emissions coincided with a higher content of dietary oil in the rations at an Australian feedlot.

Separate quantification of the different sources of CH_4 (empty pens, effluent ponds and manure piles) was difficult because, although WindTrax modelled dispersion back to any defined source area, often more than one source area contributed to the gas concentration at the sensor, potentially inflating the emission estimate from the target source. More than one sensor, operating simultaneously, would have helped to resolve emissions from multiple source areas, but in this case we did not have a sufficient number of sensors to produce meaningful simultaneous results in WindTrax. It is recommended that emissions from minor sources be further addressed using more sensors, operated using a new scanning mode technology. Direct quantification of minor sources was only possible when suitable wind direction and position of a sensor, ruled out occupied pens and other sources. For example, CH_4 emission from effluent ponds was measured, on a limited sample, at 22 kg ha^{-1} d^{-1} during Feedlot B winter 2006, and 9 kg ha^{-1} d^{-1} during Feedlot A winter 2006.

There were strong two-way and three-way interactions between year, site and season in the variation of CH_4 emissions (Table 5). The main effects (site and season) were not, therefore, the direct causal factors behind campaign differences; rather CH_4 emissions probably varied in relation to average animal live weight, animal diet (in particular % forage) and animal behaviour/biology, associated with the different campaigns. These factors are discussed further in section 4.6 below.

Table 5: Analysis of variance of per-head CH_4 emissions (g head^{-1} d^{-1}) during eight field campaigns, at two feedlot sites, Feedlot B (Queensland) and Feedlot A (Victoria), during winter 2006, summer 2007, winter 2007 and summer 2008.

Source	df	F	Pr>F
year	2	19.67	<0.001
season	1	56.60	<0.001
site	1	52.47	<0.001
season*site	1	84.44	<0.001
year*season*site	2	14.58	<0.001
hour(year*season*site)	170	15.95	<0.001

Hour of day, within each campaign, was a highly significant source of variation in CH_4 emission (Table 5). The pattern of this diurnal variation was characterised by maximum CH_4 emission during early morning and late afternoon (Figure 4), and relates to increases in animal eructation and general activity (Loh et al., 2008).

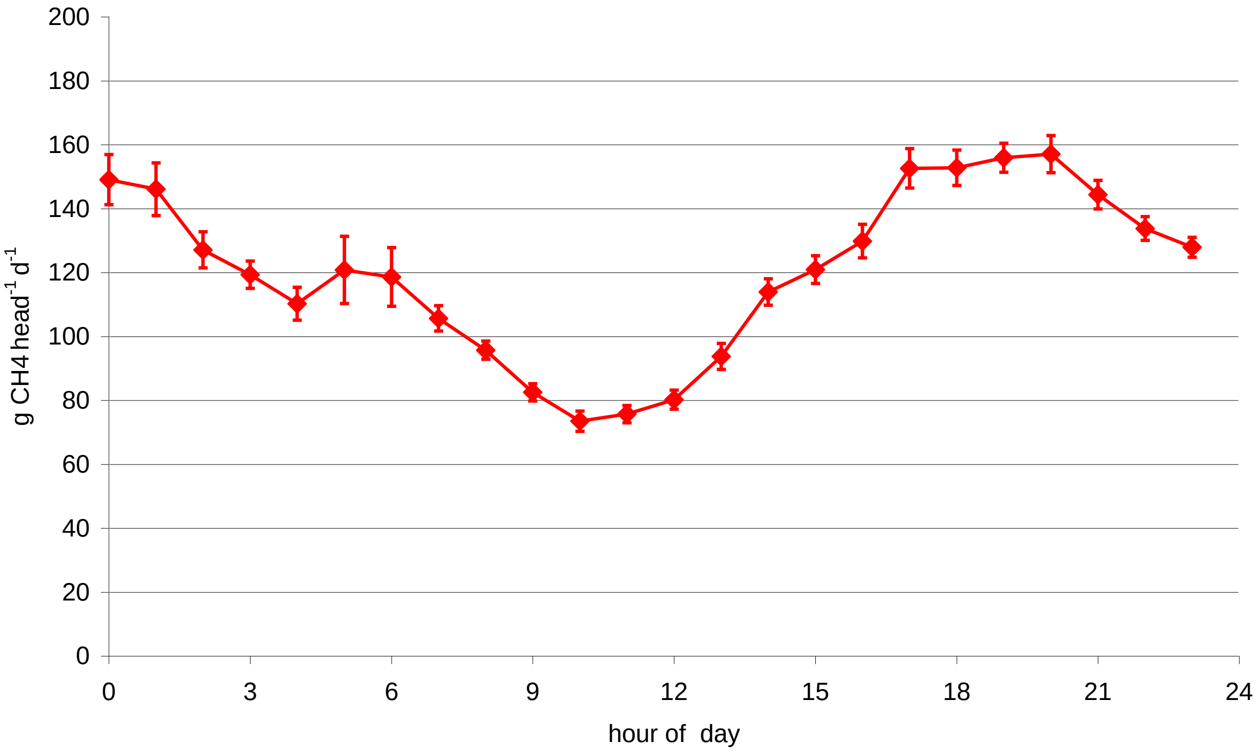

Figure 4: Diurnal variation of ensemble-averaged CH_4 emission (g head^{-1} d^{-1}) averaged over all eight field campaigns. Campaigns included two feedlots (Queensland and Victoria), during two seasons (winter and summer), over two years (2006 & 2007 or 2007 & 2008). Error bars indicate the standard error around the estimate of ensemble-average.

4.2 Ammonia (NH_3)

Average NH_3 emission was 176 g head^{-1} d^{-1} across all eight campaigns (Table 3), or 107 kg ha^{-1} d^{-1} (Table 4). This is much higher than predicted by the IPCC Tier II methodology, at 57 to 68 g head^{-1} d^{-1}, (see section 4.6 below), but only a little greater than NH_3 emissions measured in North American studies. Flesch et al. (2007) measured NH_3 emissions from a beef cattle feedlot in Texas, USA, at 150 g head^{-1} d^{-1}, while McGinn et al. (2007) measured NH_3 emissions of 140 g head^{-1} d^{-1} from a feedlot in Alberta, Canada.

NH_3 emissions from effluent ponds, measured on limited samples at Feedlot B and Feedlot A during winter 2006, were 33 and 13 kg ha^{-1} d^{-1}, respectively. This is somewhat greater than measurements, by Flesch et al. (2007), of NH_3 emissions from retention ponds, at 8-9 kg ha^{-1} d^{-1}. As for CH_4, NH_3 emission from unoccupied pens and manure piles could not be quantified separately, but could be further explored using more sensors.

There were episodes of very high NH_3 emissions, which could not be readily explained by small touchdown footprint, or heterogeneity of pen animal numbers, but were associated with relatively high sensible heat flux (H_s), particularly at Feedlot B during summer 2008. McGinn et al. (2007) found a strong positive correlation between H_s and NH_3 emissions from Canadian beef cattle feedlots. They found that this correlation was higher on drier days and subdued on wet days. The very wet conditions immediately preceding and during the summer 2008 campaign at Feedlot B may have temporarily subdued ammonia emissions while wet, resulting in enhanced episodic emissions of NH_3 as the cattle pens dried out (Todd et al., 2005; Flesch et al., 2007). Consideration of micro-environmental processes affecting emissions of NH_3, such as surface moisture, may improve modelled estimates of NH_3 (and N_2O) from beef cattle feedlots.

Ammonia emissions, like CH_4, exhibited strong two-way and three-way interactions between year, site and season (Table 6). So again, the main effects (site and season) were not the direct causal factors behind campaign differences. Underlying causal factors for the differences between NH_3 emissions were not well explained by the data. NH_3 emissions were probably a result of differences in pen environmental conditions (moisture, pH, temperature), as discussed in section 4.6 below.

Table 6: Analysis of variance of area-based NH_3 emissions (kg ha^{-1} d^{-1}) during the eight field campaigns.

Source	df	F	Pr>F
year	2	173.92	<0.001
season	1	30.54	<0.001
site	1	88.88	<0.001
season*site	1	700.23	<0.001
year*season*site	2	132.51	<0.001
hour(year*season*site)	172	15.04	<0.001

As for CH_4, hour of day within each campaign, was a highly significant source of variation in NH_3 emission (Table 6). The pattern of this diurnal variation was characterised by a maximum NH_3 emission around the middle of the day (Figure 5), when generally higher temperature increases vapour pressure and evaporation, and when generally greater near-surface wind-speed increases rate of diffusion from the boundary layer (Loh et al., 2008).

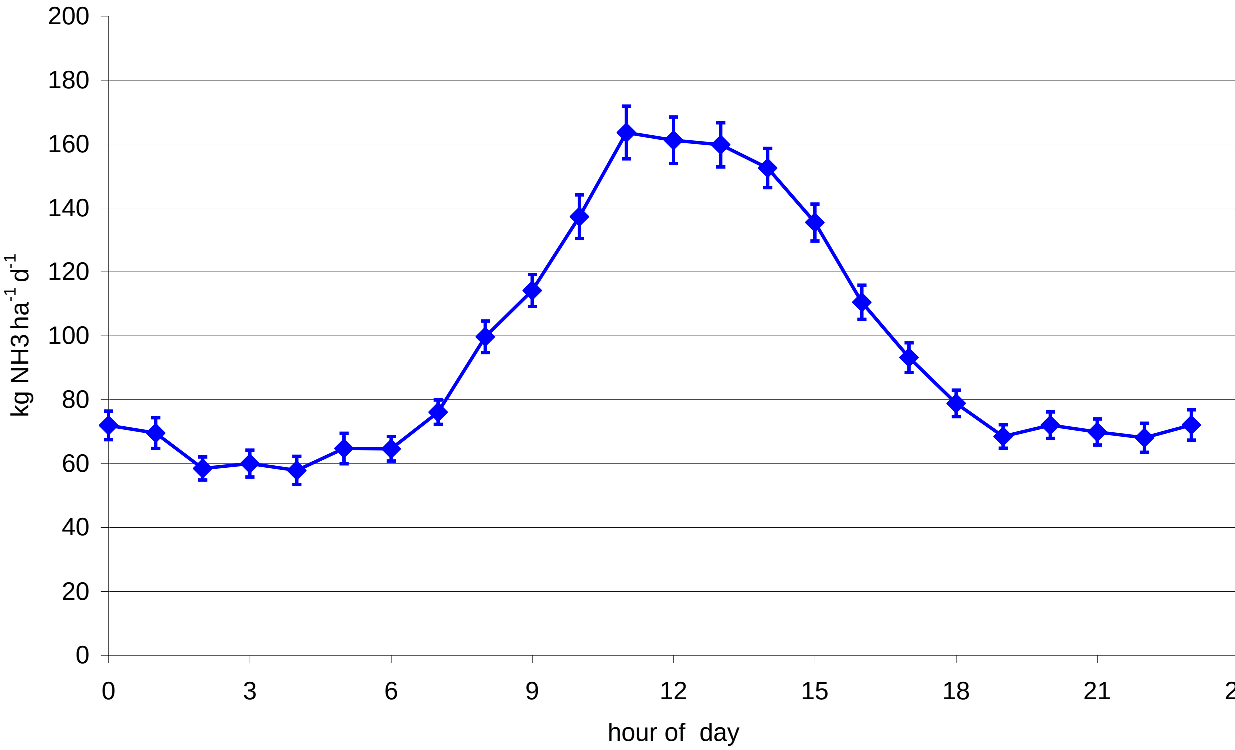

Figure 5: Diurnal variation of ensemble-averaged NH_3 emission (kg ha^{-1} d^{-1}) averaged over all eight field campaigns. Campaigns included two feedlots (Queensland and Victoria), during two seasons (winter and summer), over two years (2006 & 2007 or 2007 & 2008). Error bars indicate the standard error around the estimate of ensemble-average.

4.3 Nitrous oxide (N_2O)

Average N_2O emission was 3.3 g $head^{-1}$ d^{-1} across all eight campaigns (Table 3). This value was about half that of the IPCC-modelled N_2O (6.5 g $head^{-1}$ d^{-1}), while measured NH_3 (a progenitor of N_2O via nitrification and denitrification) was several times greater than IPCC-modelled NH_3. Thus, greater-than-expected NH_3 was lost to the atmosphere via volatilisation, leaving less-than expected ammonified nitrogen in the soil/manure, available for subsequent N_2O formation via nitrification-denitrification.

Total feedlot N_2O emissions averaged 2.0 kg ha^{-1} d^{-1} (per unit area of occupied pens) across all eight campaigns (Table 4). N_2O emissions from other sources (unoccupied pens, effluent ponds and manure piles) could not be quantified directly, as the OP-FTIR was always located under the influence of multiple source areas.

As for the other gases, highly significant two-way and three-way interactions between year, site and season (Table 7) suggested the main effects were not the direct causal factors behind differences in N_2O emissions. As for NH_3, underlying causal factors for the differences between N_2O emissions were not well explained by the data. Again, N_2O emissions were probably a result of differences in pen environmental conditions, see section 4.6 below.

Table 7: Analysis of variance of area-based N_2O emissions (kg ha^{-1} d^{-1}) during the eight field campaigns.

Source	df	F	Pr>F
year	2	8.29	<0.001
season	1	23.25	<0.001
site	1	27.04	<0.001
season*site	1	1.41	0.236
year*season*site	2	81.58	<0.001
hour(year*season*site)	131	4.62	<0.001

Hour of day, within each campaign, was a significant source of variation in N_2O emission (Table 7), with a diurnal pattern characterised by increased emissions in the middle of the day and early afternoon (Figure 6). At this time of day, generally higher temperatures and decreased atmospheric stability probably increased vapour pressure and rate of diffusion of N_2O from the soil-air boundary layer, increasing N_2O emissions. The relatively large error bars around the estimates of mean emissions (compared with CH_4 and NH_3 in previous graphs) indicate that emissions of N_2O were relatively variable, and suggest that conditions for nitrification-denitrification of NH_3 to N_2O were quite variable.

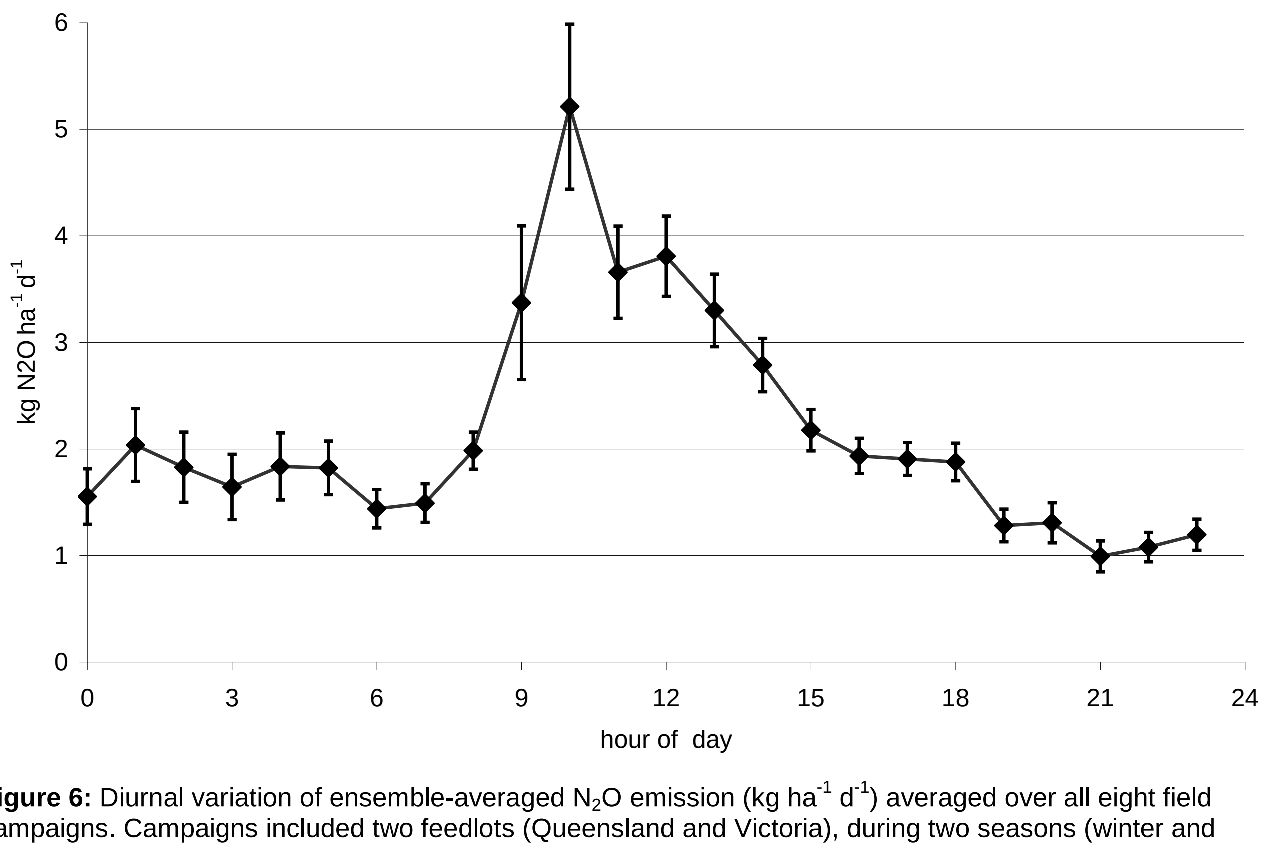

Figure 6: Diurnal variation of ensemble-averaged N_2O emission (kg ha^{-1} d^{-1}) averaged over all eight field campaigns. Campaigns included two feedlots (Queensland and Victoria), during two seasons (winter and summer), over two years (2006 & 2007 or 2007 & 2008). Error bars indicate the standard error around the estimate of ensemble-average.

4.4 Carbon dioxide (CO_2)

Average CO_2 emission was 12.9 kg head^{-1} d^{-1} across all eight campaigns (Table 3). This was greater than modelled estimates according to Kirchgessner (1991), particularly at Feedlot B (Table 10). McGinn et al. (2004) measured total respired CO_2 from beef cattle at between 3 and 4 kg head^{-1} day^{-1}. It is possible there is a contribution of soil respiration to the CO_2 emission. In any case, livestock-respired CO_2 is not considered a net anthropogenic GHG emission.

Total feedlot CO_2 emissions averaged 7.9 t ha^{-1} d^{-1} (per unit area of occupied pens) across all eight campaigns (Table 4). As for N_2O, CO_2 emissions from unoccupied pens, effluent ponds and manure piles could not be quantified directly, as the OP-FTIR was not employed downwind of these single sources in isolation.

As for other gases, highly significant two-way and three-way interactions between year, site and season in the variation of CO_2 emissions suggested main effects were not direct causal factors behind campaign differences (Table 8). Underlying causal factors for the differences in CO_2 emissions are unknown, but may be associated with increased temperatures, breed differences at the northern feedlot (see section 4.6 below), or increased non-cattle sources of CO_2 (soil respiration) at warmer temperatures.

Table 8: Analysis of variance of area-based CO_2 emissions (kg ha^{-1} d^{-1}) during the eight field campaigns.

Source	df	F	Pr>F
year	2	16.71	<0.001
season	1	134.18	<0.001
site	1	190.45	<0.001
season*site	1	6.66	0.010
year*season*site	2	87.35	<0.001
hour(year*season*site)	159	2.80	<0.001

As for all other gases, hour of day, within each campaign, was a significant source of variation in CO_2 emission (Table 8), but there was less of a distinctive diurnal pattern (Figure 7). As the diurnal pattern is somewhat different from that of CH_4, it is possible that non-cattle sources of CH_4 (e.g. soil respiration) are contributing to CO_2 emissions, as well as animal respiration.

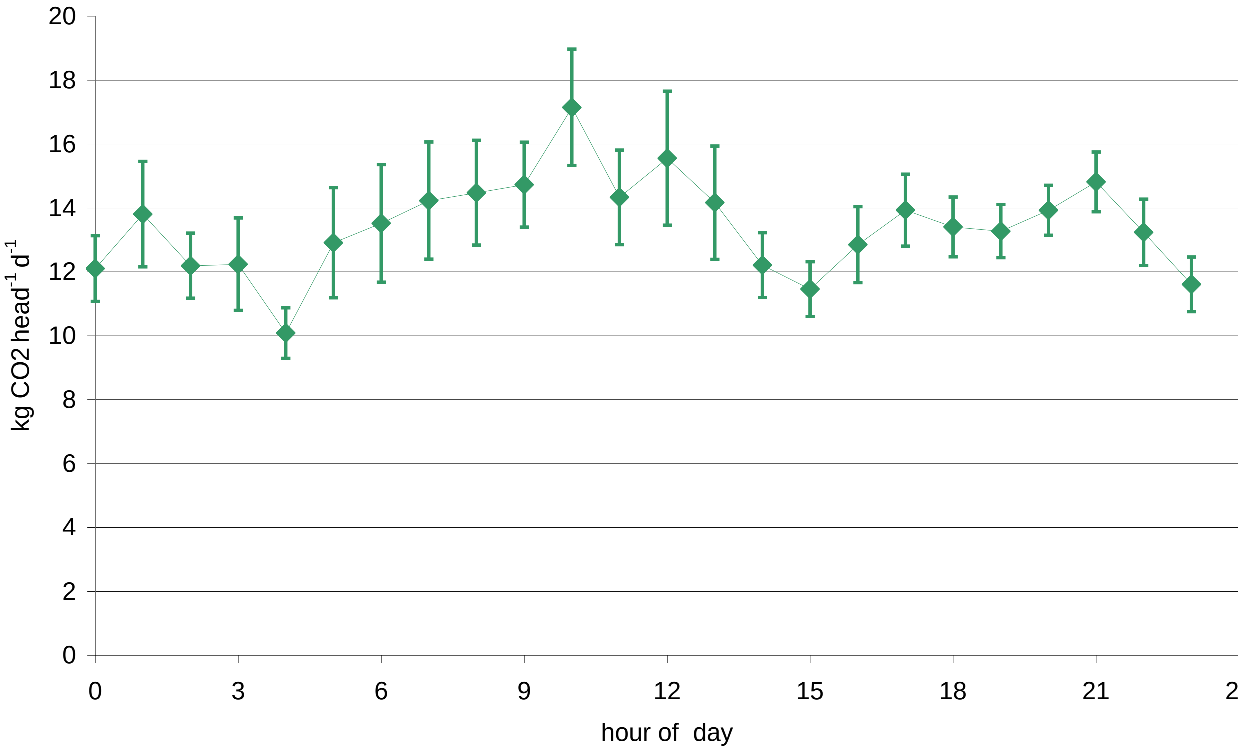

Figure 7: Diurnal variation of ensemble-averaged CO_2 emission (kg head^{-1} d^{-1}) averaged over all eight field campaigns. Campaigns included two feedlots (Queensland and Victoria), during two seasons (winter and summer), over two years (2006 & 2007 or 2007 & 2008). Error bars indicate the standard error around the estimate of ensemble-average.

4.5 Long term monitoring with trace gas station

An advantage of the TGS approach is that it can operate unattended for long periods, and so provide continuous 24-h runs when winds are favourable, thus revealing the diurnal flux pattern and allowing calculation of truly representative daily emission rates. An example of the variation in gas concentrations is provided by Figure 8, which shows concentrations of NH_3 measured over one month in periods of mostly favourable weather in late winter. The strong dependence on wind direction is evident, with concentrations dropping to background values for generally easterly wind directions, between 0° and 180°.

Some 22 whole or nearly-whole days (those with ≥ 20 h of emission data) that had favourable winds, a coverage ≥ 1% of the feedlot area and satisfying the other criteria above were available for analysis. This number is more than the 18 whole or nearly-whole days available in all the 8 campaigns described elsewhere in the report. For a coverage ≥ 2%, the number available from the TGS operation was 15.

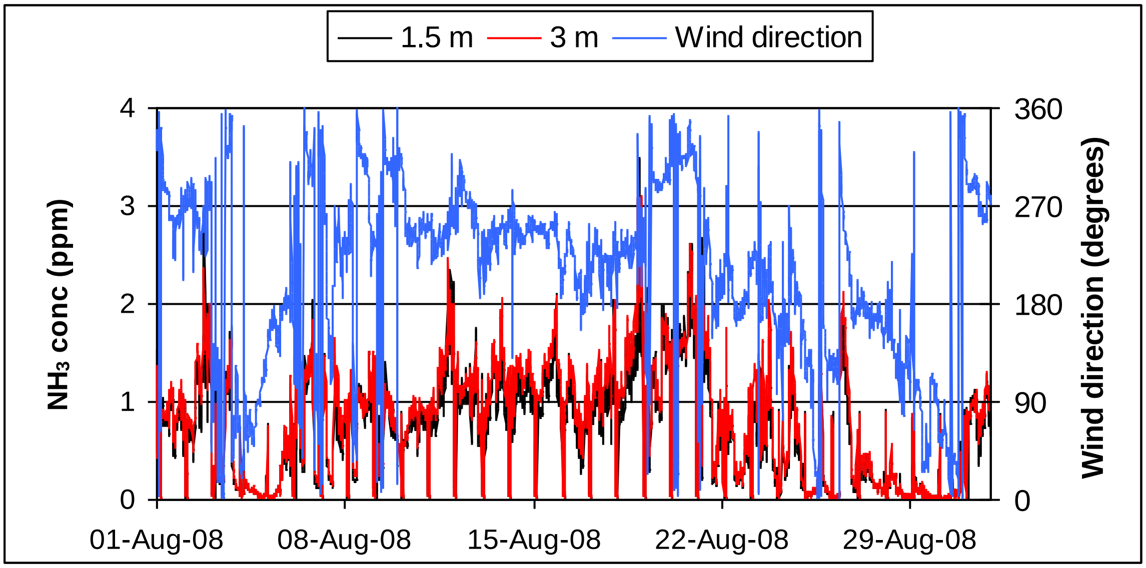

Figure 8: Influence of wind direction on measured NH_3 concentrations. When directions were between 0^o and 190^o, concentrations fell to background values

4.5.1 Ammonia (NH_3)

As expected from the diurnal variation in NH_3 concentrations evident in Figure 8, NH_3 emissions also exhibit a diurnal cycle, as demonstrated by the OP measurements (Figure 5). Emission rates measured by the TGS system over a week of favourable wind directions during the month represented in Figure 8 are shown in Figure 9. In agreement with Figure 5, the highest emissions occur in the afternoon and the lowest values just prior to sunrise, as observed in previous studies by Flesch et al. (2007) in the USA, and by Loh et al. (2008) and Denmead et al. (2008) in Australia.

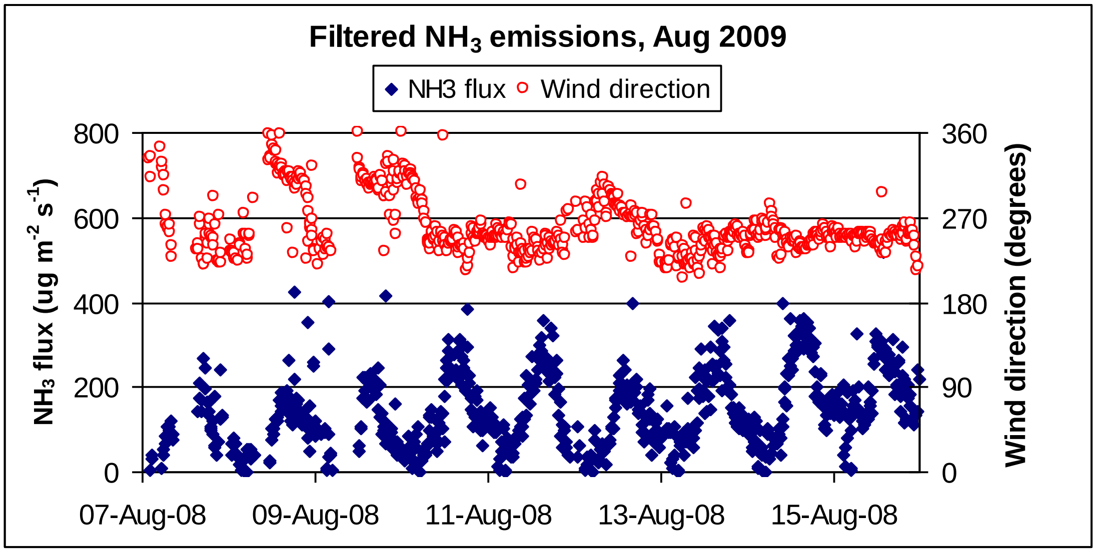

Figure 9: Diurnal cycles of NH_3 emissions calculated by TGS data during a week with favourable wind directions.

Daily totals of NH_3 emissions for whole or nearly-whole days and the corresponding standard errors of the daily means are shown in Figure 10. There were fewer days with coverage ≥ 2% of the feedlot area than days with coverage ≥ 1%, but there was no significant difference in emission rate between the two coverages for the same days.

Although emission data were sparse in June and July and no whole days of data were recorded then, there is a suggestion in Figure 10 of a seasonal cycle in the emission rate, with a significant declining trend from March to May and an increasing trend in August and September. To confirm the seasonal cycle, emission rates were calculated for the times of peak emission between 12:00 and 16:00 for all days with a coverage ≥ 1% and satisfying the other criteria for acceptance described above. The data set included many more days, especially in June and July. The mean rates and their standard errors for the 59 available days are shown in Figure 11, where it is evident that the winter emissions were reduced compared with those in autumn and spring. Undoubtedly, the cycle is linked to temperature which has been shown to have a large effect on NH_3 volatilisation because of its effect on NH_3 vapour pressure at the surface, but other factors such as surface wetness, wind speeds and diet are probably involved. The existence of the seasonal cycle points to the desirability of year-round studies of NH_3 emission, a task for which the TGS, properly maintained and sited, is very well suited.

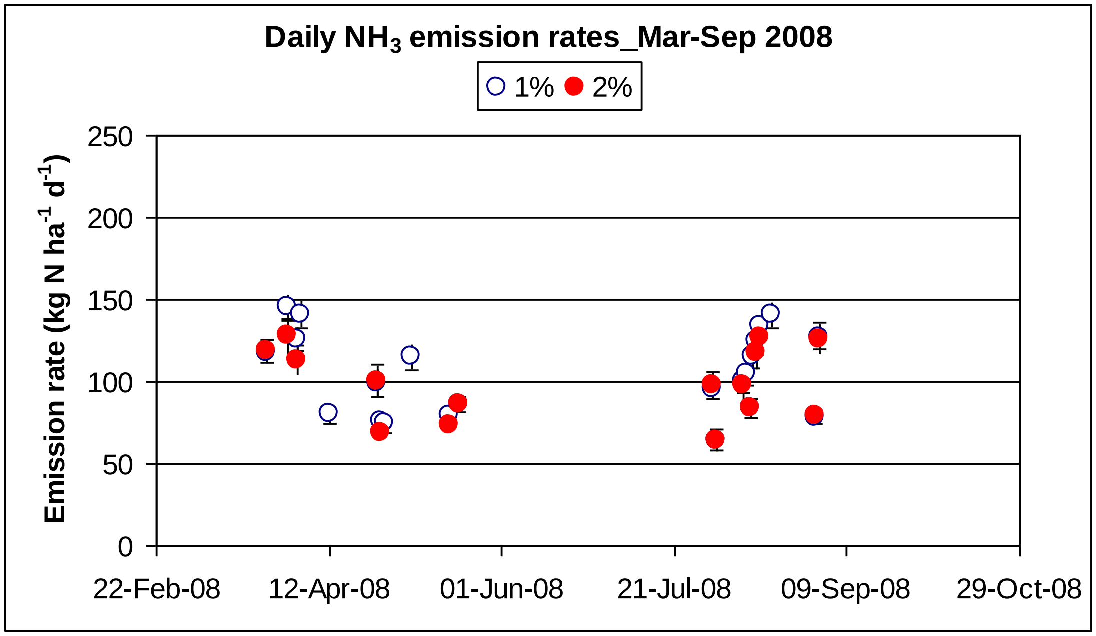

Figure 10: Whole day emission rates and standard errors for situations when touchdowns covered >1% and >2% of the feedlot area.

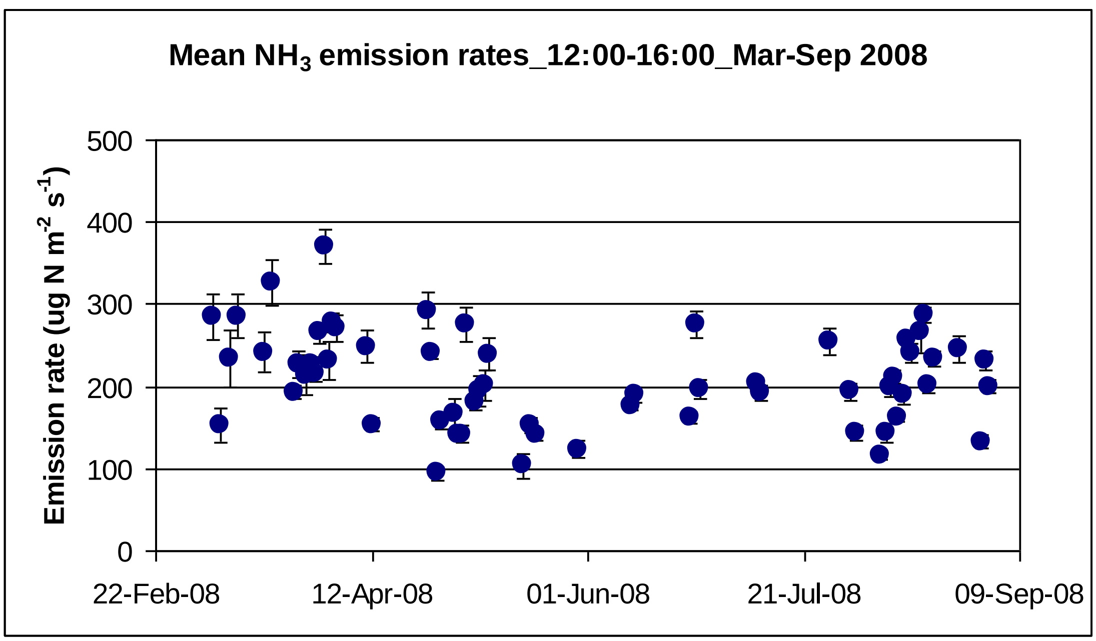

Figure 11: Mean NH_3 emission rates and standard errors for periods of peak emission from12:00 to 16:00

Table 9 summarises the mean daily emission rates of NH_3 measured in the study for coverages ≥ 1% and ≥ 2% of the feedlot area and compares them with those measured by the OP instruments in the two winter campaigns at Feedlot A conducted during the project. Both coverages estimated emission rates close to 102 kg N ha^{-1} d^{-1}. The estimates from the open-path measurements varied by a factor of 2, but their average of 126 kg N ha^{-1} d^{-1} was very close to the mean of the long-term estimates. Given the day to day variation in emission rates evident in Figures 12 and 13, this is probably fortuitous, but the standard deviations indicate the reliability of the estimates. The coefficients of variation for the TGS study were 25% for a coverage ≥ 1% and 21% for one ≥ 2%. They were almost twice these values for the short-term OP campaigns.

Table 9: Means and standard deviations of daily emission rates of NH_3 at Feedlot A as measured with the TGS in the long-term study from March to September in 2008 and with the combination of 2 open-path lasers and an open-path FTIR spectrometer in 2 short-term studies in the winters of 2006 and 2007.

System	Period	Coverage	Mean	SD
		%	kg $_N$ ha^{-1} day^{-1}	kg $_N$ ha^{-1} day^{-1}
TGS	Mar-Sep 2008	1	105	25
	Mar-Sep 2008	2	99	22
All open-path	Winter 2006	10	102	60
	Winter 2007	10	150	59

4.5.2 NO_x

Figure 12 shows 15-minute emission rates for NO_x measured over the same time interval as the NH_3 emissions in Figure 9. NO_x emissions also exhibit a diurnal cycle (noted previously by Denmead et al., 2008) although the cycle appears to be not quite as well defined as that of NH_3 emission, probably because the concentrations of the gas are smaller and more difficult to measure. Unlike emissions of NH_3, those of NO_x do not appear to show any seasonal dependence as can be seen in Figure 13, which is the counterpart of Figure 11 for NH_3. NO_x formation is also temperature dependent, but is affected strongly by other factors that influence nitrification and denitrification such as nitrogen supply, moisture status and aeration.

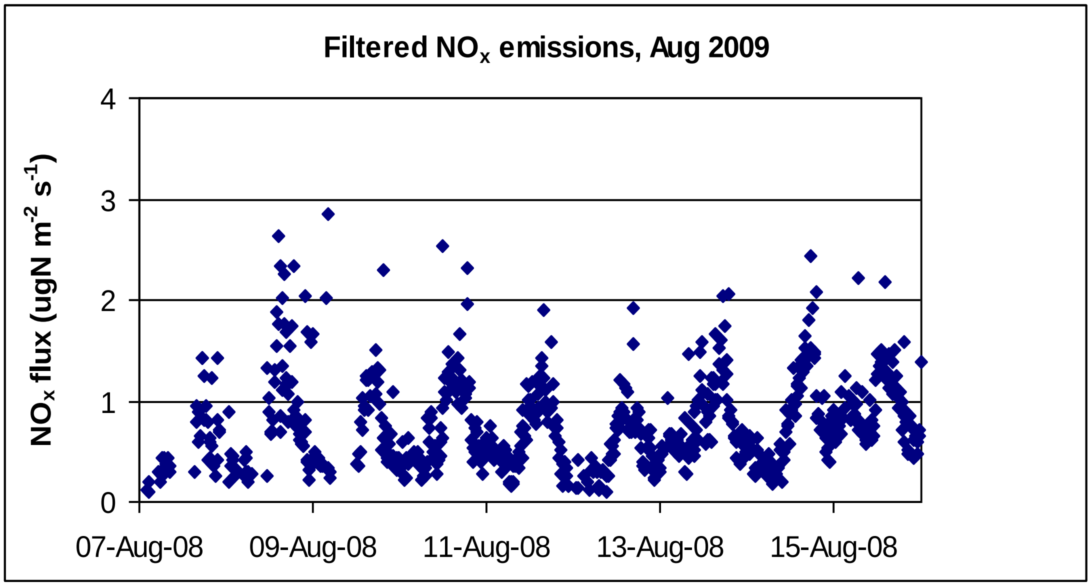

Figure 12: Diurnal cycles of NO_x emissions during the week with favourable wind directions represented in Figure 11.

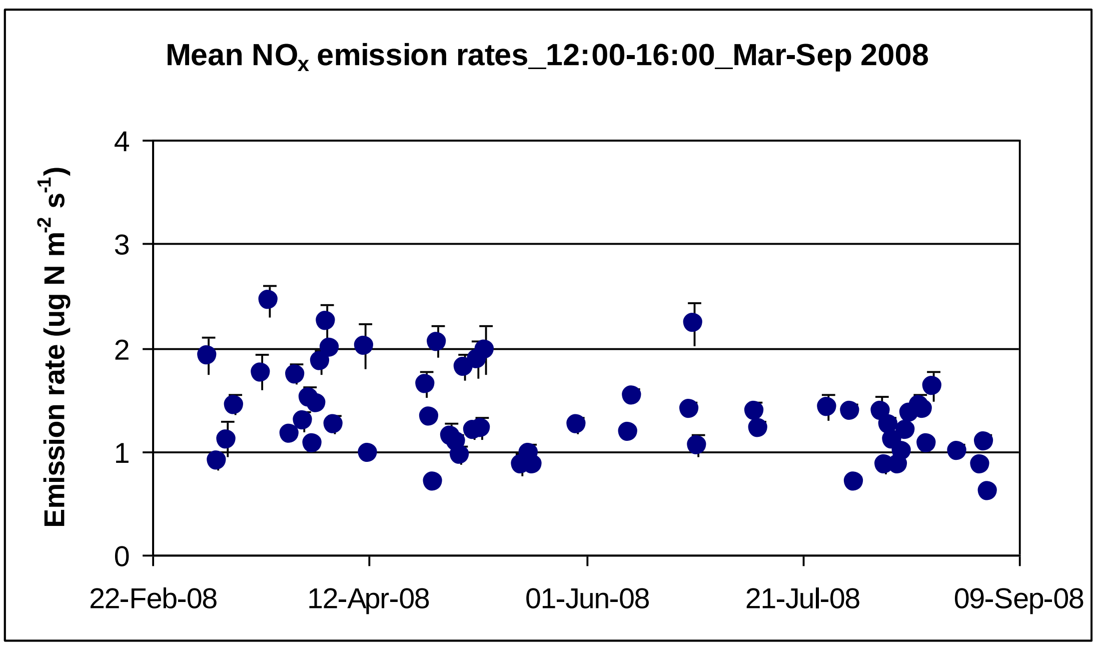

Figure 13: Mean NO_x emission rates and standard errors for periods of peak emission from12:00 to 16:00

4.5.3 Environmental impacts of nitrogen gas emissions

Since NO_x is produced during the processes of nitrification and denitrification that also produce N_2O, the emission of NO_x indicates that feedlots are sources of N_2O as well. Table 10 compares emissions of the two gases in the long-term and short-term studies. N_2O emissions measured in the latter are given in Table 3 of the report.

Table 10: Means and standard deviations of daily emission rates of NO_x and N_2O at Feedlot A as measured with the TGS in the long-term study from March to September in 2008 and with an open-path FTIR spectrometer in two short-term studies in the winters of 2006 and 2007.

System	Period	Coverage	Mean	SD
		%	kg $_N$ ha^{-1} day^{-1}	kg $_N$ ha^{-1} day^{-1}
TGS_NO_x	Mar-Sep 2008	1	1.16	0.53
	Mar-Sep 2008	2	1.23	0.63
FTIR_N_2O	Winter 2006	10	2.79	3.64
	Winter 2007	10	0.05	0.03

The mean and standard deviation of all the N_2O emission measurements over four campaigns was 1.30 ± 1.65 kg N_2O ha^{-1} d^{-1}. The corresponding amounts for the NH_3 measurements by the three OP sensors and the TGS were 95 ± 36 kg NH_3-N ha^{-1} d^{-1}, and for the TGS measurements of NO_x, 1.20 ± 0.5 kg NO_x-N ha^{-1} d^{-1}. Mosier et al. (1998) and NGGIC (2007) suggest that about 1% of the NH_3 and NO_x released into the atmosphere are eventually converted to N_2O after deposition back on the surface. Using that figure, and the above emission data, we estimate a net contribution of N_2O to the atmosphere from Australian beef cattle feedlots of 0.42 Mt CO_2-e, 43% of which comes from the indirect greenhouse gases NH_3 and NO_x. These direct and indirect N_2O emissions are substantial, equivalent to about 60% of the emissions of CH_4 from feedlots when each gas is weighted for its global warming potential (i.e. CO_2-e). Because of the apparent seasonal cycle in NH_3 emissions, the N_2O emissions for a full year are likely to be even greater than those calculated here. Further whole-year studies are needed. As well, the ecological impact of the remaining 99% of the N deposited on the surface after emission as NH_3 and NO_x requires investigation. Much of the deposition is likely to occur within a few km of the feedlot at rates of tens of kg N ha^{-1} y^{-1} (Loubet et al., 2006).

4.6 Comparison with biophysical models

Initially the enteric methane components of the biophysical models were validated against the results of 5 published studies (Beauchemin and McGinn, 2006; Boadi et al., 2004; Hegarty et al., 2007; Lovett et al., 2003). The emissions measured in these studies were compared with predictions based on the data (animal production and ration information) provided. These studies were predominantly Canadian and North American with the exception of Hegarty et al. (2007). In these studies, voluntary intake of cattle ranged from 5.3 to 14.13 kg DM head^{-1} day^{-1} with live weight estimates from 360 to 590 kg. Figure 14 outlines this analysis. The horizontal line (orange) denotes

IPCC tier I estimates for beef cattle in Oceania and the 45° line identifies unity of estimate and prediction. Vertical error bars show (average) standard deviation of the predictions, and horizontal error bars (average) standard deviation of the measurements.

The key results of this analysis (Figure 14) are:

- M&T appears to be the best estimate of enteric CH_4 emissions, predicted values are close to measured values and the linear relationship is closest to unity.
- Variability in the two mechanistic equations (B&C and M&T) is similar to the variation in measured results, However, variability of predictions of Tier II estimates are lower than measured values. The primary factor contributing to the variation of predicted results using this equation is intake.
- The apparent outlier (in B&C and IPCC tier 2, but not in M&T) represents the Australian study (Hegarty, 2007), this study has a considerably higher intake (14.1 kg DM) than the North American studies (maximum intake 8.4 kg DM) which has resulted in higher predictions from this study.

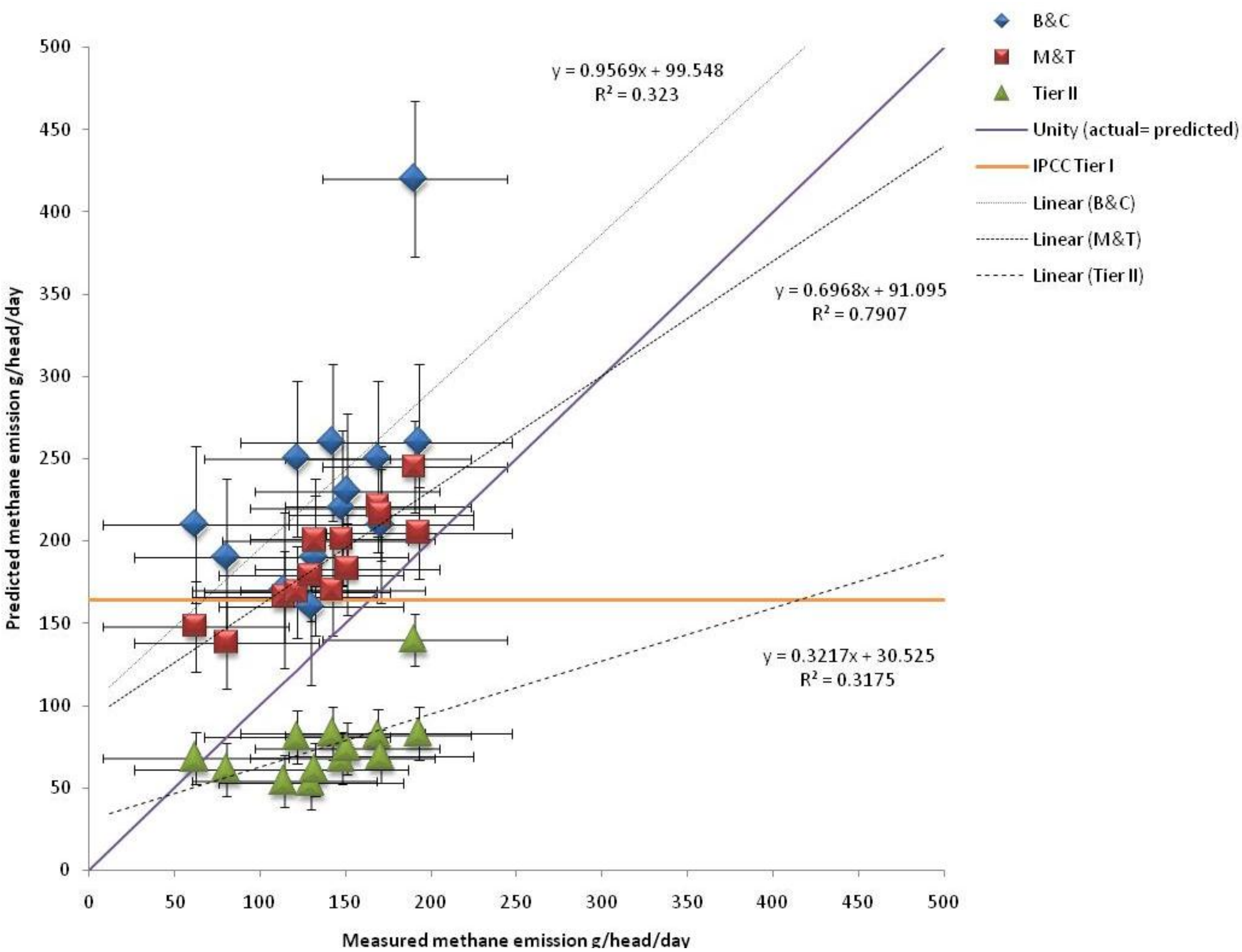

Figure 14: Measured v. predicted CH_4 emissions from 5 published studies used to validate the enteric methane emissions portion of the biophysical models.

Following the validation process emissions estimates made from animal production data collected during the four most recent campaigns and compared with measurements (as reported in this publication). Methane emissions averaged 104 g head^{-1} d^{-1} (over the final 4 campaigns), which is considerably lower than the average modelled estimates using the Blaxter and Clapperton (1965) method (307 g head^{-1} d^{-1}), or the Moe and Tyrrell (1979) method (201 g head^{-1} d^{-1}), but equivalent to estimates using the IPCC Tier II (2006) method (104 g head^{-1} d^{-1}).

While overall averages of measured and IPCC Tier II-modelled estimates were close, individual campaigns bore little resemblance (Table 11), suggesting that seasonal changes in animal number and weight were not reflected in this model and that animal diet has a stronger effect on predicted emissions than variation in the animal population.

In Figure 15, the 4 campaigns of FLOT.331 (Feedlot A and Feedlot B winter 2007 and summer 2008) are compared with the results of the validation study (emissions from northern hemisphere feedlot systems) and with the different methodologies. Whilst measured values from the Australian feedlots are within the range published in the literature (x-axis) the estimates using Tier II appears to be more accurate. This contrasts with the results of the validation exercise where M&T appears to show the best estimate of emissions.

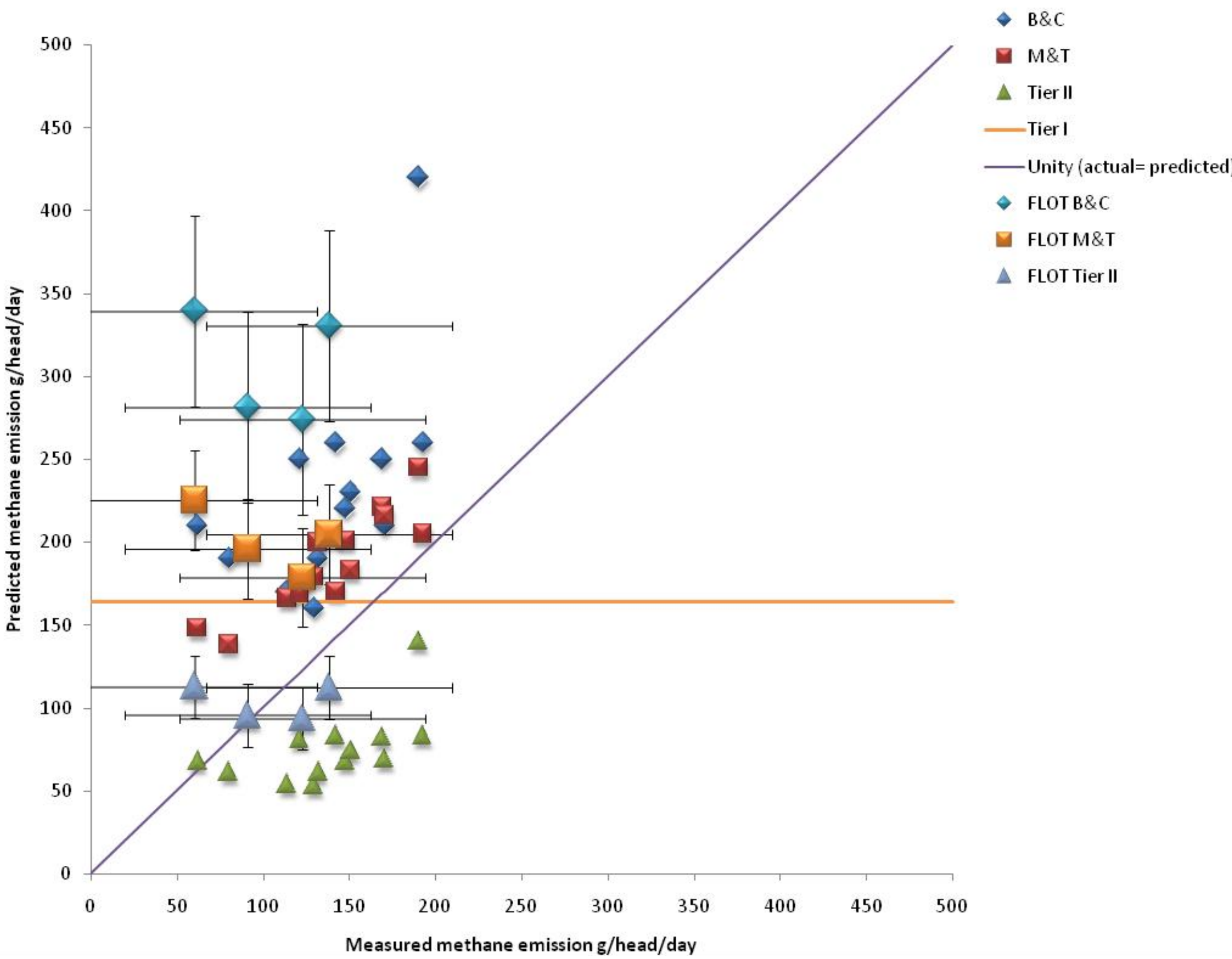

Figure 15: Measured v. Predicted CH_4 emissions with Australian feedlot results. FLOT B&C, M&T and Tier II show the observed and predicted results from this project. B&C, M&T and Tier II represent the observed and predicted results from published studies (as in Figure 14) to allow comparison between Australian and Northern Hemisphere feedlot studies.

However, statistical analysis of the results using Lins concordance (Genstat v. 10) showed concordance values (Pc) between measured values and the equations of 0.0657, 0.1248 and 0.3696 for IPCC tier II, B&C and M&T respectively. With associated 95% (two sided) confidence limits of -0.024, -0.043 and 0.1362. Suggesting M&T has the closest relationship with the measured values.

This suggests that the currently used model (M&T) is overestimating the contribution of feedlots to Australia's national inventory. However, there is concern over use of the simpler model (IPCC Tier II) insofar that there is a substantial reduction in the variation associated with the prediction (noted in Figure 14). Further statistical tests showed a lower concordance between the measured and IPCC tier II than measured and M&T.

The primary difference between the literature and the Australian data appears to be intake level, consistent with the apparent outlier produced by the data of Hegarty et al. (2007), which had almost double the intake of some of the Canadian studies, and similar to the intake levels provided by the two feedlot sites.

Variability of measured emissions was similar to variability in B&C and M&T-modelled emissions. However variability of Tier II-modelled emissions was much less than variability of measured emissions (as noted in the discussion of figure 8).

Table 11 demonstrates that B&C overestimates enteric emissions, by between 2 and 4 times the measured value. Similarly, M&T overestimates emissions, but to a lesser extent (1.5 to 2.5 times measured). However, this indicates that despite being developed on high grain diets, this equation is may be unsuitable for use in Australian feedlot systems. For both sites methane emissions appear to be best estimated using the IPCC Tier II equation (Figure 15). Summer emissions from both sites (left side) appear to be more accurately predicted than winter values, although measured values are within 2 S.D. of predictions in all cases.

Table 11: Measured and estimated CH_4 emissions (g $head^{-1}$ d^{-1}) during four campaigns, at two feedlots over two years. Mean +/- standard error. Methods of estimation include Blaxter and Clapperton 1965 (B&C), Moe and Tyrrell 1979 (M&T), IPCC 2006 (Tier II) and IPCC 1990 (Tier I).

	Measured	B&C	M&T	Tier II	Tier I*	Manure CH_4
Feedlot A winter 2007	122.8 ± 1.6^	274.2 ± 30.3	178.9 ± 16.1	93.8 ± 10.0	164.4	3.00 ± 0.6
Feedlot B winter 2007	138.3 ± 3.7	330.7 ± 33.7	204.7 ± 17.7	112.3 ± 11.2	164.4	11.72 ± 1.2
Feedlot A summer 2008	91.0 ± 1.5	281.6 ± 31.2	196.1 ± 17.0	95.7 ± 10.9	164.4	3.00 ± 0.3
Feedlot B summer 2008	60.2 ± 14.9	339.6 ± 37.4	225.5 ± 18.4	112.9 ± 11.7	164.4	11.79 ± 1.2

* IPCC Tier I value for other cattle in Oceania, 60kg.$year^{-1}$, a daily value was calculated as 60 kg/365 days.
^ For predicted values standard error was calculated using an n=3 (Domestic, SF export and LF export classes)

As enteric and manure sources of methane were not measured separately in this study, the IPCC Tier II model for methane from manure cannot be validated using this data. However the higher predicted emissions from the northern site reflect the higher emission factor used for warm conditions and further investigation into emissions from the manure pad would enable validation of this emission factor.

During the four most recent campaigns, measured emissions of CO_2 (11.0 kg $head^{-1}$ d^{-1}) were greater than modelled estimates (7.7 kg $head^{-1}$ d^{-1}). The equation developed by Kirchgessner et al. (1991) to predict CO_2 output appears to be fairly accurate for cattle at Feedlot A, but significantly underestimates values at Feedlot B (Table 12). This equation was developed for dairy cattle, but was included in the model with the additional CO_2 associated with milk production removed. As CO_2 from respiration is not considered a source under the IPCC this equation was included in the model for interest sake. Further investigation is required, but the inaccuracy of predictions for Feedlot B may be related to the model not representing the metabolism of *Bos indicus* cattle or to additional CO_2 from respiration due to higher temperatures (in comparison to Feedlot A), or non-cattle sources of CO_2, such as increased soil respiration at higher temperatures.

Table 12: Measured and estimated CO_2 emissions (kg head^{-1} d^{-1}) during four campaigns, at two feedlots over two years. Mean +/- standard error.

	Measured	Predicted
Feedlot A winter 2007	5.1 ± 0.2	6.9 ± 0.75
Feedlot B winter 2007	13.4 ± 0.3	8.3 ± 0.81
Feedlot A summer 2008	8.8 ± 0.2	7.1 ± 0.69
Feedlot B summer 2008	16.7 ± 9.3	8.6 ± 0.98

Estimates of the emissions of nitrogenous gases were also undertaken using the biophysical model. Measured NH_3 emissions averaged 206 g head^{-1} d^{-1}, which was much higher than modelled estimates using IPCC Tier II methodology (63 g head^{-1} d^{-1}), and measured and modelled estimates for individual campaigns bore little resemblance to each other (Table 13). In the same four campaigns, measured emissions of N_2O averaged about half that of modelled estimates using IPCC Tier II methodology (3.3 g head^{-1} d^{-1} and 6.5 g head^{-1} d^{-1} respectively). Measured and modelled estimates were closer to each other (and greater) during the Feedlot B campaigns (Table 13).

Table 13: Predicted and measured emissions (g head^{-1} d^{-1}) of nitrogenous gases, N_2O and NH_3, during four campaigns, at two feedlots over two years. Mean +/- standard error.

	N_2O		NH_3	
	Measured	**Predicted**	**Measured**	**Predicted**
Feedlot A winter 2007	0.1 ± 0.0	6.00 ± 0.58	305.1 ± 5.0	58.9 ± 7.16
Feedlot B winter 2007	5.7 ± 0.2	7.01 ± 0.58	94.0 ± 2.8	66.9 ± 7.56
Feedlot A summer 2008	2.5 ± 0.2	5.99 ± 0.72	100.8 ± 2.8	57.1 ± 6.93
Feedlot B summer 2008	4.8 ±4.6	7.11 ± 0.79	328.2 ± 34.5	67.9 ± 7.56

Predictions of nitrogenous gas emissions by the biophysical model are less accurate. To predict emissions of N_2O and volatilisation of NH_3, the model calculates nitrogen excretion as urinary and faecal nitrogen and uses standard emission factors to calculate volatile NH_3 and emitted N_2O. However, the emissions of these gases are influenced by a number of environmental factors which are not accounted for by the model.

These results suggest that a simpler model (than currently used) for enteric CH_4 production could be applied to Australian feedlot systems and that the current model could cause significant overestimation of the feedlot industries contribution to the overall GHG inventory. It also suggests that the current model for nitrogenous gases is not adequate to predict emissions. Further investigation of this area is required.

What are the reasons for the differences in emissions between summer and winter at each site? At both sites, measured emissions of CH_4 (Table 11) are higher in winter than in summer, in contrast CO_2 (Table 12) emissions are higher in summer than in winter.

Animal characteristics during the final four measurement campaigns are shown in Table 14. At Feedlot B, cattle population during summer 2008 was much lower than during winter 2007 (Less than 6200 head compared with 10500 head), however cattle were heavier during summer 2008 by almost 50kg (530 compared with 576 kg), although the difference in live weight was not statistically significant. Intake was not significantly different at 11.4 and 11.3 kg DMI head^{-1} for summer and winter respectively. At Feedlot A (the southern site), cattle population was less affected by season, with summer populations reduced by only 300 head compared to winter population. Live weights were also more similar (440 compared to 454 kg), and less variable than in Feedlot B. Feed offered in Feedlot A was lower than Feedlot B.

Table 14: Number, live weight (LWT), LWT gain and feed intake at each site during winter 2007 and summer 2008

	Number^	LWT	LWT Gain	Intake*
Feedlot A winter 2007	13100	440.4 ± 91.5	1.31 ± 0.35	9.4 ± 1.8
Feedlot B winter 2007	10500	529.8 ± 117.8	1.75 ± 0.23	11.3 ± 2.0
Feedlot A summer 2008	12800	454.9 ± 68.2	1.33 ± 0.33	9.7 ± 1.9
Feedlot B summer 2008	6100	576.4 ± 132.8	1.62 ± 0.43	11.4 ± 2.0

^ nearest 100 head
* offered feed

As there are no significant differences in animal characteristics which contribute to CH_4 emissions the primary causes identified for these differences are the ration type and the relative contribution of manure pad CH_4 to the total measured.

The predominant ration composition and nutritive value during each of the 4 campaigns is shown in Table 15. Forage makes up between 6 and 16% of the rations, with the lowest forage content in Feedlot B during Summer 2008 (6%) correlated with the lowest measured emission. This difference goes some way to explaining the difference in emissions between the two Feedlot B campaigns (higher forage is associated with higher emissions). However there is no difference in forage % in the Feedlot A rations. Examining the predictions using M&T, which uses carbohydrate (CHO) fractions, we can see that both summer rations are predicted to have higher CH_4 output in summer, therefore forage percentage and CHO composition is unlikely to be related to the lower emissions in summer at each site.

The other primary difference in terms of rations fed is the type of grains fed. For both sites, the winter ration consists of a single grain, wheat for Feedlot A and sorghum for Feedlot B, in summer the ration at Feedlot A contained barley and wheat and at Feedlot B more barley than sorghum. Sorghum has a slightly higher CH_4-E/GE value (0.11 compared with 0.10) (Givens and Moss 1990), indicating a greater proportion of GE is converted to CH_4.

Using data published by Givens and Moss (1990) and ration composition we can calculate weighted average GE content (feed proportion* individual feed GE), and the weighted average percentage of GE converted to methane energy. Theoretical GE values are slightly higher at Feedlot B, but the difference is unlikely to produce a significant difference in practice. Calculated CH_4-E % of GE values reflect the differences in measured emission between the seasons (lower in summer) but the differences are unlikely to reflect the magnitude of differences measured. The difference between Feedlot A and Feedlot B winter 2007 emissions is also reflected in these values (Table 15), but this relationship is not consistent when summer values are compared.

Table 15: Predominant ration composition during summer and winter at each site

Feedlot A winter 2007 (6500 head)^		**Feedlot A summer 2008** (8200 head)		**Feedlot B winter 2007** (6400 head)		**Feedlot B summer 2008** (4500 head)	
Wheat % ‡	69.9	Wheat %	27.0	Silage %	11.5	Tempered Barley %	15.5
Silage % ‡	12.5	Silage %	14.0	Recycled Oil %	0.5	Sorghum %	30.0
Hay % ‡	3.5	Grass Hay %	1.5	Straw %	1.5	LQ Supplement %	4.6
LQ Finisher % ‡	5.0	LQ Finisher %	4.8	LQ Supplement %	4.6	Straw %	1.0
Cottonseed % ‡	8.0	Cottonseed %	8.0	Sorghum %	75.9	Cotton Hulls %	1.0
Vegetable Oil % ‡	1.1	Vegetable Oil %	1.1	Cottonseed %	6.0	Cottonseed %	10.0
		Molasses %	3.1			Silage %	5.0
		Barley %	40.0			Recon Barley %	32.0
						Recycled Oil %	0.5
Total %	**100.0**	**Total %**	**100.0**	**Total %**	**100.0**	**Total %**	**100.0**
DM %	75.1		73		69.2		74.4
ME MJ/kg DM	13.2		12.8		12.8		12.3
CP %	14.4		13.6		13.5		13.5
NE_m MJ/ kg DM (mcal)	8.9 (2.14)		8.8 (2.12)		8.7 (2.07)		8.7 (2.08)
NE_g MJ/ kg DM (mcal)	6.1 (1.47)		6.0 (1.44)		5.9 (1.42)		5.9 (1.42)
Theoretical GE*	18.6		18.5		18.8		18.8
CH4-E % GE*	8.91		8.58		9.84		9.31

^ number of head reflects the proportion of total fed this ration type.

‡ ration description refers to that most commonly used during the measurement campaign

* weighted average based on individual feed values published by Givens and Moss (1990).

A further cause may be climatic conditions and changes to animal behaviour. The hotter conditions in summer may have resulted in a reduced time spent eating and ruminating and therefore lower intake (not reported in amounts of feed offered) and lower emissions. This is supported by the measured emissions of CO_2, which are higher at both sites in summer, although animal live weight and intake do not change.

Emissions of nitrogenous gases do not show a consistent seasonal pattern between sites (Table 5). Measured N_2O is variable, and effectively negligible, whilst NH_3 values are higher in winter in Feedlot A, but in summer in Feedlot B. Animal (Table 14) and feed (Table 15) factors do not show variation which reflects these differences. The nitrogen content in the rations range from 13.5-14.4% in the dry matter. However, this difference is not large enough to be reflected in the differences in measured values, this is reflected by the similarity of predicted (modelled) emissions (Table 13). This supports the observation that for these feedlot systems environmental and pen conditions (e.g. Temperature, pad nitrogen content, pH and moisture level) have a greater impact on emissions of nitrogenous gases than animal characteristics. For example, rain at the northern site during summer 2008 resulted in a wetter pad than at the southern site, which is reflected in the higher NH_3 emissions measured from the northern site.

These results suggest that ration composition and climatic conditions have a significant effect on methane emissions from feedlot systems and that environmental conditions have a greater impact on emissions of nitrogenous gases than animal characteristics.

5 Success in Achieving Objectives

The project achieved the first objective in full, providing estimates of CH_4, NH_3, N_2O and CO_2 emissions from feedlots in northern and southern Australia over four seasons. These estimates formed the basis of an informed comparison between published models of emissions of greenhouse gases and NH_3.

The project achieved the second objective in part, demonstrating the link between animal diet and CH_4 emissions in Australian beef cattle feedlots. Emissions of nitrogenous gases, NH_3 and N_2O, were not well explained by the project data, nor by currently published models. Further work is required on environmental factors that affect nitrogenous gas emissions from feedlots at a fine scale, and over an extended period.

The project achieved the third objective in full. It was the first application of open-path spectroscopy, micrometeorology and atmospheric dispersion modelling for quantifying greenhouse gas emissions from beef cattle feedlots, and it has enhanced Australian capability to quantify greenhouse gas emissions from agricultural production systems considerably.

6 Impact on Meat and Livestock Industry

6.1 Impact on Meat and Livestock Industry – now

The results of the project are immediately applicable to the meat and livestock industry, as discussion of a national emissions trading scheme (possibly inclusive of the agricultural sector) takes place. These results can inform the discussion of which of the currently used emissions models are the most appropriate for greenhouse gas emissions from beef cattle feedlots. The results also reaffirm the potential loss of N from the feedlot system as volatilised NH_3, and underscore the need for further work to mitigate against this loss.

6.2 Impact on Meat and Livestock Industry – in five years time

The results of the project will continue to have an impact on the meat and livestock industry for several years hence, as the agricultural sector becomes included in the emissions trading scheme (mooted for by 2015). These results underscore the need for ongoing refinement of emissions process-models, particularly for the nitrogenous gases, NH_3 and N_2O, which appear to be poorly estimated by current models. The results also highlight the potential for open-path spectroscopy, atmospheric dispersion modelling and long term point source monitoring using the TGS, in the ongoing refinement of emissions data.

7 Conclusions and Recommendations

The micrometeorological approach, using open-path and closed-path systems, and atmospheric dispersion modelling has proved to be a suitable methodology for quantifying direct and indirect greenhouse gases emissions from beef cattle feedlots. This approach will continue to be a valuable tool for quantifying greenhouse gas emissions from intensive livestock production systems, for evaluating mitigation options and for the ongoing refinement of greenhouse gas emissions models. More sensors, operating simultaneously in multiple locations, will help to clarify the different sources of emissions within feedlot systems. Well-defined diurnal cycles in the emissions of CH_4, NH_3, N_2O and NO_x were identified, and a suggestion of a seasonal cycle for NH_3 emissions. The existence of such seasonal cycles points to the desirability of year-round studies of greenhouse gas emissions. The TGS has much potential for longer term, seasonal studies of NH_3 emissions, and subsequent dispersion and deposition.

Measured emissions of CH_4 (average 113 g head^{-1} d^{-1}) were about 40% lower than estimates by the currently used model for Australian beef cattle feedlots (Moe and Tyrrell), and lower than measured emissions from a number of North American studies, probably due to dietary factors. Further work is required to evaluate the current Australian methodology for predicting enteric CH_4 emissions along with economic evaluation of the effect of a carbon trading scheme on feedlot profitability. For future inventory purposes it may be possible to use IPCC Tier II estimates, if further validation proves the accuracy of this model.

Ammonia emissions (176 g head^{-1} d^{-1}, or 107 kg ha^{-1} d^{-1}) were generally much higher than IPCC-modelled estimates (average 63 g head^{-1} day^{-1}), and also somewhat higher than measured emissions from North American studies. Current models are unable to accurately estimate emissions of nitrogenous gases (particularly NH_3), probably because micro-environmental conditions, such as surface moisture and temperature, were not well simulated. Further work on nitrogen partitioning between urine and faeces and the management of waste (manure) in feedlot systems is required. For future inventory purposes nitrogenous gas emissions should be calculated using a model which considers micro-environmental conditions. Measured emissions of N_2O (3.3 g head^{-1} d^{-1}, or 2.0 kg ha^{-1} d^{-1}) were generally lower than model estimates, probably because the same models underestimated the amount of NH_3 volatilised, and therefore assumed much more ammonified nitrogen remained, for subsequent N_2O formation via nitrification-denitrification.

Volatilised NH_3 and emitted NO_x are a significant source of indirect N_2O emissions, following dispersion, deposition and nitrification-denitrification. Based on emissions data in this study and an estimated 1% of volatilised NH_3 and emitted NO_x being land-deposited, and transformed to N_2O, we estimate 43% of N_2O emissions from Australian beef cattle feedlots come from the indirect greenhouse gases NH_3 and NO_x. Direct and indirect N_2O emissions may, therefore, result in a greenhouse contribution equivalent to 60% (in terms of CO_2-e) of feedlot CH_4 emissions.

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