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Long-term total greenhouse gas emissions from beef feedlots

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Abstract

One of the major challenges facing the Australian Red Meat Industry's objective to be carbon neutral by 2030 is the lack of robust long-term greenhouse gas (GHG) emissions data. The objectives of this project were to: (i) Measure long-term methane, nitrous oxide, and ammonia emissions from two Australian beef feedlots; (ii) Measure methane emissions from the animal; (iii) Use the long-term emissions data sets to evaluate current approaches (modelling); (iv) Integration of GHG and economic frameworks to understand systems interdependency and (v) communication and practice change. Successful long-term measurement of nitrous oxide, methane and ammonia emissions from the northern feedlot system were achieved. Successful long-term emissions of methane and nitrous oxide from the southern feedlot system were achieved. The work reports, in some detail, the approaches required to calculate accurate flux estimates, how to deal with gaps within data series, and the conditions where data can and can not be used for whole of systems estimates of greenhouse gas emissions. The outcomes of the long-term study identified that methane was the most significant greenhouse gas emitted from feedlots. The current National Greenhouse Gas Inventory approaches to estimate methane emissions overestimates actual emissions by approximately 30%. Measured nitrous oxide emissions were significantly lower (up to 80%) than those predicted using the National Greenhouse Gas Inventory approaches. Ammonia emissions pose a significant liability to the industry and abatement of emissions should be a priority. The use of lignite technologies to mitigate ammonia emissions was highly successful and has been demonstrated as cost effective for southern feedlot systems. Northern Australian feedlots require a different mitigation technology. Recommendations for future investment in those technologies are provided.

Executive summary

The University of Melbourne has previously developed methods and technology to measure the short-term (days to weeks) measurements of fluxes of direct and indirect greenhouse gases (GHG) from cattle feedlots, using a range of measurement technologies (open-path spectroscopic techniques, chamber methods and micrometeorological techniques including flux gradient (FG), eddy covariance (EC) and inverse-dispersion model (backward Lagrangian stochastic dispersion model (bLS)). This project was commissioned to develop measurement technologies that can measure long term emissions of greenhouse gases at commercial feedlots, including annual measurements of CH_4, NH_3 and N_2O from feedlots. The work in this project focuses on apportioning annual emissions of direct and indirect GHG to locations or systems within the feedlot (e.g. emissions associated with animals, feeding systems, manure management including composting manure and different age of manure, lagoons and empty pens) and developing best practice options or decision tools to abate emissions.

A suite of state-of-the-art instruments to measure direct and indirect GHG emissions (N_2O, CH_4, NH_3, NOx and CO_2), fluxes of energy and climate variables, were established at each of two feedlot sites. These included closed path FTIR and open path lasers to determine the concentrations of GHG at known time points. The data and information were processed using two methods – inverse dispersion models (IDM) and eddy covariance (EC). Two approaches were used in this study (backward Lagrangian stochastic dispersion modelling (bLS) and eddy covariance footprinting) to establish emission footprints. Both methods were found to provide good estimates of fluxes but the eddy covariance method provided fluxes with higher measures of variation for methane and nitrous oxide but not, paradoxically for carbon dioxide. The project developed a new approach - multiple sampling height IDM-WINDTRAX method. This method provided greater stability in flux estimates. Sampling at three heights above the feedlot allows better estimates of greenhouse gas mixing in the surface boundary layer and better predictions of the vertical migration of gases through the surface to 10 m air column especially in non-homogenous area source situations.

Loss of data and information resulting in gaps in the data series poses some interesting statistical issues. The important issue is not the approach to modelling of the gaps within the data series (e.g. autoregressive integrated moving average (ARIMA) methods), but the acceptance that the data series collected represents the long-term emissions of GHG from the feedlot. The use of the ARIMA model to test the concept of pass/fail for a fragmented data series is not novel but provides a realistic picture of how much data can be lost before a model cannot be fitted to the measured time series. This was a significant issue with the EC footprinting model using a single measurement point at the southern site where only CO_2 and CH_4 emissions were able to be measured and modelled (ARIMA) with any precisions. There was a considerable lack of reliability in the measurement of nitrous oxide and ammonia fluxes at this site. The data series from the northern site (concentration of gas being converted to a flux using a modified IDM-WINDTRAX model) was more robust and good estimates of fluxes of all gases were calculated. The northern site data series for the two direct GHG (CH_4 and N_2O) represents the first long-term series of data for a feedlot system.

Measurements before, during and after a single mitigation strategy was deployed (lignite amendment to manure processing system at the southern site) were undertaken to understand the impact of the change on whole farm systems productivity. The composting study compared gaseous emissions during the composting of lignite and non-lignite treated cattle manure. The lignite addition was effective in reducing N losses by 54% during the windrow composting process, but promoted CH_4 and

N_2O emissions (due to the composting process maintaining aerobic conditions within the manure stockpile), and CO_2 emissions (due to addition of labile C from lignite). The total greenhouse gas emissions (CO_2–e) from composting lignite treated manure was 1.7 times greater than that of the control treatment. However, addition of lignite in the feedlot pen delivers a significant reduction in reactive N losses in terms of direct ammonia emissions but the effectiveness of retaining N in lignite windrow was not obvious after about 25 days of composting.

A series of calculations to understand the financial trade-offs between direct environmental costs (e.g. valuation of greenhouse gas emissions, impact of ammonia on the environment) and the use of a mitigation technology such as lignite were undertaken. The total environmental benefits of treating manure within lignite and composting are about 2-fold that of stockpiling. This outcome reflects an interesting environmental dilemma that even though the processing of the manure with lignite and composting yields higher rates of nitrous oxide production, it reduces ammonia emissions that may have a greater direct impact on other aspects of the environment (e.g. ecosystems and human health – short-term environmental impact) compared to the emissions of greenhouse gases (longer-term environmental impact).

As part of this project methane emissions from whole feedlot pens were measured. The area corrected measured emissions of methane from the southern and northern feedlots respectively were 41.4 and 20.5% lower than emissions calculated using the current National Inventory (2017) approach. The differences between sites are difficult to directly ascribe to practice, however, the major factor to be considered is the feed processing technologies used at the sites (southern feedlot = steam flaking whereas the northern feedlot used grain re-constitution). This is an important observation and supports the data reported in two previous projects (B.FLT.0148 & FLOT.331). If these emissions are scaled to a national scenario, the total estimated emissions (National Greenhouse Gas Inventory) from 1,110,689 (animals on feed December 2018) was estimated as 2,343,014 t CO_2-e per annum (about 97,500 t methane). However, the measured data in this report suggest the scaled national emissions would be 1,677,714 t CO_2-e per annum (about 70,000 t methane).

The long-term data series was evaluated against the water and nitrogen management model (WNMM), DeNitrification-DeComposition (DNDC) and the National Greenhouse Gas Inventory models. A Critical Control Point (CCP) analysis was conducted for methane emissions across the two years of measurement. The WNMM and DNDC models were found to not predict greenhouse gas or ammonia emissions with any certainty, and outcomes from modelling suffer from the potential systemic bias resulting from climatic and other processes.

In previous reports (FLOT.331 and B.FLT.0148), some differences in the actual emissions from feedlot cattle compared to the current approach used by the National Greenhouse Gas Inventory to model emissions from feedlot systems have been discussed in depth. The findings in this report re-iterate the issues about the lack of congruency between the methods used to determine feed intake and methane emission in the National Greenhouse Gas Inventory and measured feed intake and measured emissions, which are frequently 30% less than the estimates used in the national inventory.

The current commitment by Meat & Livestock Australia to support the Australian red meat industry to become carbon neutral by 2030 requires long-term measurements of GHG from feedlot systems to verify inventory models and provide guidance on the economic benefits to use novel mitigation technologies to reduce the footprint of production. In this report we demonstrate a benefit of $7.76

per cubic metre of compost treated using lignite technologies (or an equivalent of $4.99 to $6.96 per head net abatement return) and a further $5.71 to $16.93 per cubic metre compost processed in intangible benefits (broader environmental and social benefits). This scenario assumes the extra costs of abatement ($13.87 to $24.5/t CO_2-e) are accounted for as a notional applied carbon price ranges reflected in current Australian Emissions Reduction Fund auctions. It does not rely on returns to animal productivity.

Table of contents

Table of Tables

Table of Figures

1 Background

Previous work undertaken in MLA funded projects FLOT.331 (Greenhouse gas emissions from Australian beef cattle feedlots), B.FLT.0148 (Reducing feedlot nitrogen-based greenhouse gas emissions) and B.CCH.1020 (Manure measurement to reduce greenhouse gas emissions from cattle feedlots) has led to a greater understanding of the greenhouse gas emissions, as well as the fate of nitrogen, in beef feedlot systems. These studies have been conducted using a range of measurement technologies (open path laser, open path FTIR, chamber studies and integrated flux calculations) that provide measures of concentrations and fluxes of direct and indirect greenhouse gases over short periods of time (days to weeks).

Research was also conducted to accurately determine livestock numbers, days on feed and diets fed, in order to predict emissions using available prediction equations in the Life Cycle Assessment area.

All of this research was subject to an external review in early 2015, and data from the review process was used to underpin a full revision of the Australian National Greenhouse Gas Inventory, released in 2015. The accepted changes to the national inventory resulted in the following change in reportable emissions:

- Reportable emission sources for feedlot beef production increased from 5% to 11%, with a marginal increase in reported emissions per animal.
- Predicted feed intake and manure excretion decreased per animal.
- Inventory numbers (total number of livestock head days) decreased by 30-39% depending on the inventory year.
- Net reduction in reportable emissions of approximately 30-40%.

Key recommendations from the review process were the need to collect information on the annual emissions of a range of gases (NH_3, N_2O, NOx, CH_4 and CO_2), apportioning of these annual emissions to locations or systems within the feedlot (e.g. emissions associated with animals, feeding systems, manure management, lagoons or downwind atmospheric deposition), and the need for improved modelling to develop best practice options or decision tools to abate emissions.

The need for this data has been further highlighted by recent, considerable interest in the concept of the nitrogen footprint of livestock and cropping systems. For example, the UNECE Task Force on Reactive Nitrogen: Options for ammonia mitigation (2014), and the US Environmental Protection Agency – Reactive nitrogen in the United States: An analysis of inputs, flows, consequences, and management options (2011), have identified that the consumer has raised concern over the levels of nitrogen (and other resources) that are offered and apparently wasted by agricultural production systems. These reports identify that there is a lack of robust data and information from southern hemisphere production systems.

This project will utilise a suite of state-of-the-art measurement technologies, including a recently acquired CW-Quantum Cascade Laser Trace Gas Analyser ($1.2m) for measuring N_2O and NH_3, which is essential for the success of the project, to measure long-term methane, nitrous oxide and ammonia emissions from two Australian beef feedlots as the basis for understanding the whole farm systems emissions profile. Data collected during the project will be utilised to further refine the Australian National Greenhouse Inventory and to update and validate the models and decision support tools currently used by industry.

Additionally, critical control point analysis (CCA) will be used to identify key control points in the production system that reduce gaseous emissions. The CCA will also aim to identify and quantify the key economic relationships between operations and long-term emissions profiles and provide recommendations to optimise management of emissions, productivity, and profitability of the system.

2 Introduction

Lot feeding in Australia has expanded in the last 30 years to meet the high demand for Australian red meat in both the domestic and international markets. During the finishing period of the cattle production cycle typical in Australia, cattle are kept in defined feedlot pens for 60 to 300+ days depending on the breed and target market category of animal. During this lot feeding phase a of greenhouse gases are produced. Namely these are methane from enteric fermentation, methane from anaerobiosis in manure stockpiles, nitrous oxide emissions from manure, and ammonia emissions from feed pads. The Australian beef feedlot sector has mature well developed environmental management codes of practice that allow all producers to be accredited through the National Feedlot Accreditation Scheme (National Beef Cattle Feedlot Environmental Code of Practice, 2nd edition: MLA, 2012).

There are a number of significant environmental challenges emerging that intensive animal industries need to consider into the future. These include the management of reactive nitrogen (ammonia, ammonium, nitrate, and nitrogen oxides) and methane, water use efficiency and climate variability. As markets and consumer awareness changes for red meat products, the industry has to ensure that it is informed on the impacts of emerging environmental challenges. For example, ammonia in the atmosphere can cause environmental issues by forming aerosols with acids (Galloway et al. 2008). It is deposition downwards can lead to soil acidification, eutrophication of lakes and waterways and decreased biodiversity of ecosystems (Erisman, 2008). Incomplete utilisation of energy and nutrients (carbon C and nitrogen N) from animal feed causes economic losses to farmers and beef industries.

Accurate measurement of gases produced in livestock at large intensive beef feedlots (methane, nitrous oxide, and ammonia), not only brings the benefits in improving the accuracy of methods used to account for these gases, by, for example, the national GHG inventory, but also could provide useful information for industries to consider alternative mitigation strategies.

Ammonia is a reportable gas to the National Pollution Inventory (NPI) by the Australian Government, Department of Climate Change, Energy, the Environment and Water but there are no requirements to account for it currently in the national Greenhouse Gas inventory. In the cropping industry production of ammonia has been recognised as an inefficiency that can reduce profitability. Feedlots produce considerable volumes of N enriched manure each year. These manures are either composted (high risk of ammonia volatilisation during early stages of processing) or field spread (loss of N via ammonia volatilisation), and therefore it is important to understand the net N balance of these products as part of the overall feedlot N balance.

The principles of product integrity need to be aligned to those of the environmental management frameworks adopted by the industry. In the case of enteric methane emissions, there are no direct framework principles identified in the Code of Practice or NFAS to abate the greenhouse gas. However, manure handling and lagoon management procedures identified by the Code provide a framework to partially abate or capture methane. The situation is somewhat different for reactive nitrogen. It is accepted that manure contributes to both direct and indirect greenhouse gas emissions via nitrous oxide and ammonia emissions.

Work by the University of Melbourne (FLOT.331 and B.FLT.0148) has demonstrated that about 60% of dietary nitrogen (N) is lost to the atmosphere via ammonia volatilization (Denmead et al., 2008). These gaseous emissions have negative impacts not only on the environment (global warming and water eutrophication), natural ecosystems (threat to species diversity), but also on human health (air pollution), and potential financial losses for producers (Chen et al., 2015). In the case of potential financial losses, the assumption that the feedlot could recover the value of N voided from the production system in either manure/compost sales or reduced fertiliser inputs into crops grown for animal production is not supported by all sectors of the industry. In cases where feedlots do not process manure into compost there is no monetising of the product but there is a cost of storage (pad management costs, machinery, labour) and management of manures (an inherently the N contained therein) irrespective of any sales or processing of a product.

FLOT.331 and B.FLT.0148 have provided compelling evidence that the management of reactive nitrogen is central to overall systems management and practice change. Three options have been provided for this – a reduction in crude protein content of rations offered, changes to manure management practices, and use of mitigation technologies such as lignite that can be readily adopted by the industry as feed pad or manure management amendments.

In B.FLT.0148 it was outlined that for efficient ration formulation, the guideline of rations containing >12.26 MJ/kg DM leads to the use of feedstuffs that contain moderate levels of fat and are derived from other agricultural sectors (for instance cottonseed meals, pressed canola products etc.). One of the consequences of this approach is that many of these feed resources contain elevated levels of crude protein (CP) thereby increasing the total CP content of ration to levels in excess of animal requirements. To maintain an acceptable growth rate (1.4 kg/d) the minimum CP content for a finishing ration that a producer is likely to offer is 11.6% or 18.6 g N/kg DM. In practice this situation may lead to a surplus of 35 to 50 g N/head/day being consumed and excreted by the growing animal, or approximately 3.5 to 5 kg N/head over a short feeding cycle. If the source of N within the feedlot system is not abated, there is scope to manage manures in a different way.

Feedlots commonly either stockpile or stockpile and compost fresh cattle manure. Composting and stockpiling decreases the mass, volume and the water content of the manure; reduces the odour, pathogens, and weed seeds; and turns the animal manure into a more stable nutrient source of fertilizer for crop production (Stentiford, 1996). However, the process of composting manure can also lead to increased emissions of GHGs and ammonia (Hao et al., 2001; Hao and Larney, 2017). There are few studies investigating optimal management practices to reduce N losses during manure stockpiling in the pens and manure composting. Our previous work (Chen et al., 2015; Sun et al., 2016) reported that applying lignite (also known as brown coal) to the cattle pen surface is a cost-effective way to reduce ammonia emissions. Lignite application increases N_2O emissions by 40 and 57%, to 0.14 and 0.22 g N_2O-N head/day. These increases are small but important incremental changes with nitrous oxide balance.

One of the major gaps in our knowledge concerning the emissions of all GHG from feedlots is the lack of a long-term measurement series (greater than one month). Work conducted by The University of Melbourne commissioned through MLA & DAFF on greenhouse gas emissions (methane and N based greenhouse gas) from beef feedlots has yielded considerable new information. Work conducted between 2006-2015 (FLOT.331, B.CCH.1020 & B.FLT.0148) using open path laser and Fourier-transform infrared (FTIR) spectroscopy techniques suggested that the Australian National Greenhouse Gas Inventory methodologies (NGGI) for estimation of emissions from feedlots overestimated nitrous oxide emissions by up to 50%, underestimated ammonia emissions by a factor of 3 times but are reasonably accurate for methane emissions from enteric fermentation and manure sources (Bai et al. 2015; Chen et al. 2015). These conclusions have been developed through the measurement of all gaseous emissions over relatively short periods of time (up to 40 days; known as campaigns) and were drawn from studies that were often focused on a single gas. However, there are still uncertainties over total and sources of emissions.

There are a number of technical and operational difficulties in determining the source of emissions, but new work conducted by Bai et al. (2015a) and Hacker et al. (2016) demonstrated that a number of these complexities can be overcome. Analysis in the Reducing Emissions from Livestock Research Program (RELRP) of open path measurement technologies that determine line average concentrations of GHG clearly demonstrated that loss of data reflecting adverse micro-climatic conditions was a major problem. For instance, in B.CCH.1020 the loss of data due to poor conditions was ca. 35% over measurement campaigns of 2 to 3 weeks duration, and there are examples from measurement campaigns in northern Australia pastoral systems where data loss can exceed 60% leading to periods of no measurement and/or extended campaign length (up to six weeks). Recent developments in wave-modulation spectroscopy have led to the development of robust methane measurement devices that can be used in remote locations as they operate at ambient temperature, have low power consumption (can be powered by solar panels) and can measure over long periods of time (months). These devices can be deployed with well-tested micrometeorological techniques (eddy covariance) for measuring fluxes of heat, water vapour and gases into the atmosphere from sources at the ground.

The work undertaken as part of this project takes a threefold approach:

(i) quantification of ammonia, other gaseous N sources (and methane) over the whole production cycle;
(ii) development of new tools and models to understand if these gases can be abated at critical points of the nutrient lifecycle and
(iii) accurately model the N footprint of feedlot systems and develop decision support tools to increase producers ability to use and manage surplus N in the production system

3 Project objectives

3.1 Objectives

The objectives of the work were to:

1. **Measure long-term methane, nitrous oxide and ammonia emissions from two Australian beef feedlots** - A suite of state-of the-art instruments to measure direct and indirect GHG (N_2O, CH_4, NH_3, NOx and CO_2), fluxes of energy and climate variables across different spatial scales will be established at the site before, during and after a single mitigation strategy is deployed to understand the impact of the change on whole farm systems productivity.

2. **Measurement of methane emissions from the animal** - there is little information on the emissions of methane from feedlot systems and, in particular, the ratio of methane emission from enteric fermentation and that derived from manure and management per se. The calibration and deployment of the portable FTIR gas analysis technology (enteric methane emissions only) is proposed to measure methane from animals, CO_2 and a range of volatiles to sub mg/m^3 accuracy

3. **Use the long-term emissions data sets to evaluate current approaches (modelling**) - The modelling framework applied to the study will be BEEF-BAL (Davis et al. 2009), Feedlot – Greenhouse Accounting Framework F-GAF (University of Melbourne), Water and Nitrogen Management Model (WNMM; Li, 2007), DNDC and National Inventory models linked to energy budgets. Whole herd data will be used to benchmark and validate the modelling as well as inform on uncertainty of emissions. There has been limited modelling conducted in other MLA/DAFF funded work – for instance B.CCH.1086. These sources of information will be used to inform the proposed work.

4. **Integration of GHG and economic frameworks to understand systems interdependency** - At a whole farm level, there is interdependency between mitigation and adaptation. It has been proposed that the strategic use of mitigation technology may reduce the impact and degree of systems adaptation. However, at the whole farm level, these causal-dependency relationships between mitigation and adaptation are not understood and have not received attention.

5. **Communication and practice change** - The project outcomes will be communicated to MLA & ALFA as well as to producer groups and other interested parties through MLA.

3.2 Outcomes

The proposed outcomes of the research are:

1. the first long-term datasets on CH_4, N_2O and NH_3 emissions from beef feedlots resolving the current lack of a robust southern hemisphere dataset (Objectives 1 & 2)

2. a number of options (technologies) to mitigate, abate or sequester N to reduce total N inputs and/or improve N capture within the whole farm system (feedlot, manure management and associated cropping enterprises) (Objectives 1, 2 & 3)

3. benchmarking of existing models that have been adopted by the industry to integrate new data and information and validate models to provide confidence in current and future operations (Objectives 3 & 4)

4. the first N foot-printing exercise (and associated decision tool) for Australian beef feedlot systems allowing the industry to develop strategic policies and marketing strategies for future growth in export opportunities for the industry (Objective 4)

4 Methodology

4.1 Southern feedlot site

The southern site study was conducted at a commercial feedlot in Victoria. The terrain around the feedlot is typical of the eastern Wimmera region – flat topography, with dry bare soil during summer or crops growing during winter. The site is not impacted by any other sources of target greenhouse and non-greenhouse gases (N_2O, NH_3, and CH_4) as demonstrated by atmospheric sampling surveys reported by Hacker et al. (2016). The main source areas at the southern feedlot included cattle pens (23.7 ha), manure stockpile area (20 ha), and run-off ponds (0.3 ha). The manure stockpile area consisted of mixed processed manure (classified as old (cured), fresh manure), compost windrows and stabilised sorted compost piles (Figure 1).

Figure 1 Southern feedlot study site

The average capacity of the feedlot was 16,190 head over the period 2015-2017 with about 230,400 cattle being finished across the period of the experiment. The major cattle breeds were Angus and Angus cross (1−1.5 years of age), fed a finishing diet of barley and silage (70 to 100 day finishing cycles), and consumed an average of 10.64 kg dry matter daily and N intake of 255 g N/day. The daily feeding regime was twice a day feeding (09:00 and 16:00).

4.2 Northern feedlot site

The northern site study was conducted at a commercial feedlot on the Darling Downs, Queensland. The terrain around the feedlot was flat surrounded by growing crops (Figure 2). The farm is about 200 ha growing barley for silage and other roughages. The business purchases the majority of grains and some hay. The average capacity of feedlot was 16,000 head during this study with cattle achieving an average live weight of 478 kg. The animals are offered custom feeding rations for 13 different clients. The site managed two major breeds: Angus, long fed for 240-260 days and Brahman cross cattle, short fed 100-110 days. All pens received the first feed between 9:00 and 11:00 and a second feeding cycle before 16:30. The average feed intake (ration dependent) ranged from 11 to 14.5 kg DM/day.

Figure 2 Northern feedlot study site

The main source areas for GHG at the northern feedlot were cattle pens and run-off ponds. Cattle manure is stockpiled in pens and directly applied to crop lands after removal. No manure stockpiles are located at this feedlot.

4.3 Measurement techniques and instrumentation

Real time measurement of gaseous emissions for large scale sources is challenging. In this project, we applied several micrometeorological techniques to make our measurements on the target sources possible.

4.3.1 Inverse dispersion method

This method was used at both the southern and northern feedlots.

An **inverse-dispersion method (IDM)** was used to calculate emissions from the feedlot. This technique is based on the change in concentration (above background) measured from a well-defined source area (Flesch et al., 2004). Inverse-dispersion methods combined with the measurement of emissions using open-path concentration sensors (FTIR spectrometers, cavity ringdown wave modulation spectrometry and tuneable lasers) have proven to be the most versatile technology to calculate emissions of GHG at a range of scales (small point sources to large lagoons, and even landscape scale catchment studies). The key constraint is the capability of the technique used to measure the concentration of the gas with sufficient sensitivity to detect changes in concentration above background downwind of the source. This is exceptionally challenging when concentrations of GHG are close to background levels reflecting low and dispersed emission sources. This is not a problem at a feedlot reflecting high intensity (compared to background) emission point sources (animals in pens, pens, manure stockpiles and lagoons).

Two open-path Fourier transform infrared (OP-FTIR) spectrometers (Matrix-M IRcube, Bruker Optics, Ettlingen, Germany) were deployed in this study. Line-averaged concentrations of N_2O, NH_3, and CH_4 were measured at 2.5-min intervals simultaneously over a path length of 80-300 m between the spectrometer and one distant retro reflector with 70 corner cubes (Figure 3).

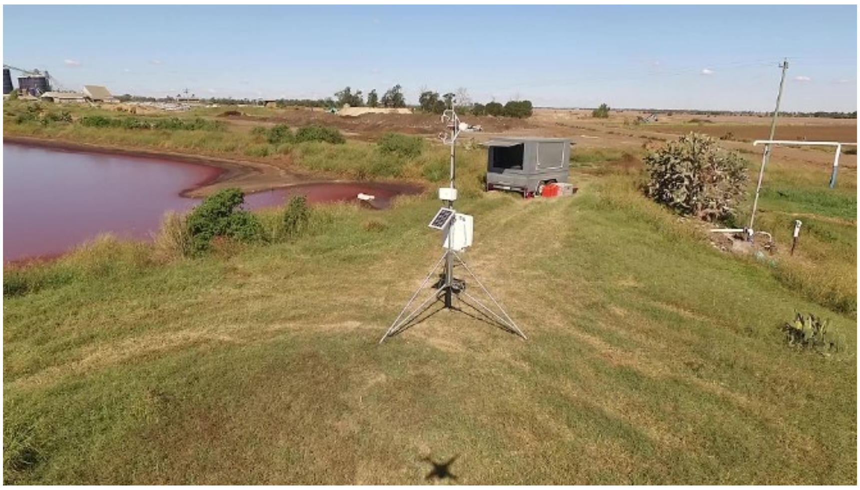
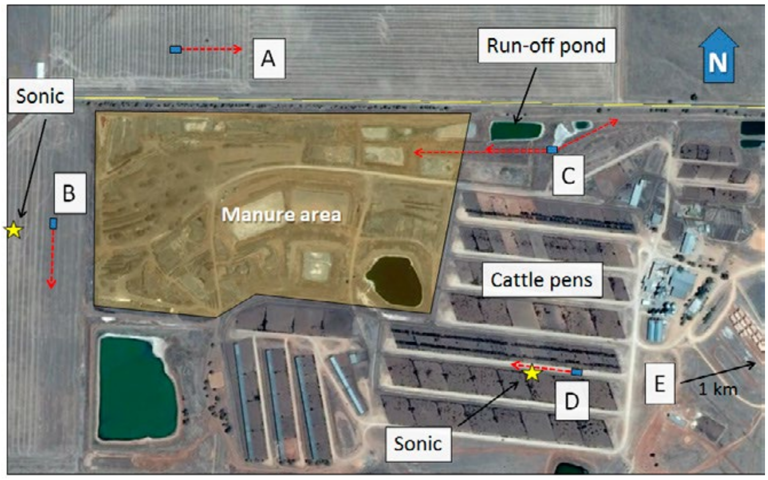


Figure 3 Open path FTIR instrumentation installed at the northern feedlot site.

The height of OP-FTIR path was 1.65 m above the ground. A motorised tripod head aiming system (developed by University of Wollongong) was used to enable one OP-FTIR spectrometer to be aimed at 2 retro reflectors located at two paths upwind and downwind of source area. In addition, two open path lasers (CH_4 and NH_3) (OP-laser; Gas Finder 2.0, Boreal Laser Inc.) were also deployed to measure summer emissions from the run-off pond, with a path length of 125 m (CH_4) and 250 m (NH_3), and one OP-FTIR was used to measure winter emissions of CH_4, CO_2, N_2O, and NH_3 with a path length of 150 m. The analyser provides precision and accuracy of the order of 0.2 ppb for N_2O, 1 ppb for CH_4 and 0.2 ppm for CO_2 (Griffith et al., 2012). A Windtrax map with instrument locations is shown in Figure 4. The information was processed using WindTrax 2.0.0.8, Thunder Beach Scientific, Canada: see Section 3.37 for more details).

March 2015 (southern feedlot)



June 2015 (southern feedlot)

Figure 4 Example of experimental configuration with locations of manure management (A & B), run off pond (C), cattle pens (D & E) and tower (F)

4.3.2 Concentration profile – inverse dispersion method

This method was used at both southern and northern feedlot sites

A **concentration profile-inverse dispersion method (IDM)** in conjunction with a low resolution (1 cm^{-1}) closed-path (CP) FTIR trace gas analyser (Spectronus, Ecotech Australia) was used to measure fluxes of N_2O, CH_4, and CO_2 simultaneously from a tower adjacent to the cattle pens. The CP-FTIR was used to obtain concentration profiles of CO_2, CH_4, and N_2O. Air was continually drawn from 3 filtered air inlets placed at heights of 7, 11 and 13 m for the southern site and 3, 5 and 8.5m at the northern feedlot site. The CP-FTIR was housed in an air-conditioned hut on the site (Figure 5 & 6). A 20L buffer volume on each line dampened short-term fluctuations and allowed the CP-FTIR to sample from each of these 3 volumes in succession to obtain a complete concentration profile over a 30-min period. Every 10 min, the CP-FTIR initiated a sampling protocol which involved flushing and purging the internal sample lines and the sample measurement cell with gas from the new height. The sample cell was then evacuated and re-filled at 1 SLPM to 950 hPa. After a settling time, the CP-FTIR's broadband infrared source and detector collected spectral information of the air within the sample cell for a 3-min interval before purging and flushing in preparation for the next measurement period. Gas concentrations were obtained through on-board spectral analysis of collected samples. All collected spectra were stored in a database within the CP-FTIR's internal computer and data were uploaded daily to a remote server backup. All data were retrieved and analyses were based on the best fitted spectrum using MALT (Multiple-Atmospheric Layer Transmission) (Griffith, 1996) and absorption line database HITRAN (High-resolution Transmission Molecular Absorption) database (Rothman et al., 2009). An initial laboratory calibration of the instrument was performed at the University of Wollongong Air laboratory using traceable gas standards. A small air tank was also analysed at this time and served as a standard for regular calibration checks of the CP-FTIR during the field campaigns. Quality control of collected spectra was performed with the cooperation of the University of Wollongong and a post-trial calibration following the southern site campaign was performed to check for any drift over the period of study and to generate an adjusted, quality-checked dataset containing 30-min average concentrations for CO_2, CH_4, and N_2O. Very little drift was noted over many months of continuous measurement. Accuracy of the CP-FTIR was assessed at 0.2 ppm, 4 ppb and 0.2 ppb for CO_2, CH_4 and N_2O respectively. The mathematical approach to modelling these atmospheric conditions is known as the backward Lagrangian Stochastic model (bLS). bLS has been published frequently as the preferred approach to estimate fluxes of GHG from landscapes. The project will deploy WINDTRAX simulations to convert measured concentrations of methane and nitrous oxide and report as fluxes. Further details on WINDTRAX can be found at: http://www.thunderbeachscientific.com/.

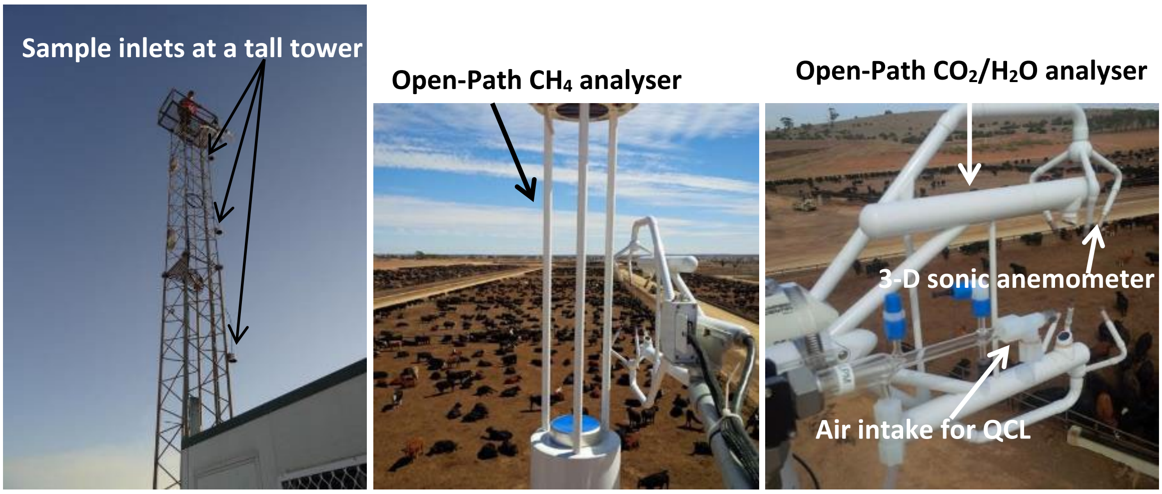


Figure 5 Measurement tower, methane analyser and air intake/QCL analyser at southern feedlot

Figure 6 Measurement tower at northern feedlot

4.3.3 Eddy covariance flux footprint method

This approach was taken at both the southern and northern feedlot sites

The **eddy covariance (EC) flux footprint model** coupled with fast-response sensors was used to calculate total emissions of each gas from cattle pen area. EC is a relatively new micrometeorological technique that allows the calculation of emissions of gases from surfaces. It is highly suited to landscape scale measurement, but it also requires a known measurement footprint. IDM technologies that use line-average or point source concentration measurements have a well understood enabling technology to predict the footprint of the measurement. Currently, the footprint for eddy covariance measurements is less well understood. Eddy covariance is based on the direct measurement of a vertical flux of gas at a single measurement point in the atmosphere. This flux represents a spatially weighted average of the gas exchanges between the surface (mostly upwind of the measurement) and the atmosphere. Areas of the surface that contribute to the calculated flux is the footprint. The extent and shape of the footprint varies with sensor height, characteristics of the surface (e.g. roughness) and atmospheric conditions. In landscape scale studies, the flux is assumed to be derived from a spatially extensive but homogeneous source, so footprint analysis is not required. This is not the case for feedlots where considerable spatial heterogeneity occurs as a result of the orientation of pens, manure handling areas, lagoons etc. There are a number of complex computational approaches to estimate the footprint in spatially heterogeneous environments (for example footprint weighting tool or 2-dimensional analytical footprint model) but all have limitations especially if the spatial heterogeneity reflects substantial differences in localised point source fluxes. Recently, the Lagrangian footprint model (the model used in IDM measurement approaches) has been utilised with good success in agriculture (Coates et al. 2018).

EC instrumentation was mounted on the top of the 13m feedlot tower at the southern site and at 6-m at the northern site on a telescopic tower. Instrumentation for both sites consisted of a 3-dimensional sonic anemometer (CSAT-3, Campbell Scientific), an open path CO_2 / H_2O analyser (EC-150, Campbell Scientific; precision of 0.2 ppm CO_2 and 3.5 ppm H_2O) and an open-path CH_4 analyser (Li-7700, Licor Biosciences, Lincoln, NE, USA; resolution of 5 ppb). The EC-150 was mounted directly to the sonic anemometer, at the midpoint of the CSAT-3 transducers. The Li-7700 was mounted close to the sonic anemometer (slightly eastward) with vertical and horizontal offsets entered into the analysis software. Gas concentration data from open-path analysers as well as all wind statistics were recorded at a frequency of 10 Hz with data stored on a datalogger (CR-3000, Campbell Scientific). In contrast to the CP-FTIR, the Quantum Cascade laser (QCL) units are flow-through gas analysers capable of 10Hz measurements with an appropriate pump (Agilent TriScroll 600). An air inlet mounted near the mid-point of the CSAT-3 allowed a 10 Hz measurement of CH_4, N_2O and NH_3. Due to the tendency of NH_3 to adsorb onto non-inert surfaces, a blown glass, virtual impactor was used at the inlet to allow for particulates in the airstream to be removed without the requirement for a physical filter which could affect concentration data. An insulated heated line was maintained at 40ºC to reduce adsorption of NH_3 on the Teflon sample tubing surface. The mathematical approach to modelling atmospheric conditions using eddy covariance is outlined in Kjilun et al. (2015). The project deployed Eddy Pro simulations to convert measured concentrations of methane, nitrous oxide and ammonia and report as fluxes. Further details on EDDY Pro can be found at:
https://www.licor.com/env/products/eddy_covariance/software.html

4.3.4 Snapshot measurements

Southern feedlot site only

A number of 'snapshot' measurements of greenhouse gas emissions were conducted. These included measurements of the manure stockpile areas and run-off ponds. Measurements were conducted between March and May in 2015, and from June to December in 2016 using inverse-dispersion method combined with OP-FTIR techniques and chamber methods. Static closed-chamber measurements were also used in the manure composting study at the southern site feedlot.

4.3.5 Static chamber and measurement of composting processes

Southern feedlot site only

Fresh manure from one pen (pen #131) was transported to the west of feedlot (June 2016: Figure 7) and divided into two parts, one quantity for composting and one quantity for stockpiling. A total of 185.1 ts of wet manure was used for compost row (north south alignment: 52 m (length) x 5.1 m (width) x 1.4 m (height)), and 37.7 t of manure was used for the stockpile (8.9 m diameter and 1.65 m height) (Figure 8). The compost manure windrow was turned for the first time on 3 June 2015, and thereafter when ground conditions allowed. The windrow turning equipment (Komptech, Topturn X55) was operated by feedlot staff. In contrast, the stockpile remained unturned as a control treatment.

Figure 7 Manure composting study at the southern feedlot

Figure 8 Static chamber measurement of fluxes from a compost row at the southern feedlot site

Two static chamber designs, 25 cm diameter by 15 cm high (nominal volume = 7350 cm^3) and 11 cm diameter by 11.5 cm high (nominal volume = 1525 cm^3) were used to measure fluxes of CH_4, CO_2 and N_2O from manure treatments. The larger chambers were used to verify emissions from the compost row with those derived utilising the inverse-dispersion method during snapshot measurements. The smaller chambers were used to quantify source strength associated with the manure storage time.

The windrow was divided into 4 sections of 10 m length. Following each compost turning, 12 large chambers were manually inserted to a compost manure depth of 5 cm and settled for few hours: three chambers were installed on each section, located on both the eastern and western sides, as well as the top of the row (Figure 8). Gas samples from the chamber headspace were drawn by a syringe through a rubber block on the lid surface. The first 5 mL of samples were discarded to remove any contamination and residual air. A further 20 mL gas was collected at 0, 20, 40 minutes during chamber enclosure, and transferred to evacuated 12 mL vials (ExetainerH, Labco Ltd.). Gas samples were analysed for all gases using gas chromatography (Agilent 7890A) at laboratory. Manure samples from compost row and stockpile were also collected every two days in the first month after manure row and pile were created. After one month, the sampling frequency was weekly. Manure samples were stored in the freezer for chemical analysis at laboratory. Manure samples were later oven-dried at 40°C and analysed for physical and chemical properties including pH (1:5 H_2O), total carbon (TC), total nitrogen (TN), ammonium-nitrogen (NH_4^+−N), and nitrate-nitrogen (NO_3^-−N) (TrACESS Soil Node, University of Melbourne). For TC and TN analysis, samples were ground (< 2 mm) and analysed on a LECO Trumac CN Analyser. For NH_4−N and NO_3−N analysis, sample (~ 4 g) was extracted with 2M KCl (1:20) and analysed using Skalar SAN++ segmented flow analyser. Inverse-dispersion measurements commenced 2 days before the compost row and stockpile were constructed to gather background data.

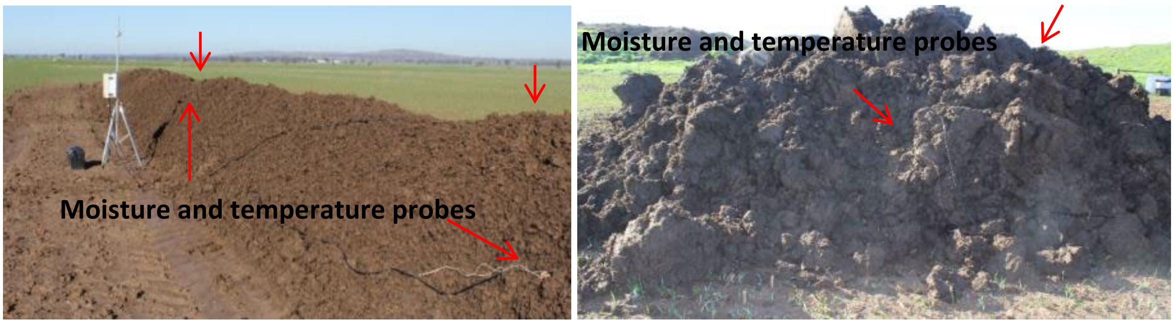


Figure 9 Moisture and temperature measurement in a compost windrow at the southern feedlot site

Four pairs of moisture and temperature probes (Campbell Scientific) were installed in the compost row (two on the eastern side and the other two on the western side, at height of 0.7 m above ground). Two pairs of moisture and temperature probes (Thetha probe, UK) were installed on the eastern and western side of the stockpile (Figure 9). Manure moisture and temperature were recorded at 15-min intervals by a data logger (CR800, Campbell Scientific).

Two three-dimensional (3-D) sonic anemometers were used in this study. One was set up on the tall tower (13 m), 30-min average of wind speed, wind direction and wind statistics were recorded for flux gradient and EC flux calculations. The second 3-D sonic anemometer was set up on a mast at height of 2.8 m above ground located at the west of the compost site. Fifteen-min average of wind turbulence data was recorded at a frequency of 10 Hz, and atmospheric stability parameters, e.g., friction velocity (u_*, m s^{-1}), atmospheric stability length (L, m) and surface roughness (z_0, m), wind direction (β) were retrieved for Windtrax flux calculations. Software SAS (version 9.4) was used to merge sonic data and gas concentrations to 15-min average values.

4.3.6 Lignite amendment of manure for compost manufacturing

Southern feedlot site only

Two side-by-side cattle pens (29 × 50 m) were selected for this study and resurfaced with clay to provide a stable base to collect animal manure. Prior to admitting the cattle, one pen surface was uniformly applied with 16.2 t lignite (60% moisture, pH: 5.76, labile carbon (C): 45.7 g kg^{-1}, conductivity C: 1515.7 µS cm^{-1}) on 9 November 2017, while the other pen was left as the control pen with no lignite applied.

The applied lignite properties are shown in Table 1. Each pen was then populated with 135 Angus beef steers (460 kg) on 15 November. After 90 days, cattle were removed, and the manure was scraped from the surface of both pens, utilising standard feedlot pen cleaning procedures. The accumulated manure was then weighed and transported to the west side of the feedlot and two windrows were formed, one from the control pen manure (43.96 t) and one from the lignite treated pen manure (25.14 t).

The physical and chemical properties of initial windrow manure are shown in Table 1. The composting measurement site was located just west of the feedlot, where the terrain was open and flat with short crop residues (harvested in December the previous year). The two windrows were oriented north-south (30 m apart) to allow concurrent emission measurements during periods with westerly winds (Figure 10), when feedlot emissions would not ”contaminate” our measurement site. There were no other emission sources in the area as the nearest farms were several kilometres away from the measurement site. The lignite compost windrow (14 m long × 4.3 m wide × 1.2 m high) was on the south, and the non-lignite compost windrow (20 m long × 4.3 m wide × 1.2 m high) was on the north. During the measurement period of 87days, both windrows were turned 12 times, from the fresh windrow to the final compost-product as fertiliser, with each turning taking about 10 minutes. The windrow turning equipment (Komptech, Topturn X55) was operated by feedlot staff. Emission measurements began on February 15, immediately after the compost windrows were formed, and ended on 16 May 2018.

Table 1 Characteristics of windrow manure used in composting trials at southern feedlot

	Moisture (%)	pH	NH_4^+ (%)	NO_3^- (%)	TC[#] (%)	TN[§] (%)
Lignite amended manure	31.1	7.4	0.8	0	29.3	2.8
Non-lignite amended manure	28.9	7.3	0.9	0	27.0	2.5

[#], total carbon, [§], total nitrogen,

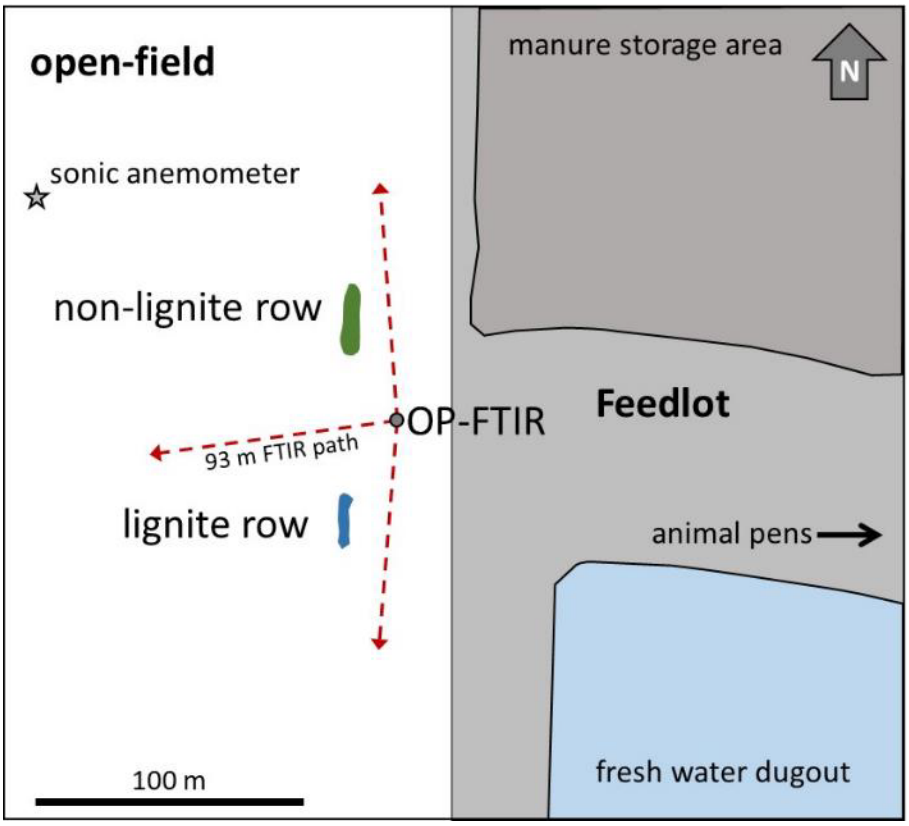


Figure 10 Configuration of composting study site at the southern feedlot

Manure sampling was done immediately after each turning from 5 separate locations along the windrow. Four sub-samples were collected using a core (3 cm diameter, 90 cm long) at each location (2 samples from the eastern side, and 2 samples from the western side of the windrow) and mixed to one sample. Each collected sample (~500 g) was stored in a plastic bag and frozen at −20°C for further processing and analysis. These manure samples were later oven-dried at 40°C and analyzed for physical and chemical properties including pH (1:5 H_2O), total carbon (TC), total nitrogen (TN), ammonium-nitrogen (NH_4^+−N), and nitrate-nitrogen (NO_3^-−N) (TrACESS Soil Node, University of Melbourne). For TC and TN analysis, samples were ground (< 2 mm) and analysed on a LECO Trumac CN Analyzer. For NH_4−N and NO_3−N analysis, sample (~ 4 g) was extracted with 2M KCl (1:20) and analysed using Skalar SAN++ segmented flow analyser.

One OP-FTIR (Matrix-M IRcube, Bruker Optics) was deployed to measure the line-average concentrations of CH_4, CO_2, N_2O, and NH_3, between the spectrometer and a distant retroreflector. The analysis to determine the gas concentrations from the OP-FTIR spectra is based on non-linear least squares fitting procedure of the measured spectra against a computed spectrum given by the HITRAN database of spectral line parameters (Rothman et al., 2009). The expected OP-FTIR spectrum is iteratively calculated until a best-fit to the measured spectrum is obtained. The concentrations of absorption species of CO_2, N_2O (2130−2283 cm^{-1}), CH_4 and water vapour (2920−3020 cm^{-1}), and NH_3 (900−980 cm^{-1}) are obtained using Multiple-Atmospheric Layer Transmission (MALT) software (Griffith, 1996; Griffith et al., 2012). Coupled to the concentration measurement, ambient temperature and pressure are also measured by OP-FTIR for concentration retrievals. The concentration measurement precisions are: 2 ppb for CH_4, 0.4 ppb for NH_3, 0.3 ppb for N_2O, and 1 ppm for CO_2 at a 100 m path length. A motorised aiming system enabled the spectrometer to aim at different retro reflectors at three paths (placed to the south, the north, and the west of the spectrometer) (Fig. 10). The three retro reflectors were each located 93 m from the spectrometer, and the OP-FTIR path height was 1.65 m above the ground. Three-min gas concentrations were obtained from each path for periods with westerly and south-easterly wind directions.

An inverse-dispersion model (Windtrax, Thunder Beach Scientific) was used to calculate gas fluxes. The principles of this technique can be found in Flesch et al. (2004). A 3-dimensional sonic anemometer (CSAT3, Campbell Scientific) was set up west of the compost site at 2.8 m above the ground. Wind and temperature were measured at a frequency of 10 Hz, and the average wind statistics were recorded at 15-min intervals. The wind statistics were later processed to give the atmospheric properties needed for a flux calculation: the friction velocity (u_*), Obukhov stability length (L), surface roughness (z_0), wind direction, and wind velocity standard deviations ($\sigma_{u,v,w}$). We used the software SAS (version 9.4) to process gas concentration and wind data into 15-min average timeseries.

Statistical models were used to estimate daily and accumulative flux for each gas and each windrow. We estimated the trend in mean daily fluxes for the whole measurement period by fitting generalized additive models (Hastie and Tibshirani, 1990) to the daily time series data using the 'gam' function in the 'mgcv" package (Wood, 2006) in R.3.3.3 (RCoreTeam, 2018). Model predictions were used to impute emission values for days without measurement. We used Monte Carlo methods to propagate uncertainties in the daily fluxes arising from the imputation of missing data, as well as uncertainties (mean, 95% confidence intervals) in the cumulative fluxes.

4.3.7 Statistical analysis of micrometeorology and flux data

This section addresses the broad methodology that was used to process gas-micrometeorology data collected from both feedlot sites.

4.3.7.1 Inverse dispersion model

Concentration profiles obtained with the CP-FTIR, as well as concentration data obtained from open-path instruments (lasers for NH_3 and open-path FTIR for CH_4, CO_2 and NH_3) were processed through the freely available Windtrax software package (http://www.thunderbeachscientific.com/) to obtain gas emission estimates from the feedlot sites.

The Windtrax software consists of a unique map interface and an atmospheric surface layer model which simulates the transport of trace gases in the atmosphere. The map interface allows for accurate placement of all source areas in relation to concentration sensor locations. Once the spatial information has been entered and the concentration data linked to sensors on the map, Windtrax then uses wind statistics obtained from the 3-D sonic anemometer to model atmospheric conditions and simulate transport of trace gases using a Lagrangian stochastic numerical model. A model run involved a backward-time simulation of released "particles" from concentration sensor locations on a 30-min time-step. Windtrax tracks the along-wind particle trajectories and quantifies touchdown points that fall within source areas. A touchdown indicates the particle originated from the source area and contributes to the measured concentration (Figure 11). Through these simulations, Windtrax is able to model the relationship between concentration and source emission at any point in the plume and provide estimates of source emissions.

When processing the feedlot data, only occupied pens were identified as source areas of GHG emissions with all other areas assumed to be non-emitting surfaces by the model. This is justified for CO_2 and CH_4 as the animals themselves are the principle contributors. The presence of animals is also associated with NH_3 emissions, as urinary-N is hydrolysed to NH_3 on the feedlot pen surface. Emissions of N_2O are less dependent on the presence of animals but baseline emissions of N_2O are low and elevated fluxes tend to be driven by weather events. The low baseline emissions noted during emission measurements from empty feedlot pens provided further support for this approach to our analysis.

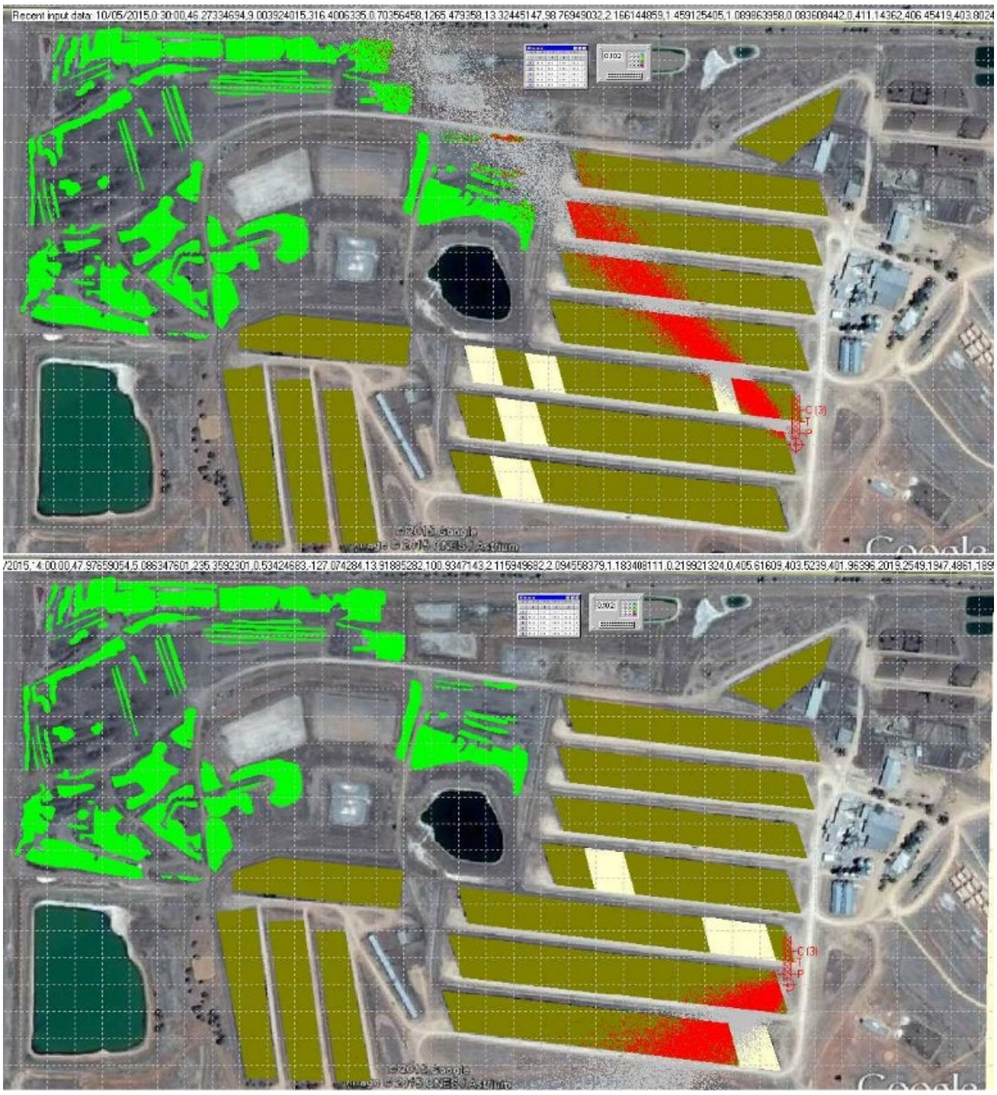


Figure 11 WINDTRAX simulation for the southern feedlot showing particle touchdown patterns (red)

Windtrax emission estimates are based on the assumption that all source areas are equal emitters. Within the confines of the feedlot environment, where animal density for each pen is similar, this assumption is reasonable. Windtrax emission estimates are reported on a mass per unit-time per unit-area basis (referenced to the source area). Emissions on a per animal basis are easily obtained by multiplying by the occupied pen area and dividing by the number of animals for the period.

4.3.7.2 Flux determination – Eddy Covariance Data

Eddy covariance is a micrometeorological technique which utilises fast response gas analysers to measure gas concentration at the same frequency as the 3-dimensional wind speed components. Processing involves a statistical correlation of gas concentration with vertical wind speed over a set averaging interval (typically 30-min) to obtain a spatial weighted average flux of emissions of the underlying surface. A common time-server was utilised to ensure accurate compilation of 10 Hz meteorological and gas analyser datasets. Eddypro™ software was then used to process gas concentration data, wind statistics and site metadata to generate quality checked 30-min gas fluxes.
The approach to footprint correction is outlined. EC fluxes generated through Eddypro processing yielded gas fluxes in terms of mass per unit-area per unit-time (i.e. kg CH_4 hr^{-1} m^{-2}). The flux calculated from a tower-based measurement represents a spatially weighted average of surface fluxes occurring in the immediate area of the tower and extending for some distance upwind with areas close to the tower contributing more to the calculated flux than areas further upwind. Collectively, this area of the surface that contributes to the calculated flux at the tower is known as the flux footprint (Schuepp et al., 1990). The shape and areal extent of this footprint are determined by the wind conditions, the strength of atmospheric turbulence, the surface roughness and the height of the measurement tower. One of the assumptions underlying the eddy covariance technique is that measurements are taking place over an infinite homogeneous source. In such an idealised situation, changes in wind direction, wind speed and atmospheric stability would have no effect on the calculated flux. When taking measurements over an inhomogeneous source area such as a feedlot with a defined boundary and a mix of emitting (animal pens) and non-emitting sources (empty pens, road surfaces etc.), it becomes important to correct the calculated flux to account for periods where the footprint extends beyond the feedlot boundary (Figure 12) and to account for empty pen surfaces and other surfaces such as alleys and roads that we know are not contributing to the calculated flux.

This footprint correction process is based on principles outlined in Flesch (1996) and further developed in Coates et al. (2017; 2018) where a Lagrangian stochastic program was used to calculate particle trajectories and generate footprint corrected EC fluxes for the purpose of deriving CH_4 emissions from grazing cattle. This program was reconfigured for the feedlot environment by treating the cattle pens as source areas, rather than individual animals as was required in a grazing environment.

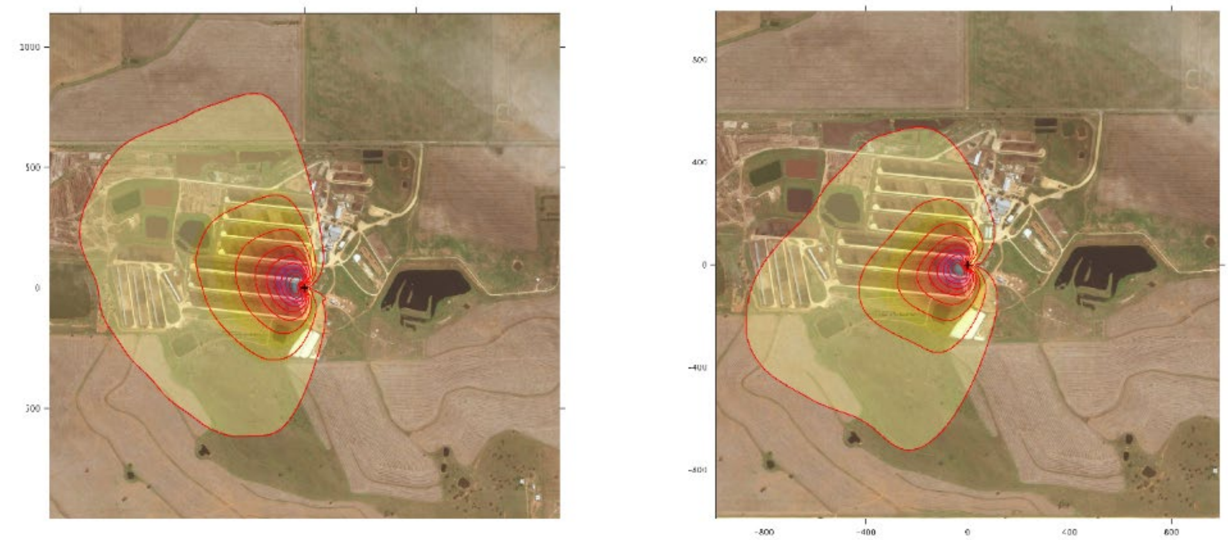


Figure 12 Visualisation of the flux footprint at the southern feedlot

This footprint correction model employs the same Lagrangian stochastic numerical simulation approach as Windtrax, however, while the Windtrax program models the relationship of concentration to source emission, the footprint correction program models the relationship between a calculated tower flux and source emission. A controlled gas release validation study using this approach (Coates et al., 2017) yielded emission estimates within 10% of the true emission rate which is typical of the expected accuracy of micrometeorological techniques (Harper et al., 2010). Key to both model simulations in a feedlot application is access to the daily pen report data, which provides the animal inventory information necessary for source allocation of feedlot pens. For each feedlot, daily feed reports were compiled and processed to create a daily cattle inventory for each pen of the feedlot. Using this inventory file, all occupied pens were identified as source areas and a new source map was created for each period of changed pen occupancy. Polygon files containing perimeter coordinates of all occupied pens were imported directly into Windtrax to create the project file maps required for Windtrax simulation runs.

Concentration data and EC flux data were parsed to create input files for Windtrax and the footprint correction program respectively, which corresponded to the date ranges of the source area maps. A separate map file consisting of the corner coordinates of each source area (pen perimeter) was loaded to accompany each line of input data processed through the flux footprint correction program. As with Windtrax, model runs of the footprint program tracked trajectories of particles released at the sensor location (EC flux tower). The generated touchdown catalogues from the simulation runs represent the flux footprint by identifying the source areas that contribute to the calculated flux at the tower. This touchdown analysis produced correction factors which were applied to the EC data to yield corrected fluxes representative of the source area emissions

4.3.8 Critical control point analysis

A critical control point is defined as a step at which control can be applied and is essential to prevent or eliminate a hazard or reduce it to an acceptable level. In the case of this project, the potential hazards that are reasonably likely to cause a major emission event. Complete and accurate identification of CCPs is fundamental to controlling emission events. The information developed during the hazard analysis is essential for the management of the feedlot through the identifications of steps in the management process that an intervention (mitigation or systems adaptation) can be deployed. All critical control points are located at any step where hazards can be either prevented, eliminated, or reduced to acceptable levels, for example, methods to prevent anaerobiosis of manure through windrow management could reduce methane emissions and also affect the nitrous oxide and ammonia emissions from manure. The approach taken was to establish critical limits, as a critical limit is a maximum and/or minimum value to which a biological, chemical or physical parameter must be controlled at a CCP to prevent, eliminate or reduce to an acceptable level the occurrence of a hazard.

The statistical approach was to create a quality control chart by plotting data consecutively, together with a line at the mean, and at −2s, +2s, −3s and +3s (s = standard deviation), i.e. at 95% and 99.7% confidence limits. A thin dashed line represents the ± 1s interval. A series of CCP rules were used to set ‘warning’ or intervention limits.

For feed lot systems, the 1:2s rule was used, where an intervention is identified when a measurement exceeds the mean ± 2SD (or the warning limits). A 1:3s rule was also used to determine random error (for example system errors associated with measurement technique rather than environmental variation). Control data sets were screened for 4:1s errors or measures of systemic bias if more than 4 consecutive measures exceed the 1s rule.

4.3.9 Modelling

All animal performance data were used to estimate emissions of methane and nitrous oxide using the approaches of the National Greenhouse Gas Inventory (2017). Outputs from the National Inventory models were developed for known feed intakes and for scenarios that represent IPCC reported data (in the case of beef cattle in feedlots, NRC models for feed intake and volatile solids were used rather than actual measured data).

In a general sense, cattle dietary nutrients (N, C, and P) are fed to cattle, discarded via manure or GHGs, then applied to the croplands as fertilizer. Biogeochemical processes in feedlot waste treatment including manure composting play an important role in regulating these nutrients *in* and *out within the feedlots*. The animal performance and climate data were also used to train the catchment nutrient management model (WNMM) to determine if that modelling system could be used in the future as a representative approach to determine all the greenhouse gas emissions from feedlots. This objective is similar to the work conducted in project B.FLT.0148, where Manure DNDC was evaluated.

5 Results

5.1 Study duration and quality of data

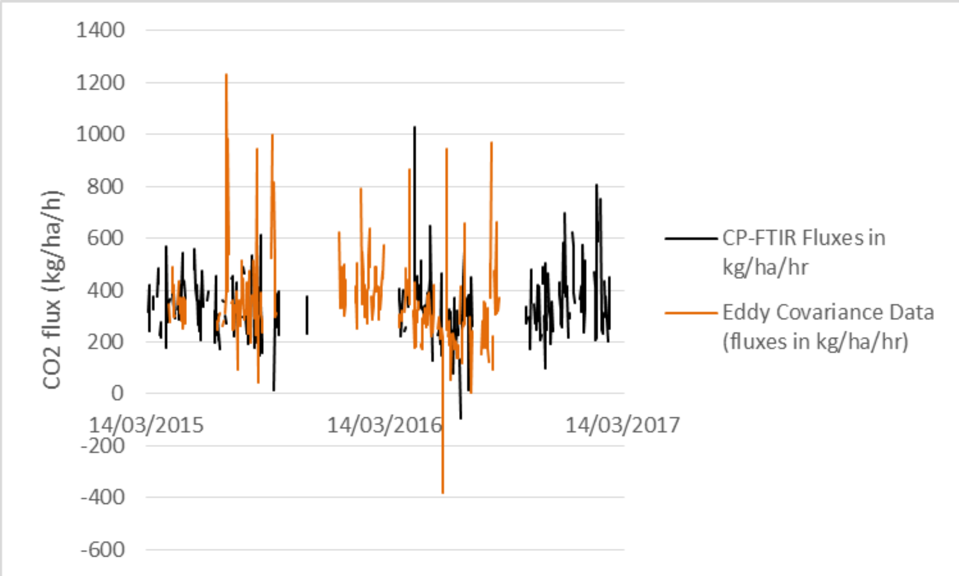
It is also acknowledged that the major constraints to open-path micrometeorology techniques is that measurements can only be made over limited periods of time (campaign length, labour costs and constraints associated with working in remote locations), and the lack of representation of the data over a long period (several months) of time (Tomkins and Charmley, 2015). Furthermore, these concerns are compounded by the impact of loss of data from long-duration time-series and how to develop strategies to develop robust models from constrained data series. A common problem that is faced with the measurement of a long duration time series is missing data. This issue is of critical importance when considering:

(i) if a method is appropriate to deliver long-term meaningful information (resilience of the method);
(ii) if one method is superior to another; and
(iii) how much data and information can be lost before rendering the data series invalid for further analysis.

5.1.1 Carbon dioxide flux

Two data series are available for the southern feedlot site (IDM and EC methods) and one data series for the northern site (IDM). An analysis of the data series was conducted for the southern and northern feedlot carbon dioxide flux data series (Figure 13). At the southern site, the data series measured using CP-FTIR (IDM) represented 39.4% of day observations of CO_2 flux (n= 289) over a period of 734 days (14 March 2015 to 16 March 2017) after statistical processing. The EC data series represented 34.7% of day measurements (255 days). The longest period of time without a measurement at the southern site was 82 days or 11.1% of total series duration using the IDM method and was 93 days (12.6% of time series for the EC method. However, the data series at the northern site was less extensive being 94-day measurements in one calendar year (or 25.8% of data series).

(a) Southern feedlot



(b) Northern feedlot

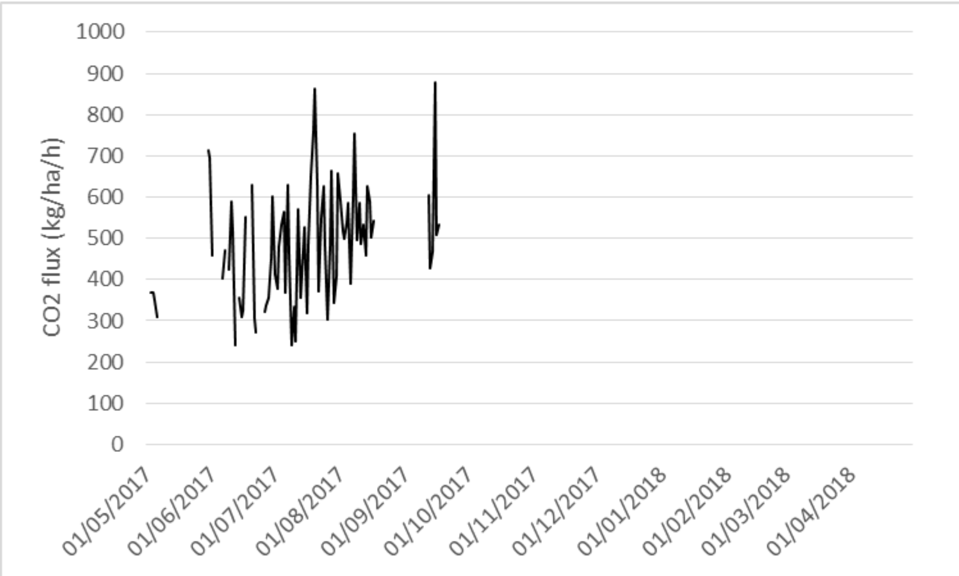


Figure 13 Carbon dioxide fluxes measured at (a) the southern and (b) northern feedlot sites

Cross tabulation of the southern site data demonstrates that only 147 individual day measurements were represented as paired data (synchronous measurement of CO_2 flux using CP-FTIR and EC methods: Table 2). Using these data series only, no significant difference in measured CO_2 flux between methods was observed.

Table 2 Comparison of CP FTIR and EC methods for measuring carbon dioxide fluxes (kg/ha/h) at the southern feedlot site

	CP-FTIR flux	EC flux
Sample size	147	147
Arithmetic mean	321.5068	298.3342
95% CI for the mean	301.1895 to 341.8240	279.9655 to 316.7030
Variance	15535.3429	12698.3912
Standard deviation	124.6409	112.6871
Standard error of the mean	10.2802	9.2943

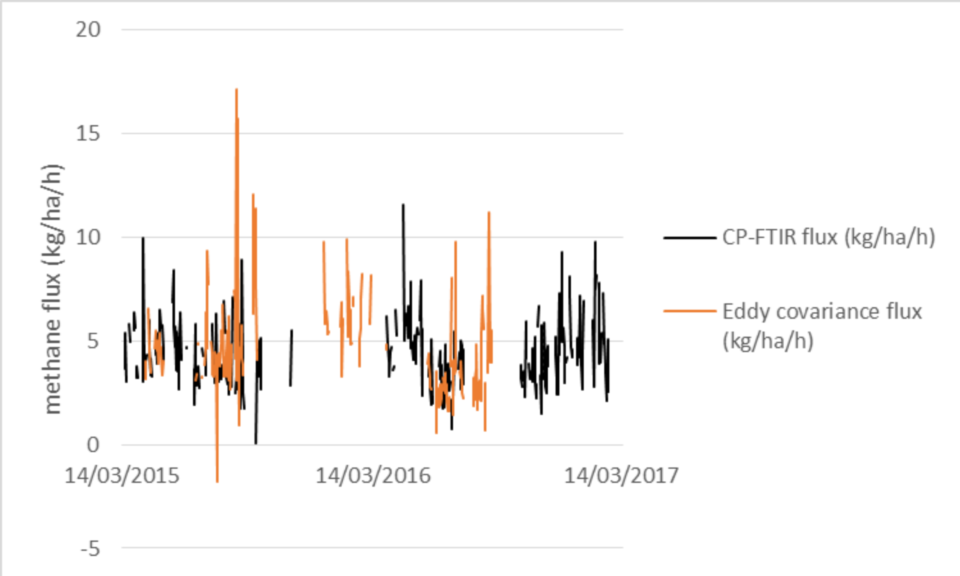
Paired samples t-test

Mean difference	-23.1725
Standard deviation of differences	168.4606
Standard error of mean difference	13.8944
95% CI of difference	-50.6327 to 4.2876
Test statistic t	-1.668
Degrees of Freedom (DF)	146
Two-tailed probability	P = 0.0975

5.1.2 Methane

In a similar fashion to that of carbon dioxide, two data series are available for the southern feedlot site (IDM and EC methods) and one data series for the northern site (IDM). An analysis of the data series was conducted for the southern and northern feedlot methane flux data series (Figure 14). At the southern site, the data series measured using CP-FTIR (IDM) represented 39.4% of day observations of CH_4 flux (n= 289) over a period of 734 days (14 March 2015 to 16 March 2017) after statistical processing. The EC data series represented 24.5% of day measurements (180 days). The longest period of time without a measurement at the southern site was 82 days or 11.1% of total series duration using the IDM method and was 93 days, 12.7% of time series for the EC method. The basis for the northern feedlot measurement was the same as for carbon dioxide and therefore a less extensive data set was available being 94-day measurements in one calendar year (25.8% of data series).

(a) Southern feedlot



(b) Northern feedlot

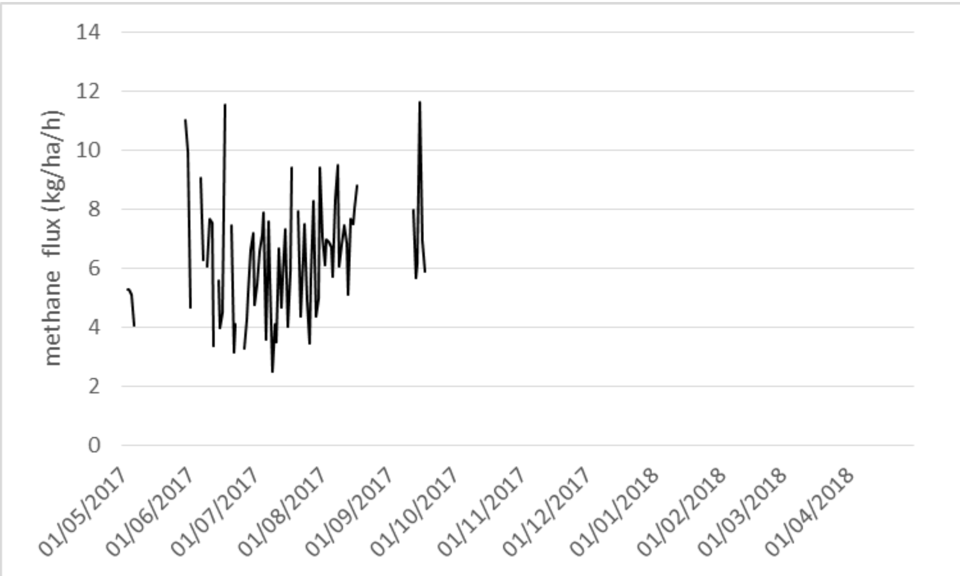


Figure 14 Methane fluxes measured at (a) the southern and (b) northern feedlot sites

In contrast to the carbon dioxide flux data series, only 116 individual paired days could be identified to compare methods for methane flux. No significant difference in methane fluxes (kg/ha/h) between measurement methods were observed with an average flux of 3.99 (CP-FTIR) and 4.06 (EC method) (Table 3).

Table 3 Comparison of CP FTIR and EC methods for measuring methane fluxes (kg/ha/h) at the southern feedlot site

	CP-FTIR	EC method
Sample size	116	116
Arithmetic mean	3.9879	4.0620
95% CI for the mean	3.7305 to 4.2453	3.7323 to 4.3917
Variance	1.9590	3.2138
Standard deviation	1.3996	1.7927
Standard error of the mean	0.1300	0.1664

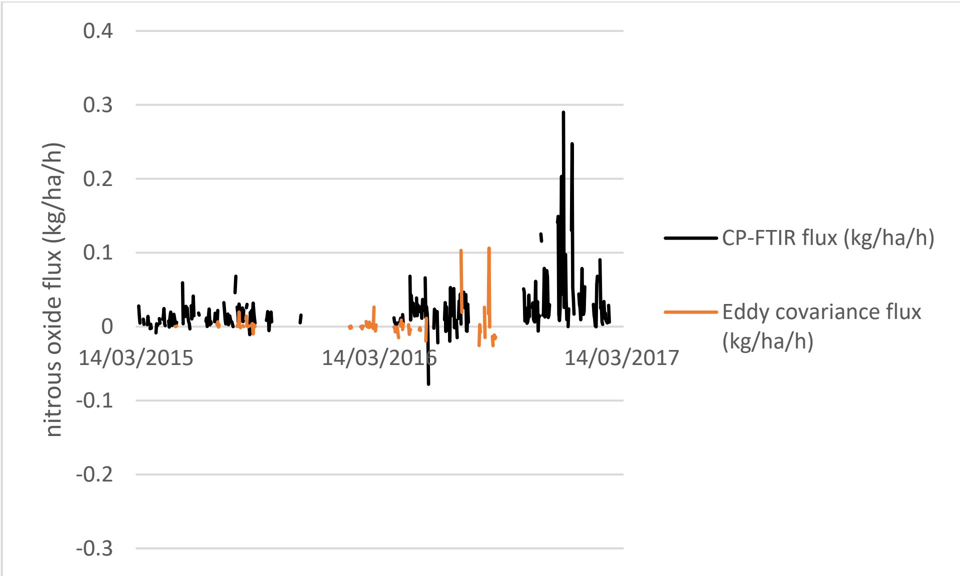
Paired samples t-test

Mean difference	0.07409
Standard deviation of differences	2.2122
Standard error of mean difference	0.2054
95% CI of difference	-0.3328 to 0.4809
Test statistic t	0.361
Degrees of Freedom (DF)	115
Two-tailed probability	P = 0.7190

5.1.3 Nitrous oxide

Two data series for nitrous oxide emissions are available for the southern feedlot site (IDM and EC methods) and one data series for the northern site (IDM). At the southern site, the data series measured using CP-FTIR (IDM) represented 39.4% of day observations (n= 289) over a period of 734 days (14 March 2015 to 16 March 2017) after statistical processing. The EC data series represented 13.3% of day measurements (98 days). The longest period of time without a measurement at the southern site was 137 days or 18.7% of total series duration using the IDM method and was 93 days (12.7% of time series for the EC method. The basis for the northern feedlot measurement was the same as for carbon dioxide and therefore a less extensive data set was available being 91-day measurements in one calendar year (or 25.4% of data series) (Figure 15).

(a) Southern feedlot



(b) Northern feedlot

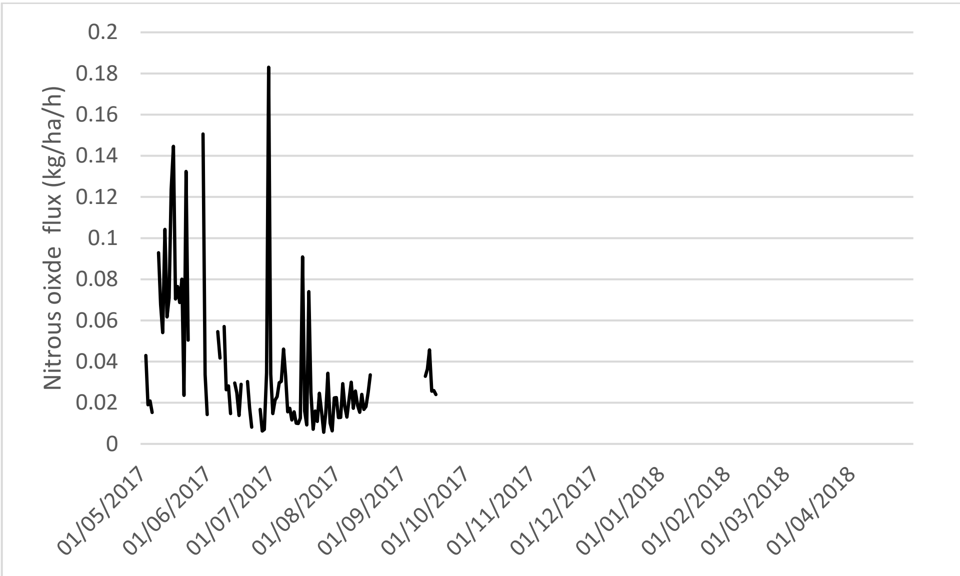


Figure 15 Nitrous oxide fluxes measured at (a) the southern and (b) northern feedlot sites

The nitrous oxide paired data series (CP-FTIR vs. EC) was very limited – only 12.4% of total series. A statistical difference between the fluxes measured using CP-FTIR and the eddy covariance method was observed ($P<0.001$). The differences in the measured fluxes were about 10-fold (EC lower than CP-FTIR).

Table 4 Comparison of CP FTIR and EC methods for measuring nitrous oxide fluxes (kg/ha/h) at the southern feedlot site

	CP-FTIR	EC
Sample size	51	51
Arithmetic mean	0.01479	0.001015
95% CI for the mean	0.01127 to 0.01830	-0.003605 to 0.005636
Variance	0.0001565	0.0002699
Standard deviation	0.01251	0.01643
Standard error of the mean	0.001752	0.002301

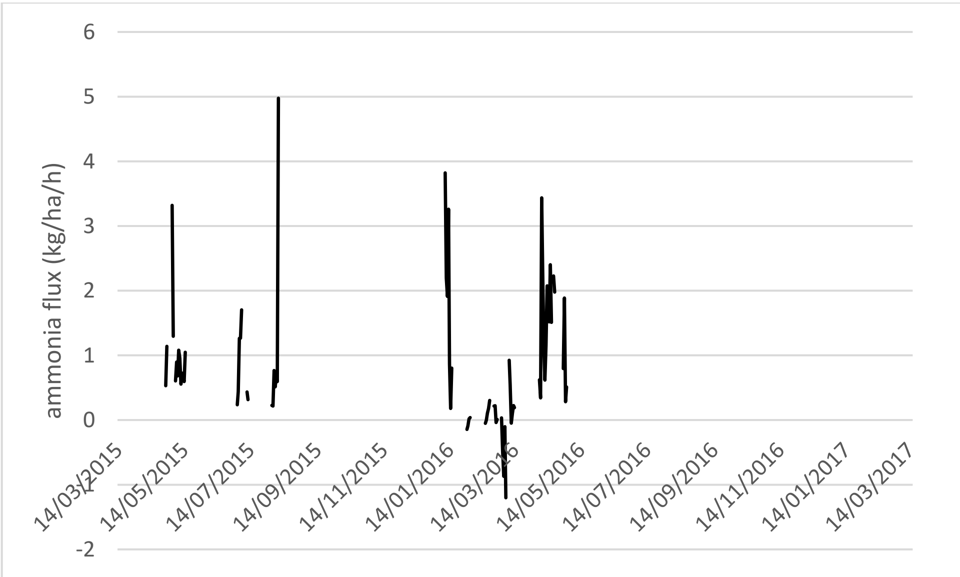
Paired samples t-test

Mean difference	-0.01377
Standard deviation of differences	0.02210
Standard error of mean difference	0.003095
95% CI of difference	-0.01999 to -0.007555
Test statistic t	-4.450
Degrees of Freedom (DF)	50
Two-tailed probability	P < 0.0001

5.1.4 Ammonia

The ammonia flux series for the southern feedlot was highly fragmented and only accounted for 11.0 % of total collected at the site. However, the measured fluxes from the northern feedlot occurred on 43.8% of days (total of 160-day measurements in one year).

(a) Southern feedlot



(b) Northern feedlot

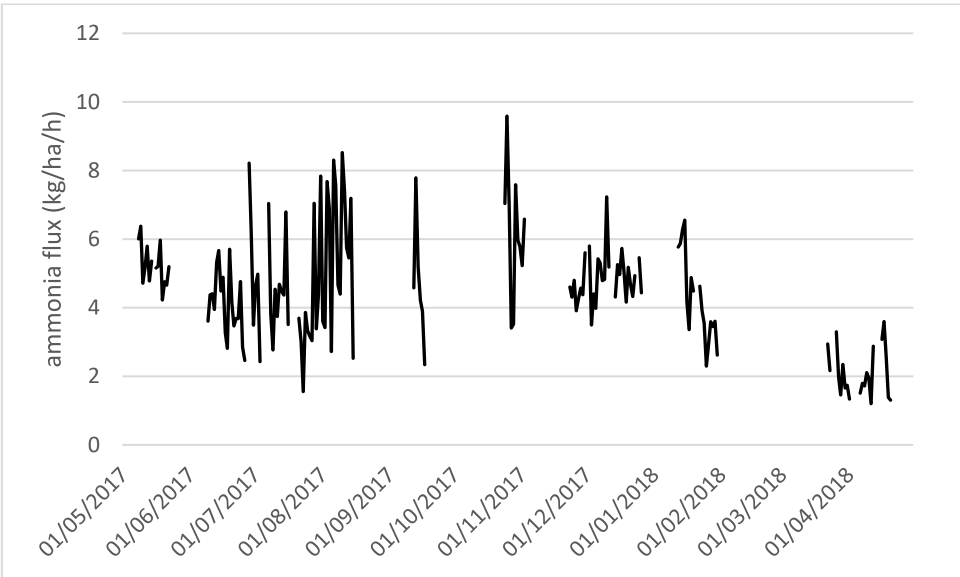


Figure 16 Ammonia fluxes (kg/ha/h) measured at (a) the southern and (b) northern feedlot sites

5.1.5 How much data and information can be lost before rendering the data series invalid for further analysis.

Often, in time series experiments, some measurements are missed for some reason. This is most likely to reflect equipment failure or data processing protocols. Emissions measurements from feedlots or any agricultural system can suffer from both of these issues – for instance equipment failure has been observed in many studies. Data processing of micrometeorological data series that are implicit to the calculation of greenhouse gas fluxes can reduce the number of actual data points used in a time series – for instance if the wind speed drops below a certain point, friction velocity (u*) and stability (L) calculations are affected and the measurement of flux becomes unreliable. Most studies that are impacted by gaps in data series try to solve the issue of missing data by using ARIMA-type methods of time-series analysis (Box and Jenkins, 1970). ARIMA type approaches are not perfect in terms of their use to solve the issues of gaps within data series, but they are robust enough to ensure that a good understanding of how much data and information can be lost before the series is invalid.

5.1.5.1 ARIMA modelling of southern feedlot data

An ARIMA model was constructed for all data series (CO_2, CH_4, N_2O and NH_3) measured at the southern feedlot site. The data series for CO_2 and CH_4 measured using CP-FTIR were concordant with the ARIMA model and passed all validation tests. However, the nitrous oxide data series (CP-FTIR) passed all ARIMA validation tests but demonstrated lower fidelity. It is recommended that the outcomes from the analysis of this data set are viewed with caution. Even though the data series for CO_2 (Figure 17 & 18) and CH_4 measured using eddy covariance passed all ARIMA validation tests, they suffered from significant structural issues. It is concluded that those data are useful in the overall analysis but some caution may be required to interpret the outcomes. The eddy covariance data series for ammonia and nitrous oxide emissions at the southern feedlot site were not valid (Table 5).

Table 5 Comparison between actual measured fluxes of greenhouse gases and ARIMA predictions for the southern feedlot site

	Flux (kg/ha/h)	ARIMA prediction (kg/ha/h)	Residual (kg/ha/h)	Pass/Fail
CO_2 (CP-FTIR)	333.9	302.1	31.8	Pass
CO_2 (EC)	346.0	280.9	62.1	Pass
CH_4 (CP-FTIR)	4.382	3.998	0.384	Pass
CH_4 (EC)	4.790	4.130	0.660	Pass
N_2O (CP-FTIR)	0.022	0.012	0.01	Pass
N_2O (EC)	0.023	-0.013	0.046	Fail
NH_3 (EC)	0.980	-0.275	1.255	Fail

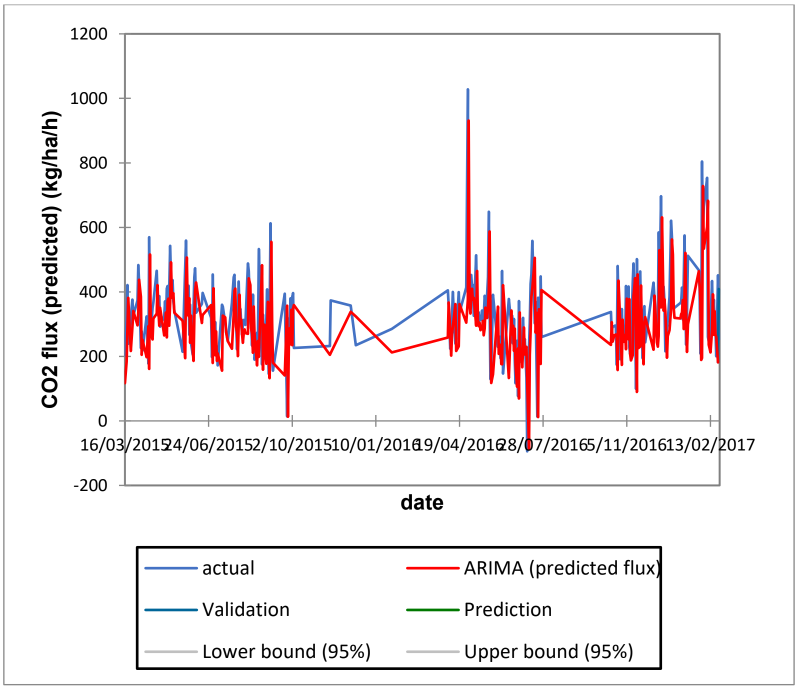


Figure 17 ARIMA predictions and actual measurements of carbon dioxide flux from the southern feedlot site

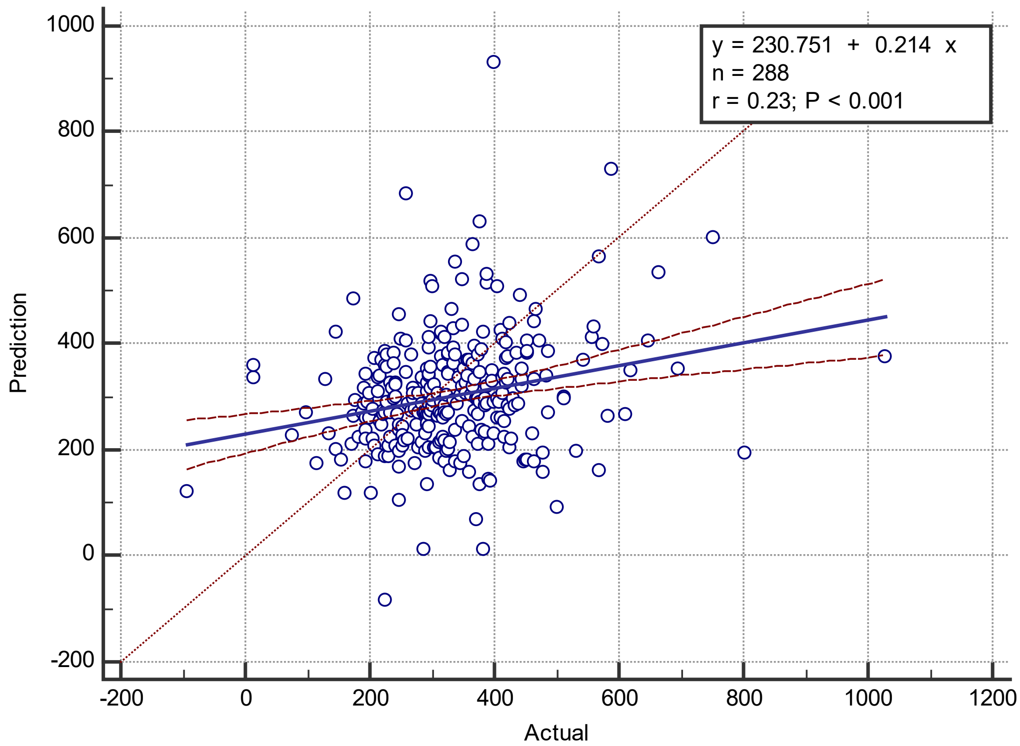


Figure 18 Relationship between actual measured carbon dioxide emissions from the southern feedlot and ARIMA predictions

5.1.5.2 ARIMA modelling of northern feedlot data

An ARIMA model was constructed for all data series (CO_2, CH_4, N_2O and NH_3) measured at the northern feedlot site. All data series for gases measured using CP-FTIR and open path lasers were concordant with the ARIMA model and passed all validation tests (Table 6, Figures 19 and 20).

Table 6 Comparison between actual measured fluxes of greenhouse gases and ARIMA predictions for the northern feedlot site

	Flux (kg/ha/h)	ARIMA prediction (kg/ha/h)	Residual (kg/ha/h)	Pass/Fail
CO_2 (IDM-WINDTRAX)	488.4	436.9	51.5	Pass
CH_4 (IDM-WINDTRAX)	6.183	5.647	0.576	Pass
N_2O (IDM-WINDTRAX)	0.036	0.025	0.011	Pass
NH_3 (IDM-WINDTRAX)	4.447	4.139	0.172	Pass

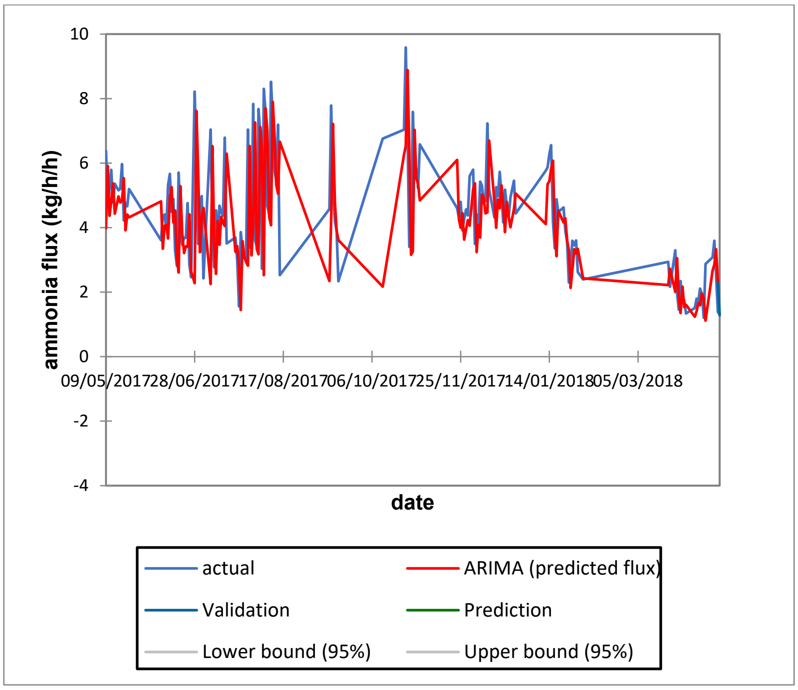


Figure 19 ARIMA predictions and actual measurements of ammonia flux from the northern feedlot site

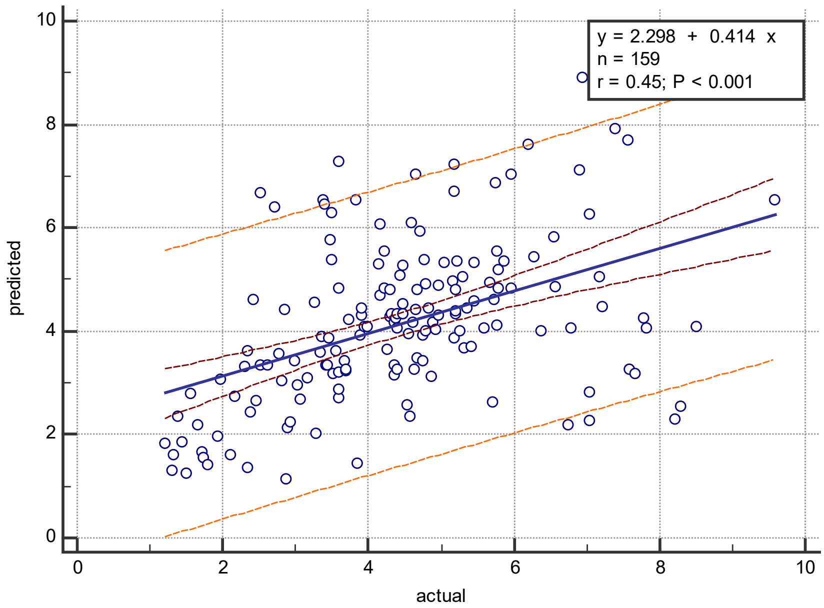


Figure 20 Relationship between actual measured ammonia emissions from the northern feedlot and ARIMA predictions

5.2 Climate conditions

5.2.1 Southern feedlot climate conditions

During the study, the minimum temperature was -3°C recorded in July 2015 and the maximum temperature was 44°C in February 2017. The average minimum-maximum temperature was 9.3 and 25.1°C. Rainfall during the study was 553 mm in 2016 (BOC, station ID 080128 average 2004 – 2019 = 361.4 mm). The minimum/maximum temperature and precipitation are shown in Figures 21 & 22. Windrose data was collected throughout the study period (Figure 23). The average windrose for all seasons differed from those normally recorded. There was a predominance of SE wind during spring, summer and autumn (normally the site would have W or NW predominant wind direction) reflecting El Nino conditions (strong southern position of high pressure to the southeast of Victoria and NSW) in 2015 and 2016, but a weak La Nina in 2017 (high rainfall conditions).

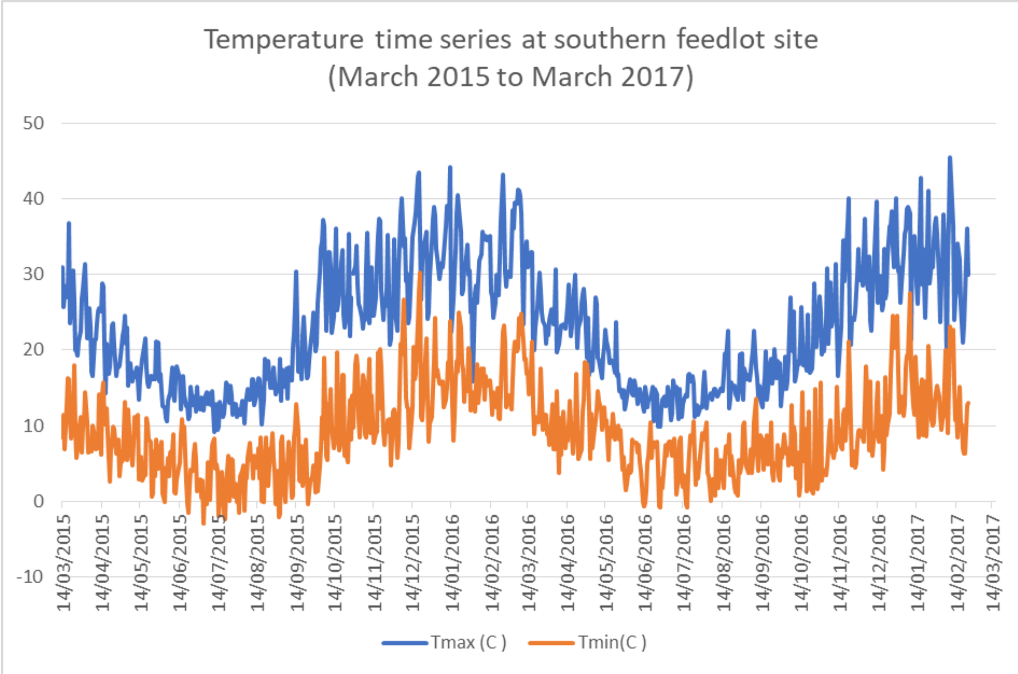


Figure 21 Temperature (max - min) times series for the southern feedlot site

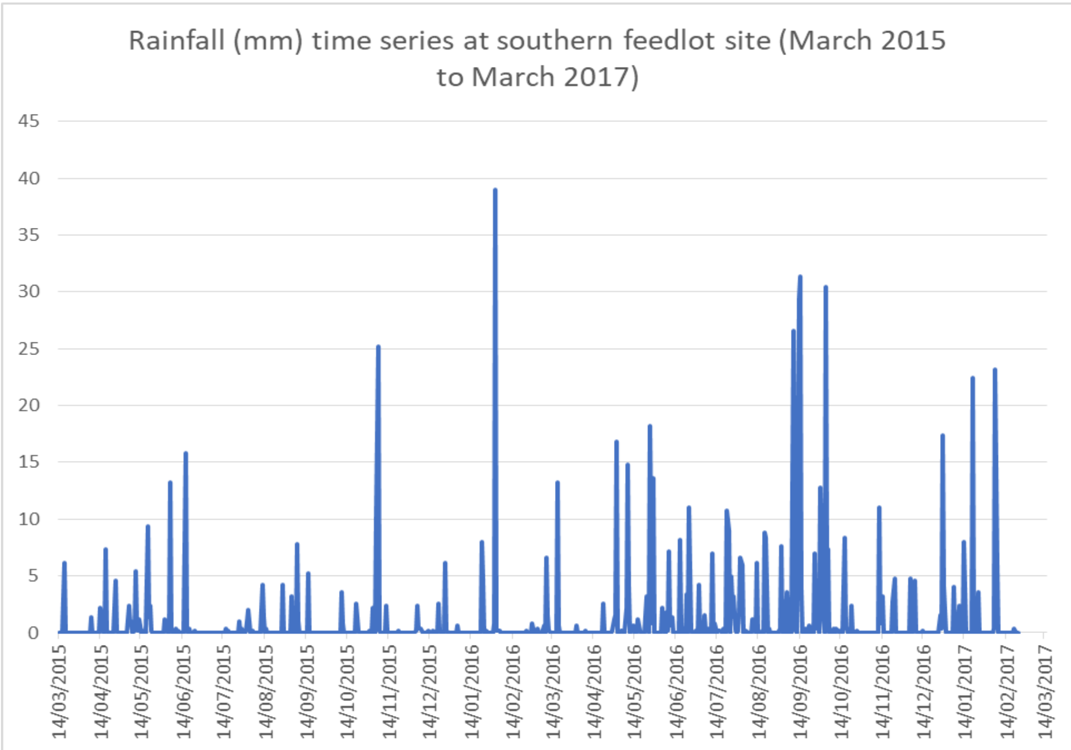


Figure 22 Rainfall data series for southern feedlot site

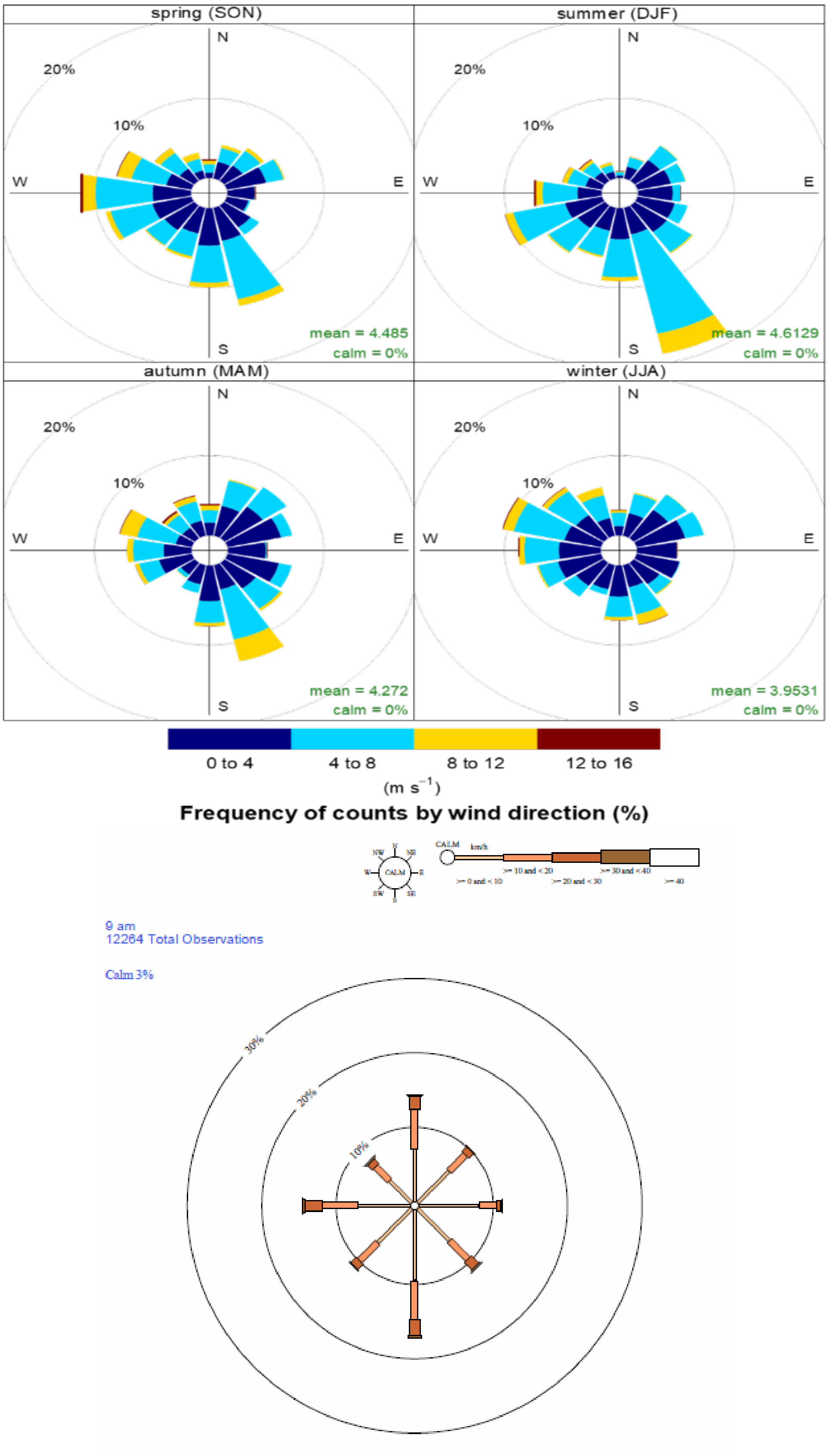


Figure 23 Windrose data for the southern feedlot site

5.2.2 Northern feedlot climatic conditions

The climatic conditions at the northern feedlot site during the measurement period were typical of the long-term averages noted for the region. The average minimum-maximum temperature was 5 and 29°C. The average minimum wind speed was 0.4 m s^{-1} in the morning, the average maximum wind speed was 5.4 m s^{-1} between 12:00 and 15:00. The total rainfall for the 12-month study period was 799 mm. The long-term average for Dalby QLD (1992-2019; BOM 041522) is 603 mm. The temperatures and rainfall are shown in Figure 24.

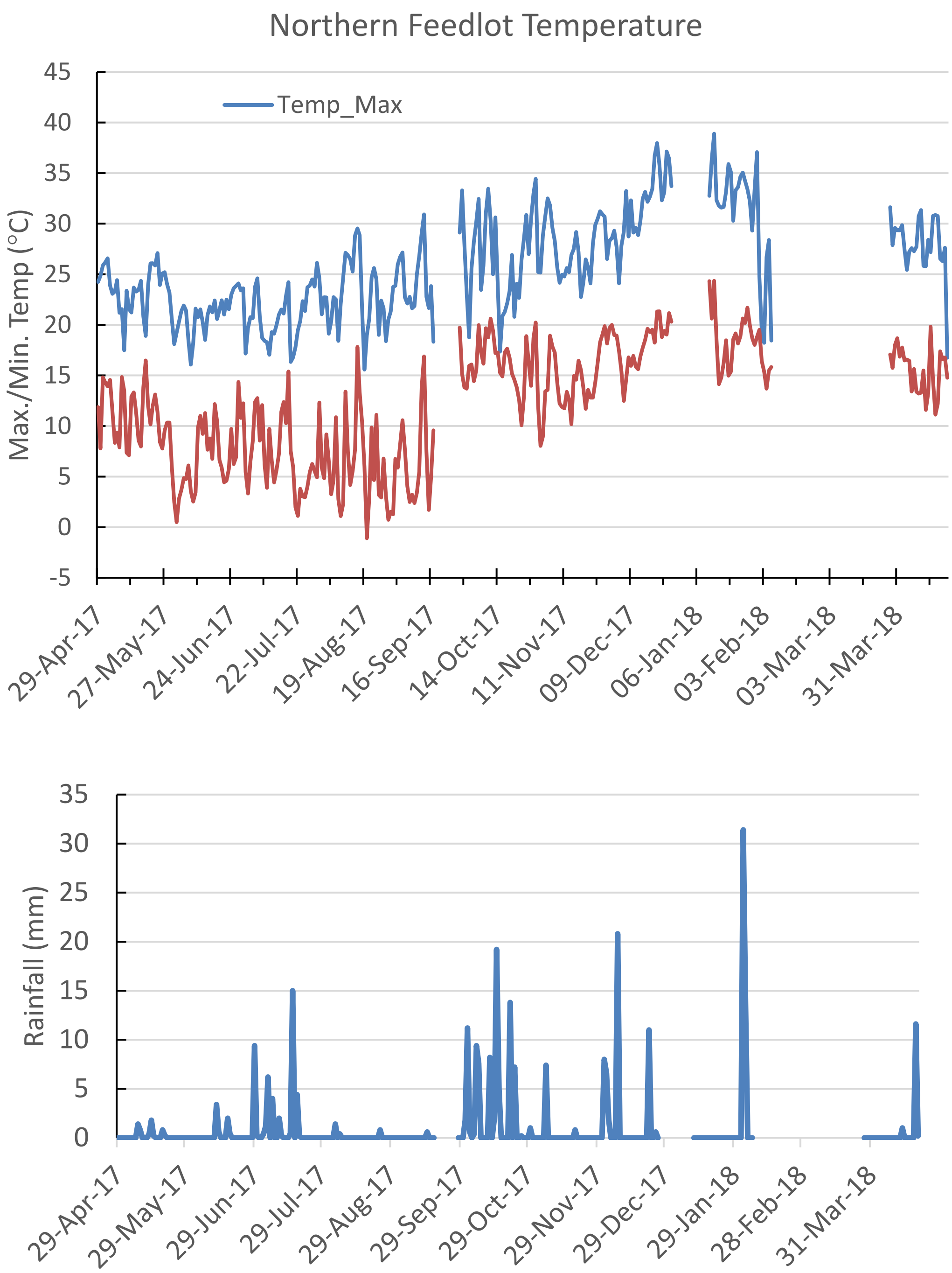


Figure 24 Temperature (upper panel) and rainfall (lower panel) times series for the northern feedlot site

The average windrose was similar to those representatives of the normal climate conditions in SE Queensland. There was a predominance of E to NE wind direction.

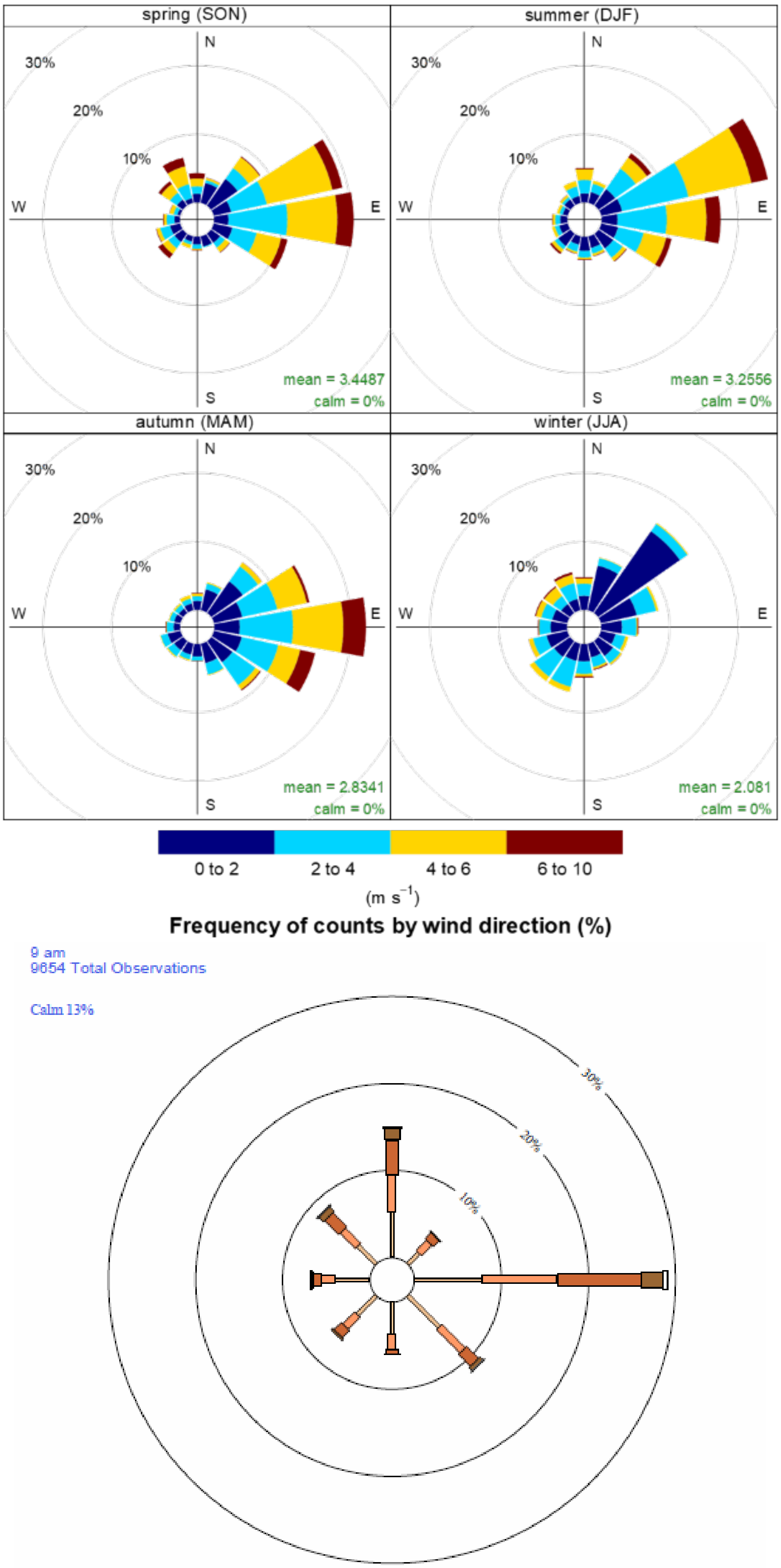


Figure 25 Windrose data series for the northern feedlot site

5.3 Physical performance of feedlot systems

Understanding the total numbers and allocation to rations provides important information in interpreting measured fluxes and outcomes from modelling CCP-A, greenhouse gas emissions using the national inventory and other methods. In feedlot systems, the animal inventory drives the total energy and nitrogen consumption of the system and the excretion of sources that may further emit reactive nitrogen to the environment.

5.3.1 Inventory, feed and nitrogen intake

5.3.1.1 Southern feedlot

Total numbers of animals on feed and allocation to individual rations are outlined in Figure 26. Destocking across May to September 2016 was notable reflecting numbers of head of about 12,400 compared to normal numbers of ca. 16200+ head. The minimum – maximum numbers of animals on feed were 11000 and 23700 cattle. The majority of animals were offered ration 4 – a typical barley, canola and other protein supplement ration (Teys Australia – commercial in confidence).

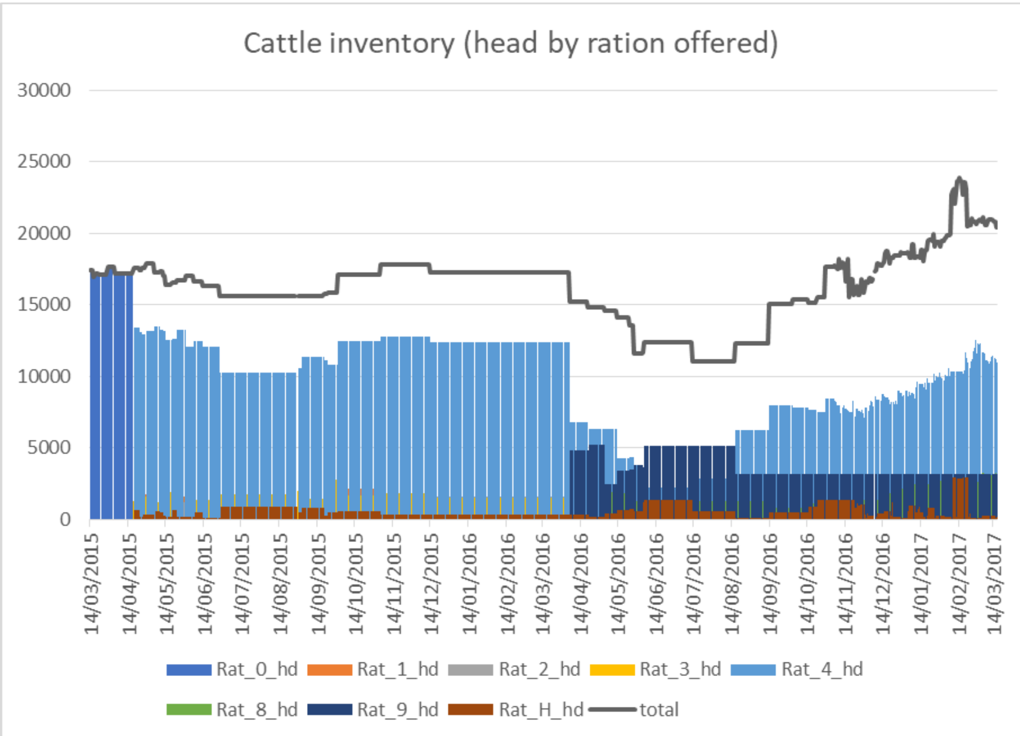


Figure 26 Cattle inventory and rations offered at the southern feedlot site

Eight rations were offered to cattle during the measurement period. Actual DM intakes of cattle (by ration) were calculated from measured feed quantities and compositional analysis. Voluntary DM intake ranged from 9.68 to 13.34 kg DM/day with an average of 12.01 kg DM/day. This intake represents 2.78% LW (average LW of animals on feed was 404 kg with recoded growth rates of 1.5 kg/d). There were a number of consecutive days during late July 2016 where animals were offered Ration 9 and had feed intakes that approached 1:3s rule for intervention and actually breached the 4:1s rule for systemic bias.

Table 7 Animal and ration information for the southern feedlot site

	Ration							
	0	***1***	***2***	***3***	***4***	***8***	***9***	***HS***
Average number of animals offered	1080	990	959	1386	9392	1629	3757	587
Days animals offered	732	697	697	697	697	317	345	697
Peak numbers	17633	3050	1910	2801	13467	3249	5192	2961
DM intake (kg DM/d)	10.51	9.76	10.73	11.23	11.72	12.48	11.36	6.85
N intake (g/day)	281	281	275	256	250	242	259	280

Measured voluntary feed intake was 31.9% higher than that predicted by the Tier II IPCC feed intake equations for beef cattle managed in feedlots (Actual = 11.25 kg DM/day vs. 8.52 kg DM/day). It should be noted that the basis of the Tier II IPCC feed intake equation is NRC (2000) (Figure 27).

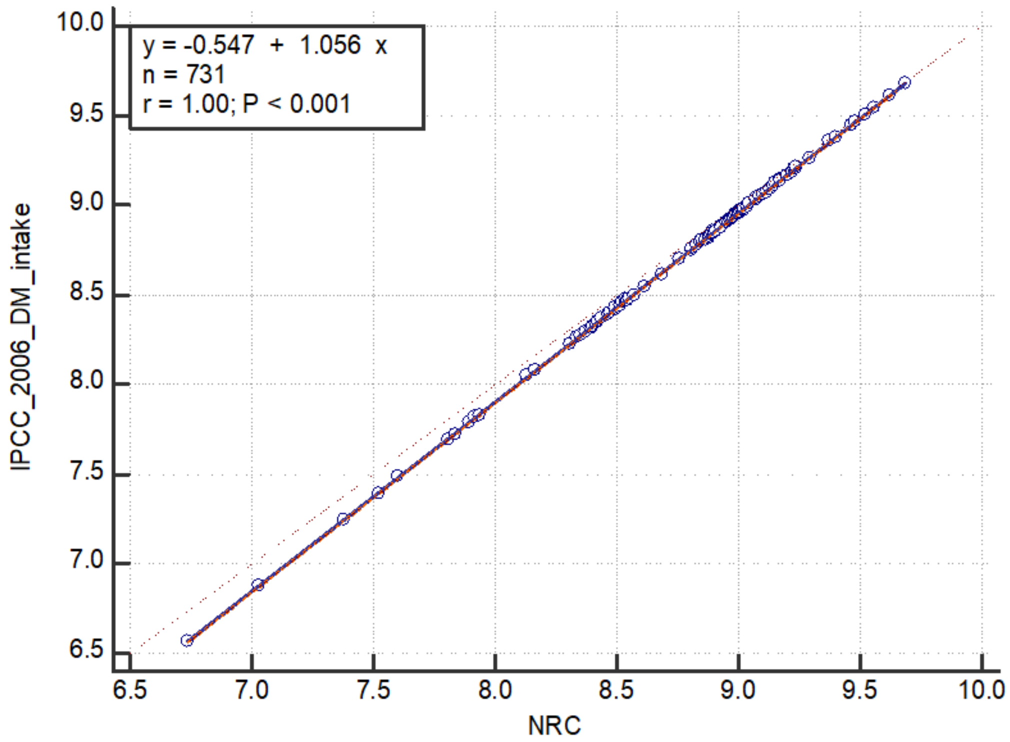


Figure 27 Relationship between IPCC (2006: basis for the National Greenhouse Gas Inventory calculations) and NRC (2016)

The concordance between Tier II IPCC and measured feed intake is poor (*p* = 0.24). Why is this important? The emissions of methane from cattle on feed, the amount of N voided through faecal deposition (volatile solids loading to the feed pad and manure management systems) and hence methane, ammonia and nitrous oxide emissions from manure management are all driven by the intake of feed by the animal. The poor concordance between measured feed intakes of cattle managed under Australian conditions and those of IPCC (and hence Australian National Inventory) means that the total greenhouse gas liability for the agricultural sector is poorly understood.

The modelling of N transactions in animals offered each feed was conducted using NRC (2016) with estimated manure, urine and faecal N voided (Figure 28). The total N partitioning observed from ration to product was 12.2% - a typical N efficiency for an intensive beef production system in Australia (range 10 to 17%).

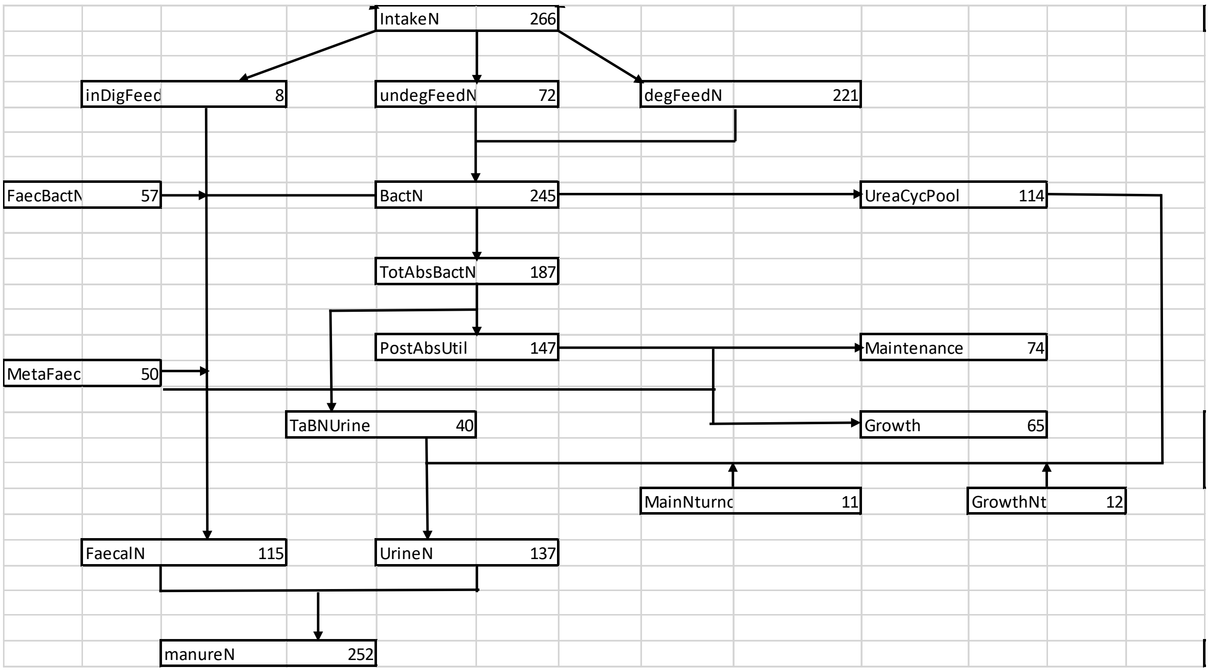


Figure 28 Metabolic nitrogen transactions in cattle offered an average feedlot ration at southern feedlot

5.3.1.2 Northern feedlot

Total numbers of animals on feed and allocation to individual rations are outlined in Figure 29. Destocking across September 2016 to the end of the measurement period (May 2018) was notable reflecting average numbers of head of about 8250 compared to normal numbers of ca. 16000+ head. The minimum – maximum numbers of animals on feed were 5100 and 17600 cattle. The majority of animals were offered ration 30.

Seven rations were consistently offered to cattle during the measurement period (Table 8). Actual DM intakes of cattle (by ration) were calculated from measured feed quantities and compositional analysis. Voluntary DM intake ranged from 9.89 to 13.26 kg DM/day with an average of 12.77 kg DM/day. This intake represents 2.62% LW (average LW of animals on feed was 486 kg achieving growth rates of 1.55 kg LW/d).

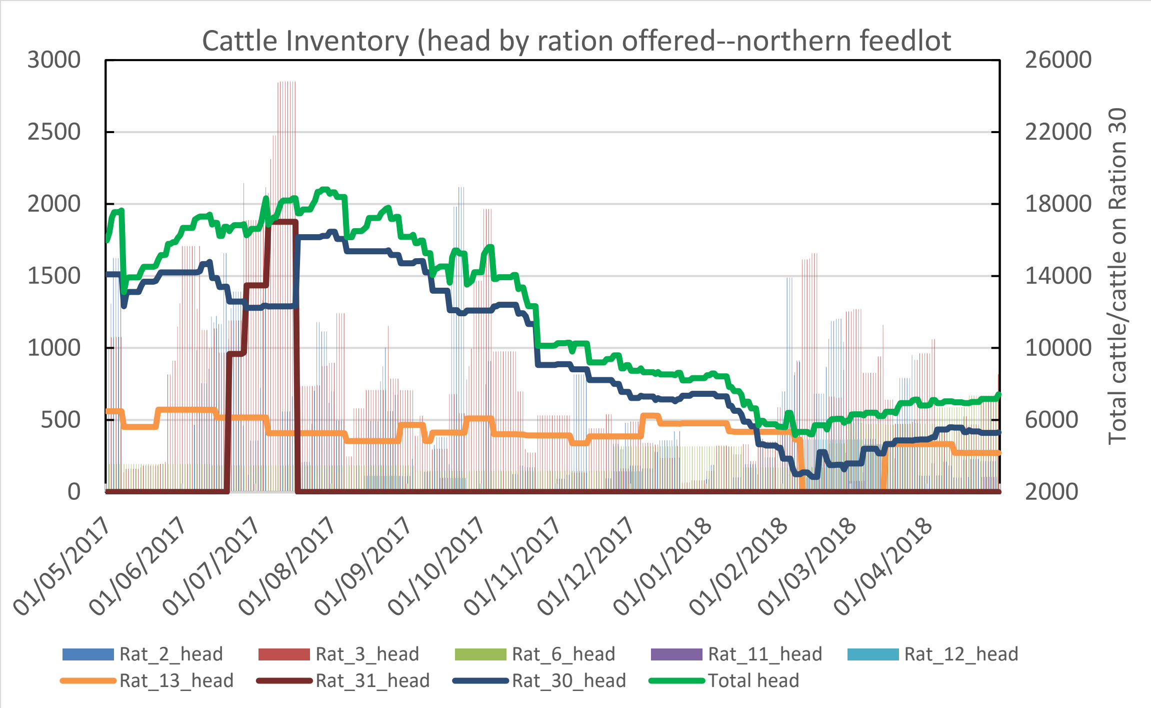


Figure 29 Cattle inventory and rations offered at the northern feedlot

Table 8 Animal performance and rations offered at the northern feedlot

	Ration						
	2	***3***	***6***	***11***	***12***	***13***	***30***
Average number of animals offered	527	754	259	8	42	384	9729
Days animals offered	266	365	365	365	365	365	365
Peak numbers	2118	2852	671	144	365	572	16460
DM intake (kg DM/d)	9.89	12.33	11.13	13.26	10.43	12.86	12.81
N intake (g/day)	223	278	251	344	235	290	289

Measured voluntary feed intake was 30% higher than that predicted by the Tier II IPCC feed intake equations for beef cattle managed in feedlots (Actual = 12.77 kg DM/day vs. 9.83 kg DM/day). It should be noted that the basis of the Tier II IPCC feed intake equation is NRC (2016). In a similar fashion to that noted for the southern feedlot, the concordance between measured intake and IPCC Tier II p = 0.31).

The modelling of N transactions in animals offered each feed was conducted using NRC (2016) with estimated manure, urine and faecal N voided (Figure 30). The estimated N intake was 273 g N per head per day. The total N partitioning observed from ration to product was 11.8% - a typical N efficiency for an intensive beef production system in Australia (range 10 to 17%).

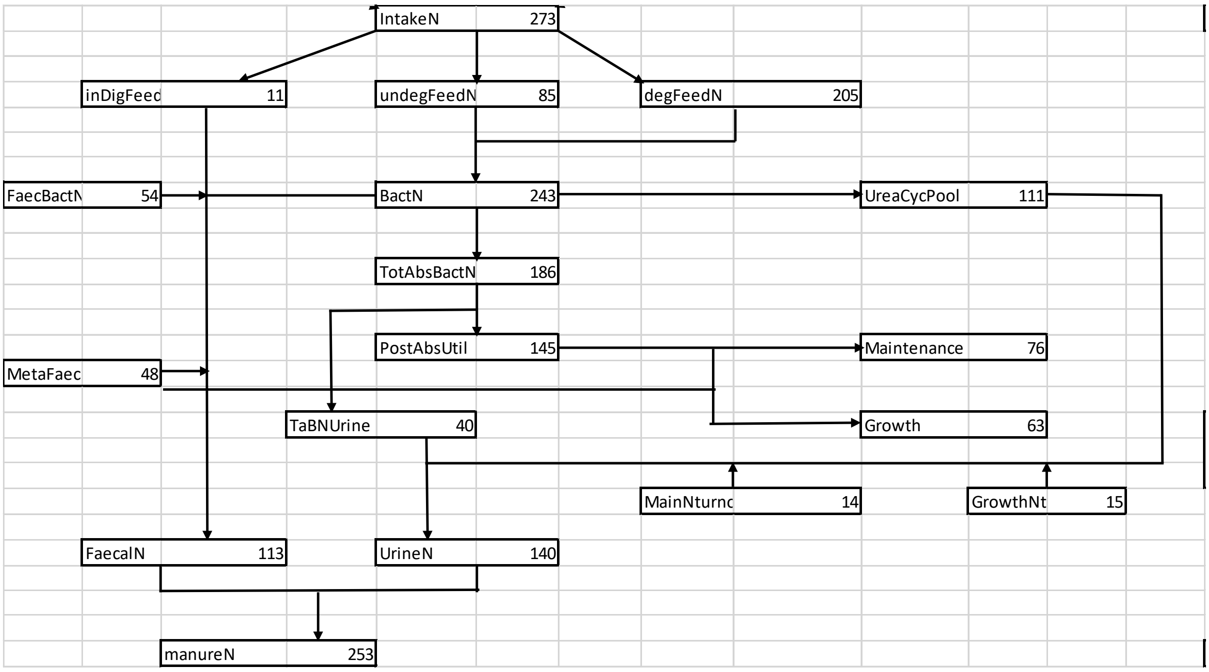


Figure 30 Metabolic nitrogen transactions in beef cattle offered an average ration at northern feedlot

5.4 Methane emissions

One of the key issues that faces the interpretation of fluxes from feedlot systems is the reliability of the footprint and the number (density) of animals within the footprint. If the residence of the animal in the footprint is not considered, discrepancies in measured concentrations and number of animals from which that methane has been eructed may lead to misinterpretation of fluxes and hence increased variability in CH_4 emissions per head. In many studies the experiments are designed in such a way that the emissions area measured falls in the EC footprint at all times. In Sections 3.3.7.1 & 3.3.7.2 the statistical approaches to consider this issue are presented. Inevitably there is a difference in the area that is contributing to the flux (eddy covariance) compared with the area that contributes to the concentration (IDM-WINDTRAX model), but there is much overlap and the differences are subtle and beyond the ability to determine from the data collected in many field experiments.

5.4.1 Southern feedlot

5.4.1.1 Per head fluxes

Fluxes of CH_4 per head were used as the initial GHG emissions validation data set. The emissions of CH_4 are tightly related to animal numbers and diets. The fluxes of CH_4 were measured using CP-FTIR and EC methods. A modelling exercise using Moe and Tyrell (1979) was conducted (Figure 31 & Table 9) according to the 2016 National Inventory for Greenhouse Gas emissions (3.A.1.c).

Table 9 Methane emissions (g/head/day of animals managed at the southern feedlot)

Method	CP FTIR	EC	IPCC Tier II model	Moe & Tyrell model
Sample size (n)	284	179	732	728
Lowest value (g/head/d)	40.3	22.1	110.6	122.8
Highest value (g/head/d)	386.9	788.2	295.7	304.8
Arithmetic mean (g/head/d)	139.5	160.7	231	238
95% CI Arithmetic Mean (g/head/d)	133.7 to 145.4	148.2 to 173.2	228.6 to 233.3	235.6 to 240.4
Geometric mean (g/head/d)	131	145.7	228.6	235.6
95% CI Geometric Mean (g/head/d)	125.7 to 136.6	136.7 to 155.4	226.5 to 230.9	233.1 to 238.1
Median (g/head/d)	131.5	145.2	218.4	225.2
95% CI for the median (g/head/d)	125.1 to 140.7	136.5 to 152.5	218.4 to 237.4	225.2 to 244.6
Variance	2503.1	7148.9	1065	1075
Standard deviation	50.03	84.55	31.8	32.79
Coefficient of Skewness	0.92 (P<0.0001)	3.44 (P<0.0001)	1.3686 (P<0.0001)	-0.37 (P=0.0001)
Coefficient of Kurtosis	1.78 (P=0.0002)	19.36 (P<0.0001)	3.8719 (P<0.0001)	1.25 (P<0.0001)

Over the two-year monitoring period (764 validation days), modelling using Moe and Tyrell used 729 to 732 validated data points whereas the CP-FTIR and EC methods were validated for 303 and 467 days. The average methane emissions from the feedlot (back calculated on a per head basis for reference and comparison with previous studies) were 238 (s=32.8) g/day (modelled using actual feed intakes), 231 (s=31.8) g/day (modelled using IPCC Tier II feed intakes), 140 (s=50) g/day (CP-FTIR; Figure 31), 161 (s=84.6) g/day (EC). The measures of emissions using CP-FTIR and EC were also corrected for emissions from the manure on the feed pad.

The impact of this study is that the current models recommended by NIR and IPCC over predict measured beef cattle emissions in feedlots by 41.4% (Figure 32). In Australia, with about 1.1 million head on feed, the total annual emissions of methane would be 95500 t methane using 2016 National Inventory for Greenhouse Gas emissions (3.A.1.c) (modelled from feed intake data), 73000 t (using

IPCC implied emissions factors for feedlot cattle or 56000 t using the measurement data from this and other MLA funded studies focussed on methane emissions from feedlot systems.

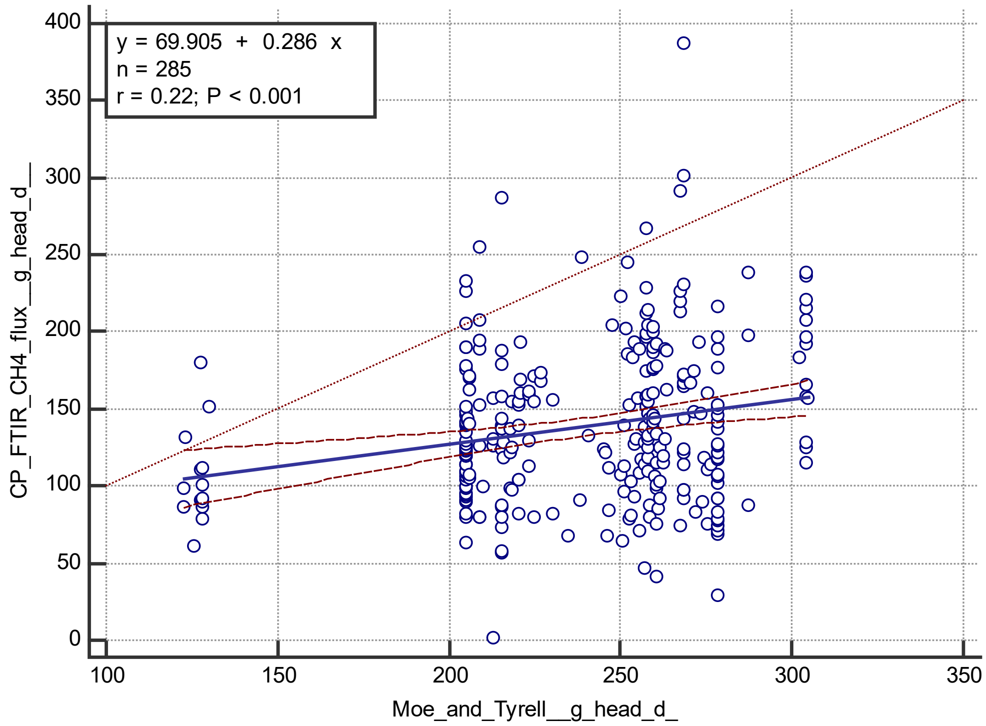


Figure 31 Comparison between methane emissions measured using CP-FTIR (measured) and calculated estimates using The National Greenhouse Gas Inventory method (Moe and Tyrell) with line of unity (short dashed line)

A CCP analysis was conducted for methane emissions across the two years of measurement. Outliers (trigger threshold) for methane fluxes measured using CP-FTIR and EC reflected scenarios were low. Even though this low frequency data set was admissible for analysis, the estimates of emissions suffered from high variability. Outliers in the modelled data series reflect missing animal ration data or an over-representation of a single high methanogenic ration (Ration H).

The EC technique is widely used for landscape-scale flux measurements with hundreds of measurement towers worldwide monitoring carbon and energy exchanges across a range of terrestrial ecosystems. EC instrumentation is well suited to long-term monitoring and is capable of un-attended operation in remote environments. While the application of EC over an extensive homogenous landscape is relatively straight forward, it's used to determine fluxes from specific source areas within a larger landscape requires a careful footprint analysis to understand the source area's contribution to the calculated flux. The flux footprint correction program utilised for this study is a powerful tool that allows the advantages of EC measurements to have application in a feedlot environment.

However, one of the limitations of EC techniques is the requirement for fast-response concentration sensors for fluxes of interest. While there are a range of options for fast-response sensors for CO_2, H_2O and more recently CH_4 (Li-7700 sensor, Licor Biosciences), analyser options for other gases are limited. The concentration profile method employed at both field sites has proven to be a valuable method to obtain valuable flux information using the CP-FTIR. The reliability and precision of the CP-FTIR concentration measurement allowed for meaningful flux measurements through regular sampling of 3 inlet heights. When comparing the CP-FTIR profile/Windtrax approach with the footprint corrected EC fluxes a similar trend in daily emissions was observed (Figure 32). Although the trends were similar showing increasing emissions beginning after the first feed of the morning, the Windtrax approach yielded higher fluxes through the early morning and evening periods with lower fluxes during the day compared with the EC fluxes. However, when averaged over a daily basis, there was no significant difference between fluxes when comparing days with sufficient good quality flux data for each method (Figure 31).

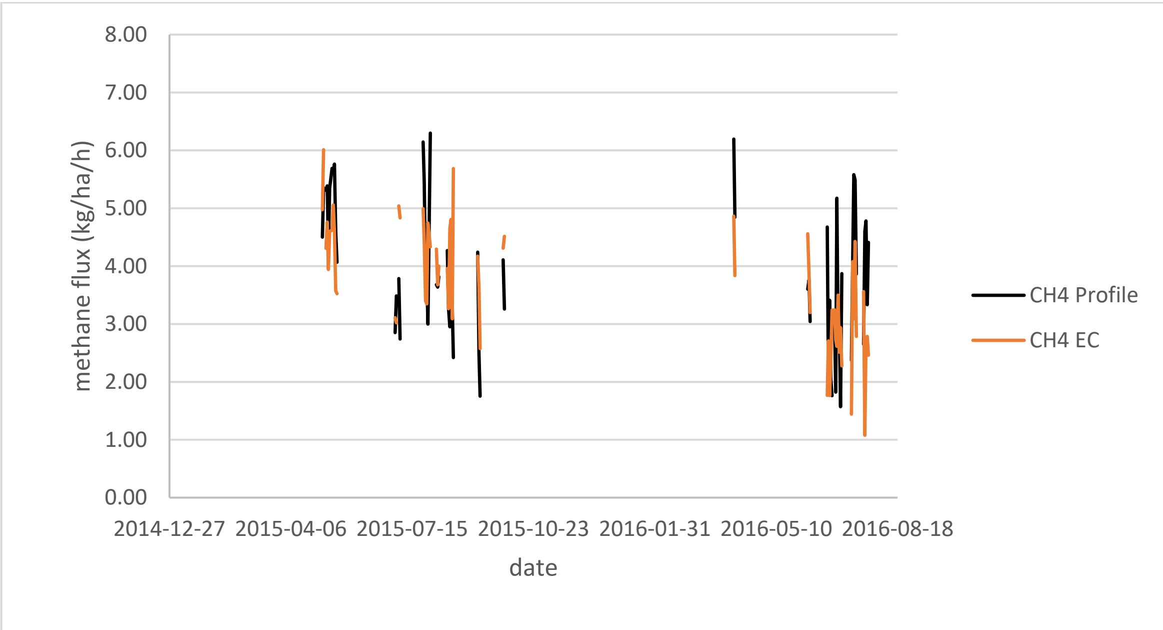


Figure 32 Comparison between WINDTRAX and EC methane fluxes averaged by hour for the southern feedlot site

5.4.1.2 Methane emissions from feedlot

The total methane emissions from the feedlot were accounted for by three sources – animals at feed, manure handling and composting, and lagoons. The estimated methane flux from these three sources were 4.39 (s = 1.419), 0.684 (s = 0.137) and 1.55 (s = 0.745) kg CH_4/ha/h respectively. The modelled estimates for methane emissions from manure handling and lagoons was 0.221 kg/ha/hour or 31.8% of the actual measured methane emissions for these areas of the feedlot. Volatile solid production for beef cattle in feedlots (VS, kg/head/day) was estimated using the calculation from the mass balance model developed for Australian feedlots (Equation 3B.1c_1; NIR, 2017) using estimates of digestibility (Appendix 5.C.2) and associated emissions factors cited in Equation 3B.1c_2; NIR, 2017). This under estimation by IPCC represents ca. -184.7 t CH_4 per annum or 4,400 t CO_2-e per annum.

These emissions represent an average stocking rate over the two years of study of 392 SCU/ha (representing full stocking rate) of 400 SCU/ha. The range of SCU was 253 to 478 SCU/ha. The CCP analysis with emission thresholds is outlined in Table 10.

Table 10 Methane fluxes (kg/ha/h) and total methane emissions (t/annum) with associated CCP thresholds

Methane flux (kg/ha/h)	*-2s*	*-1s*	*0*	*+1s*	*+2s*
Cattle	1.19	2.79	4.39	5.99	7.59
Lagoons	-0.65	-0.12	1.55	3.23	3.75
Manure handling and composting	0.41	0.48	0.68	0.89	0.96

Total methane emissions (t/annum)	*-2s*	*-1s*	*0*	*+1s*	*+2s*
Cattle pens	492.1	722.6	1137.4	1551.4	1965.8
Manure handling and composting	-111.7	-20.7	268.8	558.4	649.4
Lagoons	1.3	1.5	2.1	2.7	2.9
Total	381.7	703.4	1408.3	2112.5	2618.1

Note: The emissions represent an average stocking rate over the two years of study of 392 SCU/ha (representing full stocking rate) of 400 SCU/ha. The range of SCU was 253 to 478 SCU/ha. The CCP analysis with emission thresholds is outlined. The low SCU represents a weighed mean of animals residing and represents that there were periods of time where the stock numbers were low (destocked).

The estimated total methane emission from the southern feedlot was 1408 t/annum (365day production cycle or 39,400 t CO_2-e per annum, assuming GWP of methane =28) with 81% of those emissions derived as direct emissions from cattle on feed and 18.8 % from manure management systems. The residual 0.2% emissions were derived from lagoons. These estimates for methane emissions (per head basis) are typical of Australian feedlot systems and there was no evidence when conducting the CCP analysis that the likelihood of 1:2s thresholds were breached. The only reason for a reduction in the emission flux or total emissions are direct interventions to mitigate rumen methanogenesis. However, the likelihood of 1:2s threshold scenarios (increased rumen methanogenensis) is more common reflecting changes in feeding regimes, impact of animal genotype (feed efficiency) or change in the within pen manure management systems (for instance poor drainage leading to pen flooding in winter).

5.4.2 Northern feedlot

Fluxes of CH_4 per head were used as the initial GHG emissions validation data set. The emissions of CH_4 are similarly tightly related to animal numbers and diets to those observations made at the Southern feedlot (Section 4.4.11). The fluxes of CH_4 were measured using CP-FTIR and EC methods. A modelling exercise using Moe and Tyrell (1979) was conducted (Table 11) according to the 2016 National Inventory for Greenhouse Gas emissions (3.A.1.c). No partitioning of methane emissions occurred as part of the monitoring exercise at the northern feedlot site. The total methane emissions from the feedlot are in Table 11.

Table 11 Methane emissions (g/head/day of animals managed at the Northern feedlot). CP-FTIR data was corrected for measures of direct emissions of methane from the feed pad to ensure that the measured data can be compared with modelled data

Method	CP FTIR	IPCC Tier II model	Moe & Tyrell model
Sample size	74	365	365
Lowest value (g/head/d)	82.5	100.7	103.8
Highest value (g/head/d)	437.1	403.2	415.8
Arithmetic mean (g/head/d)	209	255	263
95% CI Arithmetic Mean (g/head/d)	194.1 to 224.4	247.2 to 262.7	254.8 to 270.9
Geometric mean (g/head/d)	199.3	241.0	248.5
95% CI Geometric Mean (g/head/d)	184.9 to 214.6	232.2 to 250.1	239.4 to 257.8
Median (g/head/d)	210	289	298
95% CI for the median (g/head/d)	186.4 to 226.6	282.5 to 294.4	291.3 to 303.5
Variance	4288	5678	6035
Standard deviation	65.48	75.35	77.68
Coefficient of Skewness	0.6733 (P=0.0194)	-0.6585 (P<0.0001)	-0.6585 (P<0.0001)
Coefficient of Kurtosis	1.1565 (P=0.0760)	-0.6629 (P=0.0001)	-0.6629 (P=0.0001)

The emissions derived from modelling of animal performance data using Moe and Tyrell & IPCC (365 days validated) were compared with the CP-FTIR method (74 validated days). The average methane emissions from the feedlot (back calculated on a per head basis for reference and comparison with previous studies) were 263 (s=77.7) g/day (modelled using actual feed intakes), 255 (s=75.6) g/day (modelled using IPCC Tier II feed intakes) and 209 (s=65.5) g/day (CP-FTIR). The measures of emissions using CP-FTIR and EC were also corrected for emissions from the manure on the feed pad. The CCP analysis demonstrated no breaches of 1:2s rules for any measurement or modelling approach applied. The estimates of measured emissions from livestock managed at the northern feedlot were 20.5% lower than those modelled (Figure 33) using the current National Greenhouse Gas Inventory approach (Moe & Tyrell).

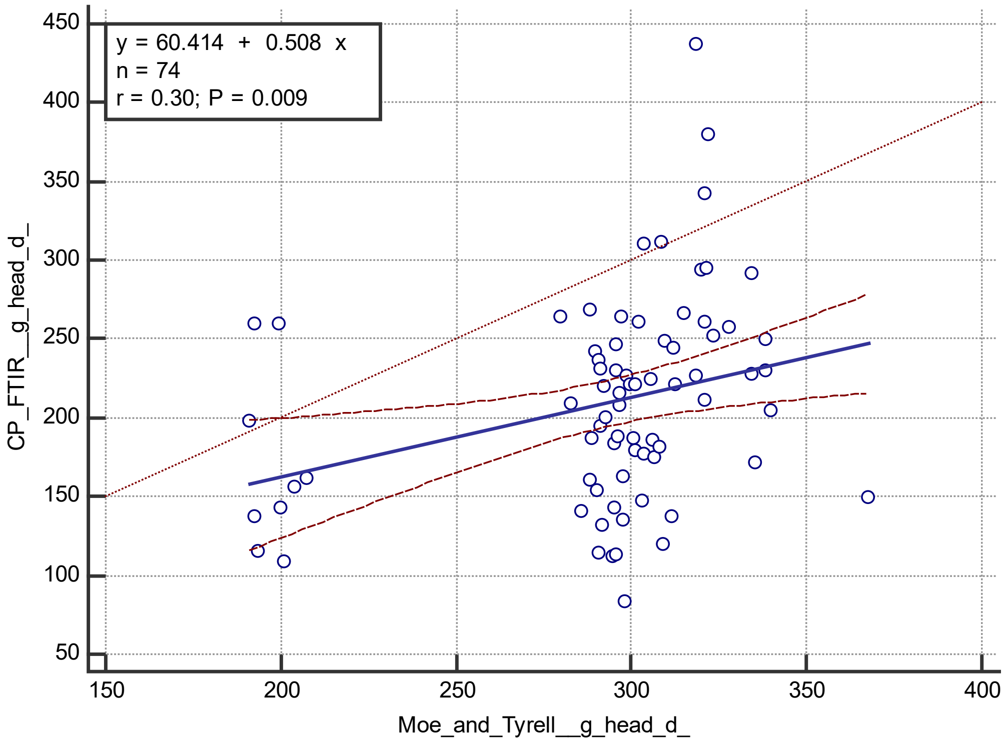


Figure 31 Comparison between CP-FTIR per head methane emissions estimates and calculated estimates using The National Greenhouse Gas Inventory method

5.4.3 Prediction of methane emissions from livestock managed in southern and northern feedlots

One of the key findings in the study were confirmatory of previous studies (e.g. Bai et al. 2015 and Bai et al. 2015a). When a comparison between actual emissions and emissions modelled using the Moe and Tyrell model adopted in the Australian National Inventory, the measured emissions at the southern site were about 40% lower than the model would predict and those measured at the northern site where about 20% lower. Methane emissions predicted using the National Inventory calculations are strongly correlated to feed intake. It should be noted that the conversion factor of organic matter digested in the rumen (as predicted using estimated for soluble carbohydrate, cellulose and hemicellulose) is fixed for each component and the only variation in emission prediction is the interaction between feed intake and composition. Therefore, if the intake of feed increases, the emissions of methane increase reflecting the differences in soluble carbohydrate, cellulose and hemicellulose. The estimates of feed intake using National Inventory and IPCC models are closely associated with the approach taken in NRC (2016). Animals managed at both the southern and northern sites consumed substantially more feed per head than the National Inventory would predict but the measured methane emissions were lower). The slopes of regression lines developed for the northern and southern feedlots (measured vs. predicted emissions) were significantly different (with the slope of the southern site being significantly lower than that of the northern site p <0.01).

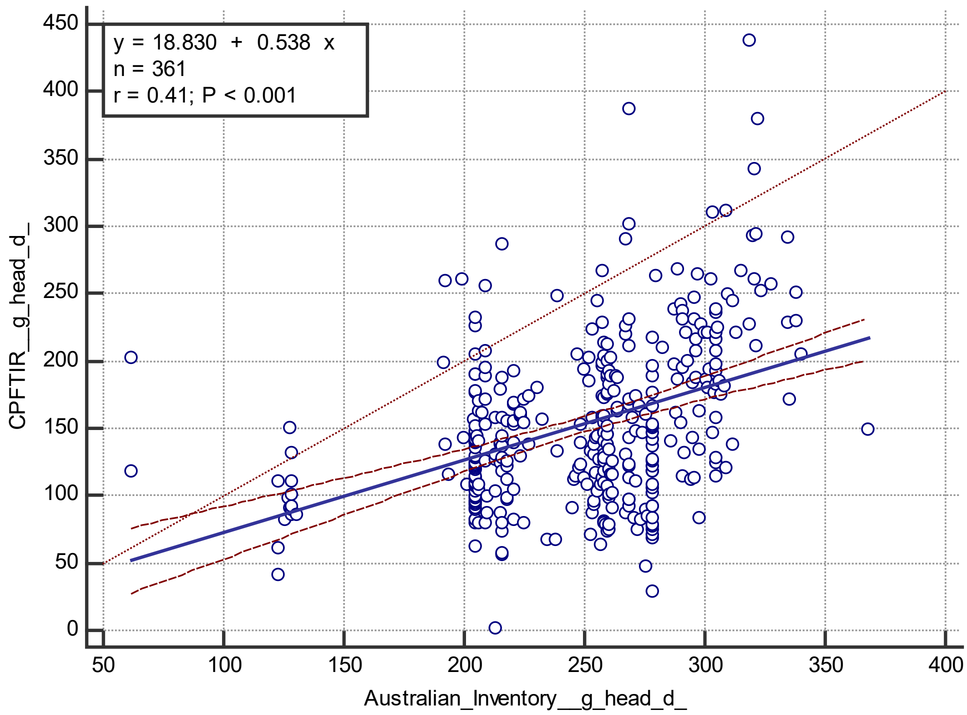


Figure 32 Federated methane emissions data from the southern and northern feedlot and comparing with estimates from the National Greenhouse Gas Inventory model

5.5 Nitrous oxide emissions

5.5.1 Southern feedlot

The drivers of nitrous oxide emissions from manure management systems based on feedlots are well understood. The key issue facing the management of nitrous oxide from manure management systems is the short duration raised flux rates observed immediately after heavy rainfall. These risk scenarios are almost impossible to mitigate against. Sections 4.1.3 and 4.1.5 outlined the lack of reliability of the measurements of nitrous oxide emissions at the southern feedlot site. The only data series admissible for further analysis was that measured using CP-FTIR (IDM – Windtrax modelling). Analysis of the actual emissions of nitrous oxide demonstrated that the thresholds for 1:3s were exceeded during November and December 2016 (Figure 35) representing periods of elevated temperature and intense rainfall.

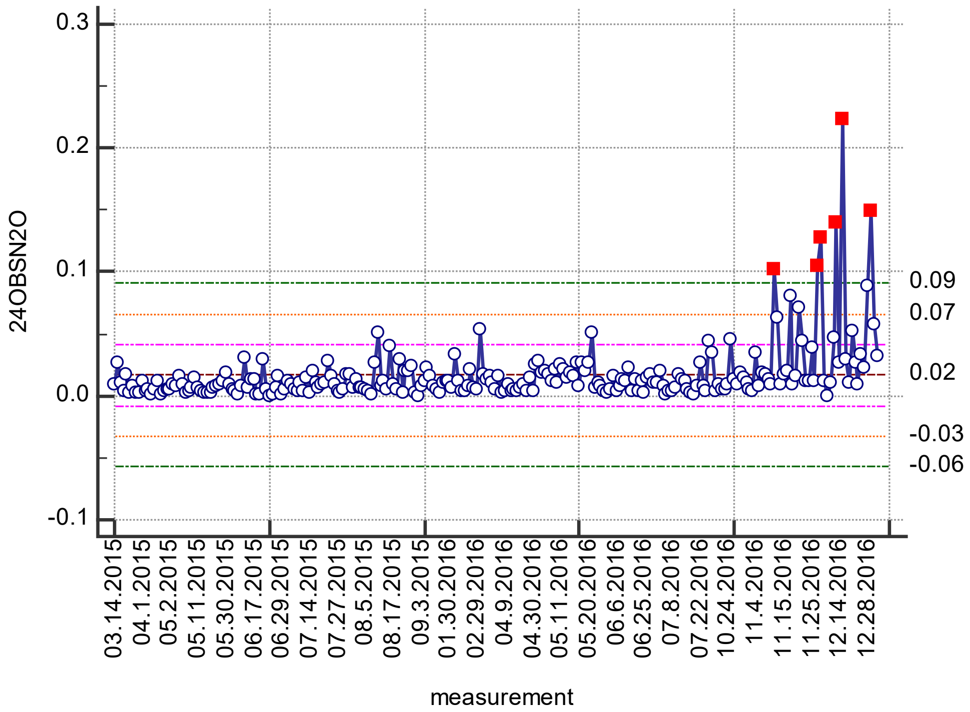


Figure 33 Critical control point analysis of nitrous oxide emissions from the southern feedlot site

The total nitrous oxide emissions from the feedlot were dominated by fluxes from the manure handling and composting systems. These systems accounted for nearly 98% of total emissions (Table 12).

Table 12 Nitrous oxide fluxes and total emissions (t/annum) including CCP thresholds

	Nitrous oxide flux (kg/ha/h)				
	-2s	*-1s*	*0*	*+1s*	*+2s*
Cattle pens	-0.1	0.002	0.014	0.026	0.038
Manure handling area (including composting)	-0.05	0.100	0.248	0.398	0.548
Lagoons	0.06	0.10	0.23	0.36	0.40
	Total emissions (t/annum)				
	-2s	*-1s*	*0*	*+1s*	*+2s*
Cattle pens	-3.4	0.7	4.8	8.8	12.9
Manure handling area (including composting)	-8.7	17.3	42.9	68.9	94.8
Lagoons	0.2	0.3	0.7	1.1	1.2
Total			48.4		

The estimated total emission of nitrous oxide (tCO_2–e) from the feedlot system was 12826 t/annum (assuming a GWP of 265) of which only about 1.3 t were derived directly from the feed pad and less than 1 t was from lagoon sources. The NIR (2017) estimates for nitrous oxide emissions were approximately 5.5-fold higher than those measured (Figure 36).

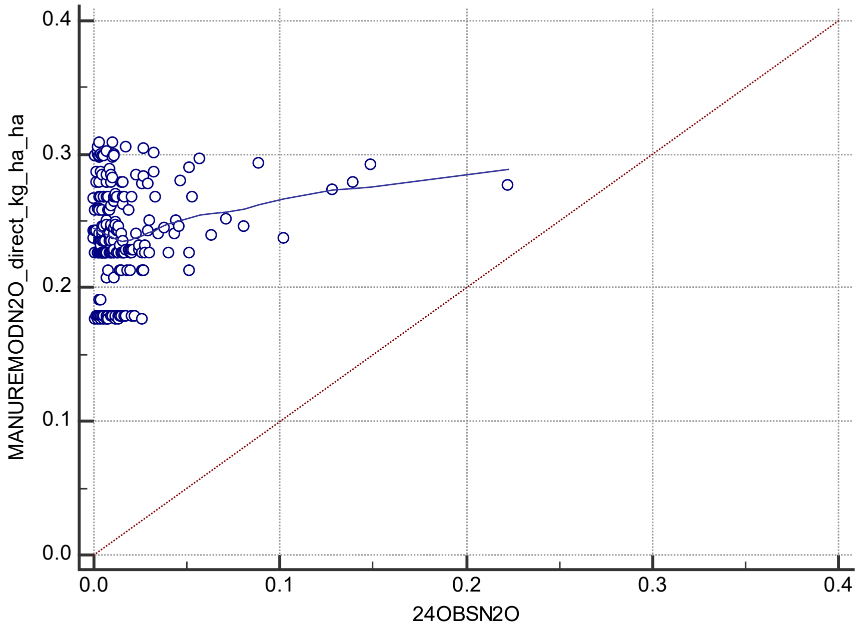


Figure 34 Comparison between nitrous oxide emissions (24OBSN20) and predicted emissions (direct_kg_ha_ha) using the Australian National Inventory

There are a number of scenarios where 1:2s and even 1:3s thresholds for nitrous oxide fluxes can be approached or breached. These scenarios are however very short duration and, as noted, exceptionally difficult to manage. The results demonstrate that it would be more beneficial if manure handling was separated into stockpile and compost emissions. Previous research (Bai et al. 2020) demonstrated that N lost as N_2O was 3.8% of the initial N in windrow and 0.8% in the stockpile. This would suggest the results reported in manure handling could be dominated by N_2O emissions from composting process. However, composting process can reduce ammonia emissions (indirect N_2O emissions).

5.5.2 Northern feedlot

In a similar fashion to that reported for the southern feedlot, the emissions of nitrous oxide suffered from considerable variation driven by the local climate and rainfall. Fluxes of nitrous oxide from the complete feedlot are shown in Table 13. As noted in previous studies (B.FLT.0148, FLOT.331) the emissions of nitrous oxide were very low in systems that do not have extensive manure handling and composting systems, and rely on pen management – recycling directly to agricultural land. The estimated total emission (t CO_2-e) was 4500 t per annum or about 9% of that observed at the southern site.

Table 13 Nitrous oxide fluxes and total emissions (t/annum) with associated CCP thresholds

	Nitrous oxide flux (kg/ha/h)				
	-2s	*-1s*	*0*	*+1s*	*+2s*
Cattle pens and lagoons	-0.032	0.002	0.036	0.070	0.104
	Total emissions (t/annum)				
	-2s	*-1s*	*0*	*+1s*	*+2s*
Total	-10.7	0.7	16.9	32.9	48.8

Furthermore, the average measured fluxes of nitrous oxide were about 30% of those predicted using National Greenhouse Gas Inventory calculations. (Figure 37).

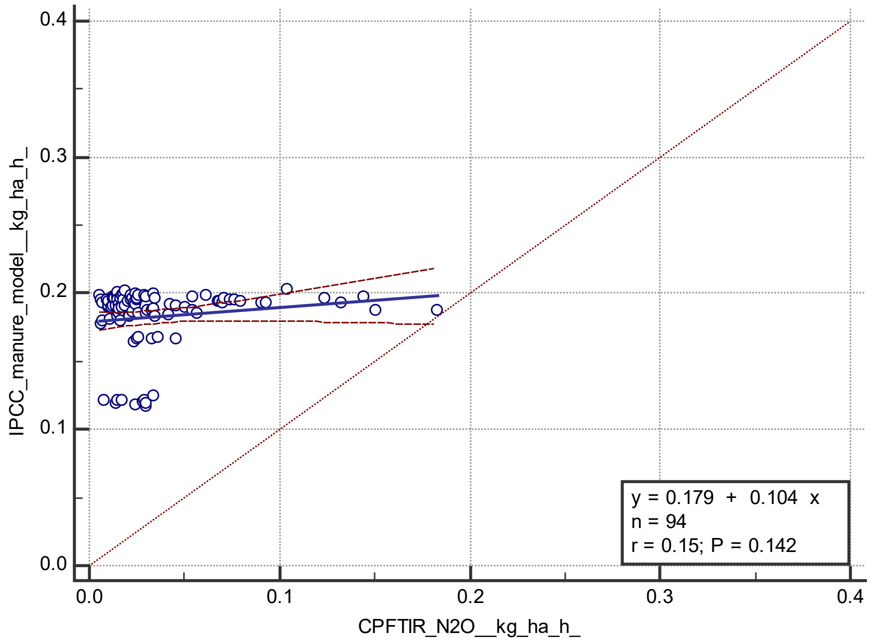


Figure 35 Comparison between measured nitrous oxide emissions (CPFTIR_N20_kg_ha_h) and National Greenhouse Gas Inventory emissions (IPCC_manure_model_kg_ha_h)

5.6 Ammonia emissions

5.6.1 Southern feedlot

The data series collected for ammonia emissions at the southern site was so unreliable that no conclusions can be drawn with any certainty. The theoretical ammonia emissions from the site were modelled using the WNMM approach. The major driver of these emissions is the rapid conversion of urinary N and labile faecal N to ammonia immediately after manure has been voided by the animal. The WNMM model did not predict ammonia emissions with any certainty and suffered from the potential systemic bias resulting from elevated temperatures during summer 2015-2016 (Figure 38).

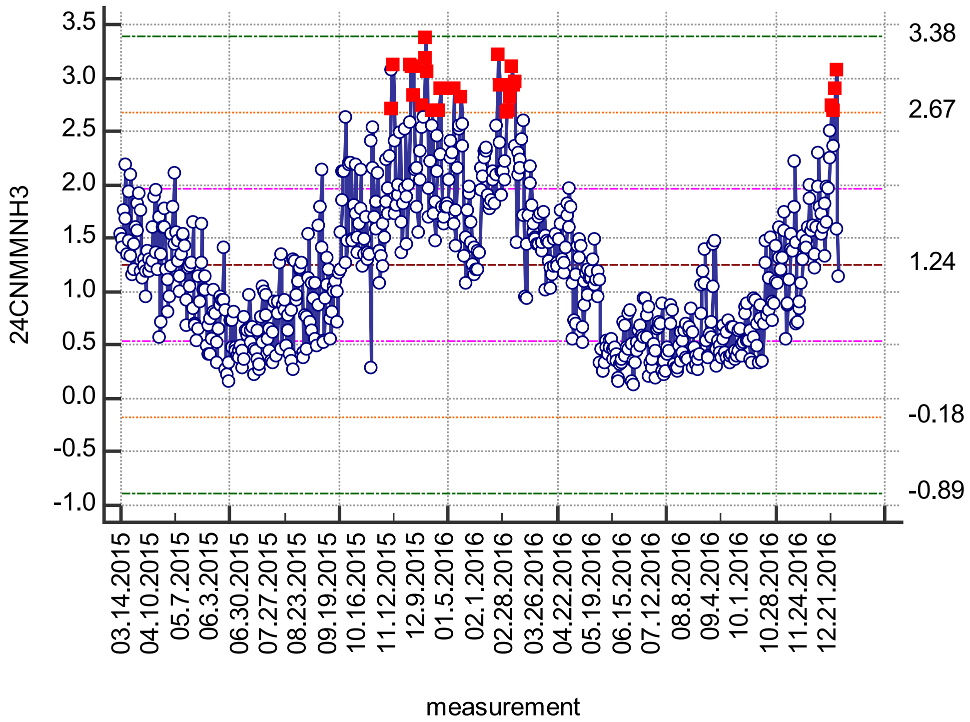


Figure 36 Critical control point analysis of ammonia fluxes as predicted using the WNMM model

The US EPCRA (Emergency Planning and Community Right-to-Know Act, 1986) has recently outlined guidelines for ammonia emissions from beef feedlots in the USA. The basis of the calculation is somewhat obscured, but the lower bound trigger is 0.16 lb/head and the upper trigger is 0.48 lb/head. If these trigger points are back calculated and applied to the measured ammonia data then there are very few events that would result in a threshold of emissions being breached (Figure 39).

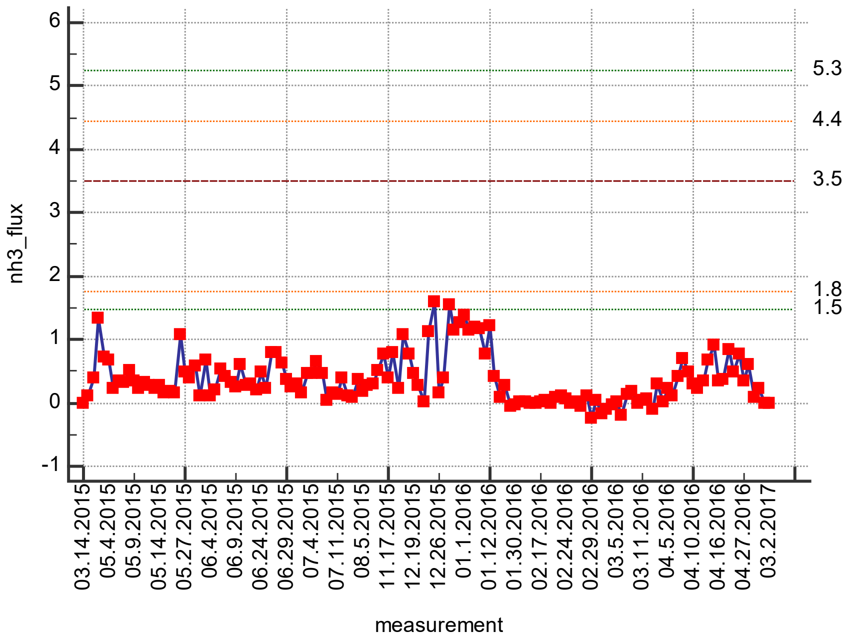


Figure 37 USEPCRA threshold model applied to ammonia emissions from the southern feedlot (OPL snap-shot data series)

Using the snapshot data and open path laser validation data sets, the likelihood of ammonia fluxes from manure handling systems to approach 1:3s thresholds is low (Table 14). This reflects the inherent variability of ammonia emissions in feedlot systems and the impact of those changes will not have a material impact on total greenhouse gas emissions. Of greater significance is the likelihood that 1:2s thresholds for ammonia emissions from feedlot pens are exceeded. This could result in a major odour / environmental impact but have a moderate to low impact on total greenhouse gas emissions. These relatively uncontrolled emissions can be abated through a number of technologies – for example lignite or altering the crude protein content of the ration.

Table 14 Ammonia fluxes and total emissions (t/annum) with associated CCP thresholds for the southern feedlot site

	Ammonia flux (kg/ha/h)				
	-2s	-1s	0	+1s	+2s
Cattle pens	2.21	2.38	2.92	3.46	3.63
Manure handling area (including composting)	-0.26	-0.03	0.70	1.43	1.66
Lagoons	0.50	0.52	0.60	0.68	0.71

	Total emissions (t/annum)				
	-2s	-1s	0	+1s	+2s
Cattle pens	572.3	616.2	755.9	895.6	939.5
Manure handling area (including composting)	-45.8	-5.9	121.1	248.1	288.0
Lagoons	1.5	1.6	1.8	2.1	2.2
Total	528.1	611.9	878.8	1145.7	1229.6

5.6.2 Northern feedlot

The measured data series from the northern feedlot study was more extensive and a series of conclusions can be drawn from this part of the study. The average flux of ammonia was 4.456 kg/ha/h (s = 1.685) from an average area of 20.12 ha. The estimated total annual emission of ammonia from the feedlot was 785 t. If this ammonia is re-distributed to the environment and 1% is re-emitted as nitrous oxide (National Inventory, 2017) the total CO_2-e per annum from this emission was estimated as 2080 t. Hill et al. (2016) reported emission estimates ranging of 0.2% to 2.5% in pot experiments with soils receiving a range of manures and urea applications – emissions factors that do not differ from those calculated in the Australian National Inventory (2016).

As part of a benchmarking exercise whereby global ammonia emissions policies were examined in relation to data collected in this experiment. A comparison of the US EPCRA guidelines was conducted (EPA, 2015). USEPCRA is one of the only global examples where thresholds in ammonia emissions are reported for feedlots. If the US EPCRA guidelines for ammonia emissions from beef feedlots are applied, there are a significant number of events that trigger breaches at 1:3s (Figure 40). This warrants further attention into the future for the Australian lot feeding industry.

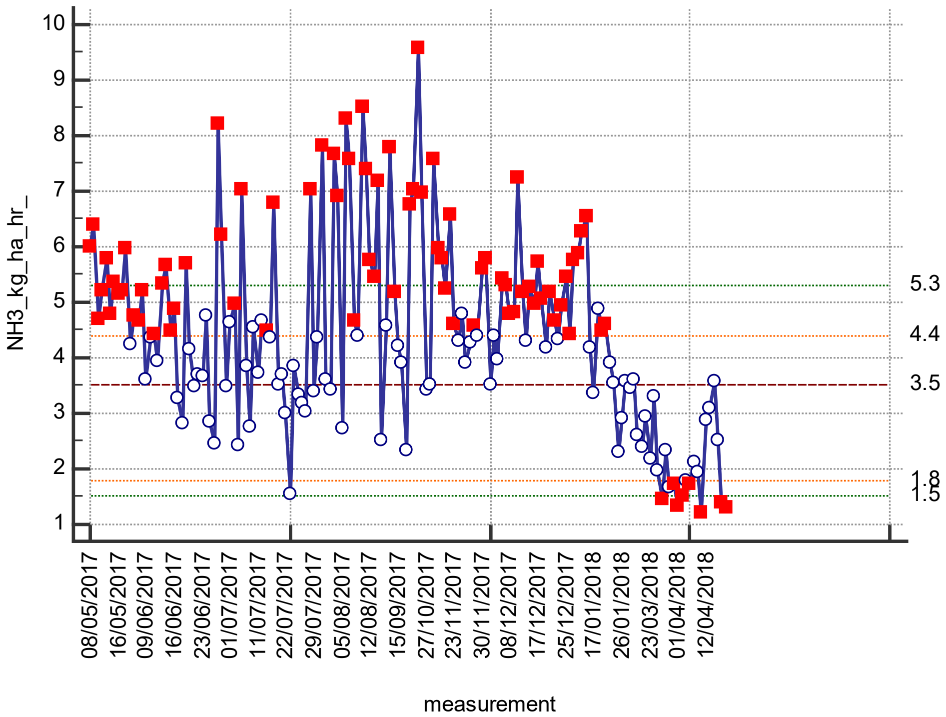


Figure 38 Application of USEPCRA thresholds to ammonia emissions from the northern feedlot site

5.7 Total greenhouse gas emissions

5.7.1 Southern feedlot

The total greenhouse gas emission (Table 15) demonstrated that about 72% of greenhouse gas liability is methane emissions (of which about 90% are direct emissions from animals via rumen methanogenesis) and 24% are ascribed to nitrous oxide. Ammonia emissions play a relatively minor role in total emissions with only 4% of emissions accounted for through the conversion of ammonia to nitrous oxide.

Table 15 Total annual greenhouse gas emissions (CO_2-e) and relative proportion of each gas emission at the southern feedlot site. Ammonia is an indirect greenhouse gas and reported as a measured gas calculated as CO_2-e. The Australian National Inventory does not consider ammonia emissions within the livestock model currently used (including no re-cycle estimates through ammonia to nitrous oxide conversion).

	Total Greenhouse emissions tCO_2–e/annum	Australian national inventory
Methane	39424	67960
Nitrous oxide	12826	69580
Ammonia (indirect GHG)	2329	0

Total	54579	137540

The measured emissions were about 40% of that modelled using the National Greenhouse Gas Inventory method. The major differences lie in cattle methane production (about 41.4% of modelled estimates) and modelled nitrous oxide emissions overestimating actual emissions by more than 4 -fold. Wiedemann et al. (2017) reported mean greenhouse gas (GHG) emissions in the feedlot stage ranged from 4.6 to 9.5 kg CO_2-e/kg LWG (excluding land use and direct land-use change emissions). The estimated mean greenhouse gas emissions for beef cattle managed at the southern feedlot was 6.6 kg CO_2-e/kg LW gain or 106.8 g CO_2-e/kg LW $^{0.75}$/d.

5.7.2 Northern feedlot

The total greenhouse gas emissions (Table 16) demonstrate that about 90% of greenhouse gas liability is methane emissions (of which about 90% are direct emissions from animals via rumen methanogenesis) and 6% are ascribed to nitrous oxide. Ammonia emissions play a relatively minor role in total emissions with only about 3% of emissions accounted for through the conversion of ammonia to nitrous oxide.

Table 16 Total annual greenhouse gas emissions from the northern feedlot

	Total Greenhouse emissions tCO_2–e/annum	**Australian national inventory**
Methane	68330	82338
Nitrous oxide	4479	13776
Ammonia	2080	0
Total	74889	96114

The total emissions measured from the northern feedlot were nearly 29% lower than those that would have been predicted using the National Greenhouse Gas Inventory calculations. The major difference between the southern and northern sites is the extent of manure handling and management (composting in particular) at the southern site increasing the concentrations of nitrous oxide that could be emitted from the feedlot system. The estimated mean greenhouse gas emissions for beef cattle managed at the northern feed lot was 10.7 kg CO_2-e/kg LW gain or 169.7 g CO_2-e/kg LW $^{0.75}$/d.

5.8 Composting and manure management at the southern feedlot

5.8.1 Environmental conditions

During the measurement period, average daily ambient temperatures ranged between 15 and 25°C. Temperatures decreased over the period of study with minimum temperatures dropping below 8°C 60 days from start of experiment (DOE). The prevailing winds were north or northwest during this period. Wind speeds typically ranged between 1 and 5 m s^{-1}, with the strongest winds recorded on DOE 32 (> 11 m s^{-1}). A total of 10 days with rain were recorded with three of these days recording over 5 mm. Maximum daily rainfall was recorded on DOE 78 (~15 mm). Total rainfall for the measurement period was 38.9 mm (Figure 40).

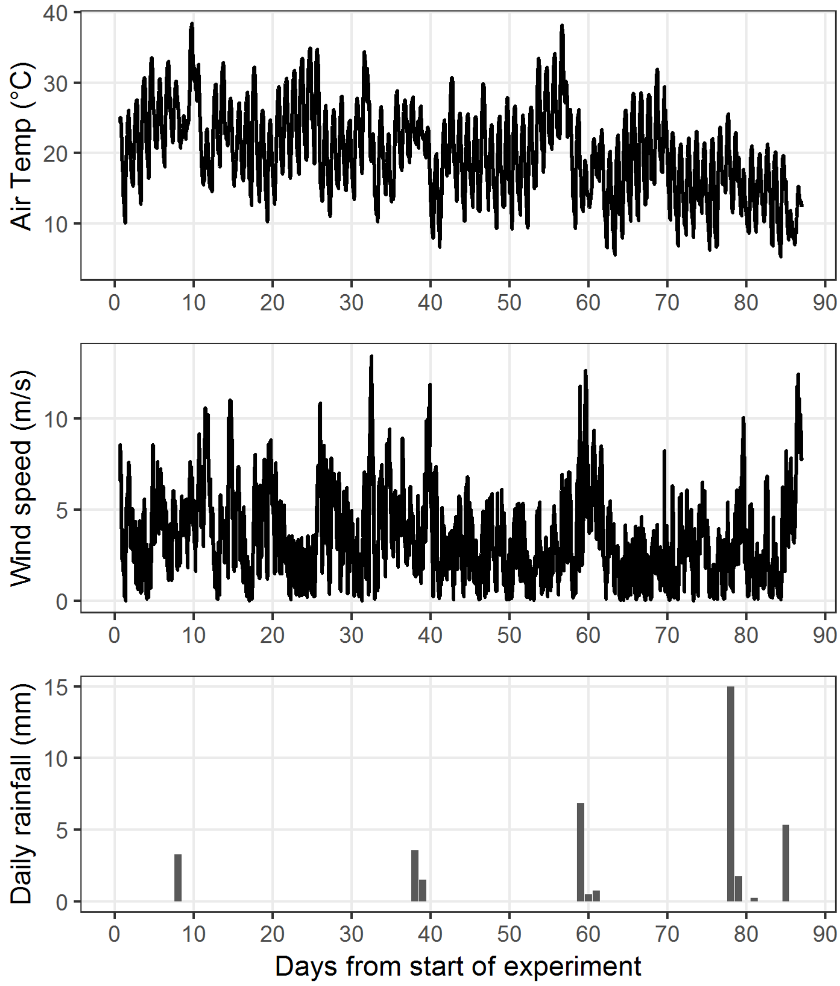


Figure 40 Climate conditions during the composting study at southern feedlot

5.8.2 Windrow manure pH, total carbon, total nitrogen, ammonium, and nitrate contents

The pH of the lignite windrow increased from an initial 7.35 to 7.74 on DOE 9, and remained at ~ 7.75 until a peak value of 7.95 on DOE 59, followed by a slow decrease to 7.83 on DOE 85 (Figure 41). Following a similar trend, the pH of the non-lignite windrow increased from the initial 7.33 to 7.82 on DOE 9, and reached the peak value of 7.98 on DOE 59, followed by a gradual decrease to 7.83 on DOE 85. The initial rapid increase in pH was attributed to the onset of organic matter mineralization and release of ammonium or volatile NH_3 (Gigliotti et al., 2012). The observed gradual reduction in pH after the peak value could be caused by NH_3 ammonification from the compost when the NH_3 was volatilized. Optimum pH for microbial activity during composting ranges between 5.5 and 8.0. However, a pH above 7.5 may lead to high N loss through NH_3 volatilization (Bernal et al., 2009). The lower pH in the lignite windrow compost compared to the non-lignite windrow was attributed to the acidic properties of the added lignite.

The NH_4^+−N content in the lignite windrow increased rapidly form an initial 0.81% to 1.38% on DOE 9, then dropped to 1.02% on DOE 19. After DOE 24, the NH_4^+−N slowly declined. The NH_4^+−N content was 0.47% on DOE 85. The NH_4^+−N content in non-lignite windrow followed a similar pattern: an increase from the initial 0.94% to the peak of 1.23% on DOE 9, then a decrease to 0.96% on DOE 19. The NH_4^+−N content was 0.54% on DOE 85. A similar observation was also reported in (Hao et al., 2004) who suggested the initial increase in NH_4^+−N content was probably due to sufficient NH_4^+−N content in the beginning of the composting process even when the NH_4^+−N was consumed through nitrification and NH_3 emission. In this study, higher initial NH_4^+−N contents in the lignite windrow could be due to the higher ammonification rate compared to that of the non-lignite windrow. The decrease in NH_4^+−N content in the later stage of composting could be attributed to its conversion to NH_3 and subsequent volatilization (Hao et al., 2011), or to the nitrification process of turning NH_4^+−N to NO_3^-−N (Bernal et al., 2009; El Kader et al., 2007).

The NO_3^-−N contents in both windrows followed an increasing trend over the 87-day study period. However, the increase did not correspond to the decrease in NH_4^+−N. Similar observations were made by Tiquia (2002) who reported that some of the NH_4^+−N might have been lost through NH_3 volatilization and/or denitrification. In this study, NO_3^-−N loss through leaching and/or runoff is expected to be insignificant. It was also observed that NO_3^- content in both windrows was below 30 mg kg^{-1}, reflecting a slow nitrification process during the windrow composting.

The Total Nitrogen (TN) content in the lignite windrow increased rapidly from an initial 2.84% to 3.40% on DOE 9 after formation, followed by a gradual decrease to 2.83% on DOE 19. After DOE 24, the TN slowly dropped from 2.18% to 1.98% on DOE 85. The TN content in the non-lignite windrow followed a similar trend over the measurement period, but the changes were relatively slow. After DOE 24, the TN remained consistent with an average of 1.98%. The transformation and transfer of ammoniacal nitrogen has been reported as the main mechanisms for nitrogen removal from material during composting (De Guardia et al., 2010).

The Total Carbon (TC) contents in the lignite and non-lignite windrows decreased over the 87-day study period. The TC in the lignite windrow rapidly decreased from 29.1% on DOE 2 to 18.6% on DOE 35, with a gradual decline observed thereafter. By the end of the study period on DOE 85, the TC content was 18.3%. The TC in the non-lignite windrow decreased from 27.0% on Day 2 to 25.5% on DOE 35, and thereafter remained at this level until the end of the study. Over the first 35 days after compost formation, 37% and 12% of the initial TC was lost in the lignite and non-lignite windrows, respectively. The substantial loss of TC in the lignite windrow could be due to enhanced microbial activity as a result of the high labile C fraction of the lignite present. However, the observation of C loss was lower than the 67% loss reported in Bernal et al. (2009). From DOE 35 to the end of the composting period, the total C loss was 1% for the lignite windrow and 4 % for the non-lignite windrow. The decrease in TC content in the lignite windrow could be attributed to the degradation of organic C to labile C, which provides a C source to microorganisms. This also suggests a higher microbial activity and faster degradation rate of organic C in the lignite compost compared to the non-lignite windrow, particularly in the first 20 days after compost formation.

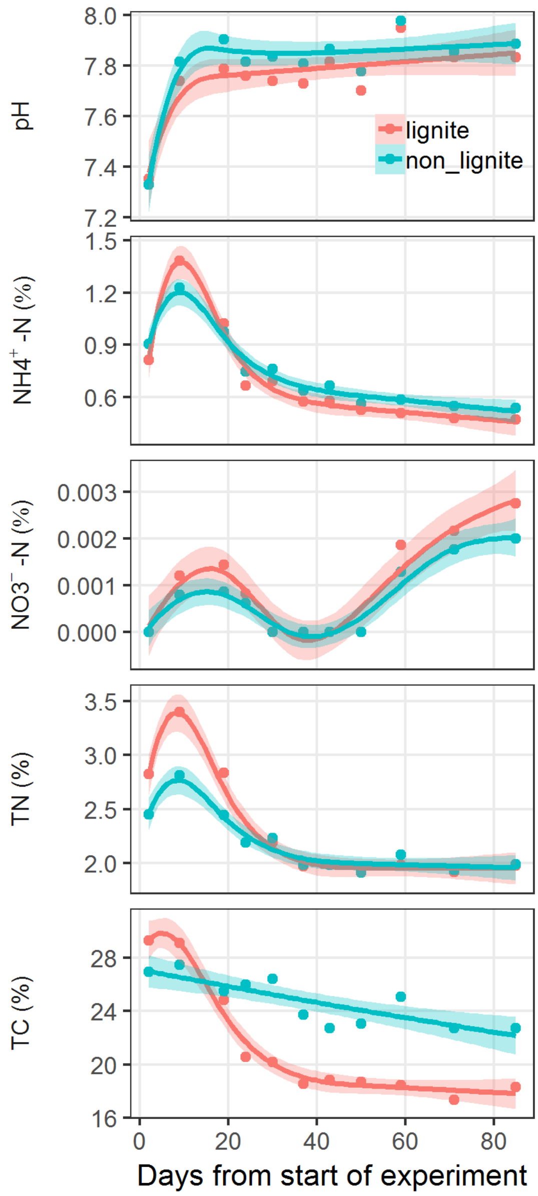


Figure 41 Changes in chemical composting of manures during composting

5.8.3 Gas fluxes

The greenhouse gas fluxes were calculated on a dry matter basis, per kg of initial manure dry matter (MDM).

5.8.3.1 NH_3 emissions

The daily average NH_3 emissions from the lignite windrow decreased from 0.06 g day^{-1} (kg MDM)$^{-1}$ on DOE 1 to 0.040 g day^{-1} (kg MDM)$^{-1}$ after the first turning on DOE 2 (Figure 42). After DOE 5, NH_3 emissions increased and reached an emission peak of 0.16 g day^{-1} (kg MDM)$^{-1}$ on DOE 14. This peak could be associated with the turning event on DOE 14. Thereafter, the NH_3 emission fell to near-zero flux by DOE 86. Emissions of NH_3 from the non-lignite windrow showed an initial increase from 0.13 g day^{-1} (kg MDM)$^{-1}$ on DOE 2 to a peak emission of 0.30 g day^{-1} (kg MDM)$^{-1}$ on DOE 10, which was nearly double that of lignite windrow peak emission. An observed decrease in emissions until DOE 18, and thereafter NH_3 emissions were comparable to those from the lignite windrow until the end of the study. The lower NH_3 emissions in the lignite windrow compared to that of the non-lignite windrow could be due to the slightly lower pH of the lignite treated manure. Biological immobilization of NH_4^+−N, owing to the labile C fraction of the lignite, might also contribute to the lower NH_3 emission from the lignite windrow.

A diurnal pattern of NH_3 emissions as observed from both windrows: with higher afternoon emissions between 12:00 and 15:00, and lower emissions at night-time. This pattern can be explained by the correlations between NH_3 fluxes and wind speed and ambient temperature (Sommer et al., 2004). We also observed a correlation between NH_3 flux and N_2O flux in the lignite windrow (R = 0.21, P < 0.001).

5.8.3.2 N_2O emissions

Daily N_2O emissions from lignite manure windrow was 0.01 g day^{-1} (kg MDM)$^{-1}$ on DOE 1, and reached a peak emission rate of 0.013 g day^{-1} (kg DM)$^{-1}$ on DOE 18. After DOE 39, the N_2O emissions slowly declined, but remained between 0.01 and 0.008 g day^{-1} (kg MDM)$^{-1}$ by the end of the study. Nitrous oxide emissions from non-lignite manure windrow decreased from 0.004 g day^{-1} (kg MDM)$^{-1}$ on DOE 1 to 0.002 g day^{-1} (kg MDM)$^{-1}$ on DOE 4. Thereafter, the N_2O emissions rose to ~0.005 g day^{-1} (kg MDM)$^{-1}$ on DOE 39 probably due to the rainfall on previous day. After DOE 39, the N_2O emissions decreased gradually to near-zero on DOE 60, and thereafter no N_2O emissions were detected. Negative N_2O emissions were observed, but this is attributed to the fact that elevated N_2O concentrations were close to the FTIR detection limit during these events.

Low N_2O emissions from both windrows were attributed to low NO_3^-−N content in the windrows that reflected the slow nitrification process during windrow composting. Furthermore, N_2O could also be produced by the denitrification process near the compost bed where the anaerobic conditions favoured the conversion of NO_3^- to N_2O or N_2. The lower N_2O level at the end of the composting process in the non-lignite windrow suggested that a large proportion of N could be emitted in the form of N_2. However, N_2 emissions were not measured in this study. In the lignite-treated compost, N_2O emissions become prevalent when available C became depleted.

5.8.3.3 CO_2 fluxes

The daily CO_2 flux in the lignite manure windrow followed a decreasing trend over the composting period. The initial daily CO_2 flux was 14.2 g day^{-1} (kg MDM)$^{-1}$, reached a peak flux of 32.8 g day^{-1} (kg MDM)$^{-1}$ on DOE 18, thereafter decreased to a range between 5 and 10 g day^{-1} (kg MDM)$^{-1}$ between DOE 40 and DOE 60. Daily CO_2 flux increased from 8.7 to 14.4 g day^{-1} (kg MDM)$^{-1}$ due to the last turning on DOE 85. In contrast, the CO_2 fluxes in the non-lignite windrow decreased substantially from the initial 19.4 g day^{-1} (kg MDM)$^{-1}$ on DOE 1 to 1.9 g day^{-1} (kg MDM)$^{-1}$ on DOE 6, then gradually declined.

Near-zero CO_2 fluxes were observed after DOE 60. Similarly, the response of CO_2 fluxes to turning events decreased with the time. The high CO_2 fluxes in the lignite windrow likely corresponded to the high labile C contents, reflecting stronger microbial activity and faster degradation of labile C.

5.8.3.4 CH_4 fluxes

The daily average CH_4 flux in the lignite windrow was 0.012 g day^{-1} (kg $MDM)^{-1}$ (a range of between near-zero and 0.06 g day^{-1} (kg $MDM)^{-1}$), while a range of between near-zero to negative emissions were observed from the non-lignite windrow over the same period probably because the CH_4 oxidation by methanotrophs was dominant (Chen et al., 2014; Lessard et al., 1997). The addition of lignite to the manure may have allowed anaerobic conditions to develop in some area (due to fewer pores in the mixture) which led to higher CH_4 emissions compared with the non-lignite windrow.

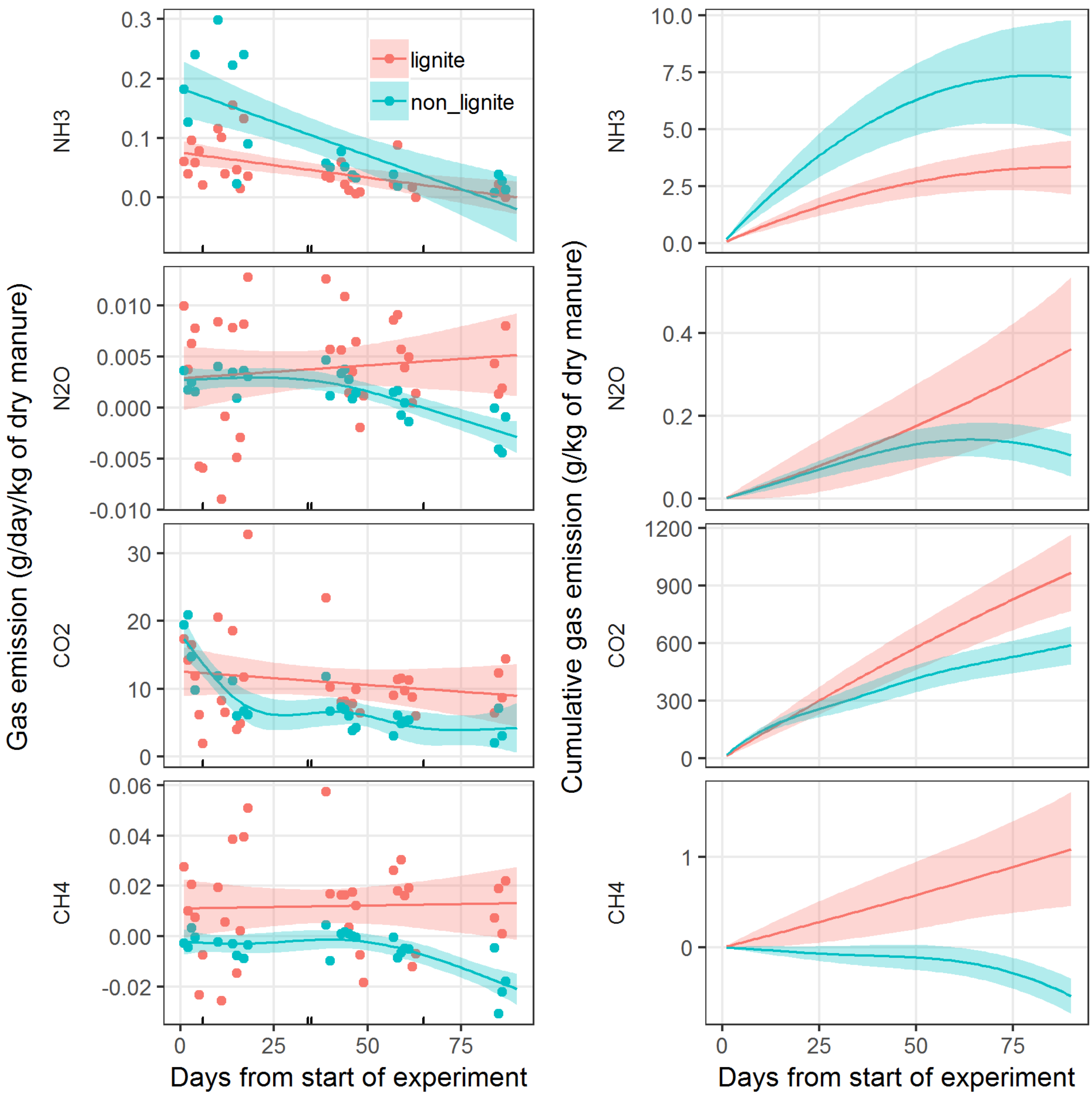


Figure 42 Greenhouse gas emissions from composting study

5.8.3.5 Cumulative gas fluxes

The cumulative fluxes of NH_3, N_2O, CO_2, and CH_4 over the 87-day windrow composting period were 3.4, 0.4, 967.6, and 1.1 g (kg MDM)$^{-1}$ in the lignite windrow, and 7.2, 0.1, 588.2, and 0 g (kg MDM)$^{-1}$ in the non-lignite windrow, respectively (Table 17). The N lost as N−NH_3 was 9.7 and 24.4% of the initial total N for the lignite and non-lignite windrow, respectively. The N lost as N−N_2O was 0.8 and 0.3% of the initial total N for lignite and non-lignite windrow, respectively. The results reported here do not differ from those reported in the Australian National Inventory. The estimates used in the Australian National Inventory for N lost as N-N_2O is 0.5%. The total N losses as N−NH_3 and N−N_2O were 11% and 25% of the initial total N for lignite and non-lignite windrow, respectively (Bai et al., 2020). These results show that the addition of lignite to the manure reduced N losses as NH_3 and N_2O during the composting process.

The calculated total GHG emissions (equivalent to CO_2, CO_2−e) were estimated by assuming a global warming potential of 28 for CH_4, and 265 for N_2O (in a 100-year life span), and that 1% of N−NH_3 emissions will be contributed to indirect N−N_2O emissions (Hartmann et al. 2013). It was noted that the total GHG emissions in the lignite windrow (1104.4 g (kg MDM)$^{-1}$) were higher than in the non-lignite windrow (643.5 g (kg MDM)$^{-1}$). The direct N_2O emissions and indirect NH_3 emissions contributed 9.7% and 8.4% of the total GHG emissions from lignite and non-lignite windrow, respectively, of this, 1.0% and 3.9% is from the indirect contribution of NH_3 emissions, respectively.

Table 17 Daily fluxes of greenhouse gases from lignite and non-lignite amended composts. Measured CO_2 fluxes are reported as a reference and are not reported as part of GHG emissions estimates.

	NH_3	N_2O	CO_2	CH_4
Daily mean flux (g (kg MDM)$^{-1}$) §				
Lignite windrow	0.04	0.004	11.1	0.01
Non-Lignite windrow	0.08	0.001	6.8	0‡
Cumulative flux (g (kg MDM)$^{-1}$)				
Lignite windrow	3.4	0.4	967.3	1.1
Non-Lignite windrow	7.3	0.1	589.5	0
N Loss (% of total initial N)				
	N−NH_3	N−N_2O	Total N losses (%)	
Lignite windrow	9.7	0.8	10.6	
Non-Lignite windrow	24.4	0.3	24.6	
GHG emissions (CO_2-e) # **(g (kg MDM)$^{-1}$)**				
Lignite windrow	11.5	106.9†		30.2
Non-Lignite windrow	24.9	54.0†		0

§, DM, initial manure dry matter.

#, global warming potential: 1 for CO_2, 28 for CH_4, and 265 for N_2O. CO_2−e, equivalent to CO_2.

‡, Actual calculation was -0.01 g (kg MDM)$^{-1}$.

†, calculation assumes 1% emitted NH_3−N (NIR, 2018) Eq. 3DA_4 is deposited and re-emitted as N_2O−N. $N_2O\_indirect = NH_3 * (14/17) *1\% *(44/28)$

5.8.3.6 Impact of changing the manure management systems on total greenhouse gas emissions

A modelling scenario was undertaken to mimic the impact of changing the manure management system to 75% volume as composting and 25% as stockpiled systems. The current practice at the southern feedlot is about 25% composting and 75% stockpile management (Tables 10, 12 & 14). The model was developed using the findings of FLOT.331 and B.FLT.0148 (lignite amendments and general greenhouse gas emissions) and the recently published data of Chen et al. (2015). These studies demonstrated the clear ammonia abatement potential of lignite, however, transport and logistics considerations would make this product unlikely to be deployed into feedlots that are more than 200 km from brown coal reserves. The modelling therefore did not consider the addition of lignite and only considered composting using windrowing (non-lignite data – Table 17). The estimated impact of changing the current system to 75% composting without lignite addition was an increase in ammonia flux rate from 0.7 kg/ha/h to 1.3 kg/ha/h or an increase in ammonia emissions from 121.1 t/annum to 225.2 t/annum. Based on Tables 12, 14, a reduction in direct nitrous oxide emissions from 1.1 kg/ha/h to 0.5 kg/ha/h as a result of an increase in composting activity was observed (Table 18).

Table 18 Simulation of greenhouse gas changes during composting (whole of systems model)

Ammonia (75% composting systems)	Average flux (kg/ha/h)				
	-2s	*-1s*	*0*	*1s*	*2s*
Cattle pens	2.21	2.38	2.92	3.46	3.63
Manure handling area (including composting)	0.34	0.57	1.30	2.04	2.27
Lagoons	0.50	0.52	0.60	0.68	0.71

Nitrous oxide (75% composting system)	Average flux (kg/ha/h)				
	-2s	*-1s*	*0*	*1s*	*2s*
Cattle pens	-0.17	-0.29	0.01	0.55	0.72
Manure handling area (including composting)	-0.12	0.03	0.50	1.23	1.46
Lagoons	0.06	0.10	0.23	0.31	0.34

Ammonia (75% composting system)	Total emissions (t/annum)				
	-2s	*-1s*	*0*	*1s*	*2s*
Cattle pens	572.3	616.2	755.9	895.6	939.5
Manure handling area (including composting)	58.3	98.3	225.2	352.2	392.1
Lagoons	1.5	1.6	1.8	2.1	2.2
Total	632.2	716.1	983.0	1249.9	1333.7

Nitrous oxide (75% composting system)	Total emissions (t/annum)

	-2s	*-1s*	*0*	*1s*	*2s*
Cattle pens	-43.2	-74.8	3.4	143.0	186.9
Manure handling area (including composting)	-21.3	4.4	86.1	213.1	253.0
Lagoons	0.2	0.3	0.7	0.9	1.0
Total	-64.3	-70.2	90.2	357.1	440.9

Even though there was a substantial increase in ammonia emissions the net impact of changing the manure management system from current practice to 75% composting was to reduce the total greenhouse gas N emissions from the site by about 31% or from 89000 t/annum to 61750 t per annum. The reduction in N based greenhouse gas emissions was estimated to be more than 27000 t per annum or about 1.68 t CO_2-e/head/annum (Table 19).

Table 19 Total N based greenhouse gas emissions from two composting simulations

	25% composting		**75% composting**	
	tCO_2–e	**%**	**tCO_2–e**	**%**
N based GHG	53831	60.45	26498	42.93
Methane	35223	39.55	35223	57.07
Total	89054		61720	
% reduction			31	

6 Discussion

6.1 Overview of success

Five objectives for the project were outlined in the original project plan. In brief these were:

1. Measure long-term methane, nitrous oxide and ammonia emissions from two Australian beef feedlots
2. Measurement of methane emissions from the animal
3. Use the long-term emissions data sets to evaluate current approaches (modelling)
4. Integration of GHG and economic frameworks to understand systems interdependency
5. Communication and practice change

6.1.1 Measurement of long-term greenhouse gas emissions from two Australian feedlots

A suite of state-of the-art instruments to measure direct and indirect greenhouse gas emissions (N_2O, CH_4, NH_3, NO_x and CO_2), fluxes of energy and climate variables, were established at each site. These included closed path FTIR and open path lasers to determine the concentrations of GHG at known time points. The data and information were processed using two methods – inverse dispersion models (IDM) and eddy covariance (EC). The long-term measurement of greenhouse gas emissions has to consider:

1. the suitability of the instrumentation used to measure concentration and micro-meteorological conditions
2. the modelling approaches used to calculate the flux
3. the impact of gaps within the data series and,
4. the reported outcomes – per ha or per head basis of reporting.

The analyser used in these experiments are based on either tuneable laser diodes or Fourier transform infrared (FTIR) spectroscopy to quantify the mole fractions of several trace gas species (including CO_2, N_2O, CH_4, CO, and H_2O). These instruments have been used for many years in the measurement of greenhouse gas emissions and are highly resilient (low drift, low bias, very low concentration detection with high signal: noise ratio). When used in conjunction with micrometeorological and chamber systems they can all be used to estimate the fluxes of these gases to and from the atmosphere. The instrumentation used for monitoring of micro-meteorological conditions was again selected on the basis of its resilience and accuracy of measurement of atmospheric conditions. Arguably the most important micro-meteorology instrument is the sonic anemometer-data logging system. The outputs from these instruments drive the modelling of the measurement of concentration to a flux. Again, the selection criteria were resilience (low drift, low bias and repeatability). All instruments deployed conformed to ISO and Australian Standards – important criteria if, in the future, emissions models are reviewed and re-designed according to Method 4 approaches outlined by NGERS (2007).

The relationship between concentration (m/v) of a gas at a known point in the environment and flux is determined as the concentration of a gas that has moved irrevocably past some point in the environment (transport). To calculate the latter (flux) the micrometeorological model must describe the spatial extent and position of the surface area that is contributing to a turbulent flux measurement at a specific point in time, for specific atmospheric conditions and surface characteristics (Kljun et al. 2015). Furthermore, the area containing the sources and sinks contributing to a given measurement point must be estimated to be able to report a flux and a footprint of the emissions. This is critically important for reporting of fluxes of GHG emitted from agricultural systems and their attribution to an area of land or a *per head* animal model. Two footprinting models were used in this study (bLS approach and eddy covariance footprinting according to Kljun et al. (2015). Both methods were found to provide good estimates of fluxes but the eddy covariance method provided fluxes with higher measures of variation for methane and nitrous oxide but not, paradoxically for carbon dioxide. The 95% CI for methane fluxes calculated using the IDM-bLS WINDTRAX model and EC were respectively 3.73 – 4.25 and 3.73 to 4.39 kg/ha/h - differences that were not significantly different when calculated on a per head basis (138 vs 153 g/head/d). A 15-fold difference in nitrous oxide fluxes were reported between the two methods with the IDM-bLS method reporting a range of fluxes from 0.011 to 0.015 kg/ha/h and the EC method reporting -0.003 to 0.005 kg/ha/h). When scaling the emissions to an effective area of 43.7 ha the total N_2O emissions reported using the bLS and EC methods were 96.4 to 131.4 kg/annum, and -2.2 to 43.8 kg/annum. From work conducted in B.FLT.0148 and FLOT.331, the bLS method represents the more realistic annual nitrous oxide emissions from the southern feedlot system. The development of the multiple sampling height IDM-WINDTRAX method provided greater stability in flux estimates. Sampling at three heights above the feedlot allows better estimates of greenhouse gas mixing in the surface boundary layer and better predictions of the vertical migration of gases through the surface to 10 m air column especially in non-homogenous area source situations. This approach is important for the measurement of direct and indirect greenhouse gas emissions from feedlots as the pen structure and occurrence of manure stockpiles and composting windrows can result in significant turbulence (Flesch, 2015 pers. comm. Figure 43).

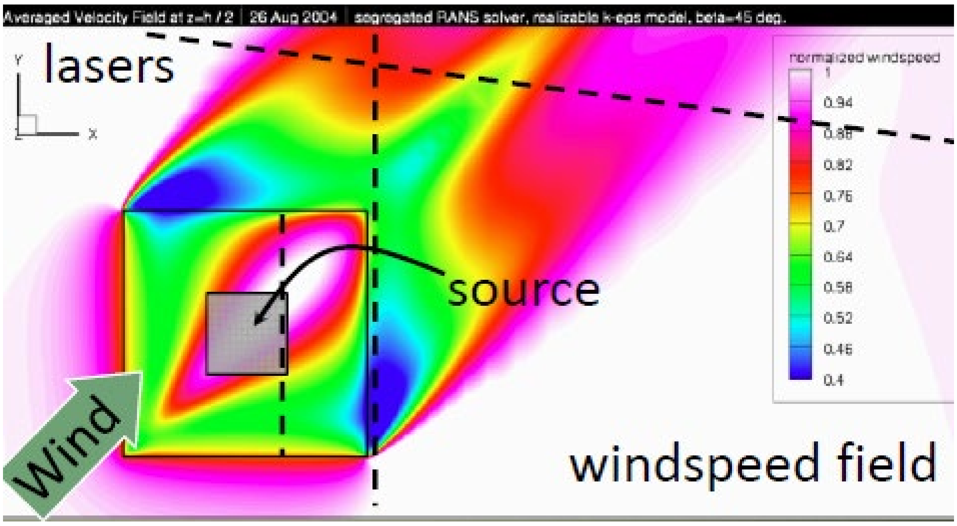


Figure 43 Impact of feedlot pen structure on turbulence

Loss of data and information resulting in gaps in the data series poses some interesting statistical issues. The important issue is not the approach to modelling of the gaps within the data series (e.g. ARIMA methods), but the acceptance that the data series collected represents the long-term emissions of GHG from the feedlot. The use of the ARIMA model to test the concept of pass/fail for a fragmented data series is not novel but provides a realistic picture of how much data can be lost before a model cannot be fitted to the measured time series. Fragmentation of data can represent (i) lack of precision in the measurement of concentration, (ii) a loss of information when the boundaries for data processing using the micro-meteorological model are breached (e.g. low or very high wind speed), or (iii) a fragmentation in source emissions (e.g. all cattle immediately adjacent to the measurement location are moved). In the case of the studies conducted at both feedlot sites, there is no evidence that there are any issues with the precision of measurement of concentration of any greenhouse gas. There is, however, considerable periods of time where the micrometeorological conditions led to poor resolution of the flux footprint and hence no stable estimate of the flux. This was a significant issue with the EC footprinting model using a single measurement point at the southern site where only CO_2 and CH_4 emissions were able to be measured and modelled (ARIMA) with any precision. There was a considerable lack of reliability in the measurement of nitrous oxide and ammonia fluxes at this site. The major issue identified with both nitrogen-based gas emissions was the fragmentation of data (sometimes gaps in data series of about 20% of the total measurement period) and the very low concentrations of nitrous oxide measured at the site. The data series from the northern site (concentration of gas being converted to a flux using a modified IDM-WINDTRAX model) was more robust and good estimates of fluxes of all gases were calculated. The northern site data series for the two direct GHG (CH_4 and N_2O) represents the first long-term series of data for a feedlot system – a period of time of continuous measures that can be validated through modelling longer than one month. This advance allows the feedlot industry to address the key criteria for the so-called 'Method 4' approaches outlined for emissions intensive sectors.

Method 4 uses a direct monitoring of emission systems, either on a continuous or periodic basis, and therefore provides a validation data series and a different approach to stochastic models for the estimation of emissions. The basis of Method 4 approaches is direct monitoring of gases rather than analysing the chemical properties of inputs (or in some case, products). This is of particular interest for methane and nitrous oxide emissions from manure management systems where the conversion of organic matter to the gas is modelled using a number of chemical and biochemical transactions. Furthermore, the studies reported in this project can provide evidence that the measured emissions of methane and nitrous oxide are substantially lower than those modelled using the approaches of the Australian National Inventory.

6.1.2 Ability to measure the impact of a single mitigation strategy

Measurements before, during and after a single mitigation strategy was deployed (lignite amendment to manure processing system at the southern site) were undertaken to understand the impact of the change on whole farm systems productivity. The composting study compared gaseous emissions during the composting of lignite and non-lignite treated cattle manure. The lignite addition was effective in reducing N losses by 56% during the windrow composting process but promoted CH_4 and N_2O emissions (due to the composting process maintaining anaerobic conditions within the manure stockpile). The total greenhouse gas emissions (CO_2–e) from composting lignite treated manure was 1.7 times greater than that of the control treatment. Addition of lignite in the feedlot pen delivers a significant reduction in reactive N losses in terms of direct ammonia emissions. However, the effectiveness of retaining N in the lignite windrow was not obvious after about 25 days of composting. These data also suggest that the role of lignite within a feedlot system as a mitigation technology may compromise any gains in abatement through ammonia losses with an increase in nitrous oxide emissions. Furthermore, in systems where reductions of total GHGs are a focus, a move away from stockpiling and post processing of manures towards applying the product directly from the pen to agricultural land may reduce total GHG losses. This reduction of nitrous oxide may well be a result of losses of volatile N compounds and changes in total C content of in the non-lignite treated manure.

This system occurs at the northern feedlot site where measured nitrous oxide emissions accounted for only 6% of total greenhouse gas emission (CO_2-e) and was about one-third of the predicted emissions using the Australian National Inventory. Even though the measured emissions of nitrous oxide from lignite treated manures were increased compared to the stockpile emissions, the total emissions from the manure management system at the southern feedlot site were about 20% of the estimates calculated from the Australian National Inventory. Technologies such as lignite could be applied to the manure management system and composting undertaken resulting in some increases in nitrous oxide but significant reductions in ammonia losses to the environment. Furthermore, composting reduces the water content of the manure, and stabilizes the organic matter so that handling manure compost becomes easier and less costly.

The environmental cost of increased greenhouse gas emissions can be estimated by applying a carbon price used for emission trading and a direct carbon taxation model in emission policy reduction schemes as implemented in some countries ($/t CO_2–e). Carbon prices vary between countries and over time. Currently, the nominal price of carbon in Sweden is the highest in the world at US$139/t CO_2–e; whereas the Australia notional applied carbon price ranges from $13.87 to $24.5/t CO_2–e (Clean Energy Regulator data from 2017-2019).

Price of carbon assumption: If indirect costs are added to the pricing structure, the estimated cost for the abatement of greenhouse gas emissions from windrow composting process is \$24.5/t CO_2–e (the upper boundary of the Australian auction price. This reflects extra costs associated with machinery, processing and packing of the composted manures to the point of wholesale.

Environmental cost of increased greenhouse emissions (Table 17 CO_2e emissions data): The lignite treated manure emitted 137.1 kg CO_2 e per t DM compost or financially equivalent to \$3.36 whereas the non-lignite treated compost emitted 54 kg CO_2e per t DM compost of equivalent to a cost of \$1.32.

Economic benefit of retaining N (Table 17 N retention data): The current study results confirm those of previous work (Chen et al. 2014, 2015) that lignite treatment of manure results in lower emissions of ammonia and other N compounds. The estimated N losses in this study are shown in Table 17. For the analysis we will assume that 40% of N in the compost is plant available (Chen et al. 2015). If N retained is valued at \$1.37 per kg N (or the fertiliser equivalent price of N), the composts treated with lignite would retain \$9.70 of N and those not treated with lignite would retain \$8.16 of N.

If we account for the potential cost of NH_3 to human health and ecosystem (eutrophication, biodiversity; van Grinsven et al., 2013; van Grinsven et al., 2018), **the impact of lignite would represent a benefit** ranging from \$0.28 to 0.83 kg DM (median value of \$0.55/kg DM)

The benefit cost ratio of lignite amendment and composting compared to the potential cost of ammonia emissions to human health and the ecosystem would be for lignite \$3.05:1 and no lignite \$6.18:1.

The total environmental benefits of not treating manure with lignite and composting are about 2-fold that of treatment. This outcome reflects an interesting environmental dilemma that even though the processing of the manure without lignite and composting yields higher rates of ammonia production, it reduces nitrous emissions.

Measurement of methane emissions from the animal

There were no direct measurements of methane emissions from feedlot cattle made in this trial. The approaches taken to methane emissions from cattle sources were based on monitoring across pen areas (discounting emissions measured from pens without animals). Those fluxes were then evaluated against the current National Greenhouse Gas Inventory method and the National Greenhouse Gas Inventory method corrected for measured DM intake. Combining the data from the northern and southern sites results in 28% lower actual emissions compared to the predictions using the National Greenhouse Gas Inventory (174 g CH_4/head/d (Measured) vs. 243 g/head/day (Inventory)). This is an important observation and supports the data reported in B.FLT.0148 & FLOT.331. If these emissions are scaled to a national scenario, the total estimated emissions (Australian National Inventory) from 1,110,689 (animals on feed December 2018) is reduced from 2,343,014 t CO_2-e per annum (about 97,500 t methane) to 1,677,714 t CO_2-e per annum (about 70,000 t methane).

From a whole of systems point of view, the contribution of methane to total emissions from feedlots range from about 70% (southern feeding systems with extensive manure management systems) to 90% in northern systems where manure is recycled directly to land. Reducing enteric methane emissions from cattle at feed is a priority for the industry to manage greenhouse gas liabilities and improve environmental sustainability. There are a range of technologies emerging that may mitigate direct methane emissions from the animal (e.g. asparagopsis algae, changing the ratio of rumen protected starch to readily degraded starch) and those technologies should be adopted with proactive management of reactive nitrogen sources and emissions points (for instance reducing the crude protein content of the rations offered to align more closely with NRC (2016) best practice.

6.1.3 Use the long-term emissions data sets to evaluate current approaches (modelling)

The long-term data series was evaluated against WNMM, DNDC and the National Greenhouse Gas Inventory models. A CCP analysis was conducted for methane emissions across the two years of measurement. Outliers (trigger threshold) for methane and nitrous oxide fluxes measured using CP-FTIR and EC reflected scenarios where low frequencies of measurements were admissible to the analysis resulting in higher variability and greater uncertainty in the measured flux. Outliers in the modelled data series reflect missing animal ration data or an overrepresentation of a single high methanogenic ration. The WNMM approach has a consistent 1:3s and 4:1s threshold breach throughout the summers of 2015-2017 for both GHG. The WNMM model requires climate, actual animal and manure data series to develop the prediction for emissions of these gases. It is suggested that the major driver of the 4:1s systemic bias and hence the threshold 1:3s being exceeded is elevated temperatures during the summer rather than consistent changes in animal performance, feed consumed, or manure voided.

The WNMM model did not predict ammonia emissions with any certainty, again suffering from the potential systemic bias resulting from elevated temperatures during summer 2015-2016.

The use of DNDC modelling did not perform well, even in comparison with the WNMM outcomes. Both the WNMM and DNDC models are designed as input-output balance models with a strong focus on soil-manure interactions. In simple terms, these models are driven by the total carbon and nitrogen transactions at different stages of manure transformation into soil systems. Any livestock-based model is simple and estimates the manure and urine outputs from the animal (using digestibility calculations). Furthermore, in WNMM, there is a requirement for a whole systems carbon budget to be calculated including estimates of total carbon sequestered in animal products and manure. WNMM modelling outcomes are also sensitive to seasonal climate conditions, especially elevated temperatures. It is not recommended that DNDC and WNMM are used in feedlot systems to estimate emissions for methane, nitrous oxide or ammonia.

In previous reports (FLOT.331 and B.FLT.0148), the major criticisms of the current approach used by the National Greenhouse Gas Inventory to model emissions from feedlot systems have been discussed in depth. The findings in this report re-iterate the issues about the lack of congruency between the National Greenhouse Gas Inventory approaches for feed intake and measured feed intake. Often measured feed intakes are 30% more than the estimates used in the current models. As feed intake drives both methane and nitrogen-based gas emissions, the measured fluxes of GHG from feedlots are, approximately 30% lower in terms of methane and up to five -fold lower in terms of nitrous oxide estimates derived using the National Inventory. In the previous section, the issues surround the accuracy of the estimates of methane emissions from cattle have been outlined. The key issues are the poor agreement between the estimates of feed intake using the National Inventory method and the measured feed intake, and the use of the Moe and Tyrell methane emissions model. Work undertaken by Benchaar et al (1998) demonstrated that the Moe and Tyrell model (and the Blaxter and Clapperton model – used in estimation of emissions from dairy cows) resulted in poor correlations with actual emissions measurements (R^2 = 0.42 and 0.57; error of prediction = 33.72% and 22.93%, respectively). In the case of nitrous oxide (and ammonia), the situation is somewhat more complex. The issue concerning the underestimation of feed intake is apparent when evaluating the potential sources of nitrogen base gas emissions from feedlots. Australian feedlot systems offer rations containing higher than necessary supply of crude protein to maintain high growth rates. Therefore, the excretion of nitrogen onto the feed pad is higher than that noted in the National Inventory calculations. However, measured emissions of nitrous oxide are substantially lower than those predicted by the National Inventory where fixed integrated emissions factors, and the use of fixed nitrous oxide emission factors are used routinely. It is recommended that a complete review of all nitrous oxide emissions models is undertaken. Finally, one of the significant issues facing the industry in terms of reactive nitrogen management is the high temporal variation noted for nitrous oxide emissions. Feedlots could consider changes in manure management practices. For example rapid transport of manure from pens or stockpiles to land to reduce the risk of rapid short-term but high flux rate events such as rainfall events that saturating manure stockpiles or cause effluent to drain into holding ponds.

6.1.4 Integration of GHG and economic frameworks to understand systems interdependency

The current commitment by Meat & Livestock Australia to support the red meat industry to become carbon neutral by 2030 requires long-term measurements of GHG from feedlot systems to verify inventory models and provide guidance on the economic benefits to use novel mitigation technologies to reduce the footprint of production. There is very little scope for a feedlot system to adopt adaptation approaches to reduce greenhouse gas emissions reflecting the small physical footprint of the feeding system. Therefore, the focus of the integration of greenhouse gas emissions models and economic frameworks should be mitigation unless the business that owns the feedlot has other operations that can adopt adaptation or sequestration (land use change) approaches. B.CCH.6000 outlined the use of marginal abatement cost curve approach to rank mitigation potential and future investment options. Red algae, 3-nitroxypropanol (NOP), some plant bioactives and vaccination play the most significant role in mitigating methane emissions from ruminant livestock (Table 20).

Table 20 Assessment of future research investment for mitigation of rumen methane production (Meat & Livestock Report B.CCH.6000)

Scenario	Animal methane mitigation potential (%)	National methane mitigation potential[a] (% total)	Productivity gain (%)	Barrier/cost to implement[e] (Relative score)	Technical risk/cost research[e] (Relative score)	Investment priority (Relative value: subjective NLMP managers)
Genetics B/S[i]	6	3.5	0.8	20	20	Low
Genetics dairy	12	0.2	2	15	15	Medium
Grape marc	10	1.1	0	10	5	Low
Algae	60	25.4	8b	15	25	High
Nitrate	6	2.8	0	50	10	Low
Wheat feeding	40	0.4	20	30	5	Medium
Plant bioactives	25	10.6	3.5b	15	30	High
NOP	35	12.7	4b	15	10	Medium
Biochar	15	6.4	15	15	30	M-H
Leucaena	28	0.9	20	20	5	High
Other legumes	10	9.7c	10	10	20	Medium
Native shrubs	4	0.1	5	15	5	Low
Energy capture	25	10.6d	18f	35	40	High
Vaccination	15	10.2	2b	5	50	M-H
BMPg	3	5.2	20	20	10	Low
NIR forages	NA	NA	NA	5	5	High
ELLE database	NA	NA	NA	10	20	M-H
IRDh	NA	NA	NA	40	40	Low

The work in this report provides a positive cost benefit analysis (CBA) for the nitrogen greenhouse gas mitigation technologies based on lignite amendment to manure as well as composting. However, the focus of each technology is different – lignite being a potent adsorbent of ammonia and composting a way of reducing nitrous oxide emissions. This technology is focussed on the nitrogen cycle and therefore cost benefit analysis do not rely on any retention of energy to support animal growth (as with the current anti-methanogenesis technologies). The technology can be adopted readily across the southern feedlot industry and work is planned for a product that has similar mitigation characteristics but is made from black coal – a suitable option for the northern feedlot industry. The positive benefit cost of adopting lignite technologies in southern industry feedlots was highlighted in B.FLT.0148, which indicated that were a Carbon Farming Initiative (CFI) method to be developed for the lignite technology, the net abatement return would be equivalent to $4.72 to $6.67 per head per annum (exclusive of transaction and compliance costs). In this report we report $7.76 per cubic metre of compost (or an equivalent of $4.99 to $6.96 per head net abatement return) and a further $5.71 to 16.93 per cubic metre compost processed in intangible benefits (broader environmental and social benefits). This scenario assumes the extra abatement costs ($13.87 to $24.5/t CO_2-e) are accounted for, as a notional applied carbon price ranges reflected in current Australian Emissions Reduction Fund auctions. It does not rely on returns to animal productivity.

One concern is the inherent variability and risk of scenarios where the mitigation of reactive nitrogen is overwhelmed by environmental conditions that are not under the control of the feedlot business. One such example is intense heavy rainfall events resulting in spikes in nitrous oxide or losses of ammonium/ammonia to lagoons or as run off. Events such as these will reduce the per head benefits of adopting lignite technologies and will affect the total methane budget of the feedlot (increasing the risk of elevated methane emissions from flooded stockpiles and feed pads. The use of critical control point frameworks can reduce the financial impacts of these risks as the net benefit of abatement can be adjusted by the incidence of 'emissions failure' of 1:3s and 1:4s thresholds. If the incidence of failure is low (as has been noted in this study), the impact on net benefit of adopting mitigation technologies is likely to be negligible. However, one area of concern is the impact of ammonia fluxes on air quality. When ammonia emissions from the Northern feedlot were compared under Emergency Planning and Community Right-to-Know Act (EPCRA) administered by USA EPA, the fluxes from the northern feedlot exceed the upper thresholds required for action. Lignite technologies can undoubtedly reduce these risks and are therefore an 'insurance' against air quality emissions regulations.

The outcomes of the research were:

1. the first long-term datasets on CH_4, N_2O and NH_3 emissions from beef feedlots resolving the current lack of a robust southern hemisphere dataset (Objective 1 & 2) - achieved

2. a number of options (technologies) to mitigate, abate or sequester N to reduce total N inputs and/or improve N capture within the whole farm system (feedlot, manure management and associated cropping enterprises) (Objectives 1, 2 & 3) - achieved

3. benchmarking of existing models that have been adopted by the industry to integrate new data and information and validate models to provide confidence in current and future operations (Objectives 3 & 4) - achieved

4. the framework for the first N footprinting exercise (and associated decision tool) for Australian beef feedlot systems allowing the industry to develop strategic policies and marketing strategies for future growth in export opportunities for the industry (Objective 4) – partially achieved in this project.

7 Conclusions/recommendations

The project has clearly demonstrated that there are approaches to measure long-term greenhouse gas emissions from feedlots, and a range of technologies that can be used to abate reactive nitrogen losses that are cost effective. The research conducted has provided for the first time an accurate long-term measurement of total CH_4, N_2O, and NH_3 emissions from a feeding system that is typical of the northern feedlot industry. The findings have major economic and environmental implications for effective nitrogen management in agriculture, especially in intensive feedlot systems.

Key recommendations from the study are:

1. We note that the N use efficiency in the feedlot system is low in Australia, often less than 10% and the main pathways of N losses are in gaseous N forms (NH_3, NO_x, N_2O, and N_2). The long-term measurement of these gases has demonstrated that nitrous oxide emissions only represent about 10-20% of total greenhouse gas emissions. This observation means that the current approaches used in the National Greenhouse Gas Inventory needs review.

2. Ammonia emissions from feedlots can be extensive and may pose an air quality risk exposure to the industry if not addressed. We have demonstrated that lignite-based technologies are cost effective and abate ammonia emissions significantly.
3. Methane is the dominant greenhouse gas emission from feedlots. This study (and others) have clearly demonstrated that the National Greenhouse Gas Inventory over-estimates the methane emissions from intensive ruminant livestock systems. This observation means that the current approaches used in the National Greenhouse Gas Inventory needs review.
4. An approach to national greenhouse gas emissions (CH_4, N_2O, and NH_3), risk management and economic analysis has been proposed.

Future work as a result of the outcomes from this project include:

1. Development of new reactive nitrogen abatement technologies appropriate to northern Australian feedlot systems (e.g. black coal products). The full GHG implications of these products would need to be evaluated by aggregating biogenic and potential fossil CO sources from lignite.
2. Review and update the current National Greenhouse Gas Inventory approaches to methane and nitrous oxide emissions accounting.
3. Development of an industry-based tool for federated (CH_4, N_2O, and NH_3) emissions – risk and economics of greenhouse gas and air quality management

8 Key messages

1. Long term measurement of greenhouse gas emissions has demonstrated that the current estimation techniques used for the National Greenhouse Gas Inventory over-estimate methane by 28% and nitrous oxide by up to 80% depending on the feedlot system.
2. New information on the use of lignite technologies demonstrates positive cost benefit with up to $7 per head increase in value.

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