Final Report

Review of nitrous oxide emission factors used in the National Inventory Report for estimating GHG from feedlots

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1. Background

The Australian feedlot industry has invested in several research programs over more than a decade to understand emissions from manure sources. This research was needed because emissions from manure management in Australian feedlots were unclear and inventory estimates had not been verified. The National Inventory Report (NIR) method for feedlot cattle was most recently updated in 2015. Many changes were made to both the methods and the activity data used by the NIR, based on better science and better industry data. The revisions implemented resulted in substantial reductions in emissions from the feedlot industry. The update was supported by MLA funded research completed by Queensland Department of Agriculture, Fisheries and Forestry (QLD DAFF) led by Dr Matt Redding, and by the University of Melbourne (UOM), led by Prof. Deli Chen, leading to an important series of changes to reflect industry practice and research findings. At the time of this update, it was identified that the emission factor for nitrous oxide (N_2O) emissions from feed pads, which is a major emission source with the factors that are currently applied, predicted emissions that were considerably higher than early research findings. It was determined that further research in this area could support revision of this factor at a later point. Since that time, additional studies have been completed and published by the same research teams, which have improved our understanding of factors that control emissions in Australian feedlots. This concise review summarises the research to date of the feedlot N cycle, specifically focusing on N_2O emissions from feedlot manure pads, with a view to presenting a more representative emission estimation approach for Australian conditions supported by peer reviewed, Australian research.

This work has been done in consultation with the Department of Industry, Science, Energy and Resources (DISER) National Inventory Team. An initial draft of this final report was provided as a discussion paper, which was peer reviewed by Dr Matt Redding (QLD DAFF) and Prof. Deli Chen (UOM) and feedlot industry representatives, Mr Des Rinehart and Dr Joseph McMeniman.

The discussion paper was also independently reviewed by Prof. Richard Eckard of the University of Melbourne and comments were accepted. This final report contains the material from the discussion paper to finalise the project and deliver clear recommendations for the National Inventory Team.

2. Objectives

The objectives for the project were as follows:

1. Develop the evidence base for recommending a change in the emission factors for nitrous oxide from feedlot manure pads via a targeted review, suitable for submitting to the Inventory Team. It is envisaged that this review would not need to be submitted to a journal, as the supporting scientific papers have been published in journals. None-the-less, peer review of report by the principal Australian GHG researchers will be welcomed.
2. Present this evidence to the NIR team and assist implementation if accepted.
3. If required, provide new activity data to enable the National Inventory to calculate emissions for the feedlot industry.

3. Review of feedlot feed pad (drylot) nitrous oxide emission research

Overview of Manure Management Systems

Australian feedlots are designed and managed to carefully control manure and manure nutrients. All commercial feedlots are constructed with compacted pen surfaces and for larger feedlots, controlled drainage; i.e. runoff is contained on the site in effluent containment dams. Managing solid manure is an important management aspect at feedlots from the perspective of animal productivity. Pens are regularly cleaned, with a maximum of about 13 weeks between manure removal. Once removed from the pen, manure is typically stored on site in controlled drainage areas until it is removed for utilisation. Storage may also include treatment such as composting, and some manure may be removed directly from the pens and spread to land without storage.

Manure volatiles and nitrogen (N) flow through the system sequentially and the mass of material entering secondary and tertiary systems must take into account losses from the earlier stages. A very simple diagram is provided in Figure 1.

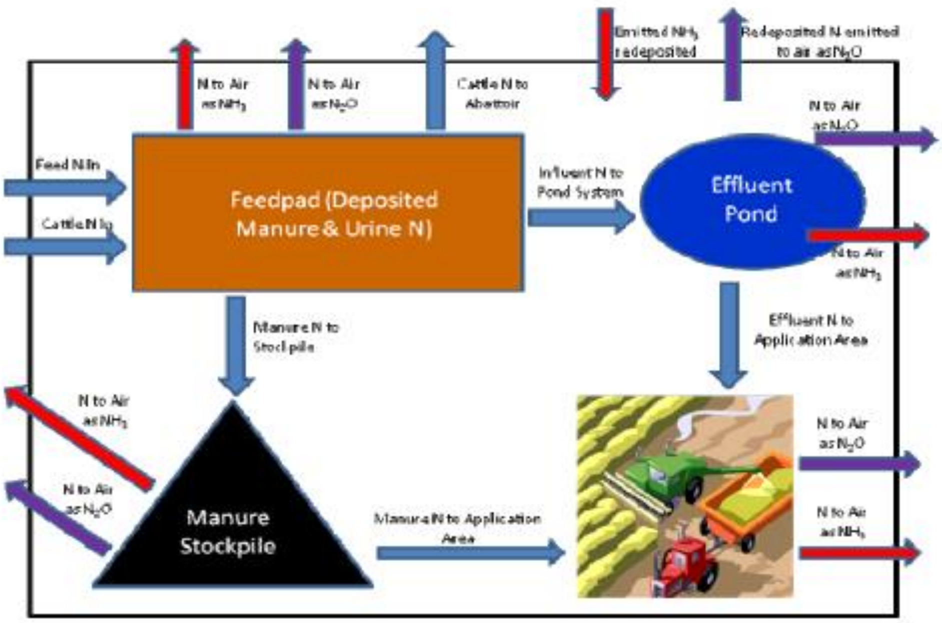

Figure 1 - Nitrogen flow diagram. Reproduced from Watts et al. (2012).

3.1 Review of current emission factor

Historically, there were no validated emission measurement studies available that accurately define emissions from pen manure in Australia or globally. Hence, many of the Intergovernmental Panel on Climate Change (IPCC) defaults are based on limited data. The current emission factor, reported in the NIR, for direct N_2O emissions from the feedlot pen ("dry lot") is 0.02 kg N_2O - N kg N excreted^{-1}. This N_2O emission factor for the feed pad is derived from the IPCC (2019), Volume 4, Chapter 10, which was also the same factor in the IPCC (2006), Volume 4, Chapter 10. This factor was derived from "expert judgement" from the IPCC, which provide a global benchmark for developing GHG inventories, in combination with Külling et al. (2003). Külling et al. (2003) investigated short-term emissions from dairy cattle farmyard manure, in laboratory conditions, to replicate European housing conditions. A dynamic closed chamber was used to measure emissions from stored wet slurry. It is known that chambers provide variable emission values for emitting surfaces and require several factors to be controlled to minimise disruption. Redding et al. (2015a) questioned the relevance of this study to beef cattle manure emissions in an Australian, dry packed feedlot pen due to key differences in moisture, temperature, manure physical characteristics, the addition of straw to the material and the duration of the trial. Pratt et al. (2015) also examined the appropriateness of the N_2O emission factor to Australian feed pen conditions by acknowledging the contrasting difference in temperatures between an Australian beef feedlot pen surface, upwards of 45 °C, and the 20 °C wet slurry analysed in Külling et al. (2003). Additionally, Redding et al. (2015a) identified that Külling et al. (2003) did not determine a relationship between N excretion and direct N_2O emissions, though the IPCC (Dong et al. 2006; Gavrilova et al. 2019) bases the emission factor on excreted N. Chen et al. (2009) noted that the predictions of nitrogenous gas emissions from the IPCC model are less accurate and do not account for several environmental factors that influence N_2O emissions. While the initial research by Külling et al. (2003) contributed data in this topic when little information was available, it is essential to reassess this emission factor to ensure the development of accurate emission profiles as a prerequisite to GHG mitigation research (Pratt et al. 2015). The NIR recognises that when data from additional Australian research studies become available the direct N_2O emission factor for feedlot pens can be reviewed.

3.2 Review of Australian Research

Until recently, there has been limited Australian studies that measure direct N_2O emissions from livestock. The primary reason for this was that measurement techniques, such as dynamic and static chambers and flow-through steady-state chambers, commonly used to measure GHG fluxes from land-management practices are difficult to apply to livestock production systems where GHGs are often emitted from a point source or non-uniform areas (Loh et al., 2008). This is specifically difficult in intensive agriculture where multiple on-farm sources of GHGs are within close proximity of each other. Australian researchers have overcome these challenges by utilising large chamber methods (Redding et al., 2015a) and open path FTIR (Bai et al., 2015, 2016; Chen et al., 2009). Improvements in chamber measurements have been made with the development of a large vented, non-flow through, non-steady-state chamber (Redding et al., 2015a). This method was validated against the backward Lagrangian stochastic (bLS) measurements, which will be discussed in further detail below, and consistently produced similar, if not more accurate results (Redding et al., 2013). To determine carbon accounts for livestock systems and develop mitigation strategies for major emissions sources, accurate measurement techniques of GHG fluxes are essential.

Over the last decade there has been extensive development in micrometeorological techniques, namely the development of the bLS method that uses an open-path Fourier transform (OPFTIR) spectrometer. This technique has been tested and extensively applied in feedlots as a high density of cattle, in a confined space, with clear sources of GHG emissions provide an ideal environment to assess new methodologies (Loh et al., 2008). Many validation studies have reported close to 100 % recovery and average within-study standard deviations of around 21 % (Harper et al. 2010). While the recovery of N_2O emissions may be high, it is likely that N_2O emissions from multiple sources will be included if exclusion techniques of these surrounding sources are not well managed. Initial Australian experiments using this emerging micrometeorological technique were conducted by Denmead et al. (2008) and Loh et al. (2008) to make line averaged measurements of CO_2, CH_4, N_2O

and NH_3 concentrations within two feedlots. Loh et al. (2008) used the OPTIR spectrometer to measure N_2O emissions but did not report these values. Denmead et al. (2008) only measured mean NH_3 and NO_x deposition emission rates and used these values to estimate that the potential direct N_2O emissions would be of the same magnitude. These initial experiments may have experienced difficulties in measuring N_2O fluxes and techniques have then been refined in more recent years.

Here we review four studies published in the peer reviewed literature that examined emissions under experimental or commercial Australian feedlot conditions. These studies were Bai et al. (2015); Bai et al. (2016); Redding et al. (2015a); Sun et al. (2016). Additionally, the grey literature findings of Chen et al. (2009) were cited as foundational research from this research team. Data contained in this study have been attributed to a further peer reviewed conference paper; Denmead et al. (2013). Nitrous oxide emission rates from these studies are summarised in

Table 1 and the boxplot shows the distribution of literature values and clearly identifies Bai et al. (2016) as an outlier (Figure 2). On discussion with Prof. Chen, it was agreed that this study should be treated as an outlier for two reasons: firstly, the study was conducted at an experimental feedlot where pen conditions such as establishment of a manure pack had not occurred at the time of the trial. If the manure pack was not well developed across the whole trial, then elevated oxygen permeability could be a contributing factor to high N_2O emissions. Secondly, the study did not exclude emissions from surrounding sources. The bLs OFTIR method requires real time background concentrations of N_2O emissions, which was not measured in this study. The study used a default atmospheric concentration of 330 ppb of N_2O. Acknowledging that there is considerable amounts of NO_3^- and NH_3 in surrounding agricultural soil and these surrounding fields received nitrogen fertiliser applications 1-2 weeks prior to the experiment, it is likely that the N_2O flux has been overestimated.

All data are presented in units reported in original literature and have then been standardised to kg N_2O-N per kg N excretion, which aligns with the current inventory approach to estimation. Where emission rates were reported in N_2O, this was multiplied by 28/44 to standardise to N_2O – N. Since Redding et al. (2015a) reported N_2O emissions in kg N_2O ha^{-1} day^{-1}, we have assumed an average stocking density of 20 m^2 $head^{-1}$ (from a reported range of 13 – 27 m^2 $head^{-1}$) to convert into N_2O $head^{-1}$ $year^{-1}$. Where N excretion was not reported, it was assumed N excretion was 90 % of N intake (Dong et al., 2014).

Chen et al. (2009) reported emissions from the whole feedlot. To determine feed pad N_2O emissions, stockpile emissions were deducted from total N_2O using an N-mass flow calculation and the N_2O emission factor from the NIR. These assumptions and modifications were reviewed and accepted by the key Australian researchers. The process knowledge behind these papers is described in further detail below.

Using these modifications and excluding Bai et al. (2016), the average emission rate expressed relative to N excretion was 0.0054 kg N_2O – N per kg of N excreted (Table 1). This was substantially lower than the factor currently used in the NIR of 0.02 kg N_2O – N per kg of N excreted.

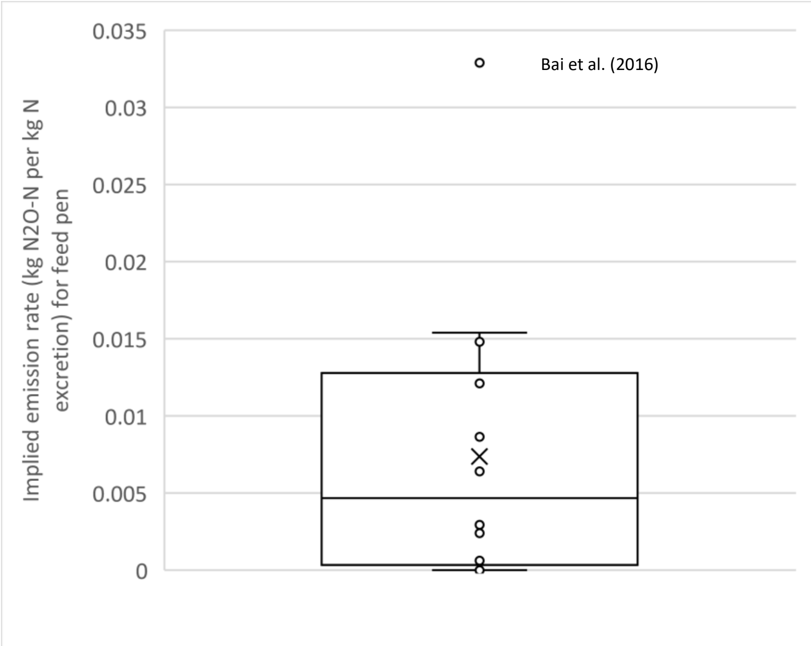

Figure 2 – Boxplot of implied emission rates (kg N_2O-N per kg N excretion) for beef cattle feedlot feed pens

Table 1 – Review of Australian nitrous oxide (N_2O) emissions from beef cattle feedlot feed pads

Location	N intake (g N head^{-1} day^{-1})	N excretion	Units	Emission rate presented in research	Units	g N_2O-N head^{-1} day^{-1}	Stockpile Emission based on N mass – Flow (g N_2O-N)	g N_2O-N head^{-1} day^{-1} (est. stockpile emission removed)	Emission rate standardised to kg N_2O-N head^{-1} year^{-1}	Implied emission rate (kg N_2O-N per kg N excretion) for feed pen	Reference
South	255*	240	g N head^{-1} day^{-1}	0.1	g N_2O-N head^{-1} day^{-1}	n.a	n.a	n.a	0.04	0.0004	Sun, et al. (2016)
South	255*	240	g N head^{-1} day^{-1}	0.14	g N_2O-N head^{-1} day^{-1}	n.a	n.a	n.a	0.05	0.0006	Sun, et al. (2016)
North	n.r	82.88	kg N head^{-1} year^{-1}	0.428	kg N_2O ha^{-1} day^{-1}	n.a	n.a	n.a	0.20	0.0024	Redding, et al. (2015a)
South	n.r	82.88	kg N head^{-1} year^{-1}	0.00405	kg N_2O ha^{-1} day^{-1}	n.a	n.a	n.a	0.00	0.0000	Redding, et al. (2015a)
South	219*	n.r	g N head^{-1} day^{-1}	0	g N_2O head^{-1} day^{-1}	n.a	n.a	n.a	0.00	0.0000	Bai, et al. (2015)
South	217*	n.r	g N head^{-1} day^{-1}	5.3	g N_2O head^{-1} day^{-1}	3.37	0.3735	3.00	1.23	0.0154	Chen, et al. (2009)
South	211*	n.r	g N head^{-1} day^{-1}	2.5	g N_2O head^{-1} day^{-1}	1.59	0.3735	1.22	0.58	0.0064	Chen, et al. (2009)
South	217*	n.r	g N head^{-1} day^{-1}	0.1	g N_2O head^{-1} day^{-1}	0.06	0.3735	0.00	0.02	0.0000	Chen, et al. (2009)
South	211*	n.r	g N head^{-1} day^{-1}	2.5	g N_2O head^{-1} day^{-1}	1.59	0.3735	1.22	0.58	0.0064	Chen, et al. (2009)
North	244*	n.r	g N head^{-1} day^{-1}	1.6	g N_2O head^{-1} day^{-1}	1.02	0.3735	0.64	0.37	0.0029	Chen, et al. (2009)
North	246*	n.r	g N head^{-1} day^{-1}	3.6	g N_2O head^{-1} day^{-1}	2.29	0.3735	1.92	0.84	0.0087	Chen, et al. (2009)
North	244*	n.r	g N head^{-1} day^{-1}	5.7	g N_2O head^{-1} day^{-1}	3.63	0.3735	3.25	1.32	0.0148	Chen, et al. (2009)
North	246*	n.r	g N head^{-1} day^{-1}	4.8	g N_2O head^{-1} day^{-1}	3.05	0.3735	2.68	1.11	0.0121	Chen, et al. (2009)
Mean emission rate										**0.0054**	

* Assumes N excretion is 90% of N intake
n.r = not reported
n.a = not applicable

More recently, Chen et al. (2009) was the first Australian study to measure GHG emissions from beef cattle feedlots using OPFTIR spectroscopy and atmospheric dispersion modelling. The study identified four sources of GHG emissions within the feedlot including occupied cattle pens, empty cattle pens, effluent ponds and manure piles. However, the study did not separate N_2O emissions by source location due to a limited number of sensors and instead reported N_2O emissions from the whole feedlot. A feedlot in Victoria and Queensland were selected to provide a representation of Australian beef cattle feedlot conditions. The reported N_2O emission rates from the whole feedlot, for Victoria and Queensland, were 2.6 and 3.9 g N_2O head^{-1} day^{-1}, respectively. Emission rates were also expressed relative to area (kg N_2O ha^{-1} d^{-1}). Emission rates were well below that modelled by IPCC (6.5 g N_2O head^{-1} day^{-1}). Chen et al. (2009) suggested that the greater than expected NH_3 volatilisation reduced the amount of N remaining in the manure for subsequent nitrification and denitrification reactions to N_2O to occur. Additionally, the authors recognised that that N_2O emissions were variable between the two feedlots and are essentially negligible to the emission profile (Chen et al., 2009). Researchers concluded that animal factors (liveweight, liveweight gain and dry matter intake) and feed ration composition (including N intake), between the two feedlots, did not have a large enough difference to drive the variation reported in N_2O emissions. The study proposed that environmental and pen conditions (temperature, pad N content, pH and moisture level) may have a greater impact on emissions of nitrogenous gases than animal characteristics used in the IPCC methodology. Nitrogen excretion was not measured, so the relationship between N excretion and N_2O emissions cannot be explored. However, the authors concluded that the current IPCC model used to calculate N_2O emissions was not adequate to predict N_2O emissions (Chen et al., 2009).

Another study, from the same research team, recognised the lack of GHG measurements from different feedlot sources (Bai et al., 2015). This study quantified N_2O emissions from the feedlot pen, manure stockpiles and surface run-off pond in the same Victorian feedlot used in Chen et al. (2009) using similar inverse dispersion technique with the OP-FTIR spectrometer. The key finding from this research was that there was 0 g N_2O head^{-1} day^{-1} from the feedlot pen. Nitrogen intake in this study and Chen et al. (2009) were not different, 219 and 221 g N head^{-1} day^{-1} respectively. Although, N excretion was not measured in either study, it can be assumed that N excretion would be similar considering 90% of dietary N is typically excreted (Dong et al., 2014). Beef cattle excrete 60-80% of N in urine and 20-40% in faeces (Dong et al., 2014; Varel, 1997). This is significant since the standard inventory calculation protocols predict N_2O emissions using the mass of N excreted by the animal. Faecal N consists of 50% organic N (undigested feed residues, enzymes and microbes) and 50% ammonia (NH_3) (Mackie et al., 1998). Nitrogen excretion in the faeces will continue to occur even if the animal was fed a N free diet. This is because the majority of N in the faecal matter is obtained from within the body, otherwise known as Endogenous Faecal N.

Redding et al. (2015a) was the first Australian study to measure GHG emissions directly from the pen surface and report statistical correlations between measured variables. A large, vented, non–flow-through, non–steady-state chamber was used that is known to produce highly accurate results consistent with the bLs technique. This study was conducted at a Darling Downs feedlot in Queensland and a feedlot in the Riverina region of New South Wales. The northern feedlot experienced higher rainfall and temperatures than the southern feedlot. Emission rates for the northern and southern feedlot were 0.429 kg N_2O ha^{-1} d^{-1} and 0.00405 kg N_2O ha^{-1} d^{-1}, respectively. The deposition of manure is considered for an individual animal using the national inventory approach. This was one of two Australian studies to report emission rate relative to area.

Our current understanding of N_2O emissions from manure is largely derived from our knowledge of nitrification and denitrification reactions in soils. A review of N_2O emissions from Australian soils concluded that the relationship between water filled pore space (WFPS) of soils and the relative fluxes of N_2O from nitrification and denitrification reactions follows a negative quadratic relationship (Dalal et al., 2003). In soils, N_2O production from nitrification is low before 40% WFPS and rapidly increases when the WFPS increased up to 55-65%. Above 60-70% WFPS, increased moisture reduces aeration, limiting oxygen diffusion and promotes denitrification. As the water content exceeds 75% WFPS, the ratio of N_2O to N_2 decreases and N_2O emissions are negligible (Dalal et al., 2003). This quadratic relationship may help explain results from manure pens.

In the study by Redding et al. (2015a), higher manure moisture content was strongly correlated with decreased N_2O emissions ($r < -0.5$, $P < 0.001$), possibly due to decreased oxygen diffusion and supply. However, Bai et al. (2015) and Sun et al. (2016) observed the opposite relationship. Sun et al. (2016) showed N_2O emissions were strongly correlated with rainfall events ($P < 0.001$, $r^2 = 0.79$). Sun et al. (2016) notes that this relationship is similar to observations made in soil systems with increased nitrification and denitrification activity occurring with increased soil moisture (Klemedtsson et al., 1988; Maag & Vinther, 1996). These results suggest that the relationship between direct N_2O manure emissions and moisture is not linear and remains inconclusive.

Using this quadratic relationship between moisture and N_2O emissions from soil, N_2O emissions from manure are negligible from a dry pen surface, however, begin to increase as the pen surface moisture increases. At high pen surface moisture levels, N_2O emissions are negligible. However, not all relationships observed in soils may be replicated for manure due to differences in physicochemical properties, particularly higher organic matter content and variable particle density in manure (Redding et al. 2015a; Waldrip et al. 2016). For example, it is unlikely that feedlot pens will have a WFPS > 80% as they are designed with a slight slope to promote runoff and drying of the manure surface (Parker et al., 2017). More evidence is needed to confirm this relationship between manure moisture and N_2O emissions.

Redding et al. (2015a) observed a strong relationship between N_2O emissions and temperature ($r > 0.5$, $P < 0.001$). When the data during the rainfall events were removed, Sun et al. (2016) observed a similar relationship where N_2O emissions were significantly correlated to daily average temperature ($P < 0.001$, $r^2 = 0.54$). This is expected as many biological processes, including nitrification and denitrification reactions, increase with increasing temperature to a certain threshold (Dalal et al., 2003). Both Redding et al. (2015a) and Chen et al. (2009) reported N_2O higher emission rates from Queensland feedlots than Victorian feedlots in their studies. It is likely differences will be driven by seasons, as results are influenced by both temperature and moisture. Victoria typically experiences winter dominant rainfall (cold and wet) and warm dry summers and Queensland typically experiences summer dominant rainfall (warm and wet) and dry winters, thus there is reason to believe Queensland may experience higher emission rates.

Redding et al. (2015a) investigated other indicators of N_2O emissions. Cattle density, pen cleaning frequency and manure depth were not strong indicators of N_2O emissions. Nitrous oxide emissions increased as manure bulk density and pH increased. A negative relationship was observed between organic carbon and N_2O emissions. However, pH, organic carbon, manure bulk density and manure mass were not good indicators as they were correlated with other parameters that influenced their predictive potential. Additionally, no relationship between N_2O emissions and mass or concentration of N or nitrate (NO_{3-}) was observed. Redding et al. (2015a) postulated that the absence of an association with N mass or concentration could be influenced by poor oxygen permeability of the compacted manure. Hence, for feed pen manure, oxygen, not N mass in manure, may be limiting

N_2O emissions. A key finding of this research was N supply is not the first limiting factor and that other drivers of N_2O emissions; gas permeability, temperature and moisture, governed emissions. This was because the supply of N in all measured feed-pad manure samples was in excess of that required by the microbial N_2O emission processes, and as a result did not limit emissions. This study is important as it provides quantitative evidence to support earlier research by Chen et al. (2009) that the N-mass approach used in the current IPCC model is not appropriate to estimate N_2O manure emissions from the feed pen. The main indicators of N_2O emissions from this study were moisture and temperature.

The most recent published Australian study investigated lignite application as a mitigation strategy for nitrogenous gases from manure (Sun et al., 2016).This study used Integrated Horizontal Flux with close path FTIR to improve the exclusion of N_2O emissions from surrounding sources. The experiment was conducted in Victoria with an experimental pen (20 x 20m) significantly smaller than commercial feedlot conditions. Nitrous oxide emissions from the control pen were small and averaged 0.12 g N_2O – N head^{-1} day^{-1} (< 0.1% of excreted N). Again, this emission rate is well below what is modelled by the IPCC. Moisture and temperature were shown to be significant indicators of N_2O emissions as discussed above. The addition of lignite to abate N_2O emissions, had the opposite effect and increased N_2O emissions by 49%. Researchers concluded that when moisture was not limiting, denitrification reactions were higher with lignite application because organic carbon is a required microbial substrate for N_2O emissions. This relationship has been observed in soil systems where the addition of organic C content including plant litter, root exudates, degradable organic materials and organic matter, has increased the rate of denitrification (Aulakh et al., 1991; Dalal et al., 2003; Dorland & Beauchamp, 1991).

3.3 Review of International research

Recently there have been studies conducted in the United States to further quantify feedlot N_2O emissions and understand the dynamics of N_2O emissions in these systems. While American feedlots are not representative of Australian climatic or management conditions, this research can provide further understanding to this topic. These studies were reviewed, and particular emphasis was placed on those that had the most similarities in terms of conditions, such as studies done in southern US states with warmer weather. It is notable that the reported emissions are considerably lower than the IPCC would indicate, further supporting the revision of the Australian emission factor.

A laboratory study was conducted to replicate feed pad manure in a semi-arid West Texas environment and it was found that there was a strong linear relationship between cumulative N_2O-N emissions over a 45 day period and stimulated rainfall events ($r^2 = 0.997$, $P < 0.001$) (Parker et al., 2017). From these results, a prediction equation was derived for ambient temperatures ranging from 16.2 °C to 41.7 °C, with a mean of 28.0 °C, and rainfall amounts ranging from 6.3mm to 50.8mm (Equation 1).

$$N_2O_{Cum} = 167.9 + 58.2 \qquad (1)$$

where N_2O_{Cum} is an area based cumulative N_2O-N emissions (mg m^{-2}) following a sporadic rainfall event (mm), and the *y*-intercept of 58.2 mg m^{-2} is the baseline cumulative N_2O-N emissions from manure. This is the first regression equations available to predict N_2O emissions from rainfall.

Another laboratory study showed that N_2O emissions were highly influenced by temperature and proposed an empirical regression model for predicting cumulative N_2O-N emissions from three temperature ranges, with 88% confidence between predicted and field observations of N_2O fluxes (Parker et al., 2018). This study replicated feedlot conditions in the Southern High Plains. Additionally, this study does not account for moisture addition to the feedlot surface from urine or faecal deposition. Nitrous oxide emissions from beef manure increased with manure temperature from 5°C to 38°C, with a step-increase at 31°C. A stimulated rainfall event occurred at 26.8 °C which elevated N_2O emissions. Another significant finding of this study was that N mass was not a good indicator of N_2O production which is in agreement with previous findings (Redding et al., 2015a). The key limitation to the development of Australian prediction models is the limited amount of field data. While laboratory experiments eliminate environmental variation and assist in determining key factors controlling emissions, they do not represent varying conditions and interactions that occur in field environments (Parker et al., 2019).

Additionally, Parker et al. (2019) measured N_2O emissions from commercial feedlots in semi-arid Texas Panhandle to confirm earlier laboratory findings. Similar to earlier studies, N_2O emissions peaked after stimulated rainfall events. Peak manure temperatures were 2 to 3 hours behind ambient temperatures, as solar radiation warms manure from the surface to deeper depths. Unlike soil N_2O emissions, there was no quadratic relationship observed between water addition and manure N_2O emissions. There was also no correlation between N_2O emissions and manure properties including NO_3^-, ammonium (NH_4^+), N mass, pH, water content, volatile solids and electrical conductivity. The key finding of this research was that mean N_2O emissions, 0.74 g N_2O-N head^{-1} day^{-1}, from this feedlot is substantially less than the IPCC estimate, as found with the Australian research. Parker et al. (2019) also reviewed measured N_2O-N emission rates of other field feedlot studies. When we excluded studies from Canada and North Dakota, due to extreme differences in climatic conditions to Australia, emission rates were well below the IPCC estimate (Table 2). Waldrip et al. (2017) reported a mean N_2O-N emission rate of 1.60 g N20-N head^{-1} day^{-1} across all seasons, over three years, at the same Texas feedlot as Parker, et al. (2019). From these measurements a simple empirical model was developed to predict N_2O emissions as a function of manure NO_x, water content and temperature. Although this was one of the first models developed from field experiments this model over estimated lower emissions and had an $R^2 = 0.26$. Additionally, the study conducted in Kansas was not reflective of Australian conditions, as they included measurements of N_2O fluxes over winter (temperatures as low as –24 °C) (Aguilar et al., 2014). However, a key finding of this research was that N_2O emission fluxes were influenced by pen surface conditions, particularly that extreme wet, dry and compacted conditions supressed N_2O emissions. It is clear that American research has identified similar drivers of N_2O emissions to Australian studies and that emission rates are substantially lower than IPCC estimates.

Table 2 – Measured N_2O-N emission rates of American feedlots

Location	Emission Rate (g N_2O-N head^{-1} day^{-1})	Reference
Texas Panhandle	0.74	Parker et al. (2019)
Texas Panhandle	1.60	Waldrip et al. (2017)
Texas Panhandle	0.36	Borhan et al. (2011)*
Kanas	0.61 (moist) 0.05 (dry, loose) 0.04 (dry, hard pack) 0.03 (flooded) 0.12(area-weighted)	Aguilar et al. (2014)*

* Values reported are medians. All other values are means.

The process knowledge regarding emissions is continuing to advance, and it is reasonable to expect that with further research, a rainfall and temperature effect may be established for Australian conditions. This would result in a much more sophisticated estimation approach that reflects the known factors that influence emissions. However, at the present time this process knowledge still requires further development and verification.

3.4 Review of feedlot N cycle and other emission factors in the context of a change in the feed pad factor

While not the focus of this review, we have briefly considered the other major N emission sources from feedlots for verification. Currently, the total emissions of N_2O from different manure management systems (MMS) uses an integrated N_2O emission factor for each state derived from the allocation of waste to different MMS, specific methane conversion factors, direct N_2O emission factors via source location and the fraction of N volatilised by MMS. This section will briefly review the appropriateness of the direct N_2O solid storage (stockpile) emission factor.

The current manure stockpile emission factor is 0.005 kg N_2O - N kg N excreted^{-1}. There are limited published Australian studies that measure emissions from manure stockpiling. Most recently, Bai et al. (2019) measured N_2O emissions from stockpiled manure using OPTIR, while avoiding gas contamination from the feedlot. The study reported 0.008 kg N_2O - N kg N excreted^{-1}, which is slightly higher than the IPCC value for stored manure. An MLA study on compacted stockpile emissions measured 0.00032 kg N_2O - N kg N excreted^{-1} and annual estimate of 85.7g tonne of manure^{-1} year^{-1}, using closed-cell fourier transform infrared spectra photometer (Spectronus FTIR) (Redding et al., 2015b). This is lower than the current emission factor. It is proposed that the current conservative emission factor for stockpile manure emissions remains, since there are minimal published Australian studies available to support a change in this factor.

3.4.1 Worked example of N flows within a feedlot with revised emission factor

Accounting for N flows between the feed pad, stockpile, composting and anaerobic pond allows the integrated emission factors for ammonia (kg NH_3 -N per kg N excreted) and N_2O (kg N_2O-N per kg N excreted) to be determined. Table 3 outlines an example of the approach used to develop this factor and an integrated factor would then be applied for each state.

Table 3 - Example of Feedlot ammonia (NH_3) and nitrous oxide (N_2O) emissions and N flows

MMS	MMS allocations	N mass flow (kg N)	FracGASM %	Total Ammonia - N lost (kg)	Direct N_2O - N EF	Total N_2O-N Emitted (kg)	N applied to Soil (kg)
Feed pad (Dry lot)	100%	1.000	60%	0.600	0.005	0.005	
Uncovered anaerobic pond	2%	0.018	35%	0.006	-	-	0.012
N flow to manure handling		0.376					
Stockpile (Solid storage)	54%	0.203	25%	0.051	0.005	0.001	0.151
Composting (Passive windrow)	38%	0.143	40%	0.057	0.010	0.001	0.084
Direct application	8%	0.030	0%	-	-	-	0.030
Integrated factor				0.714		0.008	
Total N applied to soil							0.278

4. Conclusions

4.1 Revised N_2O emission factor for the feed pad

This review of feedlot feed pad (drylot) N_2O emission research has determined that the current emission factor is not supported by Australian research. On average, Australian studies report 73% lower emissions than the current IPCC inventory estimates. Here we propose that the emission factor for feed pads should be revised to 0.0054 kg N_2O – N per kg of N excreted. This recommendation is based on the current research at the time and could be further developed following research into a modelling approach that explores the relationship between environmental pen conditions and N_2O emissions.

4.2 Context for the Revised N_2O emission factor for the feed pad

The national inventory currently relies on a factor that is derived from total excreted N. Both Australian and International researchers have shown that this N-mass approach is not strongly supported by the studies examining the factors driving emissions from the feed pen, because N is not limiting in this environment. Further research from American feedlot studies have proposed prediction equations based on temperature and rainfall. No studies have provided an alternate model to explain this relationship for Australian conditions.

Considering this lack of strong evidence of the association between N excretion rates and nitrous oxide, we consider it necessary to also recommend some explanatory text for the NIR, to help direct future research and mitigation. We propose the following text:

Manure nitrogen is not the first limiting factor driving nitrous oxide emissions from the feed pad. Consequently, reducing manure N is less likely to influence emissions than would be suggested by the emission factor. Future research to provide a prediction method based on key drivers; temperature, rainfall and manure moisture (Parker et al., 2018, Redding et al., 2015a, Sun et al., 2016, Waldrip et al., 2016), may lead to better process knowledge and a revised emission factor or prediction method in the future.

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