Nitrous oxide production in ruminants - a review*

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The objective of this paper is to summarise available literature on the concentrations and emissions of nitrous oxide from ruminant livestock buildings and manure management systems (storage and treatment units). Ruminant production operations are a source of numerous airborne contaminants, especially gases. Nitrous oxide is generated from manure decomposition, during storage and treatment as well as field application, formed by nitrifying bacteria in two processes: nitrification and denitrification. The major contributor is normally the denitrification process under anaerobic conditions, while nitrification under aerobic conditions can also contribute. The quantification of N_2O emissions or emission rates from ruminant buildings, land surfaces, manure storage facilities and manure applied on land is being intensely researched in many countries. Recent studies on the effects of environmental temperature, housing, feed and pasture, feeding, internal and genetic factors, and emission from excrements on N_2O production are discussed. Finally, emission factors for dairy and beef cattle are listed in tables.

KEYWORDS: cattle / emission / housing / manure

Abbreviations

CM – concentrate mixture; CP – crude protein; CS – corn silage; d – day; DIM – days in milk; DL – deep litter; DM – dry matter; DMI – dry mater intake; FC – flux chamber; FTIR – Fourier transform infrared spectroscopy; GC – gas chromatography; GLAS – emissions measuring from ground-level area sources; GS – grass silage; h – hour; H – hay; HC – Holstein cattle breed; hd – head; HE – heifers; hs – hours; LBW – live body weight; LBWG – gain of live body weight; LU – livestock unit (500 kg of LBW); LSU – livestock standard unit (grazing equivalent

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of 1 adult dairy cow producing 3 000 kg of milk annually, without concentrates); M – month; MBIGA – mass balance method from 24 h gas sampling; MF – milk fat; MJ – mega joule; MP – milk protein; MR – milk replacer; MS – manure system; MY – milk yield; N – nitrogen; NH_3 – ammonium; OPL – open-path laser; PAR – parity; PIGM – Photoacoustic infrared gas monitor INNOVA; ppmv – parts per million volume; RC – respiration chamber; S – silage; TDL – Tuneable Diode Laser absorption spectrometer; TMR – total mixed ration; yr – year; WS – wheat silage; wk – week.

Nitrous oxide is an important greenhouse gas with 298 times or 310 times more potent the global warming potential than CO_2 [Borhan *et al*. 2012, Boon *et al.* 2014]. Atmospheric nitrous oxide concentrations have been increasing since the industrial revolution and currently account for 6% of total anthropogenic radiative forcing [Davidson 2009]. Tropospheric N_2O concentrations have increased at a rate of 0.73 $ppb.yr^{-1}$ over the last three decades [Uschida and Clough 2015]. Nitrous oxide emissions caused by human activities represent more than two thirds of the total emissions [Regaert *et al*. 2015]. Anthropogenic activities are predominantly responsible for this rate of increase with fertilising during crop cultivation stage and animal excreta being primarily responsible [Uschida and Clough 2015, Pardo *et al*. 2015]. Nitrogen volatilisations occur during and after production, storage and application of organic and mineral fertilisers [Guerci *et al*. 2013].

The generation rates of nitrous oxide vary depending weather, time, species, housing, manure handling system, feed type, and management system. Therefore, it is extremely difficult to reliably predict the concentrations and emissions of these constituents.

The main sources of N_2O from agriculture are connected with nitrification and denitrification processes in the soil. Farms primarily emit N_2O arising mainly from nitrogen fertilisers (organic manures or inorganic fertilisers) applied to the soil, direct N deposition by housed animals, or manure storage [Whalen *et al*. 2000, Crosson *et al.* 2011, Adler *et al*. 2015].

In many countries one of the problems facing ruminant producers is disposal of manure due to the growing concerns over environmental pollution. It appears that management practices (feeding, slaughtering age) and manure treatment, especially manure removal frequency, are presented as efficient ways to reduce emissions. However, generally variability in the literature results results from the different measurement methods and equipment used.

Several mitigation techniques are available to reduce N_2O emissions from barns. However, some strategies show contradictory effects depending on the conditions and the respective gas.

Creating

The nitrous oxide is formed by nitrifying bacteria in two processes. One is referred to as nitrification and takes place under aerobic conditions, while the other

is named denitrification and occurs under anaerobic conditions [Clough *et al*. 2003, Chianese *et al*. 2009a, Bell *et al*. 2015a]. According to Philippe and Nicks [2013], the formation of N_2O proceeds during incomplete nitrification/denitrification processes that normally convert NH_3 into non-polluting N_2. If conditions are suboptimum and these processes do not run to completion, the air-polluting volatile intermediates N_2O (nitrous oxide) and NO (nitric oxide) are emitted [Groenestein *et al.* 1996, Pahl *et al.* 2001, Wolter *et al*. 2004].

Nitrification progresses under aerobic conditions where ammonium is first oxidised to nitrite, and nitrite is then converted to nitrate with N_2O as a by-product [Oenema *et al*. 2005, Kebreab *et al*. 2006, de Klein and Eckard 2008, Saggar *et al*. 2015, Li *et al*. 2012]. The ratio of denitrification N conversion to N_2O revealed nitrification as the major N_2O producing process at all sites. Predictors of temporal changes in N emissions include nitrate, pH and temperature, indicating the heterogeneity of management [Monaghan and Barraclough 1993, Mogge *et al*. 1999]. The nitrification process occurrs in animal housing mainly in the surface layer of the manure [Montes *et al*. 2013].

Denitrification is a series of microbial reactions during dissimilated NO_2^- reduction when the oxygen (O_2) supply is limited [Chadwick *et al*. 1999, Pahl *et al*. 2001, Oenema *et al*. 2005, Kebreab *et al*. 2006, de Klein and Eckard 2008, Saggar *et al*. 2013, Li *et al*. 2012, Akiyama *et al*. 2010, Li *et al*. 2014 b, Li *et al*. 2015, Regaert *et al*. 2015, Alberdi *et al*. 2016]. However, no correlation was found between N_2O concentration and temperature or O_2 concentration. Initial N_2O emission is relatively high. Obviously, N_2O is produced mainly at the beginning by thermophilic organisms [Wolter *et al*. 2004]. In their study Selbie *et al*. [2015] found that N_2 emissions accounted for 95% of gaseous N losses, with 55.8 g N. m^{-2} emitted as N_2 in the process of co-denitrification, compared to only 1.1 g N m^{-2} from conventional denitrification. This highlights the large N_2 fluxes and the importance of co-denitrification in contributing to N dynamics in urine amended grassland soil.

The N_2O production during denitrification is promoted by the presence of NO_{3-}, N_2O reductase activity, heterotrophic bacteria, reductants such as organic carbon, lack of oxygen and low availability of degradable carbohydrates, while it is also affected by pH, moisture content, soil porosity, amount of solids, under soil and climatic factors [Monaghan and Barraclough 1993, Beauchamp 1997, Chadwick *et al*. 2000, Dobbie and Smith 2001, Külling *et al*. 2001, Saggar *et al*. 2004ab, Kebreab *et al*. 2006, de Klein and Eckard 2008, Chianese *et al*. 2009a, Montes *et al*. 2013, Saggar *et al*. 2013, Li *et al*. 2014b, Li *et al*. 2015, McGahan 2016].

Housing

We may observe global interest in quantification of N_2O emissions from animal housing operations [Rahman *et al*. 2013]. It is well known that the dairy sector contributes to climate change through emission of greenhouse gases, mainly N_2O [Ross *et al*. 2014, Podkowka *et al*. 2015]. According to Sneath *et al*. [1997], dairy

cattle hounding facilities produce twice as much N_2O emissions than piggery facilities (per 500 kg LBW). However, Rzeźnik and Mielcarek [2016] reported opposite results (dairy cows 1.5 g·d^{-1}·LU^{-1} vs. pigs 3.2 g.d^{-1}·LU^{-1}). Borhan *et al*. [2012] found N_2O emissions from a free-stall dairy cow housing at 3.4 g.d^{-1}. In a similar study emissions from a beef feedlot were reported as 0.68 g.d^{-1} [Borhan *et al.* 2011a].

Most of these N_2O losses depend on a variety of factors, including surface conditions of open-lot dairy or beef feedlot facilities. Manure management practices on farms vary, but usually pens are cleaned several times a week or after the turnings, which creates conditions for emissions off the pen surface or barn floors [Eckard *et al.* 2003, Chianese *et al.* 2009b, Maeda *et al* 2010, Van Middelaar *et al* 2013, Montes *et al* 2013]. Quantifying N_2O from feedlots is difficult due to the low N_2O concentration in free air [Redding *et al*. 2015, Sun *et al*. 2016]. The pen surface was estimated to contribute about 84% of the aggregate N_2O emission [Montes *et al*. 2013].

Owen and Silver [2015] compiled published data on field-scale measurements of N_2O emissions from dairies. Whole barns had the greatest N_2O emissions with 10.3 kg.d^{-1}.yr^{-1}. Barn floors and hardstandings, surfaces which were scraped or flushed frequently, generally release low N_2O emissions (0.03 kg.d^{-1}.yr^{-1}, 0.0004 kg.d^{-1}.yr^{-1}). According to Leytem *et al.* [2010], open lot areas generate the greatest emissions of N_2O, contributing 57%, respectively, to total farm emissions.

Corrals and solid manure piles are the next largest N_2O source with 1.5 kg.d^{-1}.yr-1 and 1.1 kg.d^{-1}.yr^{-1} [Owen and Silver 2015]. Nitrous oxide emissions from anaerobic lagoons and slurry stores are also substantial, with 0.9 kg.d^{-1}.yr^{-1} and 0.3 kg.d^{-1}.yr^{-1}, respectively [Owen and Silver 2015].

Amon *et al*. [1999] compared N_2O emissions from solid and liquid manure storage at a tie-stall housing for dairy cattle and found no differences between these manure storage systems. However, straw cover and slurry aeration showed negative environmental effects and thus are not recommended [Amon *et al*. 2006b].

Higher manure density observed with sawdust may impair the composting process, which normally increases manure temperature and promotes air exchange through the compost heap. Consequently, NH_3 emissions are reduced, which increases the amount of ammonium available for non-thermopilic nitrifying bacteria, with higher N_2O emissions released as a consequence [Sommer 2001, Hansen *et al.* 2006].

In a deep-litter housing system, animals are kept on a thick layer of a mixture of manure with sawdust, straw or woodshavings. In this system microbial processes are stimulated to enhance composting processes, nitrification (aerobic conditions) of NH_3 and denitrification (anaerobic conditions) of nitrate [Groenestein *et al.* 1996]. Deep-litter bedding is associated with high greenhouse gas production (+125% compared to slatted floor) and slurry composting on straw is associated with high NH_3 emission (+15% compared to slatted floor) [Rigolot *et al*. 2010].

Groenestein *et al*. [1996] showed increasing N_2O emission with decreasing O_2 concentration in the straw bed, indicating that N_2O is mainly produced in the course of nitrification. Also, it appears that deep-litter systems emit more N as NH_3 and that

air-polluting nitrogen gases were not reduced with traditional housing systems. This leads to the conclusion that deep-litter systems are not recommended [Groenestein *et al.* 1996].

Chadwick *et al.* [1999] showed that dairy cattle housing with slurry-based systems have significantly lower N_2O emissions than dairy housing that used straw bedding. The straw flow system thus combined recommendations of animal welfare and environmental protection, although emissions during storage may be increased due to the higher average retention time in the store [Amon *et al.* 2006a, Amon *et al.* 2007]. Increasing the amount of substrate also impacts emissions, typically with reduced N_2O production [Yamulki *et al*. 2006]. The relatively large net N_2O flux from liquid manure storage is associated with the predominantly anaerobic conditions typical of unaerated systems. Nitrogen in liquid manure is mostly found in the form of ammonium and organic N, and while anaerobic lagoons are as a rule anaerobic, aerobic conditions which could promote denitrification exist at inlets. Other N_2O formation reactions are also possible, such as denitrification of nitrate (NO_3) produced through anaerobic NH_{4+} oxidation [Maeda *et al*. 2010, Owen and Silver 2015].

Feed and pasture

Animal feeding operations are an important source of pollutants affecting air quality due to nitrous oxide (N_2O) and nitric oxide (NO) emissions [Li *et al*. 2012]. Dietary lipids also may increase manure emissions either through reduced ration digestibility or increased N contents (if lipids are supplied from oil cakes rich in CP [Hristov *et al*. 2013, Gerber *et al*. 2013]. Nitrates can possibly increase N emissions as their addition to the ration may lead to increased urea amounts excreted in urine. Results of Luo *et al*. [2015] showed that feeding forage rape reduced the N_2O-N emission factor during the 3-month measurement period for sheep urine by about 60%, compared with feeding perennial ryegrass [Luo *et al*. 2015]. Shifting N excretion from urine to faeces by supplementing the diet with tannins or feeding tanniferous forages can also decrease the N release rate from manure [Hristov *et al*. 2013].

In grazed pasture systems, a major source of N_2O is nitrogen (N) returned to the soil in animal urine [Bhandral *et al*. 2003a, Di and Cameron 2006]. The N excreted by sheep and cattle onto grazed pastures provides high, localised concentrations of available N and C in soils, and is the main source of anthropogenic N_2O emissions [Saggar *et al*. 2004a,b]. Nitrous oxide emissions from field urine/faecal deposition during grazing (i.e. pasture, paddock, range emissions) are principally based on the amount of N excreted/hd for each population category [Crosson *et al*. 2011].

The results of Ball *et al.* [1997] suggested that denitrification is the main N_2O production process at grassland sites. A number of studies have shown that soil denitrification and N_2O emission rates are highly variable throughout the season, with high rates associated with grazing and fertiliser application in grazed pastures [Ruz-Jerez *et al*. 1994, Williams *et al*. 1998, Luo *et al*. 1999, Saggar *et al*. 2004a,b]. The

highest losses by denitrification occurred in winter when soil moisture was at or above field capacity for extended periods [Ruz-Jerez *et al*. 1994].

Denitrification losses increased with temperature in pastures treated with cattle slurry, while N losses from pastures treated with farmyard manure remained unaffected by temperature [Saggar *et al*. 2004b]. The fluxes were more variable during winter and spring, when the soils were wet, than during the dry autumn period [Ruz-Jerez *et al*. 1994, Carran *et al*. 1995, Saggar *et al*. 2004a, Saggar *et al*. 2003, Saggar *et al*. 2015].

Large emissions were detected immediately following cow urine application to pasture. These coincided with a rapid and large increase in soil water-soluble C levels, some of the increase being attributed to solubilisation of soil organic matter by high pH and ammonia concentrations [Monaghan and Barraclough 1993]. Overall, urine significantly increased N_2O emissions up to 14 days after application, with rates amounting to 6 kg N ha^{-1} d^{-1} [Saggar *et al*. 2004b].

Klein *et al.* [2003] applied cow urine and synthetic urine to pastoral soils. The largest emission factor was found in a poorly drained soil, while the lowest emission factor was recorded for a well-drained stony soil. The N_2O emissions did not reach background levels 4 months after urine application. At a study of Lovell and Jarvis [1996] urine was added to intact turfs taken from long-term permanent pasture on clay loam and sandy loam soils. Emissions of nitrous oxide following urine application were high (0.36 µg N_2O-N.m^{-2} min^{-1} and 29 µg N_2O-N.m^{-2} min^{-1}), but limited in duration (<40 days).

Sometimes the results of published investigations are not comparable and most of them do not meet the minimum requirements mentioned above. In certain cases, no significant emissions were registered for N_2O since they were consistently near the detection limit for the measuring equipment.

However, the relationship between small-scale studies and actual field emissions is poorly constrained, with only one study making a qualitative comparison. Direct measurements of N_2O emissions from animals are scarce. Mosier *et al*. [1998] concluded that annual N_2O emissions from many agricultural systems may be substantially underestimated, because many studies of field-based N_2O emissions did not account for cold season emissions. All N_2O data should be recalibrated for reference purposes [Osada *et al*. 1998]. Emissions of nitrous oxide arise both directly and indirectly from multiple on-farm sources [Ross *et al*. 2014].

As a result, there has been limited information on N_2O emissions from feedlot pens, particularly using non-intrusive micrometeorological techniques. Most studies on trace gas emissions focus individually on N_2O. The emissions of this gas from animal wastes and waste-management systems are influenced by very different factors [Saggar *et al.* 2015].

Table 1. N_2O emission factors of dairy cows facilities (per animal)

Breed	Number of animals	LBW (kg)	Milk	Housing system	Feeding system	Measuring method, season	Unit	Emission factor	Reference
HC	12	no data	no data	tie-stall	no data	No data	$g.LSU^{-1}.d^{-1}$	0.14-1.19	Amon et al. [1998]
HC	27	no data	no data	loose housing, DL	no data	No data, summer	$g.LSU^{-1}.d^{-1}$	2.01	Amon et al. [1998]
HC	12	600	no data	tie-stall, slurry MS	no data	24 hours a day, all seasons, mobile RC, FTIR and GC	$mg.LSU^{-1}.d^{-1}$; $mg.LU^{-1}.d^{-1}$	609.6; 508.0	Amon et al. [2001]
HC	12	600	no data	tie-stall, straw MS	no data	24 hours a day, all year, mobile RC, FTIR and GC	$mg.LSU^{-1}.d^{-1}$; $mg.LU^{-1}.d^{-1}$	619.0; 516.0	Amon et al. [2001]
HC	90	500	o data	loose housing, slurry MS, solid floor, scraper, naturally ventilation	no data	GC, 12 days	$g.LU^{-1}$ day^{-1}	0.8	Sneath et al. [1997]
HC	no data	598	MY 6970 $L.lactar^{-1}$, MF 273 $kg.lactar^{-1}$, MP 228 $kg.lactar^{-1}$	no data	no data	model	$g.d^{-1}$	6.0	Bell et al. [2013]
Jersey	no data	444	MY 5030 $L.lactar^{-1}$, MF 243 $kg.lactar^{-1}$, MP 188 $kg.lactar^{-1}$	no data	no data	model	$g.d^{-1}$	5.0	Bell et al. [2013]
HC	no data	632	MY 8965 $kg.lactar^{-1}$, MF 358 $kg.lactar^{-1}$	no data	no data	model	$g.d^{-1}$; $kg.yr^{-1}$	22.0; 8.0	Bell et al. [2015 b]
HC	700 milking, 80 dry	no data	no data	open-lot, loose housing (60 m^2 cow^{-1})	no data	3 areas (pens, wastewater storage pond, composting area); 2 ds, January, March, June, September, OPL, FTIR	ppmv	0.31 to 0.33 for all areas	Bjorneberg et al. [2009]
HC	3,200 milking	no data	no data	open free-stall, barn (manure lane and bedding area), loafing pen, open lot, settling basin, lagoons, and compost pile	TMR (wheat hay and silage, alfalfa hay, corn silage, corn grain, cotton and canola seed, beet pulp)	5 ds, 87 air samples, summer, FC, GC	$g.d^{-1}$	0.68	Borhan et al. [2011 a]
HC	500	no data	no data	free-stall (manure lane, bedding area, loafing pen, lagoon, settling basin, silage pile, walkway)	TMR (wheat H, WS, alfalfa H, CS, CM)	FC, GLAS	$g.d^{-1}$	summer 7.96; winter 3.59; annualized 6.13	Borhan et al. [2011 b].
HC	18	556	no data (103 DIM)	no data	control vs. monensin diet (600 $mg.d^{-1}$ monensin)	21 lhs, 2 days, RC, PIGM	$g.h^{-1}$	d 14: 0.02 vs. 0.02; d 60: 0.01 vs. 0.01	Hamilton et al. [2010].
No data	55 and 20 HE	no data	no data	loose housing, natural ventilation	No data	6 ds, spring, fall, winter, GC	$g.h^{-1}$; $g.LU^{-1}.d^{-1}$	5.6 1.6	Jungbluth et al. [2001].
HC	10,800	635	no data	free-stall, 3 areas (20 open-lots 60 ha, wastewater storage pond 10 ha, compost yard 10 ha)	TMR	2 or 3 days, each month (spring, summer, fall, and winter), MBIGA, PIGM	$kg.d^{-1}$; $g.m^{-2}.d^{-1}$; $g.m^{-2}.d^{-1}$; $kg.d^{-1}$	open lots 0.01, waste-water pond 0.49; compost yard 0.90 total 0.02	Leytem et al. [2010].
HC	176 and 45 HE	662	no data	free-stall, slurry MS	TMR (corn silage, alfalfa-grass silage, grass hay, concentrate)	PIGM	$mg.LU^{-1}.h^{-1}$	spring 41.3, fall 29.4	Ngwabie et al. [2014].
Brown Swiss	12	637	52 DIM, 30.9 kg MY	individual stalls, slatted floor	TMR (175, 150 and 125 g CP.kg DM^{-1}	7 wks, TDL	$mg.d^{-1}$; $ng.m^{-2}.s^{-1}$	according CP: 407, 444, 89 205.7, 196.4 , 35.4	Külling et al. [2001].
HC	no data	no data	no data	no data	no data	PIGM	$g.d^{-1}.LU^{-1}$	median 1.5	Rzeźnik and Mielcarek [2016]

Conclusions

Substantial research has been conducted to quantify the emission rates of N_2O from ruminant facilities and waste management systems. Much of the work related to emission rates has been conducted over the past twenty years. The knowledge summarised in this paper shows substantial variability in emission rates. In part this variability is inherent in the ruminant husbandry systems and in part is due to external influences such as climatic differences and feed rations. Manure management practices are of considerable importance, especially the frequency of manure removal.

For example slatted housing reduces the emitting floor surface. Dairy cattle housing facilities with slurry-based systems have significantly lower N_2O emissions than dairy housing systems with straw bedding. However, increasing the amount of substrate impacts emissions, typically with a reduction in N_2O productions. Moreover, the straw flow system is associated with slightly reduced N_2O emissions. In grazed pasture systems large emissions were detected immediately following cow urine application to the pasture. Farmers should prevent soiling of the solid or passage sections of the floor.

However, a main contribution to the variability in the literature sources results from the use of differing measurement methods and equipments. Accurate quantification of emissions is difficult, since so many factors are involved (e.g. time of year and day, temperature, humidity, wind speed, ventilation rates, solar intensity, housing type, manure characteristics, stocking density and age of animals). Furthermore, there are no standardised methods for the collection, measurement and calculation of such constituents, resulting in the variability and considerable ranges of recorded values.

This review indicates a definite need for the development and application of standard methods to measure N_2O emission rates for gases from ruminant facilities.

Table 2. N_2O emission factors of dairy cattle facilities (per animal)

Breed	Number of recording animals	Age	LBW (kg)	Housing system	Feeding system	Measuring method and season	Unit	Emission factor	Reference
HC, HE	3,750	no data	no data	open lots (feedlot pen, holding pond, compost pile)	TMR (93.6 % forage, 2.3 % grain, 3.7 % protein, and 0.44 % mineral)	5 ds, 87 air samples, summer, FC, GC	g.d^{-1}	0.68	Borhan *et al.* [2011a]
HC	9 bull calves	1 to 2 wk	54	no data	MR, CM	24 hs, RC, PIGM	mg.hd^{-1}.h^{-1}	0.66	Stackhouse *et al.* [2011]
HC	9 steers	4 to 6 M	159	no data	high concentrate diet	24 hs, RC, PIGM	mg.hd^{-1}.h^{-1}	11.8	Stackhouse *et al.* [2011]
HC	9 steers	8 to 10 M	340	no data	high concentrate diet	24 hs, RC, PIGM	mg.hd^{-1}.h^{-1}	15.43	Stackhouse *et al.* [2011]
HC	9 steers	15 to 18 M	544	no data	high concentrate diet	24 hs, RC, PIGM	mg.hd^{-1}.h^{-1}	16.53	Stackhouse *et al.* [2011]

Table 3. N$_2$O emission factors from beef facilities (per animal)

Breed	Number of recording individuals	Age	LBW (kg)	Housing system	Feeding system	Measuring method and season	Unit	Emission factor	Reference
Angus	28 steers	1 yr	404	pen (20x20 m)	grass H, 60 % CM	41 days, OPL, FTIR	g.d⁻¹	from 4 to 23, average 14	Bai et al. [2016]
No data	192	no data	no data	feedlot, pens, 50×16 m, slope 3 %	concentrated diet (corn, distillers grains, CS, H, condensed corn distillers solubles, limestone)	24 hs, MBIGA, GC	ppm; g.m⁻² d⁻¹; g.d⁻¹	0.67, 0.90, 26.0 estimated emissions (summer, fall, winter and spring)	Rahman et al. [2013]
No data	15,000	no data	no data	feedlot pen 3000 m², 22.4 m² hd⁻¹, 3 % slope, manure mound (8 m², height of 0.4 m, harvested every 3-4 M)	No data	RC, FTIR	kg.ha⁻¹.d⁻¹	0.428	Redding et al. [2015]
No data	17,000	no data	no data	feedlot pen 3016 m², 14.6 m² hd⁻¹, 3 % slope, manure harvested every 2 M	No data	RC, FTIR	kg.ha⁻¹.d⁻¹	0.00405	Redding et al. [2015].
Black Angus	24 steers	no data	no data	20×20 m feedlot	diet 50 % grain, 50 % H (13.5% crude protein, 12 MJ kg⁻¹ DM, 10.9 kg DM, 255 g N.d⁻¹);	FTIR	g N₂O-N.d⁻¹	from 0.10 to 0.14	Sun et al. [2016].
Black Angus	24 steers	no data	no data	20×20 m feedlot, 3 kg.m⁻² lignite in pen surface	diet 50 % grain, 50 % H (13.5% crude protein, 12 MJ kg DM⁻¹, 10.9 kg dry matter, 255 g N.d⁻¹)	FTIR	g N₂O-N.d⁻¹	0.14	Sun et al. [2016]
Black Angus	24 steers	no data	no data	20×20 m feedlot, 6 kg.m⁻² lignite in pen surface	diet 50 % grain, 50 % hay (13.5 % crude protein, 12 MJ kg DM⁻¹, 10.9 kg dry matter, 255 g N.d⁻¹)	FTIR	g N₂O-N.d⁻¹	0.22	Sun et al. [2016].
Black Angus – Cross	9 steers	340	10 to 14 M	pen	high concentrate diet	24 h, RC, PIGM	mg.hd⁻¹.h⁻¹	19.87	Stackhouse et al. [2011].
Black Angus – Cross	9 steers	544	15 to 18 M	pen	high concentrate diet	24 h, RC, PIGM	mg.hd⁻¹.h⁻¹	17.58	Stackhouse et al. [2011].

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