Animal Science Papers and Reports vol. 36 (2018) no. 1, 5-19
Institute of Genetics and Animal Breeding, Jastrzębiec, Poland

Nitrous oxide production in ruminants - a review*

Jan Broucek**

National Agricultural and Food Centre, Research Institute of Animal Production Nitra,
951 41 Luzianky, Slovakia

(Accepted January 5, 2018)

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

*The Research was financed by the SRDA Bratislava (0632-10 and 15-0060), also by the projects AGB 313011B699 (CPEHHA) and CEGEZ 26220120073 funded from the European Regional Development Fund.
**Corresponding author: broucek@vuzv.sk; broucek@hotmail.com

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 $g\cdot d^{-1}\cdot LU^{-1}$ vs. pigs 3.2 $g\cdot d^{-1}\cdot LU^{-1}$). 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 $L.lactat^{-1}$, MF 273 $kg.lactat^{-1}$, MP 228 $kg.lactat^{-1}$	no data	no data	model	$g.d^{-1}$	6.0	Bell *et al*. [2013]
Jersey	no data	444	MY 5030 $L.lactat^{-1}$, MF 243 $kg.lactat^{-1}$, MP 188 $kg.lactat^{-1}$	no data	no data	model	$g.d^{-1}$	5.0	Bell *et al*. [2013]
HC	no data	632	MY 8965 $kg.lactat^{-1}$, MF 358 $kg.lactat^{-1}$	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*. [2011a]
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 hs, 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	$g{\cdot}d^{-1}{\cdot}LU^{-1}$	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_2O 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 m^2, 22.4 m^2 hd^{-1}, 3 % slope, manure mound (8 m^2, 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 m^2, 14.6 m^2 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 N_2O-$N.d^{-1}$	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 N_2O-$N.d^{-1}$	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 N_2O-$N.d^{-1}$	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].

REFERENCES

1. ADLER A.A., DOOLE G.J., ROMERA A.J., BEUKES P.C., 2015 – Managing greenhouse gas emissions in two major dairy regions of New Zealand: A system-level evaluation. ***Agricultural Systems*** 135, 1-9.
2. AKIYAMA H., YAN X., YAGI K., 2010 – Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N_2O and NO emissions from agricultural soils: meta-analysis. ***Global Change Biology*** 16, 1837-1846.
3. ALBERDI O., ARRIAGA H., CALVET S., ESTELLÉS F., MERINO P., 2016 – Ammonia and greenhouse gas emissions from an enriched cage laying hen facility. ***Biosystems Engineering*** 144, 1-12.
4. AMON B., BOXBERGER J., AMON T., ZAUSSINGER A., PÖLLINGER, A., 1998 – Emissions of NH_3, N_2O and CH_4 from a tying stall for milking cows during storage of farmyard manure and after spreading. In: J. Martinez, M.N. Maudet (Editors). Management Strategies for Organic Wastes in Agriculture. FAO European Cooperative Research Network on Recycling of Agricultural, Municipal and Industrial Residues in Agriculture (Ramiran), 269-278.
5. AMON B., AMON T., BOXBERGER J., 1999 – Emissionen von NH_3, N_2O und CH_4 aus der Festmistverfahrenskette Milchviehanbindehaltung Stall (Lagerung, Ausbringung). In: Bau, Technik und Umwelt in der landwirtschaftlichen Nutztierhaltung. Beiträge zur 4. Internationalen Tagung, Freising, MEG, KTBL, AEL (Hrsg.), 57-62.
6. AMON B., AMON T., BOXBERGER J., ALT CH., 2001 – Emissions of NH_3, N_2O, and CH_4 from dairy cows housed in a farmyard manure tying stall (housing, manure storage, manure spreading). ***Nutrient Cycling Agroecosystems*** 60, 103-113.
7. AMON B., KRYVORUCHKO V., AMON T., ZECHMEISTER-BOLTENSTERN S., 2006a – Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment. ***Agriculture Ecosystems & Environment*** 112, 153-162.
8. AMON B., KRYVORUCHKO V., MOITZI G., AMON T., 2006b – Greenhouse gas and ammonia emission abatement by slurry treatment. ***International Congress Series*** 1293, 295-298.
9. AMON B., KRYVORUCHKO V., FROHLICH M., AMON T., POLLINGER A., MOSENBACHER I., HAUSLEITNER A., 2007 – Ammonia and greenhouse gas emissions from a straw flow system for fattening pigs: housing and manure storage. ***Livestock Science*** 112, 199-207.
10. BAI M., FLESCH T.K., MCGINN S.M., CHEN D., 2015a – A Snapshot of Greenhouse Gas Emissions from a Cattle Feedlot. ***Journal of Environmental Quality*** 44, 1974-1978.
11. BAI M., SUN J., DASSANAYAKE K.B., BENVENUTTI M.A., HILL J., DENMEAD O.T., FLESCH T., CHEN D., 2015b – Non-interference measurement of CH_4, N_2O and NH_3 emissions from cattle. ***Animal Production Science*** 56, 1496-1503.
12. BALL B.C., HORGAN G.W., CLAYTON H., PARKER J.P., 1997 – Spatial variability of nitrous oxide fluxes and controlling soil and topographic properties. ***Journal of Environmental Quality*** 26, 1399-1409.
13. BEAUCHAMP E. G., 1997 – Nitrous oxide emission from agricultural soils. ***Canadian Journal of Soil Science*** 77, 113-123.
14. BELL M.J., ECKARD R.J., HAILE-MARIAM M., PRYCE J.E., 2013 – The effect of changing cow production and fitness traits on net income and greenhouse gas emissions from Australian dairy systems. ***Journal of Dairy Science*** 96, 7918-7931.
15. BELL M.J., HINTON N., CLOY J.M., TOPP C.F.E., REES R.M., CARDENAS L., SCOTT T., WEBSTER C., ASHTON R.W., WHITMORE A.P., WILLIAMS J.R., BALSHAW H., PAINE F., GOULDING K.W.T., CHADWICK D.R., 2015a – Nitrous oxide emissions from fertilised UK arable soils: Fluxes, emission factors and mitigation. ***Agriculture, Ecosystems and Environment*** 212, 134-147.

16. BELL M. J., GARNSWORTHY P.C., STOTT A.W., PRYCE J.E., 2015b – Effects of changing cow production and fitness traits on profit and greenhouse gas emissions of UK dairy systems. ***Journal of Agricultural Science*** 153, 138-151.
17. BHANDRAL R., SAGGAR S., BOLAN N.S., HEDLEY M.J., 2003 – Nitrous oxide fluxes in soil as influenced by compaction. ***Proceedings of the New Zealand Grassland Association*** 65, 265-271.
18. BJORNEBERG D.L., LEYTEM A.B., WESTERMANN D.T., GRIFFITHS P.R., SHAO L., POLLARD M.J., 2009 – Measurement of atmospheric ammonia, methane, and nitrous oxide at a concentrated dairy production facility in southern Idaho using open-path FTIR spectrometry. ***Transactions of the ASABE*** 52, 1749-1756.
19. BOON A., ROBINSON J.S., CHADWICK D.R., CARDENAS L.M., 2014 – Effect of cattle urine addition on the surface emissions and subsurface concentrations of greenhouse gases in a UK peat grassland. ***Agriculture, Ecosystems & Environment*** 186, 23-32.
20. BORHAN M.S., CAPAREDA S.C., MUKHTAR S., FAULKNER W.B., MCGEE R., PARNELL C.B., 2011a – Greenhouse Gas Emissions from Ground Level Area Sources in Dairy and Cattle Feedyard Operations. ***Atmosphere*** 2, 303-329.
21. BORHAN M.S., CAPAREDA S., MUKHTAR S., FAULKNER W.B., MCGEE R., PARNELL C.B., 2011b - Determining Seasonal Greenhouse Gas Emissions from Ground Level Area Sources in a Dairy Operation in Central Texas. ***Journal of Air and Waste Management*** 61, 786-795.
22. BORHAN M.S., MUKHTAR S., CAPAREDA S., RAHMAN S., 2012 – Greenhouse Gas Emissions from Housing and Manure Management Systems at Confined Livestock Operations. In: L. Fernando, M. Rebellon (Editors). Waste Management - An Integrated Vision Environmental Sciences, Chapter 12, 259-296.
23. CARRAN R.A., THEOBALD P.W., EVANS J.P., 1995 – Emission of nitrous oxide from some grazed pasture soils in New Zealand. ***Australian Journal of Soil Research*** 33, 341-352.
24. CHADWICK D.R., SNEATH R.W., PHILLIPS V.R., PAIN B.F., 1999 – A UK Inventory of Nitrous Oxide Emissions from Farmed Livestock. ***Atmospheric Environment*** 33, 3345-3354.
25. CHADWICK D.R., PAIN B.F., BROOKMANN S.K.E., 2000 – Nitrous oxide and methane emissions following application of animal manures to grassland. ***Journal of Environmental Quality*** 29, 277-287.
26. CHIANESE D.S., ROTZ C.A., RICHARD T.L., 2009a – Whole farm greenhouse gas emissions: A review with application to a Pennsylvania dairy farm. ***Applied Engineering in Agriculture*** 25, 431-442.
27. CHIANESE, D.S., ROTZ C.A., RICHARD T.L., 2009b – Simulation of nitrous oxide emissions from dairy farms to assess greenhouse gas reduction strategies. ***Transactions of the ASABE*** 52, 1325-1335.
28. CLOUGH T.J., SHERLOCK R.R., MAUTNER M.N., MILIGAN D.B., WILSON P.F., FREEMAN C.G., MCEWAN M.J., 2003 – Emission of nitrogen oxides and ammonia from varying rates of applied synthetic urine and correlations with soil chemistry. ***Australian Journal of Soil Research*** 41, 421-438.
29. CROSSON P., SHALLOO L., O'BRIEN D., LANIGAN G.J., FOLEY P.A., BOLAND T.M., KENNY D.A., 2011 – A review of whole farm systems models of greenhouse gas emissions from beef and dairy cattle production systems. ***Animal Feed Science and Technology*** 166/167, 29-45.
30. DAVIDSON E.A., 2009 – The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. ***Nature Geoscience*** 2, 659-662.
31. DI H.J., CAMERON K.C., 2006 – Nitrous oxide emissions from two dairy pasture soils as affected by rates of fine particle suspension nitrification inhibitor, dicyandiamide. ***Biology and Fertility of Soils*** 42, 472-480.

32. DE KLEIN C.A.M., BARTON L., SHERLOCK R.R., LI Z., LITTLEJOHN R.P., 2003 – Estimating a nitrous oxide emission factor for animal urine from some New Zealand pastoral soils. ***Australian Journal of Soil Research*** 41, 381-399.
33. DE KLEIN C.A.M., ECKARD R.J., 2008 – Targeted technologies for nitrous oxide abatement from animal agriculture. ***Australian Journal of Experimental Agriculture*** 48, 14-20
34. DOBBIE K.E., SMITH K.A., 2001 – The effect of temperature, water-filled pore space, and land use on N2O emissions from an imperfectly drained gleysol. ***European Journal of Soil Science*** 52, 667-673.
35. ECKARD R.J., CHEN D., WHITE R.E., CHAPMAN D.F., 2003 – Gaseous nitrogen loss from temperate grass and clover dairy pastures in south eastern Australia. ***Australian Journal of Agricultural Research*** 54, 561-570.
36. GERBER P.J., HRISTOV A.N., HENDERSON B., MAKKAR H., OH J., LEE C., MEINEN R., MONTES F., OTT T., FIRKINS J., ROTZ A., DELL C., ADESOGAN A.T., YANG W.Z., TRICARICO J.M., KEBREAB E., WAGHORN G., DIJKSTRA J., OOSTING S., 2013 – Technical options for the mitigation of direct methane and nitrous oxide emissions from livestock: a review. ***Animal*** 7, 220-234.
37. GROENESTEIN C.M., VAN FAASSEN H.G., 1996 – Volatilization of ammonia, nitrous oxide and nitric oxide in deep-litter systems for fattening pigs. ***Journal of Agricultural Engineering Research*** 65, 269-274.
38. GUERCI M., BAVA L., ZUCALI M., SANDRUCCI A., PENATIAND CH., TAMBURINI A., 2013 – Effect of farming strategies on environmental impact of intensive dairy farms in Italy. ***Journal of Dairy Research*** 80, 300-308.
39. HAMILTON S.W., DEPETERS E.J., MCGARVEY J.A., LATHROP J., MITLOEHNER F.M., 2010 - Greenhouse gas, animal performance, and bacterial population structure responses to dietary monensin fed to dairy cows. ***Journal of Environmental Quality*** 39, 106-114.
40. HANSEN M.N., HENRIKSEN K., SOMMER S.G., 2006 – Observations of production and emission of greenhouse gases and ammonia during storage of solids separated from pig slurry: Effects of covering. ***Atmospheric Environment*** 40, 4172-4181.
41. HRISTOV A.N., OH J., FIRKINS J., DIJKSTRA J., KEBREAB E., WAGHORN G., MAKKAR H.P.S., ADESOGAN A.T., YANG W., LEE C., GERBER P.J., HENDERSON B., TRICARICO J.M., 2013 – Mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options. ***Journal of Animal Science*** 91, 5045-5069.
42. JUNGBLUTH T., HARTUNG E., BROSE G., 2001 – Greenhouse emissions from animal houses and manure stores. ***Nutrients Cycling Agroecosystem*** 60, 133-145.
43. KEBREAB E., CLARK K., WAGNER-RIDDLE C., FRANCE J., 2006 – Methane and nitrous oxide emissions from Canadian animal agriculture: A review. ***Canadian Journal of Animal Science*** 86, 135-158.
44. KÜLLING D.R., HENZI H.K., KROBER T.F., NEFTEL A., SUTTER F., LISCHER P., KREUZER M., 2001 – Emissions of ammonia, nitrous oxide and methane from different types of dairy manure during storage as affected by dietary protein content. ***Journal of Agricultural Science*** 137, 235-250.
45. LEYTEM A.B., DUNGAN R.S., BJORNEBERG D.L., KOEHN A.C., 2010 – Emissions of ammonia, methane, carbon dioxide, and nitrous oxide from dairy cattle housing and manure management systems. ***Journal of Environmental Quality*** 40, 1383-1394.
46. LI CH., SALAS W., ZHANG R., KRAUTER CH., ROTZ A.C. , MITLOEHNER F., 2012 – Manure-DNDC: a biogeochemical process model for quantifying greenhouse gas and ammonia emissions from livestock manure systems. ***Nutrient Cycling in Agroecosystems*** 93, 163-200.

47. LI J., SHI Y., LUO J., HOULBROOKE D., LEDGARD S., GHANI A., LINDSEY S., 2014a – Effects of form of effluent, season and urease inhibitor on ammonia volatilization from dairy farm effluent applied to pasture. ***Journal of Soils and Sediments*** 14, 1341–1349.
48. LI J., SHI Y., LUO J., ZAMAN M., HOULBROOKE D., DING W., LEDGARD S., GHANI A., 2014b – Use of nitrogen process inhibitors for reducing gaseous nitrogen losses from land-applied farm effluents. ***Biology and Fertility of Soils*** 50, 133-145.
49. LI J., LUO J., SHI Y., HOULBROOKE D., WANG L., LINDSEY S., LI Y., 2015 – Nitrogen gaseous emissions from farm effluent application to pastures and mitigation measures to reduce the emissions: a review. ***New Zealand Journal of Agricultural Research*** 58, 339-353.
50. LOVELL R.D., JARVIS S.C., 1996 – Effects of urine on soil microbial biomass, methanogenesis, nitrification and denitrification in grassland soils. ***Plant and Soil*** 186, 265-273.
51. LUO J., TILLMAN R.W., BALL P.R., 1999 – Factors regulating denitrification in a soil under pasture. ***Soil Biology and Biochemistry*** 31, 913-927.
52. LUO J., SUN X.Z., PACHECO D., LEDGARD S.F., LINDSEY S.B., HOOGENDOORN C.J., WISE B., WATKINS N.L., 2015 – Nitrous oxide emission factors for urine and dung from sheep fed either fresh forage rape (Brassica napus L.) or fresh perennial ryegrass (Lolium perenne L.). ***Animal*** 9, 534-543.
53. MAEDA K., TOYODA S., SHIMOJIMA R., OSADA T., HANAJIMA D., MORIOKA R., YOSHIDA N., 2010 – Source of nitrous oxide emissions during the cow manure composting process as revealed by isotopomer analysis of and *amo*A abundance in betaproteobacterial ammonia-oxidizing bacteria. ***Applied and Environmental Microbiology*** 76, 1555-1562.
54. MCGAHAN E.J., PHILLIPS F.A., WIEDEMANN S.G., NAYLOR T.A., WARREN B., MURPHY C.M., GRIFFITH D.W.T., DESSERVETTAZ M., 2016 – Methane, nitrous oxide and ammonia emissions from an Australian piggery with short and long hydraulic retention-time effluent storage. ***Animal Production Science*** 56, 1376-1389.
55. MIDDELAAR C.E., BERENTSEN VAN P.B.M., DIJKSTRA J., DE BOER I.J.M., 2013 – Evaluation of a feeding strategy to reduce greenhouse gas emissions from dairy farming: The level of analysis matters. ***Agricultural Systems*** 121, 9-22
56. MOGGE B., KAISER E.A., MUNCH J.C., 1999 – Nitrous oxide emissions and denitrification N-losses from agricultural soils in the Bornhoved Lake region: influence of organic fertilizers and land-use. ***Soil Biology and Biochemistry*** 31, 1245-1252.
57. MONAGHAN R.M., BARRACLOUGH D., 1993 – Nitrous oxide and dinitrogen emissions from urine-affected soil under controlled conditions. ***Plant and Soil*** 151, 127-138.
58. MONTES F., MEINEN R., DELL C., ROTZ A., HRISTOV A.N., OH J., WAGHORN G., GERBER P.J., HENDERSON B., MAKKAR H.P.S., DIJKSTRA J., 2013 – Mitigation of methane and nitrous oxide emissions from animal operations: II. A review of manure management mitigation options. ***Journal of Animal Science*** 91, 5070-5094.
59. MOSIER A.R., DUXBURY J.M., FRENEY J.R., HEINEMEYER O., MINAMI K., 1998 – Assessing and mitigating N_2O emissions from agricultural soils. ***Climatic Change*** 40, 7-38.
60. NGWABIE N.M., VANDERZAAG A., JAYASUNDARA S., WAGNER-RIDDLE C., 2014 – Measurements of emission factors from a naturally ventilated commercial barn for dairy cows in a cold climate. ***Biosystems Engineering*** 127, 103-114.
61. OENEMA O., WRAGE N., VELTHOF G., GROENIGEN J.W., DOLFING J., KUIKMAN P., 2005 – Trends in Global Nitrous Oxide Emissions from Animal Production Systems. ***Nutrient Cycling in Agroecosystems*** 72, 51-65.
62. OSADA T., ROM H.B., DAHL P., 1998 – Continuous measurement of nitrous oxide and methane emission in pig units by infrared photoacoustic detection. ***Transactions of the ASAE*** 41, 1109-1114.

63. OWEN J.J., SILVER W.L., 2015 – Greenhouse gas emissions from dairy manure management: a review of field-based studies. ***Global Change Biology*** 21, 550-565.
64. PAHL O., BURTON C.H., DUNN W., BIDDLESTONE A.J., 2001 – The source and abatement of nitrous oxide emissions produced from the aerobic treatment of pig slurry to remove surplus nitrogen. ***Environmental Technology*** 22, 941-950.
65. PARDO G., YAÑEZ-RUIZ D., MARTIN-GARCIA I., ARCO A., MORAL R., DEL PRADO A., 2015 – Modelling the impact on greenhouse gas emissions of using underutilized feed resources in dairy goat systems. ***Advances in Animal Biosciences*** 6, 40-42.
66. PHILLIPS F.A., WIEDEMANN S.G., NAYLOR T.A., MCGAHAN E.J., WARREN B.R., MURPHY C.M., PARKES S., WILSON J., 2016 – Methane, nitrous oxide and ammonia emissions from pigs housed on litter and from stockpiling of spent litter. ***Animal Production Science*** 56, 1390-1403.
67. PHILIPPE F.X., CABARAUX J.F., NICKS B., 2011 – Ammonia emissions from pig houses: Influencing factors and mitigation Techniques. ***Agriculture, Ecosystems and Environment*** 141, 245-260.
68. PHILIPPE F.X., NICKS B., 2013 – Emissions of ammonia, nitrous oxide and methane from pig houses: Influencing factors and mitigation techniques. In: From the lab to the farm. European Workshop. Reconciling livestock management to the environment – Applying Best Available Technique, 19 to 20 March 2013, IRSTEA, Rennes, France. 10 p. accessed from http://hdl.handle.net/2268/146949.
69. PODKOWKA Z., CERMAK B., PODKOWKA W., BROUCEK J., 2015 – Greenhouse gas emissions from cattle. ***Ekologia, Bratislava*** 34, 82-88.
70. RAHMAN S., BORHAN S., SWANSON K., 2013 – Greenhouse gas emissions from beef cattle pen surfaces in North Dakota. ***Environmental Technology*** 34,1239-1246.
71. REDDING M., DEVEREUX J., PHILLIPS F., LEWIS R., NAYLOR T., KEARTON T., HILL C.J., WEIDEMANN S., 2015 - Field measurement of beef pen manure methane and nitrous oxide reveals a surprise for inventory calculations. ***Journal of Environmental Quality*** 44, 720-728.
72. REGAERT D., AUBINET M., MOUREAUX C., 2015 – Mitigating N_2O emissions from agriculture: A review of the current knowledge on soil system modelling, environmental factors and management practices influencing emissions. ***Journal of Soil Science and Environmental Management*** 6, 178-186.
73. RIGOLOT C., ESPAGNOL S., ROBIN P., HASSOUNA M., BELINE F., PAILLAT J.M., DOURMAD J.Y., 2010 – Modelling of manure production by pigs and NH_3, N_2O and CH_4 emissions. Part II: effect of animal housing, manure storage and treatment practices. ***Animal*** 4, 1413-1424.
74. ROSS S.A., CHAGUNDA M.G.G., TOPP C.F.E., ENNOS R., 2014 – Effect of cattle genotype and feeding regime on greenhouse gas emissions intensity in high producing dairy cows. ***Livestock Science*** 170, 158-171.
75. RUZ-JEREZ B.E., WHITE R.E., BALL P.R., 1994 – Long-term measurement of denitrification in 3 contrasting pastures grazed by sheep. ***Soil Biology and Biochemistry*** 26, 29-39.
76. RZEŹNIK W., MIELCAREK P., 2016 – Greenhouse Gases and Ammonia Emission Factors from Livestock Buildings for Pigs and Dairy Cows. ***Polish Journal of Environmental Studies*** 25, 1-9.
77. SAGGAR S., HEDLEY C., TATE K., 2003 – Methane sources and sinks in New Zealand grazed pastures. ***New Zealand Soil News*** 51, 6-7.
78. SAGGAR S., ANDREW R.M., TATE K.R., HEDLEY C.B., RODDA N.J., TOWNSEND J.A., 2004a – Modelling nitrous oxide emissions from New Zealand dairy grazed pastures. ***Nutrient Cycling in Agroecosystems*** 68, 243-255.
79. SAGGAR S., BOLAN N.S., BHANDRAL R., HEDLEY C.B., LUO J., 2004b – A review of emissions of methane, ammonia and nitrous oxide from animal excreta deposition and farm effluent application in grazed pastures. ***New Zealand Journal of Agricultural Research*** 47, 513-544.

80. SAGGAR S., JHA N., DESLIPPE J., BOLAN N.S., LUO J., GILTRAP D.L., KIM D.G., ZAMAN M., TILLMAN R.W., 2013 – Denitrification and N_2O:N_2 production in temperate grasslands: processes, measurements, modelling and mitigating negative impacts. ***Science of the Total Environment*** 456, 136-146.
81. SAGGAR S., GILTRAP D.L., DAVISON R., GIBSON R., DE KLEIN C.A.M., ROLLO M., ETTEMA P., RYS G., 2015 – Estimating direct N_2O emissions from sheep, beef, and deer grazed pastures in New Zealand hill country: accounting for the effect of land slope on the N_2O emission factors from urine and dung. ***Agriculture, Ecosystems and Environment*** 205, 70-78.
82. SELBIE D.R., LANIGAN G.J., LAUGHLIN R.J., DI H.J., MOIR J.L., CAMERON K.C., CLOUGH T.J., WATSON C.J., GRANT J., SOMMERS C., RICHARDS K.G., 2015 – Confirmation of co-denitrification in grazed grassland. ***Scientific Reports*** 5, Article No. 17361, 1-5.
83. SNEATH R.W., PHILLIPS V.R., DEMMERS T.G.M., BURGESS L.R., SHORT J.L., WELCH S.K., 1997 - Long term measurements of greenhouse gas emissions from UK livestock buildings. In: R.W. Bottcher, S.J. Hoff (Editors). Livestock Environment V, Vol. 2, Proc. the Fifth Intern. Symposium. Bloomington, Minnesota, 29-31 May, 1997, Published by ASAE, St. Joseph, Michigan, USA., 146-153.
84. SOMMER S.G., 2001 – Effect of composting on nutrient loss and nitrogen availability of cattle deep litter. ***European Journal of Agronomy*** 14, 123-133.
85. STACKHOUSE K.R., PAN Y., ZHAO Y., MITLOEHNER, F.M., 2011 – Greenhouse gas and alcohol emissions from feedlot steers and calves. ***Journal of Environmental Quality*** 40, 899-906.
86. SUN J., BAI M., SHEN J., GRIFFITH D.W.T., DENMEAD O.T., HILL J., LAM S.K., MOSIER A.R., CHEN D., 2016 – Effects of lignite application on ammonia and nitrous oxide emissions from cattle pens. ***Science of the Total Environment*** 565, 148-154.
87. UCHIDA Y., AKIYAMA H., 2013 – Mitigation of postharvest nitrous oxide emissions from soybean ecosystems: a review. ***Soil Science and Plant Nutrition*** 59, 477-487.
88. UCHIDA Y., CLOUGH T.J., 2015 – Nitrous oxide emissions from pastures during wet and cold seasons. ***Grassland Science*** 61, 61-74.
89. WILLIAMS P.H., JARVIS S.C., DIXON, E., 1998 – Emission of nitric oxide and nitrous oxide from soil under field and laboratory conditions. ***Soil Biology and Biochemistry*** 30, 1885-1893.
90. WOLTER M., PRAYITNO S., SCHUCHARDT F., 2004 – Greenhouse gas emission during storage of pig manure on a pilot scale. ***Bioresource Technology*** 95, 235-244.
91. YAMULKI S., 2006 – Effect of straw addition on nitrous oxide and methane emissions from stored farmyard manures. ***Agriculture Ecosystems and Environment*** 112, 140-145.