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METHANE YIELD FROM CATTLE, SHEEP, AND GOATS HOUSING WITH EMPHASIS ON EMISSION FACTORS: A REVIEW

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ABSTRACT

Global methane (CH_4) concentrations are increasing in all parts of the world. This review study intends to provide an integrative approach to the complex relationships between environmental systems of farm animals. It reveals that more data are needed to better quantify CH_4 emissions from farms. Methanogenic microbial functional groups play an important role in total methane flux from agroecosystems. The factors that regulate the activity of these organisms (temperature, diet composition, feeding technique, manure management) have been documented. The research based on the literature available presented was conducted under extensive and intensive management conditions. In principle, the approaches discussed can be applied to any dairy, beef or sheep production system because their aim is increasing productivity at the herd level. Recent studies on the effects of environmental temperature, feeding, internal and genetic factors, and emission from excrements on CH_4 production are discussed. Finally, emission factors for dairy and beef cattle, as well as goats and sheep, are listed in tables.

Key words: methane; dairy cattle; beef cattle; goat; sheep; emission; manure

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INTRODUCTION

Greenhouse gas emissions (GGE) from livestock and their impact on climate changes are a major concern worldwide. Enteric CH^4 production from ruminant livestock accounts for 17 – 37 % of global anthropogenic CH_4 (Lassey, 2008; Pedreira *et al*., 2009; Alemu *et al*., 2011; Cottle *et al*., 2011; Knapp *et al*., 2014).With regard to CH_4, the global livestock sector is responsible for 37 % of all human-induced CH_4 emissions, with 89 % of these livestock-derived emissions arising from enteric fermentation (Steinfeld and Wassenaar, 2007; Jiao *et al*., 2014).

Methane emissions from ruminants are the focus of scientists (Sejian *et al*., 2011; Ramin and Huhtanen, 2013; St-Pierre and Wright, 2013). With the relative global warming potential of 25 compared with CO_2, CH_4 is one of the most important GGE (Pinares-Patiño *et al*., 2007; Sejian *et al*., 2011). Decreasing methane emissions by livestock has therefore become a priority and an integral part of climate control (Martin *et al*., 2010). The leading role of livestock in methane emission has long been established (Charmley *et al*., 2008; Chagunda *et al*., 2009; Mihina *et al*., 2012).

In ruminant production systems, enteric CH_4 production is the largest contributor to GGE followed by CH_4 from manure systems, main emission sources are enteric fermentation, feed fertilization, and land application (Hensen *et al*., 2006; Klevenhusen *et al*., 2011; Hristov *et al*., 2013; Montes *et al*., 2013). Dairy cattle and beef cattle generate similar amounts of GGE, but on the basis of the numbers of animals beef production contributes 41 % of total sector emissions while emissions from milk production amount to 20 % of total sector emissions (Gerber *et al*., 2013a). Methane emissions from grazing cattle are a significant source

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of agricultural GGE, however, these emissions are difficult to quantify because of the sparse and roving nature of the source (Huarte *et al.*, 2010; McGinn *et al*., 2011).

Methane creation

Ruminant animals are the principal source of emissions because they produce the most CH_4 per unit of feed consumed. Ruminal gases, generated during the fermentative process in rumen, represent a partial loss of feed energy and are also pointed to as important factors in greenhouse effect (Cottle *et al*., 2011). Around 90 % of the enteric CH_4 produced by ruminants has its origin in the rumen (McAllister and Newbold, 2008; Eckard *et al.*, 2010; Dini *et al*., 2012).

The rumen is characterized as a large fermentation vat. Ruminant animals have coevolved with a complex gut microbiota in a manner that has mutually improved the efficiency of digestion of complex plant polymers. In ruminants, microbial fermentation primarily takes place in the pre-gastric reticulum and rumen, where fluid mixes freely through the reticulo-rumen fold in adult ruminants. The development of a multi-chambered fore-stomach allows for increased retention time of ingested plant biomass and therefore a greater degree of microbial fermentation of non-labile C in the form of lignin, cellulose and hemicellulose (Finn *et al*., 2015).

The total number of rumen archaeal species is unknown (Janssen and Kirs, 2008), but has been estimated to be approximately 360 to 1,000 on an operational taxonomic unit basis (Kim *et al*., 2011; Kong *et al*., 2013). These complex anaerobic microbial communities consist of many species from divergent groups such as protozoa, fungi, bacteria and archaea (St-Pierre and Wright, 2013). The microbes ferment the plant material consumed by the animal through a process known as enteric fermentation (Cassandro *et al*., 2013). Representatives from the following orders of methanogens have been identified in rumen microbial communities: *Methanococcales, Methanobacteriales, Methanomicrobiales, Methanosarcinales and Thermoplasmatales* (Janssen and Kirs 2008; Poulsen *et al*., 2013). Three major genera and 3 minor genera of methanogens belonging to the Archaea domain have been identified, although it is likely that more exist (Wright *et al*., 2006; Janssen and Kirs, 2008; Liu and Whitman, 2008). Only 8 methanogen species have been cultured (Kong *et al*., 2013). Methanogens are found in the hindgut as well as the rumen, although the population structure, ecology, and microbial metabolism differ between the 2 compartments (Knapp *et al*., 2014). Methanogenic microorganisms remove H_2 produced during fermentation of organic matter in the rumen and hind gut (Cottle *et al*., 2011). Enteric fermentation is thermodynamically favourable only when a hydrogen sink is present and the major hydrogenutilising microorganisms in the rumen are hydrogenotrophic methanogens. Hydrogenotrophic species belonging to the genus *Methanobrevibacter* are frequently the most active and abundant methanogens in the rumen of cattle and sheep (Wright *et al*., 2008).

A primary factor for enteric methane production is dietary carbohydrate, which influences the rate of fermentation, rate of rumen passage, and animal intake (Johnson and Johnson, 1995). The digestibility of ingested plant biomass, which is determined by the ratio of insoluble cell wall fibre to soluble carbohydrates, directs enteric fermentation to the preferential production of certain end products (Migwi *et al*., 2013). Highly fibrous, poorly digestible plant biomass leads to the production of higher proportions of methanogenic substrates and reduces rumen passage rates, resulting in higher rates of methane production (Ellis *et al*., 2009). Organisms involved in cellulose, hemicellulose, cellobiose, xylan, lipid and protein metabolism are important for animal. Most of these organisms are closely associated with particulate plant biomass and other microflora to facilitate syntrophic interactions such as plant biomass degradation and interspecies electron transfer (Edwards *et al.,* 2008; Leng, 2014; Finn *et al*., 2015).

The final products of enteric fermentation include acetate, formate, methanol, carbon monoxide, carbon dioxide and hydrogen gas, all of which are substrates for methanogenesis (Johnson and Johnson, 1995; Moss *et al*., 2000; Merino *et al*., 2011). It was found that 89 % gases are excreted through the breath and only 11 % through the anus (Madsen *et al*., 2010).

Manure methane production

Animal manure is a valuable source of nutrients and renewable energy in the agriculture. On the other hand, livestock manure management is extremely challenging and resultant gaseous emissions may contribute to global warming. Manure from livestock operations is most often stored in solid or liquid form before being applied to agricultural land.

Methane is produced from freshly deposited manure due to bacterial processes, and from storage lagoons and settling basins due to anaerobic degradation (Hensen *et al*., 2006; Chagunda *et al*., 2009; Borhan *et al*., 2011a). Many of the emission pathways are controlled by microorganisms, and thus, by the optimum temperature for each specific microorganism involved (Chianese *et al*., 2009). Klevenhusen *et al*., (2011) and Bell *et al*., (2011a) support the hypothesis that slurry methanogenesis strongly depends on storage temperature and duration, with the diet type being less important. The variation in CH_4 emission from slurry stored at cold temperature for 15 weeks was of low importance. At a low storage temperature CH_4 production is almost negligible (Klevenhusen *et al*., 2011). CH_4 emission and oxidation rates are moisture dependent. The natural crust must stay dry in order to allow for optimal aerobic conditions inside the crust. A crust that is subjected to rainfall gets wet and anaerobic. As a result, the rate of CH_4 oxidation will strongly be reduced.

Methane production from manure (faecal material) depended on the type of waste, temperature, and duration of storage, and the manner in which the manure is handled. Emissions during composting of dung depend on factors such as aeration rate, water content, thermal insulation, weather conditions, and dung composition. During anaerobic fermentation, organic wastes are biologically degraded in the absence of oxygen to CH_4, CO_2, N_2, and H_2S. The content of organic matter labile fractions is negligible in cattle faeces but the content of the anaerobically degradable fraction is utilizable. It depends not only on feed quality and quantity but also on all factors of enteric fermentation and processes determining the digestion of ruminants (Kolář *et al*., 2010). Methanogenic fermentation of organic materials occurs under strictly anaerobic and low redox potential conditions where sulphate and nitrate concentrations are low. Methanogens produce methane by breaking down organic matter in the absence of oxygen (anaerobically), releasing CO_2 and CH_4. Methane production during composting is linked to the lack of oxygen in the decomposing biomass (Saggar *et al*., 2004). Wulf *et al*. (2001) showed that anaerobic digestion of the slurry reduced CH_4 emissions after field application, because the easily degradable organic compounds were already converted to CO_2 and CH_4 during digestion in the biogas plant.

The main factor determining the extent of CH_4 production is the amount of degradable organic matter in the effluent. This fraction is commonly expressed in terms of biochemical or chemical oxygen demand. The higher the biochemical or chemical oxygen value, the more CH_4 is produced (Saggar *et al*., 2004). The potential amount of CH_4 formation from animal faeces will depend on the amount of faecal matter excreted, the physical form of the deposit (shape, size), excretal form (solid, slurry), climatic and soil conditions, and the length of time these deposits remain intact before being decomposed. Chadwick *et al*. (2000) measured CH_4 emissions from grassland following application of pig manure, beef manure, pig slurry, dairy-cow slurry, and dilute dairy-cow effluent during different times of the year. Methane emissions were greater from dairy-cow slurry than from pig slurry, but pig manure produced much greater amounts of CH_4 (47.8 $mg.kg^{-1}$) than did beef manure (2.7 $mg.kg^{-1}$) (Saggar *et al*., 2004).

Methane production in ruminants

Methane emissions in animal husbandry originate from fermentative digestion in animals, natural anaerobic ecosystems, storage of manures, and field application. Within livestock, ruminants (cattle, sheep, and goats) are the primary source of emissions. Other livestock (swine, horses, and poultry) are of lesser importance for nearly all countries. Among the ruminants, cattle population contributes most towards enteric CH_4 production (Johnson and Johnson, 1995; Zijderveld van *et al*., 2011; Sejian and Naqvi, 2012). Emissions from enteric fermentation exceed those from storage of slurry and manure and are regarded a key source in greenhouse gas emission reporting. However, the assessment of emissions from stored manures is difficult due to lack of experimental data (Dämmgen *et al*., 2012).

The amount of CH_4 produced by ruminants is affected by various factors including animal type and size, growth rate, level of production, and energy consumption digestibility and quantity of feeds, intake of dry matter, total carbohydrates, digestible carbohydrates, and environmental temperature. Both animal and dietary factors play an important role in predicting CH_4 production (Johnson and Johnson, 1995; Yan *et al*., 2000; Monteny *et al*., 2006; Chianese *et al*., 2009; Shibata and Terada, 2010).

Enteric fermentation emissions for ruminants are estimated by multiplying the emission factor for each species. The emission factors are an estimate of the amount of CH_4 produced (kg) per animal, and are based on animal and feed characteristics data, average energy requirement of the animal, the average feed intake to satisfy the energy requirements, and the quality of the feed consumed. The country level emission from enteric fermentation is computed as a product of the ruminant population under each category and its emission coefficient (Chhabra *et al.* 2009; Sejian and Naqvi, 2012).

Environmental temperature

Environmental temperature also influences CH_4 production and the production rate. Since the digestibility of feed tends to increase with the lower feed intake and slower rates of passage under high temperatures, it may be considered that energy loss as CH_4 decreases. However, in a high temperatures environment, the contents of the cell wall, acid detergent fiber and lignin tend to increase, causing lower digestibility of feed and higher energy loss, and resulting in an increase in CH_4 production per unit of product through the decrease in the efficiency of animal production. These phenomena occur in tropical regions but will also occur more and more frequently in temperate regions as global warming progresses (Shibata and Terada, 2010). Eckard (2011) and Cottle *et al.* (2011) found that mature beef cows emit approximately 350 g CH_4 daily in the tropics and 240 g daily in temperate zones; dairy cows emit approximately 430 $g.d^{-1}$ at peak lactation down to 250 $g.d^{-1}$ as milk yield declines. Kurihara *et al.* (1999) reported that the amount of CH_4 production in dry cows was decreasing as the environmental temperature was increasing because of decreased feed intake. However, CH_4 production per DMI increases under high temperatures. Kurihara *et al.* (1995, cited by Shibata and Terada, 2010) established a significant regression equation between DMI and CH_4 production at 18 °C and 30 – 32 °C, respectively, and concluded that CH_4 production per DMI increased at high temperatures and was about 10 % higher at temperatures above 26 °C than at 18 °C in cows at the maintenance level of feeding. The same authors also found that the effects of environmental temperature were different depending on the type of feed given: CH_4 production per DMI in lactating cows increased with temperature in high-roughage feeding while there were no significant differences among temperatures in high-concentrate feeding (Shibata and Terada, 2010). Temperature and manure storage time are the most important factors influencing CH_4 emissions because substrate and microbial growth are generally not limited (Monteny *et al.*, 2001; Chianese *et al.*, 2009).

Feeding

The type and amount of feed consumed are the primary drivers affecting emissions (Sejian and Naqvi, 2012). Daily CH_4 emissions were higher in grass-based systems than in intensive systems (Arias *et al.*, 2015). Gerber *et al.* (2013b) wrote that higher emission intensities are in low productivity systems. It can be explained by low feed digestibility (leading to higher enteric and manure emissions), poorer animal husbandry and lower slaughter weights (slow growth rates leading to more emissions per kg of meat produced) and higher age at slaughter (longer life leading to more emissions). Generally, the CH_4 emission intensity of milk production is the lowest in industrialized regions of the world, compared with regional averages. Better animal feeding and nutrition reduce CH_4 and manure emissions.

But sometimes there are contradictory results. According to Pedreira *et al.* (2009), intensive managed pasture systems, with fertilized pasture and concentrate use, do generate more CH_4; methane emission by heifers grazing fertilized pasture was greater than that of heifers on unfertilized pasture.

Emissions from enteric fermentation and manure are also influenced by the composition of ruminants diets (Beauchemin *et al.*, 2008; Sasu-Boakye *et al.*, 2014). A large proportion of the variation in enteric CH_4 emissions from animals can be explained by diet composition and feed intake (Bell *et al*., 2012; Bell *et al*., 2014a). Ricci *et al.* (2014) observed significant differences between diets in finishing steers, emissions were greater for the low concentrate ration than the high concentrate ration. Jiao *et al.* (2014) demonstrated that offering concentrates to grazing dairy cows increased milk production per cow and decreased CH_4 emissions per unit of milk produced. Methane emissions of grazing animals are strongly related to feed intake, which is likely to vary with seasonal pasture conditions. When the beef cattle were grazed on pasture, they produced significantly (3.5 times) higher CH_4 than the same cattle fed a highly digestible, high-grain diet. These measurements clearly document higher CH_4 production for cattle receiving low quality, high-fiber diets than for cattle fed high-grain diets (Harper *et al.*, 1999).

Lovett *et al.* (2005) found that CH_4 production.kg MY^{-1} was unaffected by concentrate supplementation, but CH_4 production.kg FCM^{-1} decreased with increasing concentrate feed level. Young and Ferris (2011, cited by Jiao *et al*., 2014) observed that daily CH_4 emissions were unaffected by concentrate feeding, however, CH_4 emissions per kg DMI^{-1} and per kg ECM^{-1} decreased with increasing concentrate level.

The CH_4 production during feed ration 30 % hay and 70 % concentrate was significantly lower than that in 70 % hay and 30 % concentrate (Shibata *et al.*, 1992). It is also known that fat supplements reduce CH_4 production (Beauchemin *et al.*, 2009; Ramin and Huhtanen, 2013; Moate *et al.*, 2014). Fraser *et al.* (2015) indicated that forage type had a greater impact than breed type on CH_4 emissions from growing weaned lambs.

Internal and genetic factors

Variation in enteric CH_4 emission has been reported between animals, between breeds, and across time, providing potential for improvement through genetic selection (Haas de *et al.*, 2011). It was concluded that CH_4 emissions vary considerably between dairy cows housed under commercial conditions, but ranking of cows for CH_4 emissions is consistent across time. Variation is related to LBW, MY, parity, and stage of lactation, in accordance with changes in metabolizable energy requirements (Garnsworthy *et al.*, 2012b). There was no indication of individual cows with persistently low or high CH_4 yield.kg DMI^{-1} and CH_4 yield.kg MY^{-1} (Münger and Kreuzer, 2008). Pinares-Patiño *et al.* (2008) tested low bloat vs. high bloat cows. The mean CH_4 emissions were not different from each other.

CH_4 production is significantly different among animal species and breeds. Heifers produced about 7 times and 9 times as much as sheep and goats, respectively (Pedreira *et al.*, 2009). Lactating cows produced more methane than dry cows and heifers.

Holstein cows produced less CH_4 per unit of dry matter intake than the crossbred (Pedreira *et al*., 2009). Holstein and Simmental cows had a similar CH_4 emission rate for dry period and entire lactation, while that of the Jersey cows was lower (Münger and Kreuzer, 2008). CH_4 values were significantly higher for the crossbred steers with 67 % of Angus (Limousine 33 %) compared with 67 % of Limousine (33 % Angus) (Ricci *et al*., 2015). Higher DM intake and a longer lactation period were positively correlated with lower lifetime CH_4 emissions.kg ECM^{-1} (Bell *et al*., 2011a).

Emission from excrements

Manure has often been identified as a significant source of CH_4 production. It carries an appropriate population of microorganisms, and has a readily available supply of substrate carbon (Saggar *et al*., 2004). Methane emission rates vary depending on the type of dung. Measurements made by Jarvis *et al*. (1995) on dung patches from dairy cows, heifers, calves, and steers fed various diets at different times of the grazing season, showed a good deal of variability in emission rates amongst dung types. The total CH_4 emissions during a 10-day measurement period ranged between 300 and 2040 $mg.m^{-2}$ of dung pat. Williams (1993) also noted that CH_4 emission rates with dung from similar types of animals varied markedly, and suggested this might reflect the variation in the number of dung microorganisms that are responsible for CH_4 production. Williams (1993) measured methane emissions from fresh cattle faecal deposits and found the emissions were low but highly variable, and the dung deposits quickly dried out in the hot, dry climate. Rahman *et al.* (2013) reported CH_4 emission rates from the pen surface of a beef feedlot 38 $g.d^{-1}$.

Methane emissions from animal excreta are influenced by how they are stored (Saggar *et al*., 2004). The same authors concluded that CH_4 emission from dung would be greatly reduced if the cattle were allowed to spend most of their time in pastures during the grazing season. The highest emission measured from the pat in the field was only 11 % of the emission that would have resulted from solid manures, or 4 % of that from slurry. Methane emission factors from cattle manure produced under diverse climates (cool, temperate, and warm), systems (intensive, semi-intensive, and extensive) and cattle production functions (dairy, non-dairy, and dual purpose) have recently been studied (González-Avalos and Ruiz-Suarez, 2001). Results suggest that the dominant factor in CH_4 emissions is the feed ration, followed by fermentation temperature and the excreta moisture content.

Methane is also generated when manure is stored in anaerobic and warm conditions (Cassandro *et al*., 2013). Most of the CH_4 emission from manure is produced under anaerobic conditions during storage with very little following land application. Manure produces less CH_4 when handled as a solid (e.g., in stacks or pits) or when deposited on pasture or rangelands. Therefore, opportunities to reduce CH_4 emission are centred on preventing anaerobic conditions during storage or capturing and transforming the CH_4 that is produced, if anaerobic conditions are present (Montes *et al*., 2013). Data summarized by Chianese *et al.* (2009) indicate average CH_4 emissions from covered slurry, uncovered slurry, and stacked manure to be 6.5, 5.4, and 2.3 $kg.m^{-2}.yr^{-1}$ although rates vary with temperature and time in storage. CH_4 emissions from manure storage averaged 4.5 $kg.m^{-3}.yr^{-1}$ being about half that from stacked manure.

It was observed that the faecal matter of animals grazing in the morning emitted much more methane than that of steers grazing in the afternoon. The difference in the emissions was in qualitative agreement with the pronounced loss of organic matter from the morning samples (Priano *et al*., 2014).

Composting is the natural biological breakdown of dung into more stable organic substances and is an alternative to conventional management of agricultural wastes. Composting reduces volume and mass and the composted product can be trucked further distances, stored, and spread on land with little or no odour, fly breeding potential, pathogens, or weed seeds. There are four general types of composting methods on farms: passive, windrows, aerated piles, and in-vessel composting. These results suggest that composting could contribute to about one-third of CH_4 emission from livestock agriculture (Saggar *et al*., 2004). Amon *et al.* (2001) found much higher CH_4 emissions during storage and after spreading of manure from the anaerobically stacked manure than from the composted manure. Soil type had no effect on these emissions, and interaction with soil appeared to be relatively minor. It is apparent that emissions from stored animal excreta are much higher than from the dung voided in the field.

List of abbreviations

AC = accumulation chamber
AL = ad libitum
ASDM = air sampled during milking
CM = concentrate mixture
CS = corn silage
d = day
DIM = days in milk
DMI = dry mater intake
ECM = energy corrected milk
FC = flux chamber
FCM = 4 % fat corrected milk
FMFT = flux method from feed trough
FS = fattening steers
FTIR = Fourier transform infrared spectroscopy
GA = gas analyzer
GC = gas chromatography
GF = green feed system (head position sensors)
GLAS = emissions measuring from ground-level area sources
GS = grass silage
H = hay
HA = haylage
HCD = high concentrate diet
HE = heifers
IPCC Tier 2 = guidelines for national greenhouse gas inventories, method Tier 2
LBW = live body weight
LBWG = gain of live body weight
LMD = laser methane detector
LU = live unit (500 kg of LBW)
M = month
MBIGA = mass balance method from 24 h gas sampling
MF = milk fat
MHA = methane hydrocarbon analyzer
MMT = micrometeorological mass technique
MP = milk protein
MR = milk replacer
MS = manure system
MULTI = multiparous
MY = milk yield
OMA = open-path methane analyser
OPL = open-path laser
PCM = protein–corrected milk
PRIMI = primiparous
RC = respiration chamber
S = silage
SF$_6$ = sulphur hexafluoride tracer technique
SMAMS = snifer method in automatic milking station
SMFT = snifer method from feed trough
TDL = tuneable diode laser absorption spectrometer
yr = year

Table 1: Methane production and emission factors of dairy cattle

Calf, LBW 41 kg - 125 kg, LBWG 0.67 kg.d^{-1}; IPCC Tier 2, 9.4 kg.yr^{-1} (Dämmgen *et al.*, 2013)
23 - 50 Holstein, 1 yr; pasture, grass; FTIR, 342 g.d^{-1} (Griffith e*t al*., 2008)
12 Holstein heifers, 8 M, LBW 230 kg; rotationally grazed (flowers, clover, ryegrass); GF, 164 g.d^{-1}, 18.8 g.kg DMI^{-1} (Hammond *et al.*, 2015)
12 Holstein heifers, 8 M, LBW 230 kg; rotationally grazed (flowers, clover, ryegrass); SF$_6$, 186 g.d^{-1}, 21.5 g.kg DMI^{-1} (Hammond *et al.*, 2015)
4 Holstein HE, 14 M, LBW 317 kg; CS, GS; GF, 198 g.d^{-1}, 26.6 g.kg DMI^{-1} (Hammond *et al.*, 2015)
4 Holstein HE, 14 M, LBW 317 kg, GS; RC, GA, 215 g.d^{-1}, 28.3 g.kg DMI^{-1} (Hammond *et al.*, 2015)
4 Holstein HE, 14 M, LBW 339 kg; ryegrass HA, clover, trefoil and flowers; GF, 208 g.d^{-1}, 27.8 g.kg DMI^{-1} (Hammond *et al.*, 2015)
4 Holstein HE, 14 M, LBW 339 kg; ryegrass HA, clover, trefoil and flowers; RC, GA, 209 g.d^{-1}, 27.7 g.kg DMI^{-1} (Hammond *et al.*, 2015)
HE, grass, clover (grazed), RC (750 cm^2), GC, 1 kg dung, exposed 30 min., 1143 mg CH$_4$.m^{-2} (Jarvis *et al.*, 1995)
147 Holstein HE, feedlot; TMR, H; SF$_6$, 631 L.d^{-1} (Kaharabata *et al.*, 2000)
6 Holstein FS, LBW 334 kg; TMR, 41.4 % CS, 23.4 % grass H, 35.2 % CM; MBIGA, 103 g.d^{-1}, 0.31 g.kg LBW^{-1}, 13.6 g.kg DMI^{-1} (Newbold *et al.*, 2014)
10 Holstein FS, LBW 215 kg; grazing morning, oat; RC, GC, 92.24 mg.kg fecal matter^{-1}, 576.5 mg.kg DM^{-1}, 0.067 kg.yr^{-1} (Priano *et al.*, 2014)
10 Holstein FS, LBW 215 kg; grazing afternoon, oat; RC, GC, 16.13 mg.kg fecal matter^{-1}, 89.6 mg.kg DM^{-1}, kg.yr^{-1} (Priano *et al.*, 2014)
Holstein FS; alfalfa H, rice straw; RC, GA, 259.32 L.d^{-1}, 33.85 L.kg DMI^{-1} (Shibata *et al.*, 1993)
6 Holstein HE, LBW 401 kg, H 66.7 %, 33.3 % MC; RC, GA, 230.9 L.d^{-1}, 28.4 L.kg DMI^{-1} (Shibata *et al.*, 1992)
9 Holstein FS, LBW 150.5 kg; TMR, HCD; RC, MHA, 1.99 g.h^{-1} (Stackhouse *et al.*, 2011)
9 Holstein FS, LBW 336.4; TMR, HCD; RC, MHA, 3.16 g.h^{-1} (Stackhouse *et al.*, 2011)
9 Holstein FS, LBW 529.5 kg; TMR, HCD;RC, MHA, 4.15 g.h^{-1} (Stackhouse *et al.*, 2011)
4 Holstein HE, 18 M, LBWG 0.7 kg.d^{-1}; CS, alfalfa H; SF$_6$,168 g.d^{-1} (Westberg *et al.*, 2001)

Table 2: Methane production and emission factors of dairy cows

12 Holstein, LBW 600 kg, 38.9 kg ECM, 48, 125, 164, and 212 DIM; CS, clover S, CM; RC, GA, 669 L.day^{-1}, 30.6 L.kg DMI^{-1}, 24.2 L.kg ECM milk^{-1} (Alstrup *et al.*, 2015)
12 Holstein, LBW 600 kg, 38.9 kg ECM. 48, 125, 164, and 212 DIM; CS, clover S, rapeseed, CM; RC, GA, 588 L.day^{-1}, 29.8 L.kg DMI^{-1}, 17.7 L.kg ECM milk^{-1} (Alstrup *et al.*, 2015)
12 Holstein, LBW 600 kg, 38.9 kg ECM, 48, 125, 164, and 212 DIM; CS, clover S, CM, vegetable fat; RC, GA, 622 L.day^{-1}, 28.5 L.kg DMI^{-1}, 17.4 L.kg ECM milk^{-1} (Alstrup *et al.*, 2015)
12 Holstein, LBW 600 kg, 38.9 kg ECM, 48, 125, 164, and 212 DIM; CS, clover S, CM, calcium soaps of palm, hydrogenated palm; RC, GA, 564 L.day^{-1}, 25.6 L.kg DMI^{-1}, 14.9 L.kg ECM milk^{-1} (Alstrup *et al.*, 2015)
12 Holstein, LBW 600 kg, tie-stall, slurry MS or straw MS; mobile RC, FTIR, GC, 194.4 g.d^{-1}, 194.4 g.d^{-1} (Amon *et al.*, 2001)
36 Holstein, LBW 664 kg, MY 33.3 kg.d^{-1}; TMR, 36.0 GS, 21.0 CS, 17.8 WS; ASDM, 0.24 mg.L^{-1} (Bell *et al.*, 2014b)
36 Holstein, LBW 661 kg, MY 31.5 kg.d^{-1}; TMR, 36.1 CS, 19.3 GS, 18.4 WS; ASDM, 0.24 mg.L^{-1} (Bell *et al.*, 2014b)
36 Holstein, LBW 662 kg, MY 29.7 kg.d^{-1}; TMR, 22.6 GS, 25.3 CS, 21.5 WS; ASDM, 0.25 mg.L^{-1} (Bell *et al.*, 2014b)
Holstein, LBW 598 kg, MY 6970 L.lactation^{-1}, MF 273 kg.lactation^{-1}, MP 228 kg.lactation^{-1}; model, enteric 340 g.d^{-1}, manure 32 g.d^{-1} (Bell *et al.*, 2013)
Jersey, LBW 444 kg, MY 5030 L.lactation^{-1}, MF 243 kg.lactation^{-1}, MP 188 kg.lactation^{-1}; model, enteric 281 g.d^{-1}, manure 26 g.d^{-1} (Bell *et al.*, 2013)
Holstein, LBW 632 kg, lactation milk 8965 kg, milk fat 358 kg; model, enteric 395 g.d^{-1}, manure 114 g.d^{-1}, enteric 144 kg.yr^{-1}, manure 42 kg.yr^{-1} (Bell *et al.*, 2015)
700 Holstein, FTIR, January, March, June, September, combined emissions (pens and storage pond) 0.34, 0.55, 0.21, and 0.20 kg.d^{-1}, combined emissions 120 kg.yr^{-1} (Bjorneberg *et al.*, 2009)
3500 Holstein, free-stall, TMR (wheat H, WS, alfalfa H, CS, CM; FC, GC, 836 g. d^{-1} (Borhan *et al.*, 2011a)
500 Holstein, free-stall (barn, manure lane and bedding area, loafing pen, lagoon, settling basin, silage pile, walkway); TMR (wheat H, WS, alfalfa H, CS, CM; FC, GLAS, summer, 1.04, 0.66, 21.5, 85.0, 166.0, 0.26, 0.3 g.d^{-1}, total 274 g.d^{-1} (Borhan *et al.*, 2011b)
500 Holstein, free-stall (barn, manure lane and bedding area, loafing pen, lagoon, settling basin, silage pile, walkway), TMR (wheat H, WS, alfalfa H, CS, CM; FC, GLAS, winter, 0.58, 0.27, 5.1, 40.9, 4.7, 0.05, 0.25 g.d^{-1}, total 52 g.d^{-1} (Borhan *et al.*, 2011b)
4 Holstein, LBW 592 kg, MY 34.3 kg, 143 DIM; 54 % CS, 46 % GS, forage to MC 50:50, supplements rapeseed meal, rapeseed cake, cracked rapeseed and rapeseed oil; RC, GA, 569 L.d^{-1}, 20.4 L.kg ECM^{-1}, 29.6 L.kg DMI^{-1}, 531 L.d^{-1}, 19.0 L.kg ECM^{-1}, 29.9 L.kg DMI^{-1}, 478 L.d^{-1}, 16.9 L.kg ECM^{-1}, 25.8 L.kg DMI^{-1}, 462 L.d^{-1}, 16.7 L.kg ECM^{-1}, 26.4 L.kg DMI^{-1} (Brask *et al.*, 2013)
11 Holstein, MY 17.46 kg, 180 DIM, grass, CS, H, CM; SF$_6$, 429 g.day^{-1}, 21.9 g.kg milk^{-1} (Dehareng *et al.*, 2012)
8 Holstein, LBW 528 kg, 45.5 % cracked corn grain, 44.6 % alfalfa H; SF$_6$ vs. RC, GA, 22.3 g.kg DMI^{-1}, 431 g.d^{-1} vs. 21.9 g.kg DMI^{-1}. 455 g.d^{-1} (Deighton *et al.*, 2014)
4 Holstein, LBW 542 kg, MY 16.9 kg; TMR ad libitum vs. reduced to 2/3 (70 % silage, 4 % hay, 26 % CM); RC, GA, 420 L.d^{-1}, 328 L.d^{-1} (Derno *et al.*, 2009)
100 Holstein, MY 27.0 kg, TMR, GS, CS, CM; RC, GA, 381 g.day^{-1}, 21.5 g.kg DMI^{-1} (Dijkstra *et al.*, 2011)
8 Holstein, LBW 536 kg, MY 24.9 kg, 195 DIM; grazing, grass vs. legume, SF6, 372 g.d^{-1}, 521 L.d^{-1}, 20.6 g.kg FCM^{-1}, 22.7 g.kg DMI^{-1} vs. 364 g.d^{-1}, 510 L.d^{-1}, 18.6 g.kg FCM^{-1}, 21.6 g.kg DMI^{-1} (Dini *et al.*, 2012))
82 Holstein, LBW 454 to 786 kg, MY 11 to 61 L, DIM 20 to 430, parity 1 to 4; AL TMR; CM at milking, ASDM, GA, 369 g.d^{-1} (Garnsworthy *et al.*, 2012a)
12 Holstein, MY 20 to 40 L; AL TMR, GS, CS, alfalfa H; CM at milking, RC, GA, 395 g.d^{-1} (Garnsworthy *et al.*, 2012a)
215 Holstein, LBW 602 kg, MY 33 kg, DIM 161, parity 3; TMR AL, CM at milking; ASDM, 2.07 g.min^{-1}, 379 g.d^{-1} (Garnsworthy *et al.*, 2012b)
18 Holstein, LBW 660 kg, MY 31.7 kg; TMR, CM 27.5 % vs. 21.7 % digestible carbohydrates; ASDM, 447 g.day^{-1} vs. 438 g.day^{-1} (Haque *et al.*, 2014b)
12 pregnant Holstein, LBW 646 kg, MY 38.4 kg, GS:CS 70 : 30 vs. 30 : 70; SF6, 409 g.day^{-1}, 19.5 g.kg DMI^{-1}, 15.5 g.kg milk yield^{-1}, 316 g.kg milk fat^{-1}, 104 g.kg milk solids^{-1} vs. 397 g.day^{-1}, 17.8 g.kg DMI^{-1}, 14.7 g.kg milk yield^{-1}, 349 g.kg milk fat^{-1}, 99 g.kg milk solids^{-1} (Hart *et al.*, 2015)
16 Holstein, DIM 302.4, parity 2.8; group SL, TMR, GS 600 g.kg DMI^{-1}, CM 400 g.kg DMI^{-1},starch fermentation slowly, inclusion level low; RC, GA, 597 L.d^{-1} (Hatew *et al.*, 2015)

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16 Holstein, DIM 302.4, parity 2.8; group SH, TMR, starch fermentation slowly, inclusion level high, GS 600 g.kg DMI^{-1}, CM 400 g.kg DMI^{-1}; RC, GA, 545 L.d^{-1} (Hatew *et al*., 2015)

16 Holstein, DIM 302.4, parity 2.8; group RL, starch fermentation rapidly, inclusion level low, GS 600 g.kg DMI^{-1}, CM 400 g.kg DMI^{-1}; RC, GA,581 L.d^{-1} (Hatew *et al*., 2015)

16 Holstein, DIM 302.4, parity 2.8; group RH, starch fermentation rapidly, inclusion level high, GS 600 g.kg DMI^{-1}, CM 400 g.kg DMI^{-1}; RC, GA,557 L.d^{-1} (Hatew *et al*., 2015)

7 Dairy farms, no straw bedding, total (animals and manure), mobile TDL, 700 g.d^{-1} (Hensen *et al*., 2006)

3 Dairy farms with strawbedding, total (animals and manure), mobile TDL, 1400 g.d^{-1} (Hensen *et al*., 2006)

7 Dairy farms, slurry manure storage, winter, 1200 m^3, mobile TDL, 11 g.m^{-3}.d^{-1} (Hensen *et al*., 2006)

32 Swedish Red, LBW 664 kg, MY 30.2 kg, DIM 134; TMR (60 % forages, 40 % CM), CM from feed trough units; FMFT, 453 g.d^{-1}, SMFT 1405 ppm (Huhtanen *et al*., 2015)

107 Holstein, LBW 675 kg, MY 29.5 kg, LBWG 0.55 kg, TMR (60 % forages, 40 % concentrates), CM from feed trough AMS; FMFTAMS 447 g.d^{-1}, SMAMS 758 ppm (Huhtanen *et al*., 2015)

Dairy cow, grass, clover (grazed), CM; RC (750 cm^2), GC, 1 kg dung exposed 30 min., 1702 mg.m^{-2} (Jarvis *et al*., 1995)

Dairy cow, S, CM; RC (750 cm^2), GC, 1 kg dung exposed 30 min., 716 mg.m^{-2} (Jarvis *et al*., 1995)

Dairy cow, fertiliser grass, CM; RC (750 cm^2), GC, 1 kg dung exposed 30 min., 2040 mg.m^{-2} (Jarvis *et al*., 1995)

40 Holstein (12 PRIMI, 28 MULTI), grazing ryegrass, CM (2.0, 4.0, 6.0, and 8.0 kg.d^{-1}); SF6, 287, 273, 272, and 277 g.d^{-1}, 20.0, 19.3, 17.7, and 18.1 g.kg DMI^{-1}, 15.4, 12.9, 11.2, 10.8 g.kg milk^{-1} (Jiao *et al*., 2014)

36 Holstein, LBW 600 kg, MY 32.3 kg; diet 2.3 % fat; SF$_6$, 16.2 g.h^{-1}, 543 L.d^{-1}, 16.8 L.kg milk^{-1} (Johnson *et al*., 2002)

36 Holstein, LBW 600 kg, MY 39.3 kg; diet 4.0 % fat; SF$_6$, 16.4 g.h^{-1}, 550 L.d^{-1}, 14 L.kg milk^{-1} (Johnson *et al*., 2002)

36 Holstein, LBW 600 kg, MY 39.1 kg; diet 5.6 % fat; SF$_6$, 19.0 g.h^{-1}, 637 L.d^{-1}, 16.3 L.kg milk^{-1} (Johnson *et al*., 2002)

90 Holstein, LBW 600 kg; TMR and 1.5 kg H (timothy, alfalfa); SF$_6$, 542 L.cow^{-1}.d^{-1}, 19 L.kg of milk^{-1} (Kaharabata *et al*., 2000)

118 Holstein, tie-stall, LBW 602 kg, MY 28.5 kg; TMR, CM; MBIGA, 587 L.d^{-1}, after subtracting manure contribution 552 L.d^{-1}, 19.4 L.kg of milk^{-1} (Kinsman *et al*., 1995)

67 lactating cows, LBW 583 kg, MY 17 kg; RC, 420 L.d^{-1}, 24.7 L.kg milk^{-1} (Kirchgessner *et al*., 1991, cited by Boadi *et al*., 2004)

18 cows (11 Holstein, 7 Brown Swiss), LBW 649 kg, MY 16.9 kg, 215 DIM, parity 3.0; TMR corn diet (corn, ryegrass, barley, mixture of forage and CM 0.45 : 0.55; RC, GA, 303 g.d^{-1}, 22.8 g.kg DMI^{-1}, 22.1 g.kg milk^{-1} (Klevenhusen *et al*., 2011)

18 cows (11 Holstein, 7 Brown Swiss), LBW 649 kg, MY 16.9 kg, 215 DIM, parity 3.0; TMR corn diet (corn, ryegrass, barley, mixture of forage and CM 0.45 : 0.55; slurry stored 7 weeks at 14 °C vs. 27 °C; RC, GA, 0.4 g.d^{-1} vs. 9.8 g.d^{-1} (Klevenhusen *et al*., 2011)

18 cows (11 Holstein, 7 Brown Swiss), LBW 649 kg, MY 16.9 kg, 215 DIM, parity 3.0; TMR corn diet (corn, ryegrass, barley, mixture of forage and concentrate 0.45 : 0.55, slurry stored 15 weeks at 14 °C vs. 27 °C, RC, GA, 6.1 g.d^{-1} vs. 131.3 g.cow^{-1}.d^{-1} (Klevenhusen *et al*., 2011)

18 cows (11 Holstein, 7 Brown Swiss), LBW 649 kg, MY 16.9 kg, 215 DIM, parity 3.0, TMR barley diet (barley, corn, ryegrass, mixture of forage and CM 0.45 : 0.55); RC, GA, 364 g.d^{-1}, 24.0 g.kg DMI^{-1}, 23.6 g.kg milk^{-1} (Klevenhusen *et al*., 2011)

18 cows (11 Holstein, 7 Brown Swiss), LBW 649 kg, MY 16.9 kg, 215 DIM, parity 3.0, TMR barley diet (barley, corn, ryegrass, mixture of forage and CM 0.45 : 0.55); slurry stored 7 weeks at 14 °C vs. 27 °C, RC, GA, 0.6 g.d^{-1} vs. 7.5 g.d^{-1} (Klevenhusen *et al*., 2011)

18 cows (11 Holstein, 7 Brown Swiss), BW 649 kg, MY 16.9 kg, 215 DIM, parity 3.0, TMR barley diet (barley, maize, ryegrass), mixture of forage and concentrate (0.45 : 0.55), slurry stored 15 weeks at 14 °C vs. 27 °C, RC, GA, 5.6 g.d^{-1} vs. 108.1 g.d^{-1} (Klevenhusen *et al*., 2011)

18 cows (11 Holstein, 7 Brown Swiss), BW 649 kg, MY 16.9 kg, 215 DIM, parity 3.0; hay-only diet (low starch); RC, GA, 338 g.d^{-1}, 25.1 g.kg DMI^{-1}, 23.6 g.kg milk^{-1} (Klevenhusen *et al*., 2011)

18 cows (11 Holstein, 7 Brown Swiss), LBW 649 kg, MY 16.9 kg, 215 DIM, parity 3.0; hay-only diet (low starch); slurry stored for 7 weeks of storage at 14 °C vs. 27 °C; RC, GA, 1.5 g.d^{-1} vs. 15.8 g.d^{-1} (Klevenhusen *et al*., 2011)

18 cows (11 Holstein, 7 Brown Swiss), LBW 649 kg, MY 16.9 kg, 215 DIM, parity 3, hay-only diet (low starch), slurry stored for 15 weeks at 14 °C vs. 27 °C; RC, GA, 11.2 g.d^{-1} vs. 74.8 g.d^{-1} (Klevenhusen *et al*., 2011)

10800 Holstein, 20 open-lot pens (60 ha), wastewater storage pond (10 ha), compost yard (10 ha), LBW 635 kg; TMR; MBIGA, 490 g.d^{-1}, 103 g.m^{-2}.d^{-1}, 13.5 g.m^{-2}.d^{-1}, combined emissions (lots, wastewater pond and compost) 1.39 kg.d^{-1} (Leytem *et al*., 2010)

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24 Holstein, LBW 582 kg, MY 24.5 kg, 231 DIM; ryegrass, meadow, CM 1 kg vs. 6 kg; SF$_6$, 346 g.d^{-1} vs. 399 g.d^{-1}, 19.60 g.kg DMI^{-1} vs. 17.83 g.kg DMI^{-1}, 19.26 g.kg FCM^{-1} vs. 16.02 g.kg FCM^{-1} (Lovett *et al*., 2005)

4 Holstein cows, LBW 705 kg, 113 DIM, MY 29.3 kg; TMR (60 : 40 forage : CM); SF6, 326.6 g.d^{-1}, 15.8 g.kg DMI^{-1}, 11.7 g.kg milk^{-1}, 13.2 g.kg FCM^{-1} (Meale *et al*., 2014)

10 Holstein, LBW 593 kg, milk per lactation 6502 kg, dry period, entire lactation; grass, H AL; RC, GA, 196 g.d^{-1}, 394 g.d^{-1} (Münger and Kreuzer, 2006)

10 Jersey, LBW 354 kg, milk per lactation 4097 kg, dry period, entire lactation; grass, H AL; RC, GA, 149 g.d^{-1}, 309 g.d^{-1} (Münger and Kreuzer, 2006)

10 Simmental, LBW 636 kg, milk per lactation 5578 kg, dry period, entire lactation; grass, H AL; RC, GA, 222 g.d^{-1}, 392 g.d^{-1} (Münger and Kreuzer, 2006)

20 (4 Norwegian, 4 Norwegian × Holstein, 12 Holstein), 4 PRIMI, 16 MULTI, MY 22.9 kg, 56 DIM; GS, CM 45 % DM basis; SF$_6$, 469 g.d^{-1}, RC, GA 422 g.d^{-1}, 24.3 g.kg DMI^{-1}, 19.9 g.kg milk^{-1} (Muñoz *et al*., 2012)

24 Holstein, LBW 494 kg, 70 DIM, parity 3.4; grazing ryegrass, 1 kg CM vs. 5 kg CM (reduce herbage intake by 1.8 kg DM.d^{-1} compared to cows receiving 1 kg CM); SF$_6$, 323 g.d^{-1}, 357 g.d^{-1} (Muñoz *et al*., 2015)

24 Holstein, 70 DIM, LBW 494 kg, parity 3.4; grazing ryegrass, 1 kg CM or 5 kg CM (reduce herbage intake by 4.4 kg DM/d, compared to cows receiving 1 kg CM); SF$_6$, 349 g.d^{-1}, 390 g.d^{-1} (Muñoz *et al*., 2015)

164 – 195 Holstein, LBW 600 kg, MY 31 – 33 kg; GS, CS, CM; MBIGA, 9.0 – 13 g.LU^{-1}.h^{-1} (Ngwabie *et al*., 2009)

141 lactating Holstein vs. 75 dry Holstein; model, 363 g.d^{-1} vs. 241 g.d^{-1} (Ngwabie *et al*., 2014)

141 lactating Holstein, 75 dry, model; enteric 312 g.d^{-1}, indoor manure 73 g.d^{-1} (Ngwabie *et al*., 2014)

9 Friesian x Jersey, LBW 407 kg, 3 yr, 167 DIM; grazing, ryegrass and white clover; SF$_6$, 327 g.d^{-1} (Pinares-Patiño *et al*., 2007)

9 Friesian x Jersey, LBW 455 kg, 3 years, non-lactating, non-pregnant; fresh pasture forage; SF$_6$, 301 g.d^{-1}, 26.4 g.kg DMI^{-1} (Pinares-Patiño *et al*., 2007)

12 Friesian x Jersey, LBW 402, 3 yr; pasture ryegrass, white clover, 2 periods; SF$_6$, 144.5 g.d^{-1}, 147.9 g.d^{-1}, 346 mg.kg LBW^{-1}, 345 mg.kg LW^{-1} (Pinares-Patińo *et al*., 2008)

88 – 109 Holstein, LBW 600 kg, MY 29 kg; TMR, CS 30 %; alfalfa HA 26 %; H 9 %, CM 35 %; MBIGA, 622 L.d^{-1}, 21.4 L.kg milk^{-1} (Sauer *et al*., 1998)

6 Holstein, LBW 603 kg, MY 37.1 kg, 3.6 yr, 62 DIM; TMR, CS, alfalfa H, corn, CM; RC, GA, 557 L.d^{-1}, 15 L.kg milk^{-1} (Sechen *et al*.,1989)

Holstein, pregnant, dry; CS, alfalfa H, H, CM; RC, GA, 268.43 L.d^{-1}, 33.84 L.kg DMI^{-1} (Shibata *et al*., 1993)

Holstein lactating; CS, alfalfa H, H, CM; RC, GA, 464.04 L.d^{-1}, 27.17 L.kg DMI^{-1} (Shibata *et al*., 1993)

9 dry Holstein, Free-stall, LBW 770 kg; TMR, alfalfa, oat H, CM; MBIGA, cow and manure 12.35 g.h^{-1} (Sun *et al*., 2008)

9 lactating Holstein, Free-stall, LBW 565 kg, MY 31 kg; TMR, Corn, alfalfa, oat H, cottonseed meal, CM; MBIGA, cow and manure 18.23 g.h^{-1} (Sun *et al*., 2008)

720 Holstein, LBW 602 kg; MBIGA, 305 g.d^{-1} (Zhu *et al*., 2011)

4 Holstein, LBW 673 kg, MY 22 kg; alfalfa based diet; SF$_6$, 446 g.d^{-1} (Westberg *et al*., 2001)

4 Holstein, LBW 673 kg, MY 22 kg; corn based diet; SF$_6$, 405 g.d^{-1} (Westberg *et al*., 2001)

CONCLUSION

Agriculture is a major contributor to GGE, in particular of methane. The actual rate of CH$_4$ emission is highly dependent on the management strategies implemented on a farm. Consequently, improvements in management practices and changes in demand for livestock products will affect future CH$_4$ emissions.

Knowledge of experimental studies that quantify CH$_4$ production from agriculture is important in order to better establish typical emission ranges for farms and the effect of management factors on these emissions.

Further research will address these limitations through direct measurement of livestock methane emissions from a range of forages and through the integration of selected forage inputs. New approaches will be required in genetics and nutrition to provide perspective on the contribution of CH$_4$ emission from ruminants to global GHG emissions. Specifically, data are needed on CH$_4$ emissions from manure storage and housing facilities.

Table 3: Methane production and emission factors of beef cattle

Simbrah HE (5/8 Brahman, 3/8 Simmental), 1 yr; grazing, bermudagrass, bahiagrass, and ryegrass, winter bahiagrass H, CM;SF$_6$, 89 – 180 g.d^{-1} (DeRamus *et al.*, 2003)

Simbrah cows (5/8 Brahman, 3/8 Simmental), 3 to 7 yr, grazing, bermudagrass, bahiagrass, and ryegrass, winter bahiagrass H, CM, SF$_6$, 165 – 294 g.d^{-1} (DeRamus *et al.*, 2003)

4 Murray Gray x Charolais x Angus HE, 19 M, pregnant 3 M, LBW 435.5 kg;grazing, Yorkshire fog, Phalaris, Dead grass vs. feedlot, oats, alfalfa; MMT, 260 g.d^{-1}vs. 66 g.d^{-1} (Harper *et al.*, 1999)

Calf, fertilized (N) grass (grazed); RC (750 cm^2), GC, 1 kg dung exposed 30 min., 1655 mg CH$_4$.m^{-2} (Jarvis *et al.*,1995)

Heifer, grass-clover (grazed), RC (750 cm^2), GC, 1 kg dung exposed 30 min., 1143 mg CH$_4$.m^{-2} (Jarvis *et al.*,1995)

Heifer, low-N grass (grazed), RC (750 cm^2), GC, 1 kg dung exposed 30 min., 423 mg CH$_4$.m^{-2} (Jarvis *et al.*, 1995)

Steer, grass-clover (grazed), RC (750 cm^2), GC, 1 kg dung exposed 30 min., 406 mg CH$_4$.m^{-2} (Jarvis *et al.*,1995)

Steer, low (N) grass (grazed), RC (750 cm^2), GC, 1 kg dung exposed 30 min., 503 mg CH$_4$.m^{-2} (Jarvis *et al.*,1995)

Steer, unfertilized (N) grass (grazed), RC (750 cm^2), GC, 1 kg dung exposed 30 min., 300 mg CH$_4$.m^{-2} (Jarvis *et al.*,1995)

Suckler cow, rough grazing, RC (750 cm^2), GC, 1 kg dung exposed 30 min., 922 mg CH$_4$.m^{-2} (Jarvis *et al.*,1995)

13 Brahman steers (*Bos indicus*), LBW 227 kg; 22 diets, 5 tropical grass, 5 legumes; RC, GA, from 42.0 to 159.0 g.day^{-1} or from 17.5 to 22.4 g.kg DMI^{-1} (Kennedy and Charmley, 2012)

HE, enteric fermentation, 61 kg.yr^{-1} (Lima *et al.*, 2010; citated by Mazzetto *et al.*, 2015b)

Cow, enteric fermentation, 63 kg.yr^{-1} (Lima *et al.*, 2010; citated by Mazzetto *et al.*, 2015b)

Bull, enteric fermentation, 55 kg.yr^{-1} (Lima *et al.*, 2010; citated by Mazzetto *et al.*, 2015b)

Calf, enteric fermentation, 42 kg.yr^{-1} (Lima *et al.*, 2010; citated by Mazzetto *et al.*, 2015b)

Steer, enteric fermentation, 42 kg.yr^{-1} (Lima *et al.*, 2010; citated by Mazzetto *et al.*, 2015b)

Beef cattle, 13,800, feedlot, LBW 265 - 620 kg vs. 16,500, feedlot, LBW 280 - 700 kg; high grain diets; OPL, model, 146 g.d^{-1} vs. 166 g.d^{-1} (Loh *et al.*, 2008)

Beef cattle, faeces, 0.08 kg.yr^{-1} (Mazzetto *et al.*, 2014)

13,800 beef cattle, feedlot, Australia, LBW 350 - 600 kg vs. 22,500 beef cattle, feedlot, Canada, LBW 265 - 620 kg; high grain diet; OPL, model, 166 g.d^{-1} vs. 214 g.d^{-1} (McGinn *et al.*, 2008)

30 Brahman cattle (*Bos indicus*), LBW 425 kg, grazed, Rhodes grass, Sabi grass, and Verano Stylo; OPL, 240 – 250 g.d^{-1} (McGinn *et al.*, 2015)

6 Angus steers, 1 yr; pastures, tall fescue, white clover; SF$_6$, 95 to 200 g.d^{-1} (Pavao-Zuckerman *et al.*, 1999)

4 Angus cows, 3 yr; pastures, tall fescue, white clover; SF$_6$, 150 – 240 g.d^{-1} (Pavao-Zuckerman *et al.*, 1999)

192 cattle, feedlot; corn, distillers grains, CS, H; air samples, GC,2.66 ppm, overall emissions 1.32 g m^{-2} d^{-1} (Rahman *et al.*, 2013)

8 Belmont Red steers, LBW 436; Rhodes grass H, CM; RC, GA, 174.1g.d^{-1}, 20.0 g.kg DMI^{-1}, 0.36 g.kg LBW^{-1} (Ramírez-Restrepo *et al.*, 2014)

72 Angus and Limousin crossbred, steers, LBW 673 kg, 16 M, low concentrate diet (48:52 forage to concentrate ratio (40 % grass silage, 35 % barley silage, 15 % barley grain, and 10 % maize distillers dark grains) vs. high concentrate diet (8:92 forage to concentrate ratio (12 % straw, 68 % barley grain, and 20 % maize distillers dark grains); RC, GA, 205 g.d^{-1} vs. 145 g.d^{-1} (Ricci *et al.*, 2015)

9 Black Angus crossed steers, LBW 340 kg, high concentrate diet; RC, MHA, 2.85 g.h^{-1} (Stackhouse *et al.*, 2011)

9 Black Angus crossed steers, LBW 544 kg, high concentrate diet; RC, MHA, 4.18 g.h^{-1} (Stackhouse *et al.*, 2011)

9 Brahman (*B. indicus*) and 9 Belmont Red (*Bos taurus* x *African Sanga*) steers, LBW 222 kg; grazed, pasture Rhodes grass, OPL, 136.1g.d^{-1}, 29.7 g.kg DMI^{-1}, 0.57 ± 0.067 g.kg LW^{-1} (Tomkins *et al.*, 2011)

9 Brahman (*B. indicus*) and 9 Belmont Red *(Bos taurus* x *African Sanga*) steers, LBW 222 kg; freshly cut Rhodes grass; OPL, 114 g.d^{-1}, 30.1 g kg DMI^{-1}, 0.49 g.kg LW^{-1} (Tomkins *et al.*, 2011)

12bulls, LBW 498 kg, 9 M; pasture good (spring), poor (fall), winter feed diet;SF6, 231 g.d^{-1}, 188 g.d^{-1},228 g.d^{-1} (Westberg *et al.*, 2001)

4 suckling calves, LBW 206 kg, 4 M; pasture;SF$_6$, 53 g.d^{-1} (Westberg *et al.*, 2001)

16 cows, LBW 585 kg, 4 yr; pasture, good (spring), poor (fall), winter feed diet, early lactating diet;SF$_6$, 231 g.d^{-1}, 188 g.d^{-1}, 211 g.d^{-1}, 201 g.d^{-1} (Westberg *et al.*, 2001)

12 HE, LBW 225 – 275 kg, 18 M; grower diet, good pasture, poor pasture; SF$_6$, 135 g.d^{-1}, 179 g.d^{-1}, 223 g.d^{-1} (Westberg *et al.*, 2001)

8 beef, feedlot, LBW 544 kg, LBWG 0.9 kg vs. 0.5 kg, 12-17 M; high-grain finishing diet vs. stocker diet; SF$_6$, 193 g.d^{-1} vs. 175 g.d^{-1} (Westberg *et al.*, 2001)

Table 4: Methane production and emission factors of goats and sheep

4 Japanese goats, 2 years, LBW 26 kg; timothy H, alfalfa H, corn, MC; RC, GA, 31 mL.g DMI^{-1} (Bhatta *et al.*, 2008)

Sheep, Scottish grey face; grazing, ryegrass, 10.8 ha; OMA, 20.5 g.d^{-1}, 7.4 kg yr^{-1} (Dengel *et al.*, 2011)

16 weaned lambs, Welsh Mountain vs. Welsh Mule × Texel, fresh cut ryegrass, RC, GA, 15 g.d^{-1} vs. 17 g.d^{-1}, 16.1 g.kg DMI^{-1} vs. 16.7 g.kg DMI^{-1}, 5.4 kg.yr^{-1} vs. 6.3 kg.yr^{-1} (Fraser *et al.*, 2015)

16 weaned lambs, Welsh Mountain vs. Welsh Mule × Texel, fresh cut permanent pasture, RC, GA, 12 g.d^{-1}vs. 14 g.d^{-1}, 16.7 g.kg DMI^{-1} vs. 18.8 g.kg DMI^{-1}, 4.3 kg.yr^{-1} vs. 5.1 kg.yr^{-1} (Fraser *et al.*, 2015)

9 lambs, 90 d, LBW 20.9 kg; grass H; GA, 19.9 g.d^{-1}, 116.3 g.kg LBWG^{-1}, 31.1 g.kg DMI^{-1} (Haque *et al.*, 2014a).

9 lambs, 90 d, LBW 21.8 kg, 2.5 L.d^{-1}; 50:50 MR, dairy cream; GA, 3.2 g.d^{-1}, 11.5 g.kg LBWG^{-1}, 4.3 g.kg DMI^{-1} (Haque *et al.*, 2014a).

9 lambs, 150 d, LBW 33.7 kg; grass H; GA, 19.1 g.d^{-1}, 113.9 g.kg LBWG^{-1}, 34.3 g.kg DMI^{-1} (Haque *et al.*, 2014a).

9 lambs, 150 d, LBW 34.7 kg, 2.5 L.d^{-1}; 50:50 MR, dairy cream; GA, 2.4 g.d^{-1}, 9.1 g.kg LBWG^{-1}, 1.1 g.kg DMI^{-1} (Haque *et al.*, 2014a).

4 wether sheep, 1.5 yr, LBW 51.0 kg; white clover; RC, GA, 25.7 g.d^{-1}, 22.5 kg.DMI^{-1} (Hammond *et al.*, 2014)

4 wether sheep, 1.5 yr, LBW 51.0 kg, ryegrass; RC, GA, 24.5 g.d^{-1}, 22.0 kg.DMI^{-1} (Hammond *et al.*, 2014)

30 wether sheep, 5x6, LBW 51.4 kg; ryegrass, 0.50, 0.76, 1.02, 1.26, 1.51 kg DM.d^{-1}; RC, GA, 13.1 g.d^{-1}, 27.0 g.kg DMI^{-1}; 19.5 g.d^{-1}, 27.0 g.kg DMI^{-1}; 23.2 g.d^{-1}, 25.2 g.kg DMI^{-1}; 27.1 g.d^{-1}, 25.3 g.kg DMI^{-1}; 31.9 g.d^{-1}, 23.9 g.kg DMI^{-1} (Hammond *et al.*, 2014)

Sheep, H, CM; RC (750 cm^2), GC, 1 kg dung exposed 30 min., 598 mg CH_4.m^{-2} (Jarvis *et al.*, 1995)

4 Korean native black goats, LBW 23.5 kg; 50:50 forage, CM; RC, GA, 11.6 g.d^{-1}, 24.7 g.kg DMI^{-1} (Li *et al.*, 2010)

41 sheep, metaanalysis, LBW 47.6 kg; 19.0 g.d^{-1} , 20.3 g.kg DMI^{-1} (Patra, 2014)

20 Romney sheep, 14 M, LBW 45 kg; grazing, ryegrass, white clover; SF_6, 28.9 - 35.5 g.d^{-1} (Pinares-Patiño *et al.*, 2003)

24 Scottish Mule ewes, 29 DIM, 5.5 yr, LBW 68 kg; alfalfa AL vs. restricted alfalfa (0.8 of AL); RC, LMD, 109.7 g.pair$^{-1.d-1}$, 83.2 g.pair$^{-1.d-1}$ (Ricci *et al.*, 2015)

160 ewes, 50:50 alfalfa H, oaten H; MBIGA, 22.2 g.d^{-1} (Robinson *et al.*, 2014)

10 wethers sheep, Corriedale, LBW 71 kg; 66.7:33.3 H, CM; RC, GA, 34.3 L.d^{-1}, 25.9 L.kg DMI^{-1} (Shibata *et al.*, 1992)

11 wether goats, Japanese native, LBW 39 kg; 66.7:33.3 H, CM; RC, GA, 25.2 L.d^{-1}, 27.1 L.kg DMI^{-1} (Shibata *et al.*, 1992)

Sheep, goats; H, CM; RC, GA, 28.55 L.d^{-1}, 26.70 L.kg DMI^{-1} (Shibata *et al.*, 1993)

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