

UC Davis

UC Davis Previously Published Works

Title

SPECIAL TOPICS-Mitigation of methane and nitrous oxide emissions from animal operations:
I. A review of enteric methane mitigation options

Permalink

<https://escholarship.org/uc/item/95s326kt>

Journal

Journal of Animal Science, 91(11)

ISSN

0021-8812

Authors

Hristov, AN
Oh, J
Firkins, JL
[et al.](#)

Publication Date

2013

DOI

10.2527/jas.2013-6583

Peer reviewed

JOURNAL OF ANIMAL SCIENCE

The Premier Journal and Leading Source of New Knowledge and Perspective in Animal Science

SPECIAL TOPICS — Mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options

A. N. Hristov, J. Oh, J. L. Firkins, J. Dijkstra, E. Kebreab, G. Waghorn, H. P. S. Makkar, A. T. Adesogan, W. Yang, C. Lee, P. J. Gerber, B. Henderson and J. M. Tricarico

J ANIM SCI 2013, 91:5045-5069.

doi: 10.2527/jas.2013-6583 originally published online September 17, 2013

The online version of this article, along with updated information and services, is located on the World Wide Web at:

<http://www.journalofanimalscience.org/content/91/11/5045>



American Society of Animal Science

www.asas.org

References

This article cites 236 articles, 34 of which you can access for free at:
<http://www.journalofanimalscience.org/content/91/11/5045#BIBL>

Citations

This article has been cited by 2 HighWire-hosted articles:
<http://www.journalofanimalscience.org/content/91/11/5045#otherarticles>

SPECIAL TOPICS—Mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options¹

A. N. Hristov,^{*2} J. Oh,^{*} J. L. Firkins,[†] J. Dijkstra,[‡] E. Kebreab,[§] G. Waghorn,[#] H. P. S. Makkar,^{||} A. T. Adesogan,[¶] W. Yang,^{**} C. Lee,^{*} P. J. Gerber^{||}, B. Henderson^{||}, and J. M. Tricarico^{††}

^{*}Department of Animal Science, The Pennsylvania State University, University Park 16802; [†]The Ohio State University, Columbus 43210; [‡]Wageningen University, 6700 AH Wageningen, The Netherlands; [§]University of California–Davis, Davis 95616; [#]DairyNZ, Hamilton 3240, New Zealand; ^{||}Agriculture and Consumer Protection Department, Food and Agriculture Organization of the United Nations, 00153 Rome, Italy; [¶]Department of Animal Sciences, University of Florida, Gainesville 32608; ^{**}Agriculture and Agri-Food Canada, Lethbridge AB T1J 4B1, Canada; and ^{††}Innovation Center for U.S. Dairy, Rosemont, IL 60018

ABSTRACT: The goal of this review was to analyze published data related to mitigation of enteric methane (CH₄) emissions from ruminant animals to document the most effective and sustainable strategies. Increasing forage digestibility and digestible forage intake was one of the major recommended CH₄ mitigation practices. Although responses vary, CH₄ emissions can be reduced when corn silage replaces grass silage in the diet. Feeding legume silages could also lower CH₄ emissions compared to grass silage due to their lower fiber concentration. Dietary lipids can be effective in reducing CH₄ emissions, but their applicability will depend on effects on feed intake, fiber digestibility, production, and milk composition. Inclusion of concentrate feeds in the diet of ruminants will likely decrease CH₄ emission intensity (Ei; CH₄ per unit animal product), particularly when inclusion is above 40% of dietary dry matter and rumen function is not impaired. Supplementation of diets containing medium to poor quality forages with small amounts of concentrate feed will typically decrease CH₄ Ei. Nitrates show promise as CH₄ mitigation agents, but more studies are

needed to fully understand their impact on whole-farm greenhouse gas emissions, animal productivity, and animal health. Through their effect on feed efficiency and rumen stoichiometry, ionophores are likely to have a moderate CH₄ mitigating effect in ruminants fed high-grain or mixed grain–forage diets. Tannins may also reduce CH₄ emissions although in some situations intake and milk production may be compromised. Some direct-fed microbials, such as yeast-based products, might have a moderate CH₄–mitigating effect through increasing animal productivity and feed efficiency, but the effect is likely to be inconsistent. Vaccines against rumen archaea may offer mitigation opportunities in the future although the extent of CH₄ reduction is likely to be small and adaptation by ruminal microbes and persistence of the effect is unknown. Overall, improving forage quality and the overall efficiency of dietary nutrient use is an effective way of decreasing CH₄ Ei. Several feed supplements have a potential to reduce CH₄ emission from ruminants although their long-term effect has not been well established and some are toxic or may not be economically feasible.

Key words: enteric methane, mitigation, ruminant animal

© 2013 American Society of Animal Science. All rights reserved.

J. Anim. Sci. 2013.91:5045–5069
doi:10.2527/jas2013-6583

¹This article is part of a series of articles examining methane and nitrous oxide mitigation practices for livestock operations. The article is derived in part from a published review of mitigation options for the livestock sector funded by the Food and Agriculture Organization (FAO) of the United Nations (Hristov et al., 2013b), with the consent of FAO. The views expressed in this information product are those of the authors and do not necessarily reflect the views or policies of FAO. The authors would like to thank the reviewers of the original report by Hristov et al. (2013b): M. Doreau, R. Eckard, D. Hongmin, T. McAllister, H. Montgomery, M. Powell, S. Sommer, and M. Tibbo.

²Corresponding author: anh13@psu.edu

Received April 12, 2013.

Accepted August 18, 2013.

INTRODUCTION

The livestock sector represents a significant source of greenhouse gas (GHG) emissions worldwide, generating carbon dioxide (CO₂), methane (CH₄; i.e., enteric CH₄ in this review), and nitrous oxide (N₂O) either directly (e.g., from enteric fermentation and manure management) or indirectly (e.g., from feed-production

activities and conversion of forest into pasture). Using a life cycle assessment (LCA) approach and accounting for land-use change, Steinfeld et al. (2006) estimated that the livestock sector contributes about 18% of the total global anthropogenic GHG emissions. Based on data by the U.S. Environmental Protection Agency (USEPA, 2006), the direct livestock contribution to non-CO₂ emissions (i.e., CH₄ and N₂O) can be estimated at 7.3 and 7.5% of the global GHG emission values for 2010 and 2020 and can be even lower for some industrialized countries (3.1% of the total U.S. GHG emissions in 2009; USEPA, 2011). Enteric fermentation and manure decomposition, the processes responsible for CH₄ and N₂O emissions, are the main targets of GHG mitigation practices for the livestock industries. Discussions in this review are based on a recent comprehensive review of non-CO₂ GHG mitigation measures for the livestock sector by Hristov et al. (2013b). The second (Montes et al., 2013) and third (Hristov et al., 2013c) papers in this series address CH₄ and N₂O emissions from manure decomposition and animal management-related CH₄ and N₂O mitigation strategies, respectively. Interactions among mitigation practices for individual components of livestock production systems are discussed in Gerber et al. (2013).

ENTERIC METHANE EMISSIONS FROM FARM ANIMALS AND WILD RUMINANTS

Methane and CO₂ are natural by-products of microbial fermentation of carbohydrates and, to a lesser extent, AA in the rumen and the hindgut of farm animals. Methane emissions represent a loss of about 5 to 7% of dietary GE (to as low as 3% in cattle fed high-grain diets) and are about 16 to 26 g/kg of dietary DMI (could be lower with diets containing very high proportions of grain). Sheep and goats produce 10 to 16 kg CH₄/yr and cattle 60 to 160 kg/yr, depending on their size and DMI. Methane is produced in strictly anaerobic conditions by highly specialized methanogenic prokaryotes, all of which are archaea. In ruminants, current techniques estimate that the majority of CH₄ production occurs in the reticulorumen. Rectal emissions account for about 2 to 3% of the total CH₄ emissions in sheep or dairy cows (Murray et al., 1976; Muñoz et al., 2012). As stated by Van Soest (1994), the basic problems in anaerobic metabolism are the storage of oxygen (i.e., as CO₂) and disposal of hydrogen equivalents (i.e., as CH₄). Recently, a new group of methylotrophic methanogens (belonging to the so-called rumen cluster-C group) that does not require hydrogen as an energy source has been described and appears to play a role in CH₄ formation in ruminants (Poulsen et al., 2012).

Domestic nonruminant herbivore animals (horses, donkeys, mules, and hinnies) also produce CH₄ as a re-

sult of fermentation processes in their hindgut. Hindgut fermenters, however, do not produce as much CH₄ per unit of fermented feed as ruminants, perhaps as a result of availability of hydrogen sinks other than CH₄ (Jensen, 1996) and lower absolute amounts of CH₄ produced due to digestion of feed in the small intestine before entering the hindgut. The Intergovernmental Panel for Climate Change (IPCC, 2006) assumed CH₄ emissions from horses at 18 kg/head per yr (compared with 128 kg/head per yr for a high-producing dairy cow of similar BW).

Wild animals, especially ruminants, also emit CH₄ from enteric fermentation in their reticulorumen or the hindgut (Crutzen et al., 1986; Jensen, 1996; Galbraith et al., 1998; Kelliher and Clark, 2010). The present-day contribution of wild ruminants to the global GHG emissions, however, is relatively low. Current CH₄ emissions from wild ruminants (bison, elk, and deer) for the contiguous United States were estimated at about 6 Tg CO₂-equivalents (CO₂e)/yr, or 4.3% of the emissions from domestic ruminants (Hristov, 2012). In contrast, in the presettlement period, wild ruminants emitted from 62 to 154 Tg CO₂e/yr, depending on the assumed size of the bison population, which is on average about 86% of the present-day CH₄ emissions from domestic ruminants in the contiguous United States (Hristov, 2012). Marsupials present a special case. Although their diet is similar to that of ruminants, they reportedly produce little or no CH₄ (Kempton et al., 1976). Recent data by Madsen and Bertelsen (2012), however, reported wallabies produce CH₄ at a rate of about 1.6 to 2.5% of their GE intake (GEI), which is about one-third of the expected CH₄ emission from ruminants consuming a similar diet.

Relative to ruminants, monogastric farm animals are minor emitters of CH₄. For example, the IPCC (2006) assumed CH₄ emission factors for pigs at about 1.2 to 2.8% of the emission factors for cattle [1.5 vs. 53 (beef or growing cattle) or 128 kg CH₄/head per yr for a high-producing North American dairy cow]. Recent estimates place total GHG emissions from pigs and poultry at about 9.5 and 9.7%, respectively, of the GHG emissions from livestock (FAO, 2013).

MITIGATION DATABASE

More than 900 publications were selected and reviewed by Hristov et al. (2013b). In analyzing the effects of various mitigation practices on CH₄ emissions, the authors did not account for the effect of these practices in the whole-farm or production cycle context. This task can be accomplished through LCA. The current analysis placed particular emphasis on animal experimentation data, and therefore, LCA were generally excluded. Data generated by rumen-simulation *in vitro* batch or continuous culture systems were deliberately

excluded. In vitro systems are convenient for screening a large number of treatments, but due to various factors, they lack representativeness of the in vivo rumen (Hristov et al., 2012) and usually do not address the major question of adaptation of the rumen ecosystem to the mitigation practice. The rumen microbes can adapt to some bioactive compounds (saponins, for example) and perhaps not to others (Makkar and Becker, 1997; Wallace et al., 2002). Unfortunately, although scientists are clearly aware of this issue, very few in vivo studies have examined the long-term effect of mitigation agents or practices. Therefore, for most of the CH₄ mitigation practices discussed in this document, data for persistency of the effect are critically needed.

The vast majority of the studies covered in the original review by Hristov et al. (2013b) examined mitigation practices in isolation and rarely discussed potential interactions in the context of the whole production system. This is a significant disadvantage of the mitigation literature because mitigation practices may counteract or be synergistic to each other (del Prado et al., 2010). In the context of the whole-farm GHG emission reductions, it is important that assessments of mitigation practices take into account “pollution swapping,” that is, decreasing the emissions of one GHG while increasing another or causing an upstream or downstream increase in the emission of the same GHG.

The metrics used to quantify GHG emissions should accurately reflect the mitigation potential of various practices and should be standardized. Despite documented relationships among digestibility, intake, and CH₄ production (absolute or per unit of DMI), the CH₄ conversion rate factor (Y_m) used by the IPCC (2006) is calculated as CH₄ energy as percent of GEI. Ellis et al. (2010) evaluated 9 empirical CH₄ prediction equations and observed the Y_m factor model to perform adequately, compared with other equations. However, these authors argued that because it is based simply on GEI, Y_m does not have the capacity to fully describe changes in composition of the diet and has limited use when estimating the impact of varying nutritional strategies on CH₄ emissions. For example, the IPCC Y_m model could not decipher between an increase in CH₄ caused by an increase in DMI and a change in CH₄ caused by an increase in the fat content of the diet, which would have differing effects on the resulting CH₄ emission but may not differ in GEI. Thus, the validity of the Y_m approach is questionable, and perhaps CH₄ energy loss should be expressed on a DE basis, which will better reflect forage quality and other mitigation practices, such as grain or fat inclusion in ruminant diets. The term “emission intensity” (E_i ; in this manuscript, this is CH₄ or total GHG per unit animal product) has been introduced for CH₄ emission (Leslie et al., 2008) and, because it is based on emissions per unit of product, reflects most accurately the effect of a given

mitigation practice on the composite of feed intake, CH₄ emission, and animal productivity.

The accuracy and precision of CH₄ measurement techniques is another important consideration when examining mitigation practices. For example, several publications have reviewed various aspects of measuring CH₄, with particular emphasis on the sulfur hexafluoride (SF₆) technique (Makkar and Vercoe, 2007; Williams et al., 2011; Lassey et al., 2011; Storm et al., 2012). The SF₆ tracer method has been shown to produce larger variability than respiration chambers (Grainger et al., 2007; Hammond et al., 2009; Clark, 2010; Moate et al., 2011), but it enables emissions to be determined in a large number of animals and in free grazing conditions. Novel in vivo approaches, such as the use of CO₂ as a tracer gas (Madsen et al., 2010) and the Green-Feed system (C-Lock, Inc., Rapid City, SD; Huhtanen et al., 2013; Hammond et al., 2013b), have also been proposed. Therefore, when evaluating mitigation practices, it is important to examine critically the measurement methods used, particularly in relation to CH₄ production.

Another critical aspect of all mitigation practices, including those targeting CH₄, that must be considered is their likelihood of adoption. Farmers are unlikely to adopt practices that 1) have no production (i.e., economic) benefit or 2) are not mandatory and/or supported by governmental subsidies. Overall, unrealistic expectations on non-CO₂ GHG emission reductions from the livestock sector must be avoided. In any production system, profitability is often the most important decision-making factor that will determine adoption of any of the mitigation practices. Any practice that requires additional investment without a clear positive economic return or has a chance of decreasing animal productivity or increasing production cost is likely to be rejected by the livestock producer. Therefore, when assessing the mitigation potential of various practices, users must consider the combined effects of interactions among animal–manure–soil–crop processes related to whole-farm profitability, potential effectiveness on farms (vs. experimental results), and the likely adoption rate. Also, further attention is needed to better document variation associated with mitigation practices so that livestock producers can assess uncertainty and risk. It is important to realize, for example, that most ruminants (including beef before entering a feedlot) graze pastures under extensive, low intensity systems, which makes implementation of mitigating strategies very challenging.

MITIGATION OPTIONS

Comprehensive reviews on enteric and manure CH₄ (and N₂O) mitigation technologies and overall farm sustainability have been published (Harris and Kolver, 2001; Boadi et al., 2004; Kebreab et al., 2006; Ellis et al., 2008; Beauchemin et al. 2007b, 2009; Eckard et al.,

2010; Martin et al., 2010; Cottle et al., 2011; Goel and Makkar, 2012; for a full list see Hristov et al., 2013b) and data from these reports have been extensively used in the preparation of this document. A summary of the CH₄ mitigation practices discussed in this manuscript is presented in Table 1.

Inhibitors

Research in this area has targeted chemical compounds with a specific inhibitory effect on rumen archaea. Among the most successful compounds tested in vivo were bromochloromethane (**BCM**), 2-bromoethane sulfonate, chloroform, and cyclodextrin. These CH₄ inhibitors reduced CH₄ production by up to 50% in vivo (in sheep, goat and cattle; Immig et al., 1996; Lila et al., 2004; Mitsumori et al., 2011; Knight et al., 2011). Although some studies have suggested adaptation of the rumen ecosystem to this class of compounds (Johnson et al., 1972; Immig et al., 1996), thus reducing their long-term efficacy, the effect of BCM appeared to persist in the studies by Sawyer et al. (1974), Tomkins et al. (2009), and Abecia et al. (2012). Data by Knight et al. (2011) showed an immediate and dramatic drop in CH₄ production in dry cows administered chloroform; however, CH₄ production gradually increased to about 62% of the pretreatment levels by d 42, suggesting adaptation to chloroform by the rumen ecosystem. A banned compound, such as BCM (an ozone-depleting agent), cannot be recommended as a CH₄ mitigating agent, but compounds with similar mode of action could be developed. The long-term effect of CH₄ inhibitors is uncertain and more data are needed to establish their effects on production. In addition, public acceptance (due to perception and/or existing or future regulations or because they are known carcinogens, e.g., chloroform) could be barriers to their adoption. Nevertheless, research groups around the world are working on developing natural or synthetic compounds that directly inhibit rumen methanogenesis. A recent example of these efforts is research with 3-nitroxypropanol (**3NP**). The compound decreased CH₄ production per unit of DMI in sheep in respiration chambers (a 24% reduction; Martinez-Fernandez et al., 2013) and dairy cows using the SF₆ technique (a dramatic 60% decrease; Haisan et al., 2013). In another trial with lactating cows, the reduction in CH₄ production was only about 8% and there was no response to a fivefold increase in application rate (from 500 to 2,500 mg/d; Reynolds et al., 2013). The authors, however, observed a sharp decrease in CH₄ production (respiration chambers) immediately after 3NP administration and speculated that the compound may be rapidly absorbed, metabolized, or washed out of the rumen and continuous infusion or feeding may be a more effective method of application.

Electron Receptors

This category of CH₄ mitigating agents has recently received renewed attention. Among these, fumarate, nitrates, sulfates, and nitroethane (Gutierrez-Banuelos et al., 2007; Brown et al., 2011) have been studied the most. Leng (2008) provided a comprehensive review of the earlier literature on nitrates. Recent research with sheep (Sar et al., 2004; Nolan et al., 2010; Van Zijderveld et al., 2010) and cattle (Van Zijderveld et al., 2011b,c; Hulshof et al., 2012) has shown promising results with nitrates decreasing CH₄ production by up to 50%. Potential issues with these compounds include adaptation of the rumen ecosystem, which has not been studied in long-term animal experiments with perhaps one exception from which nitrate persistently decreased CH₄ production from lactating dairy cows during 4 successive 24-d periods (Van Zijderveld et al., 2011c). Additional issues with nitrates include potential increase in ammonia production and potential toxicity from intermediate products (nitrite). The toxicity issue was discussed in detail by Leng (2008) who emphasized the critical importance of gradual adaptation of the animal to nitrate and that low-protein diets are the natural background for successful utilization of nitrates as a CH₄ mitigating tool. If nitrates are provided as a substitute for urea in licking blocks, access to the blocks should be limited so that nitrate intake does not poison the animal. Intake of feed additives through licking blocks or liquid supplements can be extremely variable (Cockwill et al., 2000) and this variability has to be considered when the blocks contain potentially toxic substances such as nitrates. It is important to recognize that the adaptability of the rumen ecosystem to reduce nitrate may be short lived after nitrate withdrawal from the diet (Alaboudi and Jones, 1985). Nitrate level in the basal diet should also be considered when supplemental nitrate is fed. Some loss of supplemental nitrate N with urine is expected (Takahashi et al., 1998), but its effect on total urinary N losses is unclear. In one study, nitrate supplementation did not increase volatile N losses from manure (Van Zijderveld et al., 2011c) although the control diet was supplemented with urea.

Adding sulfate to the diet of sheep also reduced CH₄ production, and when both nitrate and sulfate were added, the effect on CH₄ production was additive (Van Zijderveld et al., 2010). High inclusion of distillers grains in feedlot diets in the United States has triggered intensive research on the effect of high-S diets (also in combination with high-S drinking water) on the occurrence of S-induced polioencephalomalacia (Gould, 2000; Cammack et al., 2010; Schoonmaker and Beitz, 2012), caused by excessive production of hydrogen sulfide in the rumen.

Fumaric and malic acids have also been studied as alternative hydrogen sinks in the rumen (Bayaru et al., 2001;

Table 1. Feed additives and feeding strategies targeting enteric methane (CH₄) emission mitigation

Category ¹	Potential CH ₄ mitigating effect ²	Long-term effect established	Effective ³	Environmentally safe or safe to the animal ⁴	Recommended ⁵
Inhibitors					
BCM and BES ⁶	High	? ⁷	Yes	No ⁸	No
Chloroform	High	No?	Yes	No	No
Cyclodextrin	Low	No	Yes	No	No
3-nitrooxypropanol	Medium	?	Yes	?	?
Electron receptors					
FMA ⁹	No effect to High	?	?	Yes	No?
Nitroethane	Low	No	Yes?	No	No
Nitrate	High	No?	Yes	?	Yes? ¹⁰
Ionophores ¹¹	Low ¹²	No?	Yes? ¹²	Yes?	Yes?
Plant bioactive compounds¹³					
Tannins ¹⁴ (condensed)	Low	No?	Yes	Yes	Yes?
Saponins	Low?	No	?	Yes	No?
Essential oils	Low?	No	?	Yes	No
Exogenous enzymes	No effect to Low	No	No?	Yes?	No?
Defaunation	Low	No	?	Yes	No
Manipulation of rumen archaea and bacteria	Low?	No	?	Yes?	Yes? ¹⁵
Dietary lipids	Medium	No?	Yes	Yes	Yes? ¹⁶
Inclusion of concentrate ¹⁷	Low to Medium	Yes	Yes	Yes	Yes? ¹⁸
Improving forage quality	Low to Medium	Yes	Yes	Yes	Yes
Grazing management	Low	Yes	Yes?	Yes	Yes? ¹⁹
Feed processing	Low	Yes	Yes ²⁰	Yes ²⁰	Yes ²⁰
Mixed rations and feeding frequency ²¹	?	?	?	Yes	?
Precision (balanced) feeding and feed analysis	Low to Medium	Yes	Yes?	Yes	Yes ²²

¹Mitigation strategies in this table are applicable to all ruminants.

²High, ≥30% mitigating effect; Medium, 10 to 30% mitigating effect; Low, ≤10% mitigating effect. Mitigating effects refer to percent change over a “standard practice” (i.e., study control that was used for comparison) and are based on combination of study data and judgment by the authors of this document.

³Effectiveness is determined on the basis of CH₄ mitigation potential, effect on feed intake (no negative effect is beneficial), and/or effect on animal productivity (no negative effect or improvement is beneficial).

⁴Based on available data and authors' expert opinion

⁵Based on available research or lack of sufficient research.

⁶BCM = bromochloromethane; BES = 2-bromo-ethane sulfonate.

⁷? = uncertainty due to limited research or lack of data, inconsistent or variable results, or lack (or insufficient) data on persistency of the effect.

⁸Class I ozone-depleting substance (www.epa.gov/ozone/science/ods/classone.html; EPA, 2013).

⁹FMA = fumaric and malic acids.

¹⁰Practicality of use is unknown. Caution must be exercised when feeding nitrate. Animal should be properly adapted and re-adapted if nitrate supplementation is discontinued for a period of time. Access to molasses blocks with nitrate should be limited so that nitrate intake does not poison the animal. Unwise to use when diets have high N concentrations.

¹¹Most data are for monensin. Monensin does not appear to have a consistent direct effect on CH₄ production in dairy or beef cattle. Meta-analyses have shown improvement in feed efficiency in beef cattle (Goodrich et al., 1984) and dairy cows (Duffield et al., 2008) that may reduce CH₄ emissions per unit of product (meat or milk). On this basis, the overall conclusion is that ionophores likely have a CH₄ mitigating effect in ruminants of up to 5%.

¹²Through improvement in feed efficiency, especially when diets contain concentrates; no effect when pasture is fed as a sole diet.

¹³See text for extensive discussion on these supplements. Tannins appear more effective than saponins. Results with tea saponins are encouraging but must be confirmed and data for persistence of the effect are lacking.

¹⁴Detrimental effects when dietary CP is marginal or inadequate or when condensed tannins are astringent and in high concentrations, but with adequate dietary CP some condensed tannins can have wide ranging benefits.

¹⁵Promising, but the technology is not yet developed or commercially available.

¹⁶Lipids are generally effective in reducing CH₄ production. They are recommended when their use is economically feasible (high-oil by-products of the biofuel industries, for example). Their potential negative effect on feed intake, fiber digestibility, rumen function, milk fat content, and overall animal productivity must be considered. Maximum recommended inclusion rate in ruminant diets is 6 to 7% (total fat) of dietary DM. With the lack of incentive mechanisms to reduce CH₄ emissions, the economic feasibility of supplementing diets with edible lipids is questionable.

¹⁷Higher rates of concentrate inclusion may decrease intake, but production is usually increased. Negative effects on fiber degradability and milk composition (in dairy cows) must be avoided.

¹⁸Although recommended (direct reduction in CH₄ emission or indirect through increased animal productivity), the applicability of this mitigation practice will heavily depend on feed availability. See text for further discussion.

¹⁹Not very consistent results, but recommended on the base that improving pasture quality should reduce CH₄ emissions per unit of feed intake and animal product.

²⁰Conditionally effective (if fiber degradability is not decreased), safe to the environment (energy input may counteract greenhouse gas mitigating effect; has to be determined using life cycle assessment), and recommended (if economically feasible and does not jeopardize fiber digestibility).

²¹Insufficient data.

²²Even if direct CH₄ mitigation effect is uncertain, precision (balanced) feeding and accurate feed analyses will likely enhance animal productivity and feed efficiency and improve farm profitability (and thus have an indirect mitigating effect on enteric and manure CH₄ and N₂O emissions).

Molano et al., 2008; Foley et al., 2009; Van Zijderveld et al., 2011a). Their mitigating potential has been questioned (Ungerfeld et al., 2007) because it is generally lower than that of nitrates and results have been inconsistent. In a number of experiments, fumarate addition did not affect CH₄ production (McGinn et al., 2004; Beauchemin and McGinn, 2006; Kolver and Aspin, 2006; McCourt et al., 2008; Molano et al., 2008; Van Zijderveld et al., 2011a). With the exception of one study (Wood et al., 2009), in which a 76% decrease in CH₄ production was reported 8 wk after the introduction of fumaric acid, with gaseous emissions measured using a tunnel system, the long-term effects of these compounds have not been demonstrated.

Ionophores

Monensin has been the most studied ionophore and it is routinely used in beef production and more recently in dairy cattle nutrition in North America. Ionophores are banned in the European Union even though there is no evidence of genes coding for their resistance as are with other feed-administered antibiotics (Russell and Houlihan, 2003). There have been a number of experiments with monensin as a rumen modifier in various production systems, where CH₄ production was studied as a main objective either from a mitigation or from an energy loss perspective (Sauer et al., 1998; Van Vugt et al., 2005; Waghorn et al., 2008; Grainger et al., 2010). Although some studies reported a long-term mitigating effect of monensin on CH₄ production (Odongo et al., 2007), overall the effect of the ionophore appears to be inconsistent. In a meta-analysis of 22 controlled studies, monensin (given at 32 mg/kg DM) reduced CH₄ emissions and Y_m in beef steers fed total mixed rations (TMR) by 19 ± 4 g/animal per d ($P < 0.001$) and 0.33 ± 16% ($P = 0.047$), respectively (Appuhamy et al., 2013). The corresponding reductions in dairy cows were 6 ± 3 g/animal per d ($P = 0.065$) and 0.23 ± 14% ($P = 0.095$) for monensin given at a dose of 21 mg/kg DM. Overall, the conclusion of that analysis was that monensin had stronger antimethanogenic effect in beef steers than dairy cows (mostly fed forage-based diets), but the effects in dairy cows can be improved by dietary modifications and increasing monensin dose.

Meta-analyses have shown monensin to improve feed efficiency in feedlot cattle (by 7.5%; Goodrich et al., 1984), growing cattle on pasture (by 15%; Potter et al., 1986), and dairy cows (by 2.5%; Duffield et al., 2008), which might lead to reduced CH₄ E_i. A recent meta-analysis by Duffield et al. (2012) reported an average increased in feed efficiency in feedlot cattle due to monensin inclusion of 6.4% but also found the effect decreased from 8.1 in the 1970s to 2.3 and 3.5% in the 1990s and 2000s, respectively (with the decrease attributed to continuously improving management that has resulted in a 27%

increase in feed efficiency). The analysis found a linear effect of monensin dose on feed efficiency and suggested that the expected improvement in modern feedlots should be from 2.5 to 3.5% and will depend on dose and dietary energy. Moreover, another meta-analysis has also shown a consistent decrease in acetate:propionate (Ac:Pr) ratio with monensin addition in high grain diets fed to beef cattle (Ellis et al., 2012a), which may lead to a reduction in CH₄ emission per unit of feed.

Plant Bioactive Compounds

This category includes a variety of plant secondary compounds, specifically tannins, saponins, and essential oils and their active ingredients.

Tannins and saponins have been extensively studied and show the most mitigating potential within this category. Tannins, as feed supplements or as tanniferous plants have often, but not always (Beauchemin et al., 2007a), shown a potential for reducing CH₄ emission by up to 20% (Woodward et al., 2001; Sliwinski et al., 2002; Waghorn et al., 2002; Zhou et al., 2011; Staerfl et al., 2012). Condensed (and hydrolyzable) tannins are widely distributed in browse and warm climate forages and are usually considered antinutritional although they can have considerable potential to reduce intestinal nematode numbers and allow acceptable production in the presence of a parasite burden (Niezen et al., 1995, 1998a,b; Terrill et al., 1992).

Tannins will inevitably be antinutritional when dietary CP concentrations are limiting production because they reduce absorption of AA (Waghorn, 2008). Structure, molecular weight (and hence activity), and concentration of tannins affect the nutritive value of the diet. It is important that benefits of reduced CH₄ yields do not overshadow detrimental effects of tannins on digestion and production, as observed by Grainger et al. (2009) with dairy cows on pasture supplemented with grain. In that study, CH₄ emission was reduced by up to 30%, but milk production of the cows was also reduced by about 10%.

A meta-analysis of in vivo experiments with tannins by Jayanegara et al. (2012) reported a relatively close relationship between dietary tannin concentration and CH₄ production per unit of digestible OM. These authors, however, reported a trend ($P = 0.08$) for decreased feed intake and a statistically significant decrease in nutrient digestibility, particularly of CP, with increasing dietary tannin concentration. Reduced digestibility of diets containing condensed tannins at high levels is common (Waghorn, 2008; Patra, 2010) and is unavoidable if urinary N loss is reduced because dietary N is diverted to feces (reducing apparent CP and OM digestibilities). This is an important factor that must be considered when feeding supplemental tannins or tanniferous plants. Tanniferous forages can have beneficial effects on silage quality and ruminant

health due to improved protein supply, bloat safety, and antiparasitic properties (Broderick, 1995; McMahon et al., 2000; Frutos et al., 2004); their recommendation as cattle feed, however, must involve the agronomic characteristics of these species (Waghorn, 2008).

A recent extensive review of the effect of saponins and tannins on CH₄ production in ruminants examined mostly in vivo studies with both plant bioactive compounds (PBAC; Goel and Makkar, 2012). The authors concluded that the risk of impaired rumen function and animal productivity with tannins is greater than with saponins and, for decreasing CH₄ production, the concentration range for tannins is narrower than for saponins. In some dietary situations, however, decreased protein degradability in the rumen, combined with a shift in protein digestion to the small intestine, may be beneficial. Such a shift may also have the benefit of reducing urinary N losses (vs. fecal N losses).

According to Goel and Makkar (2012), the antimethanogenic effect of tannins depends on the dietary concentration and is positively related to the number of hydroxyl groups in their structure. These authors concluded that hydrolyzable tannins tend to act by directly inhibiting rumen methanogens whereas the effect of condensed tannins on CH₄ production is more through inhibition of fiber digestion. They also pointed out that more animal research is needed with these compounds to establish their antimethanogenic effect. Hydrolyzable tannins are hydrolyzed in the rumen and some could be toxic (Lowry et al., 1996; McSweeney et al., 2003).

Of the 9 studies with saponins summarized by Goel and Makkar (2012), 6 reported decreased CH₄ from about 6 to 27% (absolute production or per unit of BW or DMI). In one of these studies, however, OM digestibility was decreased, and in another 3, digestibility was not reported. From this analysis, it appeared that there was no difference in the CH₄-mitigation effect between steroidal saponins (*Yucca schidigera*) and triterpenoid saponins (*Quillaja saponaria*); *Y. schidigera* and *Q. saponaria* have been studied the most as sources of saponins because of their commercial availability. Studies from China have reported decreased CH₄ in ruminants treated with tea triterpenoid saponins but also substantial changes in microbial populations, including a reduction in protozoal counts (Wang et al., 2012).

A large number of in vitro experiments have investigated the CH₄ mitigating potential of essential oils and their active ingredients (Calsamiglia et al., 2008; Bodas et al., 2008; Benchaar et al., 2009). Unfortunately, very few have followed up the in vitro work with in vivo experiments. In most cases, these PBAC have not been successful as CH₄ mitigating agents (Beauchemin and McGinn, 2006; Benchaar et al., 2007; Van Zijderveld et al., 2011a). In their recent review on the topic, Benchaar and Greathead (2011) concluded that some essential oils (e.g., garlic

and its derivatives and cinnamon) reduce CH₄ production in vitro. These compounds, however, have not been studied extensively in vivo, and there is no evidence that they can be used successfully to inhibit rumen methanogenesis. In some cases, as with *Origanum vulgare* leaves, the in vivo effect on CH₄ mitigation was confirmed, and there was also a trend for increased feed efficiency in dairy cows (Tekippe et al., 2011; Hristov et al., 2013a), but these results need to be confirmed in long-term experiments.

Exogenous Enzymes

The use of exogenous enzymes (EXE) in ruminants has been intensively studied during the last 20 yr, and Grainger and Beauchemin (2011) recently reviewed their potential application to reduce CH₄ production in the rumen. There is no evidence of a direct effect of these preparations on CH₄ production, but they appear to improve diet digestibility and animal production in some studies. The responses, however, are inconsistent and the factors affecting the responses are not clearly understood. Recently, some EXE were shown to increase feed efficiency in dairy cows (by 10 to 15%; Arriola et al., 2011; Holtshausen et al., 2011) and reduce CH₄ when added to the whole diet. Improved feed digestibility might decrease fermentable OM in (stored) manure, thus reducing overall CH₄ emissions from some ruminant production systems. On the other hand, some EXE products may in fact increase CH₄ production. An EXE with endoglucanase and xylanase activities, for example, increased CH₄ production per unit of DMI or milk yield by about 10 to 11% in a study by Chung et al. (2012), but no information was provided to explain their findings.

Direct-Fed Microbials

Direct-fed microbials (DFM), in one form or another, are commonly used as supplements in animal production. Probably the most common DFM used in ruminant nutrition are yeast-based products (YP). The notion of using YP to mitigate CH₄ production has been discussed (Newbold and Rode, 2006), but with the exception of some exciting and unconfirmed in vitro results (Chaucheyras et al., 1995), convincing animal data to support this concept are lacking.

Meta-analyses reported an overall positive effect of various YP on milk yield in dairy cows (Van Vuuren, 2003; Desnoyers et al., 2009; Robinson and Erasmus, 2009; Poppy et al., 2012). The Robinson and Erasmus (2009) review reported that *Saccharomyces cerevisiae* YP increased milk yield by 3.6% on average (over the control). The same YP had no effect on feed intake or milk production and composition of high-producing dairy cows (Hristov et al., 2010b), which only emphasizes the variability and conditional effects of these products.

Other DFM interventions of ruminal fermentation include inoculation with lactate-producing and lactate-utilizing bacteria to promote more desirable intestinal microflora and stabilize pH and promote rumen health, respectively. A meta-analysis by Krehbiel et al. (2003) reported a generally positive trend for improved health in young, growing dairy or beef cattle treated with various DFM (mainly based on *Lactobacillus* and *Streptococcus* and in some cases *Propionibacterium* spp.). Several studies have reported a successful establishment of DFM products based on *Megasphaera elsdenii* (one of the most important lactate-utilizing species in the rumen) in sheep and cattle, but effects on ruminal pH and fermentation have been inconsistent (Klieve et al., 2003; Henning et al., 2010). There have also been other attempts to inoculate the rumen with fungi (*Candida kefyr*) and lactic acid bacteria (*Lactococcus lactis*) along with nitrate supplementation to both control methanogenesis and possibly prevent nitrite formation, but no consistent animal data have been reported (Takahashi, 2011). Although fermentation of lactate to VFA would help prevent a decreased ruminal pH, introduction of lactate-producing DFM would require careful scrutiny in situations in which subacute rumen acidosis might occur.

Defaunation

Association and cross-feeding between ruminal protozoa and archaea have been established (Vogels et al., 1980; Lee et al., 1987; Finlay et al., 1994) and are the basis for suggesting defaunation as a CH₄ mitigation strategy (Newbold et al., 1995; Boadi et al., 2004; Hristov and Jouany, 2005). However, the response in CH₄ production to partial or complete defaunation has been variable. Morgavi et al. (2010) calculated an average decrease in CH₄ production of about 10% due to defaunation, but the data from that study were extremely variable. Moreover, all responses were attributed to loss of protozoa without accounting for depressed ruminal fiber digestibility, which promotes acetate and/or CH₄ fermentation pathways and typically accompanies defaunation (Eugène et al., 2004). Research from the latter group with beef cattle reported no effect on rumen methanogen abundance despite a 65% difference in protozoal numbers between a high-forage and a high-starch, lipid-supplemented diet (Popova et al., 2011). Similarly, a 96% reduction in ruminal protozoa had no effect on methanogenic archaea in dairy cows treated with lauric acid (Hristov et al., 2011b).

With such variability and uncertainty in the response (see Morgavi et al., 2011), defaunation cannot be recommended as a CH₄ mitigation practice. Apart from lauric acid and coconut oil (Sutton et al., 1983; Machmüller and Kreuzer, 1999; Hristov et al., 2004, 2009, 2011b; Holl-

mann and Beede, 2012), which can severely depress DMI in cattle, and some vegetable oils with a high proportion of unsaturated fatty acids (FA) such as linseed (Doreau and Ferlay, 1995), there has been no effective and practical defaunating agents tested comprehensively in vivo.

Manipulation of Rumen Archaea and Bacteria

Significant efforts have been devoted to suppressing archaea and/or promoting acetogenic bacteria in the rumen. Vaccines against rumen archaea are based on the concept of a continuous supply of antibodies to the rumen through saliva. Vaccines against archaea have been successful in vitro (Wedlock et al., 2010) but not in vivo (Wright et al., 2004; Williams et al., 2009). Vaccines prepared from New Zealand and Australian methanogen strains proved unsuccessful in reducing CH₄ production in ewe lambs (Clark et al., 2004).

New approaches have involved identification of genes encoding specific membrane-located proteins from *Methanobrevibacter ruminantium* (perhaps the most important rumen methanogen) and using purified proteins (produced in *Escherichia coli*) as antigens to vaccinate sheep (Buddle et al., 2011). In another approach, antisera were generated in sheep against subcellular fractions from *M. ruminantium*, which reduced microbial growth and CH₄ production in vitro (Wedlock et al., 2010). Sequencing the genome of *M. ruminantium* has opened new frontiers and opportunities for inhibition of rumen methanogens and the potential to mitigate ruminant CH₄ emissions (Leahy et al., 2010). Ruminal bacteria capable of utilizing hydrogen and CO₂ to produce acetate exist in the rumen (Joblin, 1999), and although these bacteria do not seem to be able to compete with methanogens for hydrogen under normal ruminal conditions (Fievez et al., 2001), they might be competitive if dissolved hydrogen concentrations increase as a result of suppressed CH₄ production (Le Van et al., 1998). The model of Janssen (2010) proposes a dynamic interaction between dissolved hydrogen, passage rate, propionate production, and the growth and activity of methanogens in the rumen. These interactions need to be acknowledged in the development of vaccines, and this is an exciting and fast-developing area of research that may produce effective CH₄ mitigation technologies in the future (Wright and Klieve, 2011).

Recent research has suggested that interventions in early life of the animal can trigger differential microbial rumen colonization and development, which may result in differential rumen CH₄ production. In a study by Abecia et al. (2011), kids from does treated with BCM had reduced CH₄ production compared with kids from untreated dams (although animals were group fed and individual DMI was not reported), introducing the pos-

sibility that responses to rumen modifiers may be influenced by the mother and remain programmed in the animal's adult life. This interesting concept may offer new opportunities for mitigating CH₄ emission in ruminants but needs to be further tested and verified. Another interesting approach, using antimethanogen antibodies to suppress CH₄ production, was shown to be ineffective in vitro (Cook et al., 2008).

Dietary Lipids: Vegetable Oils

There is a large body of evidence that lipids (vegetable oil or animal fat) suppress CH₄ production. The effects of lipids on rumen archaea are not isolated from their overall suppressive effect on bacteria and protozoa. Several reviews have attempted to develop prediction factors for the effect of feed lipids on CH₄. Giger-Reverdin et al. (2003) found the following relationship between CH₄ production and dietary fat [as ether extract (EE)]: CH₄ (L/kg DMI) = 47.3 – 0.0212 × DMI² (kg/d) – 0.680 × EE (%) (*R*² = 0.76, *n* = 37). Eugène et al. (2008) reported a 9% reduction in CH₄ production in dairy cows due to lipid supplementation of the diet, but this was accompanied by a 6% reduction in DMI, which resulted in no difference in CH₄ per unit of DMI. However, these authors also reported that lipid supplementation had no effect on 4% fat-corrected milk (FCM), which, combined with the reduced DMI, resulted in a trend for increased feed efficiency with oil supplementation. A more recent meta-analysis of 38 research papers reported a consistent decrease in DMI with all types of dietary fat examined (tallow, various calcium salts of FA, oilseeds, and prilled fat), but milk production was increased (Rabiee et al., 2012). This combination of decreased DMI and maintained or increased milk production (assuming no decrease in milk fat) results in increased feed efficiency and, consequently, decreased CH₄ Ei.

The greater inhibitory effect of unsaturated vs. saturated FA on rumen microbial activity reported by Palmquist and Jenkins (1980) and Nagaraja et al. (1997) does not appear to apply to CH₄ production in most studies (Beauchemin et al., 2007b; Van Zijderveld et al., 2011a; Sauviant et al., 2011) although a greater mitigating effect of polyunsaturated FA was observed in the analysis by Doreau et al. (2011). Biohydrogenation of unsaturated FA can also serve as a hydrogen sink, but it has been suggested that only 1 to 2% of the metabolic hydrogen in the rumen is used for this purpose (Czerkawski and Clapperton, 1984; Jenkins et al., 2008).

Meta-analyses by Moate et al. (2011) and Grainger and Beauchemin (2011) documented a consistent decrease in CH₄ production with fat supplementation. Moate et al. (2011) reported the following relationship between dietary fat and CH₄ production per unit of DMI:

CH₄ (g/kg DM) = 24.51 (±1.48) – 0.0788 (±0.0157) × fat (g/kg DM). Grainger and Beauchemin (2011) analyzed 27 studies and concluded that, within a practical feeding rate of less than 8% fat in the diet, a 10 g/kg increase in dietary fat would decrease CH₄ yield by 1 g/kg DMI in cattle and 2.6 g/kg in sheep. However, all of these studies either scale CH₄ per unit of DMI (i.e., disregarding the likelihood of an increased need for replacement animals if DMI and subsequent milk production are depressed) or included DMI as a variable (i.e., assuming that DMI can be maintained or predicted accurately). Prediction equations could account for these effects by substituting the response of fat on DMI into a subsequent equation relating the effect of fat on CH₄, as done for RDP's responses on DMI and milk protein production (Firkins et al., 2006).

The important question of persistence of the effect of lipids on CH₄ production has not been adequately addressed. In a study with dairy cows on pasture, Woodward et al. (2006) examined the effect of vegetable and fish oils on milk production and CH₄ emission after 14 d and again after 12 wk. Lipids significantly decreased CH₄ production in the short term, but this effect was not observed after 11 wk of feeding lipids. These authors concluded that lipids were not beneficial for milk production and emphasized the need for long-term studies when developing on-farm strategies for CH₄ mitigation with grazing animals. Grainger and Beauchemin (2011) examined 6 long-term studies (6 to 36 wk, mostly with dairy cows) and concluded that the effect of dietary fat on CH₄ production persists but the effect is not consistent among studies. Persistence of the mitigating effect of dietary oil was also observed in the study of Martin et al. (2011) with flaxseed in dairy cows although it was not supported by another study from the same group with young bulls (Eugène et al., 2011).

In some studies, lipids had a significant and negative impact on DMI (e.g., Martin et al., 2008), a factor that must be carefully considered both in prediction of mean responses and for risk assessment by those choosing to adopt these mitigation strategies. Another important factor to take into account with lipids is that mitigation of CH₄ tends to correspond with increased likelihood of depressing milk fat and/or protein concentration, potentially with enhanced responses when combining lipids with other strategies such as ionophores (Mathew et al., 2011). Some fats such as coconut oil, for example, can severely depress feed intake, fiber digestibility, and, consequently, milk production and cause milk fat depression in dairy cows (Hristov et al., 2004, 2009, 2011b; Lee et al., 2011; Hollmann and Beede, 2012) although they may be still beneficial as CH₄ mitigating agents (Machmüller and Kreuzer, 1999; Machmüller, 2006; Hristov et al., 2009). Even a blend of mostly saturated long-chain

FA (C16:0, C18:0, and C18:1) was found to cause a significant drop in feed intake and milk production and a marked decrease in milk fat percentage (from 3.10 to 2.51%; a clear indication of milk fat depression although not statistically significant; Hollmann and Beede, 2012). Lipids causing this kind of production effects cannot be recommended as mitigation agents.

Dietary Lipids: By-Products

Although supplementing animal diets with edible lipids for the sole purpose of reducing CH₄ emissions is debatable, high-oil by-products from the biofuel industries [dry (**DDG**) or wet (**WDG**) distillers grains alone or with solubles (**DDGS** and **WDGS**, respectively) and mechanically extracted oilseed meals] can naturally serve as a CH₄ mitigating feed, if included in the diet to decrease feed cost. McGinn et al. (2009), for example, reported up to 24% less CH₄ emissions when DDG replaced barley grain in the backgrounding diet of beef cattle by supplementing an additional 3% lipid to the dietary DM. However, the effects of distillers grains on CH₄ production are not consistent and might depend on the rest of the diet. Hales et al. (2013) fed diets containing 0 to 45% WDGS (substituting steam-flaked corn) to Jersey steers and observed a linear increase in CH₄ emission per unit of DMI (up to 64% increase with the highest inclusion rate), due primarily to increased NDF intake, although the EE content of the diet increased from 5.9 to 8.3%.

High-oil by-product feeds might have the same suppressive effect on feed intake as free lipids, so caution must be exercised to prevent negative effects on animal productivity or milk fat depression in lactating cows (Schingoethe et al., 2009). Hales et al. (2013), for example, reported about an 11% decrease in DMI with the highest WDGS inclusion rate compared with the control. Inclusion of 12 to 13% mechanically extracted canola or rapeseed meals with various FA compositions (replacing traditional, solvent-extracted canola meal) depressed DMI and, consequently, milk production in high-producing dairy cows (Hristov et al., 2011a). These feeds also contain higher total N (but less digestible than N from the original seeds) and P, which may present an environmental challenge due to high N and P content of manure and, consequently, greater ammonia and N₂O emissions. Spiels and Varel (2009) reported a linear increase in urinary N and total manure P excretion with increasing WDG inclusion (0 to 60%) in the diet of beef steers. Similarly, Hales et al. (2012) reported that inclusion of 30% WDGS in the diet of feedlot cattle increased total N excretion by 18% but also increased urinary N losses by 35% whereas dietary N intake was 23% higher compared with the control (0% WDGS). Distillers grains are also inherently variable in composi-

tion (Spiels et al., 2002) and particularly in intestinal digestibility of ruminally undegraded protein and lysine limiting production in ruminants (Boucher et al., 2009). Thus, a new trend in the bioethanol industry to partially extract oil from distillers grains will decrease the energy value of the product and is likely to also decrease the CH₄ mitigating effect discussed above.

Biodiesel by-products provide high-oil feedstuffs for livestock feeding. Biodiesel can be made from various feedstocks with relatively small capital investment. With high oil yield per hectare, canola (or rapeseed) are the preferred feedstocks for biodiesel production. Mechanically extracted canola and rapeseed meals can have very high residual oil content (up to 17%, DM basis) and might depress DMI and milk production in dairy cows (Hristov et al., 2011a). The oil in these meals has a high proportion of monounsaturated FA and can impair rumen function, if included at levels exceeding 6 to 7% total dietary fat. Another product of the biodiesel industry, glycerol, has been shown to promote CH₄ production during ruminal fermentation *in vitro* (Czerkawski and Breckenridge, 1972).

FEEDS AND FEEDING MANAGEMENT

There is a clear relationship between feed OM digestibility, concentrate feed or starch intake, and the pattern of ruminal fermentation. As argued by Wolin (1960), the stoichiometry of ruminal fermentation dictates that more hydrogen, and consequently CH₄, will be produced with fermentation of fiber as compared with starch (in the latter case reducing equivalents are used for propionate synthesis). In a meta-analysis, Bannink et al. (2008) predicted that the fermentation of sugars and starch shifted rumen fermentation towards production of propionate when pH in the rumen decreased. Indeed, a 72 vs. 52% concentrate diet produced a 59% increase in rumen propionate concentration and a 44% drop in Ac:Pr ratio in lactating dairy cows, accompanied by milk fat depression (3.20 vs. 4.20%, respectively; Agle et al., 2010). Sauvant et al. (2011) proposed a quadratic relationship between Y_m and Ac:Pr in ruminal fluid: $Y_m = -1.89 + (4.61 \times \text{Ac:Pr}) - (0.59 \times \text{Ac:Pr}^2)$ ($n = 23$ experiments). Therefore, because of the strong relationship between forage:concentrate and Ac:Pr, increasing inclusion of grain (or feeding forages with higher starch content, such as whole-crop cereal silages) in ruminant diets should lower CH₄ production.

Effect of Feed Intake and Inclusion of Concentrates

Feed intake is an important variable in predicting CH₄ emission. Johnson and Johnson (1995) stated that as feed intake increases, the Y_m factor decreases by about 1.6 percentage points per each level of intake

above maintenance. Similarly, a linear decrease in Y_m with increasing feed intake was reported by Sauvant and Giger-Reverdin (2009). Increasing feed intake, however, usually increases fractional passage rate and decreases digestibility (NRC, 2001), which may increase excretion of fermentable OM with manure and thus CH_4 or N_2O emissions, depending on the type of manure handling system.

A strong relationship of DMI with ruminal CH_4 production has been reported by Cottle et al. (2011), Kennedy and Charmley (2012), and others and was also derived from the dataset of studies used in the report by Hristov et al. (2013b): CH_4 (g/d) = 2.54 (SE = 4.89) + 19.14 (SE = 0.43) × DMI (kg/d) ($R^2 = 0.86$, $P < 0.001$; Fig. 1). This simple relationship, however, ignores diet nutrient composition, which can have a significant impact on ruminal fermentation and CH_4 production. Meta-analyses by Yan et al. (2000), Sauvant and Giger-Reverdin (2009), and more recently by Ramin and Huhtanen (2013) have proposed CH_4 prediction equations involving intake or concentration of dietary variables such as OM, NDF, ADF, nonfiber carbohydrates, EE, and level of concentrate inclusion. Ellis et al. (2010) evaluated 9 CH_4 prediction equations that are currently being used in whole farm GHG models. In their analysis, equations that attempt to represent important aspects of diet composition performed better than more generalized equations.

To investigate the relationships among dietary nutrients and CH_4 production, the authors of this document developed prediction equations and identified key animal and dietary characteristics that determine CH_4 production in cattle. Data consisted of indirect calorimetric records of lactating and nonlactating cows. Diet characteristics (fiber fractions, CP, EE, and lignin), animal information (BW and breed), GEI, and year of the study were used as possible covariates that could be selected with equal probability (for details on variables selection and statistical procedures see Moraes et al., 2013). The following equations were developed for lactating and nonlactating dairy animals [in which CH_4 is expressed on a GEI basis (Mcal/d), NDF is expressed as percent NDF in the diet (DM basis), EE is expressed as percent ether extract in the diet (DM basis), and BW is expressed in kilograms].

Lactating cows: $CH_4 = 0.37$ (0.37) + 0.0392 (0.0015) GEI + 0.0189 (0.0077) NDF – 0.156 (0.034) EE + 0.0014 (0.0003) BW

Nonlactating animals: $CH_4 = 0.074$ (0.093) + 0.0409 (0.0019) GEI + 0.0039 (0.0016) NDF – 0.0432 (0.0122) EE + 0.0014 (0.00008) BW

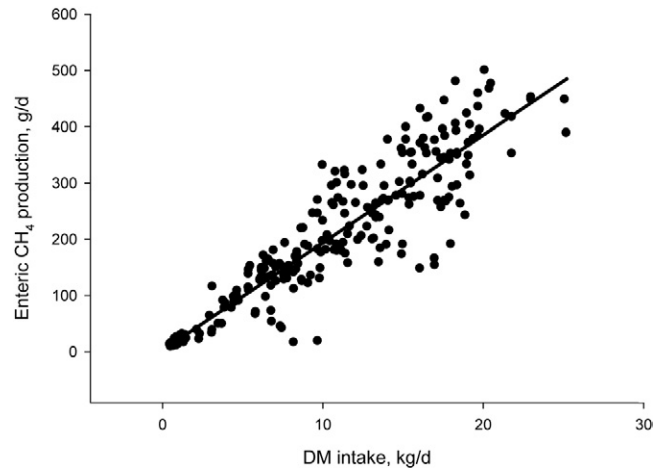


Figure 1. Relationship between dietary DM intake and enteric CH_4 (CH_4) production (from Hristov et al., 2013b): CH_4 , g/d = 2.54 (SE = 4.89) + 19.14 (SE = 0.43) × DMI, kg/d ($R^2 = 0.86$, $P < 0.001$; $n = 377$).

Although equations such as the above can be useful for predicting changes in CH_4 production triggered by changes in diet ingredient or nutrient composition, they have limitations in predicting effects of mitigation strategies. Mechanistic models that describe the mechanism of CH_4 production based on knowledge of degradation processes in the rumen and type of VFA formed give better predictions than empirical models (e.g., Alemu et al., 2011) and might provide insights into possible mitigation options. Indeed, a mechanistic model is now used for GHG inventory purposes in the Netherlands as an IPCC Tier 3 alternative to the IPCC Tier 2 fixed Y_m approach to estimate CH_4 production by dairy cattle. Unlike the Tier 2 approach, the Tier 3 approach does show different behavior in CH_4 production in the past 2 decades when compared with the Tier 2 method because the mechanistic model is capable of representing changes in CH_4 production that result from changes in diet composition that occurred over these 2 decades (Bannink et al., 2011).

Importantly, dietary variables are not independent and increasing or decreasing the concentration of one entity will decrease or increase concentration of another. For example, as discussed earlier, mitigation options aimed at reducing urinary N excretion may result in elevated CH_4 emission (Dijkstra et al., 2011). Decreasing dietary concentration of CP will result in increasing concentration of other nutrients (such as starch or NDF), and these changes may affect enteric and manure CH_4 and N_2O emissions. Therefore, effects on GHG emissions as a result of changes in one nutrient have to be interpreted in the context of potential effects resulting from changes in other dietary constituents.

Increasing the proportion of concentrate in the diet will lower CH_4 emissions per unit of feed intake and animal product if production remains the same or is increased, which has been demonstrated in the classic

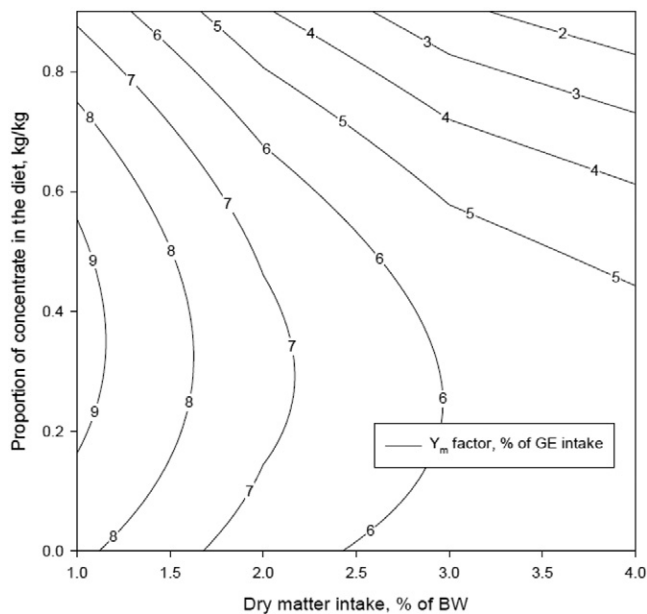


Figure 2. Effects of feed intake and proportion of concentrate in the diet on the CH_4 conversion rate factor (Y_m) (enteric CH_4 energy as percent of GE intake) (reconstructed based on the Y_m equation reported by Sauvant and Giger-Reverdin, 2009).

works of Flatt et al. (1969) and Tyrrell and Moe (1972) and reinforced by others (Ferris et al., 1999; Yan et al., 2000). Some experiments with lactating dairy cows and beef cattle have shown linear decreases in CH_4 emissions with an increase in the proportion of concentrate in the diet (Aguerre et al., 2011; McGeough et al., 2010). In a meta-analysis of 87 experiments with 260 treatments involving growing and lactating cattle, sheep, and goats, Sauvant and Giger-Reverdin (2009) concluded that marked improvements in Y_m can be expected beyond 35 to 40% inclusion of grain in the diet and this was also dependent on the level of feed intake (Fig. 2). Based on these data, small and moderate variation in dietary concentrate proportion is unlikely to affect CH_4 emission. However, concentrates generally provide more digestible nutrients (per unit feed) than roughage, which could increase animal productivity. For example, Huhtanen and Hetta (2012) in a meta-analysis of 986 dietary treatments reported a highly significant and positive relationship between dietary concentrate intake and production of milk, energy-corrected milk, and milk fat and milk protein. Hence, CH_4 expressed per unit product (i.e., E_i) is likely to decrease. Increasing the concentrate proportion in the diet above certain levels, however, might have a negative effect on fiber digestibility (Firkins, 1997; Nousiainen et al., 2009; Agle et al., 2010; Ferraretto et al., 2013), which, in addition to a potential loss of production, could result in increased concentration of fermentable OM in manure and perhaps increased CH_4 emissions from stored manure (Lee et al., 2012). Grain processing itself can have a large effect on

starch concentration in feces. Total tract digestibility of steam-flaked corn, for example, was 25% higher than that of steam-rolled corn grain in dairy cows (Firkins et al., 2001). Inclusion of steam-rolled corn (vs. stem-flaked) in beef cattle fed finishing diets (80% concentrate) resulted in extremely high starch concentrations in feces (Depenbusch et al., 2008). Thus, decreased CH_4 production (per unit of DMI) due to increased inclusion of grain in the diet may be partially offset by increased CH_4 emission from manure. To what extent these 2 processes will take place is an area that needs to be investigated and included in prediction models.

Forage Type, Quality, and Management

Forages can be categorized into fresh or conserved, with silages forming a significant portion of the latter and fed in balanced rations or as a sole diet. Silages are often fed indoors and are amenable to CH_4 measurements in respiration chambers, but fresh forages are normally grazed so intakes cannot be measured accurately in conjunction with CH_4 measurements (often with SF_6 tracer technique). Alternatively, fresh feeds can be cut and fed indoors, enabling accurate determination of intake and methane in chambers. The challenges in measuring Y_m with fresh forages are associated with imposed indoor feeding regimens and absence of selection, compared to grazing, and underestimates of Y_m measured with SF_6 from sheep fed either white clover or chicory but not ryegrass (Hammond et al., 2009, 2011; Sun et al., 2011).

An important feed characteristic that can impact CH_4 production is forage quality, specifically its digestibility. As noted by the classic work of Blaxter and Clapperton (1965), increased intake of poor-quality, less-digestible preserved forages has little effect on CH_4 production when expressed on a DMI basis (supporting the conclusion of Johnson and Johnson, 1995). For feeds with higher digestibility, however, increased DMI depresses the amount of CH_4 produced per unit of feed consumed (Hammond et al., 2009, 2013a). Moreover, it decreases CH_4 produced per unit of product by diluting maintenance energy.

The CH_4 database compiled by Hristov et al. (2013b) contained numerous references on effects of forage quality, pasture management, and processing on CH_4 production in various ruminant species. In general, CH_4 reductions are correlated with greater nutrient quality and digestibility, which are 2 attributes for which forage type and maturity might be indicators. Grazing management might be used as a potential mitigant through grazing forages at the optimal maturity for increasing forage quality, allowing for adequate pregrazing herbage mass or intensive grazing. The impact on CH_4 mitigation, when scaled per unit of animal product, should be typically greater when animals consume higher quality forage.

A meta-analysis by Archimède et al. (2011) investigated differences in CH₄ production from animals fed C3 vs. C4 grasses and warm and cold climate legumes. The database contained 22 in vivo studies with a total of 112 observations and the authors concluded that ruminants fed C4 grasses produced 17% more CH₄ (per kg of OM intake) compared with animals fed C3 grasses and 20% more than animals fed warm climate legumes. On average, C4 grasses in the database had about 16% higher NDF content than C3 grasses (64.6 vs. 55.7%, respectively), and the greater methanogenic potential of structural vs. nonstructural carbohydrates has been documented by Moe and Tyrrell (1979). Although legumes can have a CH₄ mitigation potential, problems of low persistence in pastures and the need for long establishment periods are important agronomic constraints to widespread use of legumes in a warm climate.

In contrast, Hammond et al. (2011) reported no differences in CH₄ production (23.0 g/kg DMI) measured from sheep in chambers and fed either fresh ryegrass or white clover over a range of intakes, despite a greater than 2-fold range in readily fermentable carbohydrate:NDF ratios. Sun et al. (2011) also reported similar CH₄ yields from sheep fed either fresh chicory or ryegrass (23.3 g/kg DMI), which differed widely in chemical composition. In an analysis of CH₄ emissions from sheep fed fresh ryegrass with widely varying composition, 196 records based on SF₆ and 161 from respiration chambers showed a similar CH₄ yield (as g/kg DMI) but larger SD with SF₆ (23.4 ± 5.73) than chambers (23.1 ± 2.89) and only 20% of the variation from chamber measurements was associated with the chemical composition of feed. Over 80% of the variation in CH₄ production was explained by intake (51% by SF₆) and caution is advised when interpreting methanogenesis because methodology appears to affect the results. This was even more apparent when comparing the chamber data for sheep fed either clover or chicory (above) with previous reports by Waghorn et al. (2002) who showed sheep fed white clover, chicory, *Lotus pedunculatus*, and other legumes to have much lower CH₄ yields (12 to 17 g CH₄/kg DMI) compared with sheep fed ryegrass at 21 g CH₄/kg DMI.

There do appear to be some variations in CH₄ yield from fresh forages, with Sun et al. (2012) reporting substantially lower values (g/kg DMI) from sheep fed either rape or Swedes (*Brassica napus*) compared to kale (*Brassica oleracea*), turnip (*Brassica campestris*), or ryegrass (16.4, 16.9, 19.8, 20.6, and 22.0, respectively). However, the effects of forage quality on CH₄ emissions are often contradictory (see, for example, Hart et al., 2009, and Nishida et al., 2007), with Pinares-Patiño et al. (2003) and Molano and Clark (2008) both reporting a lack of relationship between Y_m and NDF content of grasses fed to steers and sheep, respectively.

Increasing quality or digestibility of forages will increase production efficiency and this will likely result in decreased CH₄ Ei. Keady et al. (2012) recently provided a comprehensive review of the effects of silage quality on animal performance in various production systems in Ireland. These authors concluded that a 10 g/kg increase in digestible OM concentration of grass silage DM could increase 1) daily milk yield of lactating dairy cows by 0.37 kg, 2) daily carcass gain of beef cattle by 28 g/head, 3) daily carcass gain of finishing lambs by 10 g/head, 4) lamb birth weight by 0.06 kg, and 5) ewe BW postlambing by 1.45 kg. They also pointed to the critical effect of maturity on grass silage digestibility; each 1 wk delay in grass harvest reduced digestibility by 3 to 3.5 percentage points.

Keady et al. (2012) pointed out that the use of bacterial inoculants across a wide range of ensiling conditions and of formic acid under difficult ensiling conditions is expected to increase animal performance (which will reduce CH₄ Ei). Furthermore, there is indication that silage lactic acid bacteria-based inoculants may survive in the ruminal environment and perhaps positively affect fermentation by buffering rumen pH and oxygen scavenging (Weinberg et al., 2003; Hindrichsen et al., 2012). An animal trial with one of the inoculants consistently resulting in animal production responses improved N utilization, and likely increased microbial protein synthesis in the rumen compared with the untreated silage (Muck et al., 2011). Using real-time polymerase chain reaction, elevated levels of *Lactobacillus plantarum* were found in the rumens of cows consuming inoculant-treated silage (Mohammed et al., 2012).

Some studies have indicated reduced CH₄ production with corn vs. grass silages. A report by the United Kingdom Department for Environment, Food and Rural Affairs (DEFRA, 2010) indicated a 13 and 6% reduction in CH₄ per unit of DMI and per unit of milk output, respectively, when feeding a 25:75 grass silage:corn silage diet compared with a 75:25 grass silage:corn silage diet. Urinary N excretion also tended to be reduced with the higher corn silage diet. The high corn silage diet tended to increase milk yield (by about 4%, which resulted from increased feed intake) although the difference was not statistically significant. Another comparison of corn vs. grass silage reported similar results (Doreau et al., 2012).

A comprehensive overview of the various aspects of feeding corn vs. legume vs. grass silages for lactating dairy cows was recently offered by Dewhurst (2012). Based on this review, the lower fiber content and higher passage rates of legumes appeared to decrease CH₄ production compared with grasses, which was reported in earlier studies (McCaughey et al., 1999). Dewhurst (2012) also concluded that corn silage-based diets are expected to increase DMI and milk production in dairy cows; similar trends, although less conclusive, have been

reported for legume vs. grass silages. This author suggested more research is needed to elucidate the effect of various silages on CH₄ production, particularly in the case of legume silages that have the additional benefit of reducing the carbon footprint of the production system by replacing inorganic N fertilizer. The potential increase in total carbon footprint due to change in land use and increased fertilizer inputs associated with corn silage production vs. permanent pasture should be also considered (Vellinga and Hoving, 2011; Van Middelaar et al., 2012).

Corn silage inclusion in alfalfa silage-based diets for dairy cows can also improve animal production (Dhiman and Satter, 1997; Groff and Wu, 2005) and N efficiency (Wattiaux and Karg, 2004), which might lead to decreased N losses in urine and N₂O emissions from manure application. In traditional grass silage-based production systems, such as in Ireland for example, corn silage has been shown to increase performance of finishing beef cattle and lambs under a certain crop management scenario (complete cover plastic mulch system; Keady et al., 2012). Other alternative crops, such as whole crop wheat silage, have not been beneficial, but studies with silage legumes have demonstrated improvements in ADG, food conversion, and N use efficiency in lambs offered red clover, alfalfa, and kale silages compared with those offered traditional ryegrass silage (Keady et al., 2012).

Pasture management can be an important CH₄ mitigation practice. DeRamus et al. (2003) demonstrated that management-intensive grazing offered a more efficient use of grazed forage crops and more efficient conversion of forage into meat and milk, which resulted in a 22% reduction of projected CH₄ annual emissions from beef cattle. In other studies, however, stocking rate of heifers on pasture did not have an effect on CH₄ emissions (Pinares-Patiño et al., 2007).

There has been moderate interest in the so-called "high-sugar grasses" (HSG; grasses with elevated concentrations of water-soluble carbohydrates) as a tool for mitigating the environmental impact of livestock. A review by Parsons et al. (2011) concluded that the prospect for reducing CH₄ emissions, whether per hectare or per unit energy intake or animal product, with HSG is uncertain. A simulation effort suggested that HSG may actually increase CH₄ emissions, but this depends on the diet composition (for example, if sugars replace CP, NDF, or both), DMI, and the units chosen to express CH₄ emissions (Ellis et al., 2012b). No effect of HSG on CH₄ emissions in dairy cows was reported recently by Staerfl et al. (2012). In the United States, research with so-called *Ante Meridiam* and *Post Meridiam* hay (i.e., hay harvested in the morning or in the afternoon with low- and high-sugar contents, respectively) has demonstrated that sheep or cattle have a preference for PM hay, due to its higher sugar content (Burritt et al., 2005; Shewmaker et al., 2006).

In a Canadian study, PM hay increased milk yield of dairy cows (Brito et al., 2008). However, there was no effect on intake or milk production of dairy cattle when allocated to fresh grass in the morning or afternoon in a study by Abrahamse et al. (2009).

Feed Processing

Processing, through its effect on digestibility, energy losses, and passage rate, can be an effective CH₄ mitigation practice (although not necessarily economically infeasible; see, for example, Hironaka et al., 1996). Grain processing can be a key factor in improving feed efficiency and reducing GHG emissions from livestock operations. Thus, summarizing the corn (and sorghum) processing literature, Firkins et al. (2001) reported increased total tract starch digestibility of steam-flaked vs. steam-rolled corn grain. This improvement in digestibility resulted in an approximately 6% increase in milk yield in dairy cows at similar DMI, which would translate into improved feed efficiency. Yang et al. (2012) compared precision processing of barley (roller settings are adjusted based on the degree of kernel uniformity) vs. conventional processing (i.e., blend of light and heavy barley and rolling with one roller setting) and found improved feed intake, digestibility, and feed efficiency with precision processing. As a result of these improvements, the authors estimated that cattle fed precision-processed barley would stay in the feedlot 25 d less and save 163 kg feed per animal. The reduction of CH₄ emissions from this particular example would be significant. A recent study by Hales et al. (2012) with steers in respiration calorimetry chambers compared dry-rolled vs. steam-flaked corn and reported increased digestibility and about 17% less CH₄ emission (per unit of DMI) with the latter treatment. Per unit of DE intake, CH₄ energy was decreased by 21% (3.30 vs. 4.18%) and Y_m was decreased by about 19% (2.47 vs. 3.04%) by steam flaking. Although these effects are logical, grain processing may have a negative effect on NDF digestibility (Firkins et al., 2001).

Mixed Rations and Feeding Frequency

Very little research is available on the effect of feeding system (i.e., component or choice feeding of forage and concentrates vs. feeding of TMR) on CH₄ production. The advantages of feeding complete rations (i.e., TMR) are a more precise nutrient allocation (Coppock, 1977) and a more precise feeding of micronutrient supplements. Nock et al. (1986) fed dairy cows forage and concentrates separately or as TMR and observed higher FCM feed efficiency with the separate feeding system due to lower feed intake. In contrast, Maekawa et al. (2002) did not report any differences in feed intake or milk production

and composition of dairy cows fed ingredients as a TMR or separately. They concluded that the latter increased the risk of acidosis because cows ate a greater proportion of concentrate than intended (overall rumen pH tended to be lower when compared with the 50% forage:50% concentrate TMR). More research is needed to determine feeding regimes that improve feed efficiency and lower CH₄ Ei.

Very few studies have investigated the effect of feeding frequency on CH₄ emissions. The reason for including this discussion in relation to CH₄ emission is that synchronization of energy and protein availability in the rumen has long been proposed as a tool for optimizing rumen function and maximizing microbial protein synthesis. Earlier studies investigated the effect of feeding frequency from the perspective of optimizing carbohydrate fermentation in the rumen. Mathers and Walters (1982), for example, fed sheep every 2 h and concluded that, even with frequent feeding, there was considerable deviation from steady state in the rate of carbohydrate fermentation in the rumen. Methane production increased rapidly, within 30 min, after feeding and then decreased until the next 2-h cycle. A series of trials in the 1980s from the laboratory of M. Kirchgessner at the University of Munchen in Germany found that frequent feeding did not improve dietary energy use but did increase CH₄ emission when concentrate was fed more often and separately from forage or with higher CP diets (Muller et al., 1980; Röhrmoser et al., 1983). In a more recent study, feeding frequency had no effect on CH₄ production in dairy cows (Crompton et al., 2010). The literature on the effect of feeding frequency on animal production is also scarce. In practical conditions, animals consume feed multiple times during a feeding cycle, even if fed once daily. As a result, feeding frequency does not appear to have an effect on feed intake. For example, feeding first lactation dairy cows once or 4 times a day had no effect on DMI or milk production (Nocek and Braund, 1985). Similarly, Dhiman et al. (2002) did not report any production advantage of feeding lactating dairy cows once or 4 times daily. In some cases, milk production of dairy cows was reduced with frequent feeding, and this was attributed by the authors to more frequent handling (Phillips and Rind, 2001). Further discussion of this topic can be found in Hristov and Jouany (2005) and Hall and Huntington (2008).

Precision Feeding and Feed Analyses

In animal nutrition, precision feeding may have different dimensions, but from a practical standpoint and farm sustainability perspective it refers to matching animal requirements with dietary nutrient supply. Accurate prediction of animal requirements and accurate feed analyses go hand-in-hand with minimizing feed

waste, maximizing production, and minimizing GHG emissions per unit of animal product. Precision feeding would likely have an indirect effect on CH₄ emission through maintaining a healthy rumen and maximizing microbial protein synthesis, which is important for maximizing feed efficiency and decreasing CH₄ Ei.

Much progress in improving animal productivity and reducing CH₄ emissions from livestock, specifically Ei, in developing countries can be achieved through proper diet formulation. Garg et al. (2013) documented remarkable progress in animal performance using a program to feed balanced rations to lactating cows and buffaloes in India. Evaluation of the nutritional status of animals showed that for 71% of the animals, protein and energy intakes were higher, and for 65%, Ca and P intakes were lower than the requirements. Balancing the rations significantly improved milk yield by 2 to 14% and milk fat by 0.2 to 15%. Feed conversion efficiency, milk N efficiency, and net daily income of farmers also increased as a result of the ration balancing. Therefore, it is of paramount importance that science-based feeding systems and feed analysis are gradually introduced in developing countries with subsistence animal agriculture. This will not only have a measurable economic benefit for the farmer but will also help maximize production and feed utilization and consequently reduce GHG livestock emissions.

Accurate analysis of feed composition is a critical step in the precision feeding process. Even in developed countries with established feed analysis networks, there is still substantial variability in feed analysis among commercial laboratories (Hristov et al., 2010a; Balthrop et al., 2011) and hence the need for standardization of analytical procedures. In intensive dairy systems, daily monitoring of forage, particularly silage DM, can have a profound effect on precision feeding of the cow for maximum production and profitability. Feed analysis technologies, such as near-infrared reflectance spectroscopy (NIRS), have been developing rapidly since the late 1980s and has been used routinely for quality and component analysis of grain, oilseeds, and forages for the past 2 decades. The speed and low cost of NIRS analysis makes it feasible for producers to buy ingredients based on quality and to formulate rations accurately to meet the nutrient requirements of the animals to minimize over- or underfeeding.

CONCLUSIONS

There are a number of potentially effective CH₄ mitigation practices available for the livestock sector today. Conclusions for most of the mitigating agents, feed supplements, or feeding practices discussed in this review are summarized in Table 1.

Some CH₄ inhibitors, such as BCM, although effective, cannot be recommended for this purpose because of their toxicity or ozone-depleting effect. With other compounds, such as 3NP, more data are needed before any conclusions can be made. For most compounds in this category, there are insufficient long-term *in vivo* data. Nitrates may be promising CH₄ mitigation agents, particularly in low-protein diets that may benefit from NPN supplementation. When nitrates are used, it is critically important that the animals are properly adapted to avoid nitrite toxicity. More *in vivo* studies are needed to fully understand the impact of nitrate supplementation on whole-farm GHG emissions (animal, manure storage, and manure-amended soil), animal production, and animal health. Fumaric and malic acids may reduce CH₄ production when applied in large quantities, but most results indicate no mitigating effect. The long-term effects of these compounds have not been established and costs are likely to prohibit their adoption. Ionophores, through their effect on feed efficiency and reduction in CH₄ per unit of feed, would likely have a moderate CH₄ mitigating effect in ruminants fed high-grain or mixed grain–forage diets. The effect is dose, feed intake, and diet composition dependent and is less consistent in ruminants fed pasture.

Hydrolyzable and condensed tannins may offer an opportunity to reduce CH₄ production although intake and animal production may be compromised in some, but not all, instances. The agronomic characteristics of tanniferous forages as well as the concentration and structure of the condensed tannins must be considered when they are discussed as a GHG mitigation option. Based on limited research, tea saponins seem to have CH₄ mitigating potential, but more and long-term studies are required before they can be recommended. Most essential oils or their active ingredients do not reduce CH₄ production and, when CH₄ production was reduced *in vivo*, the long-term effect was not established. Limited data indicate EXE may increase feed efficiency and thus indirectly reduce CH₄ production; however, inconsistencies in the data question EXE as an effective mitigation practice. There is insufficient evidence of the direct CH₄ mitigating effect of yeast and other DFM. However, yeasts appear to stabilize pH and promote rumen function, especially in dairy cattle, resulting in small but relatively consistent responses in animal productivity and feed efficiency and possible decrease in CH₄ Ei.

Defaunation of the rumen cannot be recommended as a CH₄ mitigation practice. At this point, none of the existing rumen microbial manipulation technologies are ready for practical application, but vaccines could be applied to all ruminants, including those with limited human contact, such as sheep and beef animals on pasture. It is important to appreciate that vaccines require the host to produce antibodies against some of their micro-

biome that are part of a symbiotic relationship, enabling ruminant survival on fiber-based diets. To be effective, the vaccines have to cover the entire methanogen community and not just some individual taxa because of likely succession of the insensitive populations that can occupy the same (their only) niche. The extent of reductions in methanogenesis may only be 5 to 10%, and persistence of the effect is unknown, but the potential for widespread application makes this an exciting opportunity for future mitigation of CH₄ emissions.

Based on the existing data, it can be concluded that inclusion of lipids in ruminant diets will likely mitigate CH₄ production, but it may also depress feed intake and, consequently, animal productivity. Therefore, at least part of the mitigation effect reported with lipids is a result of decreased intake of dietary carbohydrate, which is a consequence of decreased DMI as a result of lipids replacing carbohydrate in the diet. The feasibility of using lipids to mitigate the environmental impact of animal production depends on its economic benefits to the producer and potential effects on feed intake (negative), productivity (negative), milk fat content in lactating animals (positive or negative), and ease of supplementation (i.e., grazing systems). High-oil by-product feeds such as distillers grains and meals from the biodiesel industry can serve as cost-effective sources of lipids with potential CH₄ suppressing effect. However, their mitigating potential has not been well established and in some cases CH₄ production may increase due to increased fiber intake. A large number of nontraditional oilseeds are being investigated as biofuel feedstocks that, if available, may be used as livestock feed and have a beneficial effect on animal productivity (through improvements in energy and protein supply), including a CH₄–mitigating effect, although data to support this concept are lacking (see Hristov et al., 2013b).

Inclusion of concentrate feeds in the diet of ruminants will likely decrease CH₄ Ei, particularly when inclusion is above 35 to 40% of DMI, but the effect will depend on basal forage quality, inclusion level, production response, effects on fiber digestibility, rumen function, milk fat content, plane of nutrition, type of grain, and grain processing. Supplementation with small amounts of concentrate feeds (to all-forage diets) will likely increase animal productivity and thus decrease overall GHG Ei although absolute CH₄ emissions might not be reduced. In spite of these potential gains, concentrate supplementation cannot be a feasible substitution for ruminants fed high-quality forages. In addition, in many parts of the world, this may not be an economically feasible and socially acceptable mitigation option. Several comprehensive meta-analyses have produced equations based on animal characteristics, feed intake, and diet composition that may be useful in predicting the effect of concentrate feed supplementation on CH₄ emissions from dairy cattle.

Increased forage digestibility is expected to increase animal production and decrease CH₄ Ei. It appears C4 grasses produce greater amount of CH₄ than C3 grasses and that introduction of legumes in warm climates may offer a mitigation opportunity although low persistence and a need for long establishment periods are important agronomic constraints. Methane emission may be reduced when corn silage replaces grass silage in the diet. Legume silages may also have an advantage over grass silage due to their lower fiber content and the additional benefit of replacing inorganic N fertilizer. With all silages, effective preservation will improve silage quality and reduce GHG Ei. Forage with higher sugar content (HSG or harvested in the afternoon) may reduce urinary N losses and, consequently, N₂O emission from manure applied to soil although more research is needed to support this concept. The best mitigation option in this category is to increase forage digestibility to improve intake and animal productivity, thus reducing overall GHG emissions from rumen fermentation or stored manure per unit of animal product.

Processing of grain to increase its digestibility is likely to reduce CH₄ production per unit of animal product. Caution should be exercised that this does not result in decreased fiber digestibility or excessively fast passage rates; therefore, some processing is recommended so the grain energy is better utilized for animal production. This mitigation practice may not be economically feasible in low-input production systems. There is little evidence of beneficial effects of synchronizing energy and protein delivery or frequency of feeding on ruminal fermentation and specifically CH₄ production. Feeding of TMR may have some advantages over component feeding in stabilizing ruminal fermentation and DMI. Closely matching animal requirements and dietary nutrient supply in all animal production systems and adoption of science-based feeding systems in developing countries with subsistence animal agriculture will help maximize production and feed utilization and consequently reduce CH₄ Ei.

Overall, increasing forage digestibility and digestible forage intake typically decreases CH₄ Ei. Other effective CH₄ mitigation practices include lipid and concentrate feeds supplementation of the diet, feed processing, and certain feed additives such as nitrates, ionophores, tannins, and perhaps some DFM. The long-term effects of many of these mitigation practices, however, have not been well established. Some additives are toxic or may not be economically feasible to implement. The conclusion of this review is that improving forage quality, optimizing rumen function for higher microbial protein synthesis through feeding of a balanced diet matching the physiological stage of the animal, and enhancing the overall efficiency of dietary nutrient use are the most efficient way of decreasing CH₄ emissions per unit of animal product.

LITERATURE CITED

- Abecia, L., A. I. Martin-Garcia, G. Martinez, N. W. Tomkins, C. J. Newbold, and D. R. Yañez-Ruiz. 2011. Manipulation of the rumen microbial ecosystem to reduce methane emissions in ruminants through the intervention at early life stage of pre-ruminants and their mothers. *Adv. Anim. Biosci.* 2:271.
- Abecia, L., P. G. Toral, A. I. Martin-García, G. Martínez, N. W. Tomkins, E. Molina-Alcaide, C. J. Newbold, and D. R. Yañez-Ruiz. 2012. Effect of bromochloromethane on methane emission, rumen fermentation pattern, milk yield, and fatty acid profile in lactating dairy goats. *J. Dairy Sci.* 95:2027–2036.
- Abrahamse, P. A., S. Tamminga, and J. Dijkstra. 2009. Effect of daily movement of dairy cattle to fresh grass in morning or afternoon on intake, grazing behaviour, rumen fermentation and milk production. *J. Agric. Sci.* 147:721–730.
- Agle, M., A. N. Hristov, S. Zaman, C. Schneider, P. Ndegwa, and V. K. Vaddella. 2010. Effect of dietary concentrate on rumen fermentation, digestibility, and nitrogen losses in dairy cows. *J. Dairy Sci.* 93:4211–4222.
- Aguerre, M. J., M. A. Wattiaux, J. M. Powell, G. A. Broderick, and C. Arndt. 2011. Effect of forage-to-concentrate ratio in dairy cow diets on emission of methane, carbon dioxide, and ammonia, lactation performance, and manure excretion. *J. Dairy Sci.* 94:3081–3093.
- Alaboudi, R., and G. A. Jones. 1985. Effects of acclimation to high nitrate intake on some rumen fermentation parameters in sheep. *Can. J. Anim. Sci.* 65:841–849.
- Alemu, A. W., J. Dijkstra, A. Bannink, J. France, and E. Kebreab. 2011. Rumen stoichiometric models and their contribution and challenges in predicting enteric methane production. *Anim. Feed Sci. Technol.* 166–167:761–778.
- Appuhamy, J. A. D. R. N., A. B. Strathe, S. Jayasundara, C. Wagner-Riddle, J. Dijkstra, J. France, and E. Kebreab. 2013. Anti-methanogenic effects of monensin in dairy and beef cattle: A meta-analysis. *J. Dairy Sci.* 96:5161–5173.
- Archimède, H., M. Eugène, C. M. Magdeleine, M. Boval, C. Martin, D. P. Morgavi, P. Lecomte, and M. Doreau. 2011. Comparison of methane production between C3 and C4 grasses and legumes. *Anim. Feed Sci. Technol.* 166:59–64.
- Arriola, K. G., S. C. Kim, C. R. Staples, and A. T. Adesogan. 2011. Effect of fibrolytic enzyme application to low- and high-concentrate diets on the performance of lactating dairy cattle. *J. Dairy Sci.* 94:832–841.
- Balthrop, J., B. Brand, R. A. Cowie, J. Danier, J. De Boever, L. de Jonge, F. Jackson, H. P. S. Makkar, and C. Piotrowski. 2011. Quality assurance for animal feed analysis laboratories. *FAO Animal Production and Health Manual No. 14. Food and Agriculture Organization (FAO), Rome, Italy.*
- Bannink, A., J. France, S. Lopez, W. J. J. Gerrits, E. Kebreab, S. Tamminga, and J. Dijkstra. 2008. Modelling the implications of feeding strategy on rumen fermentation and functioning of the rumen wall. *Anim. Feed Sci. Technol.* 143:3–26.
- Bannink, A., M. W. Van Schijndel, and J. Dijkstra. 2011. A model of enteric fermentation in dairy cows to estimate methane emission for the Dutch National Inventory Report using the IPCC Tier 3 approach. *Anim. Feed Sci. Technol.* 166–167:603–618.
- Bayaru, E., S. Kanda, T. Kamada, S. Andoh, T. Nishida, M. Ishida, T. Itoh, K. Nagara, and Y. Isobe. 2001. Effect of fumaric acid on methane production, rumen fermentation and digestibility of cattle fed roughage alone. *Anim. Sci. J.* 72:139–146.
- Beauchemin, K. A., T. A. McAllister, and S. M. McGinn. 2009. Dietary mitigation of enteric methane from cattle. *CAB Rev.* 4:1–18.
- Beauchemin, K. A., and S. M. McGinn. 2006. Enteric methane emissions from growing beef cattle as affected by diet and level of intake. *Can. J. Anim. Sci.* 86:401–408.

- Beauchemin, K. A., S. M. McGinn, T. F. Martinez, and T. A. McAllister. 2007a. Use of condensed tannin extract from quebracho trees to reduce methane emissions from cattle. *J. Anim. Sci.* 85:1990–1996.
- Beauchemin, K. A., S. M. McGinn, and H. V. Petit. 2007b. Methane abatement strategies for cattle: Lipid supplementation of diets. *Can. J. Anim. Sci.* 87:431–440.
- Benchaar, C., and H. Greathead. 2011. Essential oils and opportunities to mitigate enteric methane emissions from ruminants. *Anim. Feed Sci. Technol.* 166–167:338–355.
- Benchaar, C., A. N. Hristov, and H. Greathead. 2009. Essential oils as feed additives in animal nutrition. In: T. Steiner, editor, *Phytogenics in animal nutrition*. Nottingham Univ. Press, Nottingham, UK. p. 111–146.
- Benchaar, C., H. V. Petit, R. Berthiaume, D. R. Ouellet, J. Chiquette, and P. Y. Chouinard. 2007. Effects of essential oils on digestion, ruminal fermentation, rumen microbial populations, milk production, and milk composition in dairy cows fed alfalfa silage or corn silage. *J. Dairy Sci.* 90:886–897.
- Blaxter, K. L., and J. L. Clapperton. 1965. Prediction of the amount of methane produced by ruminants. *Br. J. Nutr.* 19:511–522.
- Boadi, D., C. Benchaar, J. Chiquette, and D. Massé. 2004. Mitigation strategies to reduce enteric methane emissions from dairy cows: Update review. *Can. J. Anim. Sci.* 84:319–335.
- Bodas, R., S. López, M. Fernandez, R. Garcia-González, A. B. Rodríguez, R. J. Wallace, and J. S. González. 2008. In vitro screening of the potential of numerous plant species as antimethanogenic feed additives for ruminants. *Anim. Feed Sci. Technol.* 145:245–258.
- Boucher, S. E., S. Calsamiglia, C. M. Parsons, H. H. Stein, M. D. Stern, P. S. Erickson, P. L. Utterback, and C. G. Schwab. 2009. Intestinal digestibility of amino acids in rumen-undegraded protein estimated using a precision-fed cecectomized rooster bioassay: II. Distillers dried grains with solubles and fish meal. *J. Dairy Sci.* 92:6056–6067.
- Brito, A. F., G. F. Tremblay, A. Bertrand, Y. Castonguay, G. Bélanger, R. Michaud, H. Lapierre, C. Benchaar, H. V. Petit, D. R. Ouellet, and R. Berthiaume. 2008. Alfalfa cut at sundown and harvested as baleage improves milk yield of late-lactation dairy cows. *J. Dairy Sci.* 91:3968–3982.
- Broderick, G. A. 1995. Desirable characteristics of forage legumes for improving protein utilization in ruminants. *J. Anim. Sci.* 73:2760–2773.
- Brown, E. G., R. C. Anderson, G. E. Carstens, H. Gutierrez-Bañuelos, J. L. McReynolds, L. J. Slay, T. R. Callaway, and D. J. Nisbet. 2011. Effects of oral nitroethane administration on enteric methane emissions and ruminal fermentation in cattle. *Anim. Feed Sci. Technol.* 166–167:275–281.
- Buddle, B. M., M. Denis, G. T. Attwood, E. Altermann, P. H. Janssen, R. S. Ronimus, C. S. Pinares-Patiño, S. Muetzel, and D. N. Wedlock. 2011. Strategies to reduce methane emissions from farmed ruminants grazing on pasture. *Vet. J.* 188:11–17.
- Burritt, E. A., H. F. Mayland, F. D. Provenza, R. L. Miller, and J. C. Burns. 2005. Effect of added sugar on preference and intake by sheep of hay cut in the morning versus the afternoon. *Appl. Anim. Behav. Sci.* 94:245–254.
- Calsamiglia, S., M. Busquet, P. W. Cardozo, L. Castillejos, and A. Ferret. 2008. Essential oils as modifiers of rumen microbial fermentation. *J. Dairy Sci.* 90:2580–2595.
- Cammack, K. M., C. L. Wright, K. J. Austin, P. S. Johnson, R. R. Cockrum, K. L. Kessler, and K. C. Olson. 2010. Effects of high-sulfur water and clinoptilolite on health and growth performance of steers fed forage-based diets. *J. Anim. Sci.* 88:1777–1785.
- Chaucheyras, F., G. Fonty, G. Bertin, and P. Gouet. 1995. In vitro H₂ utilization by a ruminal acetogenic bacterium cultivated alone or in association with an archaea methanogen is stimulated by a probiotic strain of *Saccharomyces cerevisiae*. *Appl. Environ. Microbiol.* 61:3466–3467.
- Chung, Y.-H., M. Zhou, L. Holtshausen, T. W. Alexander, T. A. McAllister, L. L. Guan, M. Oba, and K. A. Beauchemin. 2012. A fibrolytic enzyme additive for lactating Holstein cow diets: Ruminal fermentation, rumen microbial populations, and enteric methane emissions. *J. Dairy Sci.* 95:1419–1427.
- Clark, H. 2010. Animal vs. measurement technique variability in enteric methane production—Is the measurement resolution sufficient? In: E. J. McGeough, and S. M. McGinn, editors, *Proc. 4th International Conference on Greenhouse Gases and Animal Agriculture*, Banff, AB, Canada.
- Clark, H., A.-D. Wright, K. Joblin, G. Molano, A. Chavanagh, and J. Peters. 2004. Field testing and Australian developed anti-methanogen vaccine in growing ewe lambs. In: *Proc. Workshop on the Science of Atmospheric Trace gases*, 18–19 March 2004, Wellington, New Zealand. p. 107–108.
- Cockwill, C. L., T. A. McAllister, M. E. Olson, D. M. Milligan, B. J. Ralston, C. Huisma, and R. K. Hand. 2000. Individual intake of mineral and molasses supplements by cows, heifers and calves. *Can. J. Anim. Sci.* 80:681–690.
- Cook, S. R., P. K. Maiti, A. V. Chaves, C. Benchaar, K. A. Beauchemin, and T. A. McAllister. 2008. Avian (IgY) anti-methanogen antibodies for reducing ruminal methane production: In vitro assessment of their effects. *Aust. J. Exp. Agric.* 48:260–264.
- Coppock, C. E. 1977. Feeding methods and grouping systems. *J. Dairy Sci.* 60:1327–1336.
- Cottle, D. J., J. V. Nolan, and S. G. Wiedemann. 2011. Ruminant enteric methane mitigation: A review. *Anim. Prod. Sci.* 51:491–514.
- Crompton, L. A., J. A. N. Mills, C. K. Reynolds, J. France, D. Sauviant, J. van Milgen, P. Faverdin, and N. Friggens. 2010. Fluctuations in methane emission in response to feeding pattern in lactating dairy cows. In: *7th International Workshop on Modelling Nutrient Digestion and Utilisation in Farm Animals*, Paris, France, Wageningen Academic Publishers, Wageningen, Netherlands. p. 176–180.
- Crutzen, P. J., I. Aselmann, and W. Seiler. 1986. Methane production by domestic animals, wild ruminants, other herbivorous fauna, and humans. *Tellus* 388:271–284.
- Czerkawski, J. W., and G. Breckenridge. 1972. Fermentation of various glycolytic intermediates and other compounds by rumen micro-organisms, with particular reference to methane production. *Br. J. Nutr.* 27:131–146.
- Czerkawski, J. W., and J. L. Clapperton. 1984. Fats as energy-yielding compounds in the ruminant diet. In: J. Wiseman, editor, *Fats in animal nutrition*. Butterworths, Boston, MA. p. 249–263.
- del Prado, A., D. Chadwick, L. Cardenas, T. Misselbrook, D. Scholefield, and P. Merino. 2010. Exploring systems responses to mitigation of GHG in UK dairy farms. *Agric. Ecosyst. Environ.* 136:318–332.
- Department for Environment, Food and Rural Affairs (DEFRA). 2010. Ruminant nutrition regimes to reduce methane and nitrogen emissions. Project AC0209 Report. DEFRA, Procurements and Contracts Division (Science R&D Team). http://randd.defra.gov.uk/Document.aspx?Document = AC0209_10114_FRP.pdf (Accessed 11 July 2012).
- Debusch, B. E., T. G. Nagaraja, J. M. Sargeant, J. S. Drouillard, E. R. Loe, and M. E. Corrigan. 2008. Influence of processed grains on fecal pH, starch concentration, and shedding of *Escherichia coli* O157 in feedlot cattle. *J. Anim. Sci.* 86:632–639.
- DeRamus, H. A., T. C. Clement, D. D. Giampola, and P. C. Dickison. 2003. Methane emissions of beef cattle on forages: Efficiency of grazing management systems. *J. Environ. Qual.* 32:269–277.
- Desnoyers, M., S. Giger-Reverdin, G. Bertin, C. Duvaux-Ponter, and D. Sauviant. 2009. Meta-analysis of the influence of *Saccharomyces cerevisiae* supplementation on ruminal parameters and milk production of ruminants. *J. Dairy Sci.* 92:1620–1632.

- Dewhurst, R. J. 2012. Milk production from silage: Comparison of grass, legume and maize silages and their mixtures. In: K. Kuoppala, M. Rinne, and A. Vanhatalo, editors, Proc. XVI Int. Silage Conf. MTT Agrifood Research Finland, University of Helsinki. Hameenlinna, Finland. p. 134–135.
- Dhiman, T. R., and L. D. Satter. 1997. Yield response of dairy cows fed different proportions of alfalfa silage and corn silage. *J. Dairy Sci.* 80:2069–2082.
- Dhiman, T. R., M. S. Zaman, I. S. MacQueen, and R. L. Boman. 2002. Influence of corn processing and frequency of feeding on cow performance. *J. Dairy Sci.* 85:217–226.
- Dijkstra, J., O. Oenema, and A. Bannink. 2011. Dietary strategies to reducing N excretion from cattle: Implications for methane emissions. *Curr. Opin. Environ. Sustainability* 3:414–422.
- Doreau, M., and A. Ferlay. 1995. Effect of dietary lipids on nitrogen metabolism in the lumen: A review. *Livest. Prod. Sci.* 43:97–110.
- Doreau, M., C. Martin, M. Eugène, M. Popova, and D. P. Morgavi. 2011. Leviers d'action pour réduire la production de méthane entérique par les ruminants. In: M. Doreau, R. Baumont, and J. M. Perez, editors, *Gaz à effet de serre en élevage bovin: Le méthane*. (In French.) INRA Prod. Anim. 24:461–474.
- Doreau, M., Y. Rochette, and C. Martin. 2012. Effect of type of forage (maize silage vs. grass silage) and protein source (soybean meal vs. dehydrated lucerne) in dairy cow diet on methane emission and on nitrogen losses. In: Proc. Symp. Emissions of Gas and Dust by Livestock, Saint-Malo, France. p. 4.
- Duffield, T. F., J. K. Merrill, and R. N. Bagg. 2012. Meta-analysis of the effects of monensin in beef cattle on feed efficiency, body weight gain, and dry matter intake. *J. Anim. Sci.* 90:4583–4592.
- Duffield, T. F., A. R. Rabiee, and I. J. Lean. 2008. A meta-analysis of the impact of monensin in lactating dairy cattle. Part 2. Production effects. *J. Dairy Sci.* 91:1347–1360.
- Eckard, R. J., C. Grainger, and C. A. M. de Klein. 2010. Options for the abatement of methane and nitrous oxide from ruminant production: A review. *Livest. Sci.* 130:47–56.
- Ellis, J. L., A. Bannink, J. France, E. Kebreab, and J. Dijkstra. 2010. Evaluation of enteric methane prediction equations for dairy cows used in whole farm models. *Glob. Change Biol.* 16:3246–3256.
- Ellis, J. L., J. Dijkstra, A. Bannink, E. Kebreab, S. E. Hook, S. Archibeque, and J. France. 2012a. Quantifying the effect of monensin dose on the rumen volatile fatty acid profile in high-grain fed beef cattle. *J. Anim. Sci.* 90:2717–2726.
- Ellis, J. L., J. Dijkstra, J. France, A. J. Parsons, G. R. Edwards, S. Rasmussen, E. Kebreab, and A. Bannink. 2012b. Effect of high-sugar grasses on methane emissions simulated using a dynamic model. *J. Dairy Sci.* 95:272–285.
- Ellis, J. L., J. Dijkstra, E. Kebreab, A. Bannink, N. E. Odongo, B. W. McBride, and J. France. 2008. Aspects of rumen microbiology central to mechanistic modelling of methane production in cattle. *J. Agric. Sci.* 146:213–233.
- EPA. 2013. Class I Ozone-depleting Substances. www.epa.gov/ozone/science/ods/classone.html. (Accessed 16 Sep. 2013.)
- Eugène, M., H. Archimède, and D. Sauvant. 2004. Quantitative meta-analysis on the effects of defaunation of the rumen on growth, intake and digestion in ruminants. *Livest. Prod. Sci.* 85:81–97.
- Eugène, M., C. Martin, M. M. Mialon, D. Krauss, G. Renand, and M. Doreau. 2011. Dietary linseed and starch supplementation decreases methane production of fattening bulls. *Anim. Feed Sci. Technol.* 166–167:330–337.
- Eugène, M., D. Masse, J. Chiquette, and C. Benchaar. 2008. Meta-analysis on the effects of lipid supplementation on methane production in lactating dairy cows. *Can. J. Anim. Sci.* 88:331–334.
- Ferraretto, L. F., P. M. Crump, and R. D. Shaver. 2013. Effect of cereal grain type and corn grain harvesting and processing methods on intake, digestion, and milk production by dairy cows through a meta-analysis. *J. Dairy Sci.* 96:533–550.
- Ferris, C. P., F. J. Gordon, D. C. Patterson, M. G. Porter, and T. Yan. 1999. The effect of genetic merit and concentrate proportion in the diet on nutrient utilisation by lactating dairy cows. *J. Agric. Sci.* 132:483–490.
- Fievez, V., L. Mbanzamihiho, F. Piattoni, and D. Demeyer. 2001. Evidence for reductive acetogenesis and its nutritional significance in ostrich hindgut as estimated from in vitro incubations. *J. Anim. Physiol. Anim. Nutr.* 85:271–280.
- Finlay, B. J., G. Esteban, K. J. Clarke, A. G. Williams, T. M. Embley, and R. P. Hirt. 1994. Some rumen ciliates have endosymbiotic methanogens. *FEMS Microbiol. Lett.* 117:157–162.
- Firkins, J. L. 1997. Effects of feeding nonforage fiber sources on site of fiber digestion. *J. Dairy Sci.* 80:1426–1437.
- Firkins, J. L., M. L. Eastridge, N. R. St-Pierre, and S. M. Noftsker. 2001. Effects of grain variability and processing on starch utilization by lactating dairy cattle. *J. Anim. Sci.* 79(E. Suppl.):E218–E238.
- Firkins, J. L., A. N. Hristov, M. B. Hall, G. A. Varga, and N. R. St-Pierre. 2006. Integration of ruminal metabolism in dairy cattle. *J. Dairy Sci.* 89:E31–51E.
- Flatt, W. P., P. W. Moe, A. W. Munson, and T. Cooper. 1969. Energy utilization by high producing dairy cows. 2. Summary of energy balance experiments with lactating Holstein cows. In: K. L. Blaxter, J. Kielanowski, and G. Thorbek, editors, *Energy metabolism of farm animals*. Vol. 12. European Association for Animal Production, Warsaw. p. 235–251.
- Foley, P. A., D. A. Kenny, J. J. Callan, T. M. Boland, and F. P. O'Mara. 2009. Effect of dl-malic acid supplementation on feed intake, methane emission, and rumen fermentation in beef cattle. *J. Anim. Sci.* 87:1048–1057.
- Food and Agriculture Organization (FAO). 2013. Greenhouse gas emissions from pork and chicken supply chains, a global life cycle assessment. FAO, Rome, Italy.
- Frutos, P., G. Hervás, F. J. Giráldez, and A. R. Mantecón. 2004. Review. Tannins and ruminant nutrition. *Span. J. Agric. Res.* 2:191–202.
- Galbraith, J. K., G. W. Mathison, R. J. Hudson, T. A. McAllister, and K.-J. Cheng. 1998. Intake, digestibility, methane and heat production in bison, wapiti and white-tailed deer. *Can. J. Anim. Sci.* 78:681–691.
- Garg, M. R., P. L. Sherasia, B. M. Bhandari, B. T. Phondba, S. K. Shelke, and H. P. S. Makkar. 2013. Effect of feeding balanced rations on animal productivity, feed conversion efficiency, feed nitrogen use efficiency, rumen microbial protein supply, parasitic load, immunity and enteric methane emission to milch animals under field conditions. *Anim. Feed Sci. Technol.* 179:24–35.
- Gerber, P. J., A. N. Hristov, B. Henderson, H. Makkar, J. Oh, C. Lee, R. Meinen, F. Montes, T. Ott, J. Firkins, C. Dell Al Rotz, A. Adesogan, W. Z. Yang, J. Tricarico, E. Kebreab, G. Waghorn, J. Dijkstra, and S. Oosting. 2013. Technical options for the mitigation of direct methane and nitrous oxide emissions from livestock – A review. *Animal* 7(Suppl. 2):220–234.
- Giger-Reverdin, S., P. Morand-Fehr, and G. Tran. 2003. Literature survey of the influence of dietary fat composition on methane production in dairy cattle. *Livest. Prod. Sci.* 82:73–79.
- Goel, G., and H. P. S. Makkar. 2012. Methane mitigation from ruminants using tannins and saponins. *Trop. Anim. Health Prod.* 44:729–739.
- Goodrich, R. D., J. E. Garrett, D. R. Gast, M. A. Kirick, D. A. Larson, and J. C. Meiske. 1984. Influence of monensin on the performance of cattle. *J. Anim. Sci.* 58:1484–1498.
- Gould, D. H. 2000. Update on sulfur-related polioencephalomalacia. *Vet. Clin. North Am. Food Anim. Pract.* 16:481–496.

- Grainger, C., and K. A. Beauchemin. 2011. Can enteric methane emissions from ruminants be lowered without lowering their production? *Anim. Feed Sci. Technol.* 166–167:308–320.
- Grainger, C., T. Clarke, M. J. Auldist, K. A. Beauchemin, S. M. McGinn, G. C. Waghorn, and R. J. Eckard. 2009. Potential use of *Acacia mearnsii* condensed tannins to reduce methane emissions and nitrogen excretion from grazing dairy cows. *Can. J. Anim. Sci.* 89:241–251.
- Grainger, C., T. Clarke, S. M. McGinn, M. J. Auldist, K. A. Beauchemin, M. C. Hannah, G. C. Waghorn, H. Clark, and R. J. Eckard. 2007. Methane emissions from dairy cows measured using the sulfur hexafluoride (SF₆) tracer and chamber techniques. *J. Dairy Sci.* 90:2755–2766.
- Grainger, C., R. Williams, R. J. Eckard, and M. C. Hannah. 2010. A high dose of monensin does not reduce methane emissions of dairy cows offered pasture supplemented with grain. *J. Dairy Sci.* 93:5300–5308.
- Groff, E. B., and Z. Wu. 2005. Milk production and nitrogen excretion of dairy cows fed different amounts of protein and varying proportions of alfalfa and corn silage. *J. Dairy Sci.* 88:3619–3632.
- Gutierrez-Banuelos, H., R. C. Anderson, G. E. Carstens, L. J. Slay, N. Ramlachan, S. M. Horrocks, T. R. Callaway, T. S. Edrington, and D. J. Nisbet. 2007. Zoonotic bacterial populations, gut fermentation characteristics and methane production in feedlot steers during oral nitroethane treatment and after the feeding of an experimental chlorate product. *Anaerobe* 13:21–31.
- Haisan, J., Y. Sun, K. Beauchemin, L. Guan, S. Duval, D. R. Barreda, and M. Oba. 2013. Effect of feeding 3-nitrooxypropanol on methane emissions and productivity of lactating dairy cows. *Adv. Anim. Biosci.* 4(2):260.
- Hales, K. E., N. A. Cole, and J. C. MacDonald. 2012. Effects of corn processing method and dietary inclusion of wet distillers grains with solubles on energy metabolism, carbon-nitrogen balance, and methane emissions of cattle. *J. Anim. Sci.* 90:3174–3185.
- Hales, K. E., N. A. Cole, and J. C. MacDonald. 2013. Effects of increasing concentrations of wet distillers grains with solubles in steam-flaked corn-based diets on energy metabolism, carbon-nitrogen balance, and methane emissions of cattle. *J. Anim. Sci.* 91:819–828.
- Hall, M. B., and G. B. Huntington. 2008. Nutrient synchrony: Sound in theory, elusive in practice. *J. Anim. Sci.* 86 (E. Suppl.):E287–E292.
- Hammond, K. J., J. L. Burke, J. P. Koolaard, S. Muetzel, C. S. Pinares-Patiño, and G. C. Waghorn. 2013a. The effect of feed intake on enteric methane emissions from sheep fed fresh white clover (*Trifolium repens*) and perennial ryegrass (*Lolium perenne*) forages. *Anim. Feed Sci. Technol.* 179:121–132.
- Hammond, K. J., S. O. Hoskin, J. L. Burke, G. C. Waghorn, J. P. Koolaard, and S. Muetzel. 2011. Effects of feeding fresh white clover (*Trifolium repens*) or perennial ryegrass (*Lolium perenne*) on enteric methane emissions from sheep. *Anim. Feed Sci. Technol.* 166–167:398–404.
- Hammond, K. J., D. J. Humphries, L. A. Crompton, P. Kirton, C. Green, and C. K. Reynolds. 2013b. Methane emissions from growing dairy heifers estimated using an automated head chamber (GreenFeed) compared to respiration chambers or SF₆ techniques. *Adv. Anim. Biosci.* 4(2):391.]
- Hammond, K. J., S. Muetzel, G. C. Waghorn, C. S. Pinares-Patino, J. L. Burke, and S. O. Hoskin. 2009. Exploring variation in methane emissions from sheep and cattle fed pasture determined by either SF₆ marker dilution or direct calorimetry. *Proc. N. Z. Soc. Anim. Prod.* 69:174–178.
- Harris, B. L., and E. S. Kolver. 2001. Review of holsteinization on intensive pastoral dairy farming in New Zealand. *J. Dairy Sci.* 84(E. Suppl.):E56–E61.
- Hart, K. J., P. G. Martin, P. A. Foley, D. A. Kenny, and T. M. Boland. 2009. Effect of sward dry matter digestibility on methane production, ruminal fermentation, and microbial populations of zero-grazed beef cattle. *J. Anim. Sci.* 87:3342–3350.
- Henning, P. H., C. H. Horn, K.-J. Leeuw, H. H. Meissner, and F. M. Hagg. 2010. Effect of ruminal administration of the lactate-utilizing strain *Megasphaera elsdenii* (Me) NCIMB 41125 on abrupt or gradual transition from forage to concentrate diets. *Anim. Feed Sci. Technol.* 157:20–29.
- Hindrichsen, I. K., E. U. Augustsson, B. Lund, M. M. Jensen, M. Raun, J. Jatkauskas, V. Vrotniakiene, and C. Ohlsson. 2012. Characterisation of different lactic acid bacteria in terms of their oxygen consuming capacity, aerobic stability and pathogen inhibition. In: K. Kuoppala, M. Rinne, and A. Vanhatalo, editors, *Proc. XVI Int. Silage Conf. MTT Agrifood Research Finland, University of Helsinki. Hameenlinna, Finland.* p. 105–106.
- Hironaka, R., G. W. Mathison, B. K. Kerrigan, and I. Vlach. 1996. The effect of pelleting of alfalfa hay on methane production and digestibility by steers. *Sci. Total Environ.* 180:221–227.
- Hollmann, M., and D. K. Beede. 2012. Comparison of effects of dietary coconut oil and animal fat blend on lactational performance of Holstein cows fed a high-starch diet. *J. Dairy Sci.* 95:1484–1499.
- Holtshausen, L., Y.-H. Chung, H. Gerardo-Cuervo, M. Oba, and K. A. Beauchemin. 2011. Improved milk production efficiency in early lactation dairy cattle with dietary addition of a developmental fibrolytic enzyme additive. *J. Dairy Sci.* 94:899–907.
- Hristov, A. N. 2012. Historic, pre-European settlement, and present-day contribution of wild ruminants to enteric methane emissions in the United States. *J. Anim. Sci.* 90:1371–1375.
- Hristov, A. N., C. Domitrovich, A. Wachter, T. Cassidy, C. Lee, K. J. Shingfield, P. Kairenius, J. Davis, and J. Brown. 2011a. Effect of replacing solvent-extracted canola meal with high-oil traditional canola, high-oleic acid canola, or high-erucic acid rapeseed meals on rumen fermentation, digestibility, milk production, and milk fatty acid composition in lactating dairy cows. *J. Dairy Sci.* 94:4057–4074.
- Hristov, A. N., K. L. Grandeen, J. K. Ropp, and M. A. McGuire. 2004. Effect of sodium laurate on ruminal fermentation and utilization of ruminal ammonia nitrogen for milk protein synthesis in dairy cows. *J. Dairy Sci.* 87:1820–1831.
- Hristov, A. N., and J.-P. Jouany. 2005. Factors affecting the efficiency of nitrogen utilization in the rumen. In: E. Pfeffer and A. N. Hristov, editors, *Nitrogen and phosphorus nutrition of cattle: Reducing the environmental impact of cattle operations.* CAB International, Wallingford, UK. p. 117–166.
- Hristov, A. N., C. Lee, T. Cassidy, K. Heyler, J. A. Tekippe, G. A. Varga, B. Corl, and R. C. Brandt. 2013a. Effect of *Origanum vulgare* L. leaves on rumen fermentation, production, and milk fatty acid composition in lactating dairy cows. *J. Dairy Sci.* 96:1189–1202.
- Hristov, A. N., C. Lee, T. Cassidy, M. Long, K. Heyler, B. Corl, and R. Forster. 2011b. Effects of lauric and myristic acids on ruminal fermentation, production, and milk fatty acid composition in lactating dairy cows. *J. Dairy Sci.* 94:382–395.
- Hristov, A. N., C. Lee, R. A. Hristova, P. Huhtanen, and J. Firkins. 2012. A meta-analysis of the variability in continuous culture rumen fermentation and digestibility data. *J. Dairy Sci.* 95:5299–5307.
- Hristov, A. N., D. Mertens, S. Zaman, M. Vander Pol, and W. J. Price. 2010a. Variability in feed and total mixed ration neutral-detergent fiber and crude protein analyses among commercial laboratories. *J. Dairy Sci.* 93:5348–5362.

- Hristov, A. N., J. Oh, C. Lee, R. Meinen, F. Montes, T. Ott, J. Firkins, A. Rotz, C. Dell, A. Adesogan, W. Z. Yang, J. Tricarico, E. Kebreab, G. Waghorn, J. Dijkstra, and S. Oosting. 2013b. Mitigation of greenhouse gas emissions in livestock production – A review of technical options for non-CO₂ emissions. P. Gerber, B. Henderson, and H. Makkar, editors. FAO Animal Production and Health Paper No. 177. FAO, Rome, Italy.
- Hristov, A. N., T. Ott, J. Tricarico, A. Rotz, G. Waghorn, A. Adesogan, J. Dijkstra, F. Montes, J. Oh, J. Firkins, E. Kebreab, S. Oosting, P. J. Gerber, B. Henderson, and H. P. S. Makkar. 2013c. Mitigation of methane and nitrous oxide emissions from animal operations: III. A review of animal management-related mitigation options. *J. Anim. Sci.* 91:5095–5113.
- Hristov, A. N., M. Vander Pol, M. Agle, S. Zaman, C. Schneider, P. Ndegwa, V. K. Vaddella, K. Johnson, K. J. Shingfield, and S. K. R. Karnati. 2009. Effect of lauric acid and coconut oil on ruminal fermentation, digestion, ammonia losses from manure, and milk fatty acid composition in lactating cows. *J. Dairy Sci.* 92:5561–5582.
- Hristov, A. N., G. Varga, T. Cassidy, M. Long, K. Heyler, K. R. Karnati, B. Corl, C. J. Hovde, and I. Yoon. 2010b. Effect of yeast culture on ruminal fermentation and nutrient utilization in dairy cows. *J. Dairy Sci.* 93:682–692.
- Huhtanen, P., and M. Hetta. 2012. Comparison of feed intake and milk production responses in continuous and change-over design dairy cow experiments. *Livest. Sci.* 143:184–194.
- Huhtanen, P., S. Krizsan, E. H. Cabezas Garcia, M. Hetta, and H. Gidlund. 2013. Repeatability and between cow variability of enteric CH₄ and total CO₂ emissions. *Adv. Anim. Biosci.* 4:588.
- Hulshof, R. B. A., A. Berndt, W. J. J. Gerrits, J. Dijkstra, S. M. van Zijderveld, J. R. Newbold, and H. B. Perdok. 2012. Dietary nitrate supplementation reduces methane emission in beef cattle fed sugarcane based diets. *J. Anim. Sci.* 90:2317–2323.
- Immig, I., D. Demeyer, D. Fiedler, C. Van Nevel, and L. Mbanzihigo. 1996. Attempts to induce reductive acetogenesis into a sheep rumen. *Arch. Anim. Nutr.* 49:363–370.
- Intergovernmental Panel on Climate Change (IPCC). 2006. Chapter 10. Emissions from livestock and manure management. In: Guidelines for national greenhouse inventories. Vol. 4. Agriculture, forestry and other land use. IPCC, Geneva, Switzerland. p. 10.1–10.87.
- Janssen, P. H. 2010. Influence of hydrogen on rumen methane formation and fermentation balances through microbial growth kinetics and fermentation thermodynamics. *Anim. Feed Sci. Technol.* 160:1–22.
- Jayanegara, A., F. Leiber, and M. Kreuzer. 2012. Meta-analysis of the relationship between dietary tannin level and methane formation in ruminants from in vivo and in vitro experiments. *J. Anim. Physiol. Anim. Nutr. (Berl.)* 96:365–375.
- Jenkins, T. C., R. J. Wallace, P. J. Moate, and E. E. Mosley. 2008. Board-invited review: Recent advances in biohydrogenation of unsaturated fatty acids within the rumen microbial ecosystem. *J. Anim. Sci.* 86:397–412.
- Jensen, B. B. 1996. Methanogenesis in monogastric animals. *Environ. Monit. Assess.* 42:99–112.
- Joblin, K. N. 1999. Ruminant acetogens and their potential to lower rumen methane emissions. *Aust. J. Agric. Res.* 50:1307–1313.
- Johnson, E. D., A. S. Wood, J. B. Stone, and E. T. Moran Jr. 1972. Some effects of methane inhibition in ruminants (steers). *Can. J. Anim. Sci.* 52:703–712.
- Johnson, K. A., and D. E. Johnson. 1995. Methane emissions from cattle. *J. Anim. Sci.* 73:2483–2492.
- Keady, T. W. J., C. M. Marley, and N. D. Scollan. 2012. Grass and alternative forage silages for beef cattle and sheep: Effects on animal performance. In: K. Kuoppala, M. Rinne, and A. Vanhatalo, editors, Proc. XVI Int. Silage Conf. Hameenlinna, Finland. MTT Agrifood Research Finland, University of Helsinki. p. 152–165.
- Kebreab, E., K. Clark, C. Wagner-Riddle, and J. France. 2006. Methane and nitrous oxide emissions from Canadian animal agriculture: A review. *Can. J. Anim. Sci.* 86:135–158.
- Kelliher, F. M., and H. Clark. 2010. Methane emissions from bison – An historic herd estimate for the North American Great Plains. *Agric. For. Meteorol.* 150:473–477.
- Kennedy, P. M., and E. Charnley. 2012. Methane yields from Brahman cattle fed tropical grasses and legumes. *Anim. Prod. Sci.* 52:225–239.
- Kempton, T. J., R. M. Murray, and R. A. Leng. 1976. Methane production and digestibility measurements in the grey kangaroo and sheep. *Aust. J. Biol. Sci.* 29:209–214.
- Klieve, A. V., D. Hennessy, D. Ouwkerk, R. J. Forster, R. I. Mackie, and G. T. Attwood. 2003. Establishing populations of *Megasphaera elsdenii* YE 34 and *Butyrivibrio fibrisolvens* YE 44 in the rumen of cattle fed high grain diets. *J. Appl. Microbiol.* 95:621–630.
- Knight, T., R. S. Ronimus, D. Dey, C. Tootill, G. Naylor, P. Evans, G. Molano, A. Smith, M. Tavendale, C. S. Pinares-Patino, and H. Clark. 2011. Chloroform decreases rumen methanogenesis and methanogen populations without altering rumen function in cattle. *Anim. Feed Sci. Technol.* 166:101–112.
- Kolver, E. S., and P. W. Aspin. 2006. Supplemental fumarate did not influence milksolids or methane production from dairy cows fed high quality pasture. *Proc. N.Z. Soc. Anim. Prod.* 66:409–415.
- Krehbiel, C. R., S. R. Rust, G. Zhang, and S. E. Gilliland. 2003. Bacterial direct-fed microbials in ruminant diets: Performance response and mode of action. *J. Anim. Sci.* 81(E. Suppl. 2):E120–E132.
- Lassey, K. R., C. S. Pinares-Patiño, R. J. Martin, G. Molano, and A. M. S. McMillan. 2011. Enteric methane emission rates determined by the SF₆ tracer technique: Temporal patterns and averaging periods. *Anim. Feed Sci. Technol.* 166–167:183–191.
- Le Van, T. D., J. A. Robinson, J. Ralph, R. C. Greening, W. J. Smolenski, J. A. Z. Leedle, and D. M. Schaeffer. 1998. Assessment of reductive acetogenesis with indigenous ruminal bacterium populations and *Acetivibrio ruminis*. *Appl. Environ. Microbiol.* 64:3429–3436.
- Leahy, S. C., W. J. Kelly, E. Altermann, R. S. Ronimus, C. J. Yeoman, D. M. Pacheco, D. Li, Z. Kong, S. McTavish, C. Sang, S. C. Lambie, P. H. Janssen, D. Dey, and G. T. Attwood. 2010. The genome sequence of the rumen *Methanogen Methanobrevibacter* reveals new possibilities for controlling ruminant methane emissions. *PLoS ONE* 5:e8926.
- Lee, C., A. N. Hristov, C. J. Dell, G. W. Feyereisen, J. Kaye, and D. Beegle. 2012. Effect of dietary protein concentration on ammonia and greenhouse gas emissions from dairy manure. *J. Dairy Sci.* 95:1930–1941.
- Lee, C., A. N. Hristov, K. S. Hyler, T. W. Cassidy, M. Long, B. A. Corl, and S. K. R. Karnati. 2011. Effects of dietary protein concentration and coconut oil supplementation on nitrogen utilization and production in dairy cows. *J. Dairy Sci.* 94:5544–5557.
- Lee, M. J., P. J. Schreurs, A. C. Messer, and S. H. Zinder. 1987. Association of methanogenic bacteria with flagellated protozoa from a termite hindgut. *Curr. Microbiol.* 15:337–341.
- Leng, R. A. 2008. The potential of feeding nitrate to reduce enteric methane production in ruminants. A report to the department of climate change. Commonwealth Government of Australia, Canberra, Australia.
- Leslie, M., M. Aspin, and H. Clark. 2008. Greenhouse gas emissions from New Zealand agriculture: Issues, perspectives and industry response. *Aust. J. Exp. Agric.* 48:1–5.
- Lila, Z. A., N. Mohammed, N. Tatsuoka, S. Kanda, Y. Kurokawa, and H. Itabashi. 2004. Effect of cyclodextrin diallyl maleate on methane production, ruminal fermentation and microbes in vitro and in vivo. *Anim. Sci. J.* 75:15–22.

- Lowry, B. J., C. S. McSweeney, and B. Palmer. 1996. Changing perceptions of the effect of plant phenolics on nutrient supply in the ruminant. *Aust. J. Agric. Res.* 47:829–842.
- Machmüller, A. 2006. Medium-chain fatty acids and their potential to reduce methanogenesis in domestic ruminants. *Agric. Ecosyst. Environ.* 112:107–114.
- Machmüller, A., and M. Kreuzer. 1999. Methane suppression by coconut oil and associated effects on nutrient and energy balance in sheep. *Can. J. Anim. Sci.* 79:65–72.
- Madsen, J., and M. F. Bertelsen. 2012. Methane production by red-necked wallabies (*Macropus rufogriseus*). *J. Anim. Sci.* 90:1364–1370.
- Madsen, J., B. S. Bjerg, T. Hvelplund, M. R. Weisbjerg, and P. Lund. 2010. Methane and carbon dioxide ration in excreted air for quantification of the methane production from ruminants. *Livest. Sci.* 129:223–227.
- Maekawa, M., K. A. Beauchemin, and D. A. Christensen. 2002. Effect of concentrate level and feeding management on chewing activities, saliva production, and ruminal pH of lactating dairy cows. *J. Dairy Sci.* 85:1165–1175.
- Makkar, H. P. S., and K. Becker. 1997. Degradation of quillaja saponins by mixed culture of rumen microbes. *Lett. Appl. Microbiol.* 25:243–245.
- Makkar, H. P. S., and P. Vercoe. 2007. Quantification of methane emission from ruminants. FAO Publication, Springer Science and Business Media, Inc., New York, NY.
- Martin, C., D. P. Morgavi, and M. Doreau. 2010. Methane mitigation in ruminants: From microbe to the farm scale. *Animal* 4:351–365.
- Martin, C., D. Pomiès, A. Ferlay, Y. Rochette, B. Martin, Y. Chilliard, D. P. Morgavi, and M. Doreau. 2011. Methane output and rumen microbiota in dairy cows in response to long-term supplementation with linseed or rapeseed of grass silage- or pasture-based diets. *Proc. N.Z. Soc. Anim. Prod.* 71:242–247.
- Martin, C., J. Rouel, J. P. Jouany, M. Doreau, and Y. Chilliard. 2008. Methane output and diet digestibility in response to feeding dairy cows crude linseed, extruded linseed, or linseed oil. *J. Anim. Sci.* 86:2642–2650.
- Martinez-Fernandez, G., A. Arco, L. Abecia, G. Cantalapiedra-Hijar, E. Molina-Alcaide, A. I. Martin-Garcia, M. Kindermann, S. Duval, and D. R. Yanez-Ruiz. 2013. The addition of ethyl-3-nitrooxy propionate and 3-nitrooxypropanol in the diet of sheep sustainably reduces methane emissions and the effect persists over a month. *Adv. Anim. Biosci.* 4(part 2):368.
- Mathers, J. C., and D. E. Walters. 1982. Variation in methane production by sheep fed every two hours. *J. Agric. Sci.* 98:633–638.
- Mathew, B., M. L. Eastridge, E. R. Oelker, J. L. Firkins, and S. K. R. Karnati. 2011. Interactions of monensin with dietary fat and carbohydrate components on ruminal fermentation and production responses by dairy cows. *J. Dairy Sci.* 94:396–409.
- McCaughy, W. P., K. Wittenberg, and D. Corrigan. 1999. Impact of pasture type on methane production by lactating beef cows. *Can. J. Anim. Sci.* 79:221–226.
- McCourt, A. R. Y. T., S. Mayne, and R. J. Wallace. 2008. Effect of dietary inclusion of encapsulated fumaric acid on methane production from grazing dairy cows. In: *Proceedings of British Society of Animal Science Annual Conference*. British Society of Animal Science, Scarborough, UK. p. 64.
- McGeough, E. J., P. O’Kiely, K. J. Hart, A. P. Moloney, T. M. Boland, and D. A. Kenny. 2010. Methane emissions, feed intake, performance, digestibility, and rumen fermentation of finishing beef cattle offered whole-crop wheat silages differing in grain content. *J. Anim. Sci.* 88:2703–2716.
- McGinn, S. M., K. A. Beauchemin, T. Coates, and D. Colombatto. 2004. Methane emissions from beef cattle: Effects of monensin, sunflower oil, enzymes, yeast, and fumaric acid. *J. Anim. Sci.* 82:3346–3356.
- McGinn, S. M., Y.-H. Chung, K. A. Beauchemin, A. D. Iwaasa, and C. Grainger. 2009. Use of corn distillers’ dried grains to reduce enteric methane loss from beef cattle. *Can. J. Anim. Sci.* 89:409–413.
- McMahon, L. R., T. A. McAllister, B. P. Berg, W. Majak, S. N. Acharya, J. D. Popp, B. E. Coulman, Y. Wang, and K.-J. Cheng. 2000. A review of the effects of forage condensed tannins on ruminal fermentation and bloat in grazing cattle. *Can. J. Plant Sci.* 80:469–485.
- McSweeney, C. S., H. P. S. Makkar, and J. D. Reed. 2003. Modification of rumen fermentation for detoxification of harmful plant compounds. In: *Proc. 6th International Symposium on the Nutrition of Herbivores*. Merida, Yucatan, Mexico. p. 239–268.
- Mitsumori, M., T. Shinkai, A. Takenaka, O. Enishi, K. Higuchi, Y. Kobayashi, I. Nonaka, N. Asanuma, S. E. Denman, and C. S. McSweeney. 2011. Responses in digestion, rumen fermentation and microbial populations to inhibition of methane formation by a halogenated methane analogue. *Br. J. Nutr.* 8:1–10.
- Moate, P. J., S. R. O. Williams, C. Grainger, M. C. Hannah, E. N. Ponampalam, and R. J. Eckard. 2011. Influence of cold-pressed canola, brewers grains and hominy meal as dietary supplements suitable for reducing enteric methane emissions from lactating dairy cows. *Anim. Feed Sci. Technol.* 166–167:254–264.
- Moe, P. W., and H. F. Tyrrell. 1979. Methane production in dairy cows. *J. Dairy Sci.* 62:1583–1586.
- Mohammed, R., D. M. Stevenson, K. A. Beauchemin, R. E. Muck, and P. J. Weimer. 2012. Changes in ruminal bacterial community composition following feeding of alfalfa ensiled with a lactic acid bacterial inoculant. *J. Dairy Sci.* 95:328–339.
- Molano, G., and H. Clark. 2008. The effect of level of intake and forage quality on methane production by sheep. *Aust. J. Exp. Agric.* 48:219–222.
- Molano, G., T. W. Knight, and H. Clark. 2008. Fumaric acid supplements have no effect on methane emissions per unit of feed intake in wether lambs. *Aust. J. Exp. Agric.* 48:165–168.
- Montes, F., R. Meinen, C. Dell, A. Rotz, A. N. Hristov, J. Oh, G. Waghorn, P. J. Gerber, B. Henderson, and H. P. S. Makkar. 2013. Mitigation of methane and nitrous oxide emissions from animal operations: II. A review of manure management options. *J. Anim. Sci.* 91:5070–5094.
- Moraes, L. E., D. Casper, A. B. Strathe, J. G. Fadel, and E. Kebreab. 2013. Predicting enteric methane emissions from dairy cattle using Bayesian methods. In: *Proc. of the Greenhouse Gases and Animal Agriculture Conference*, Dublin, Ireland. (in press).
- Morgavi, D. P., E. Forano, C. Martin, and C. J. Newbold. 2010. Microbial ecosystem and methanogenesis in ruminants. *Animal* 4:1024–1036.
- Morgavi, D. P., C. Martin, J.-P. Jouany, and M. J. Ranilla. 2011. Rumen protozoa and methanogenesis: Not a simple cause-effect relationship. *Br. J. Nutr.* 107:388–397.
- Muck, R. E., G. A. Broderick, A. P. Faciola, U. C. Hymes-Fecht. 2011. Milk production response to feeding alfalfa silage inoculated with *Lactobacillus plantarum*. *J. Anim. Sci.* 89(E-Suppl. 1):546.
- Muller, H. L., J. Sax, and M. Kirchgessner. 1980. Effect of frequency of feeding on energy losses in faeces, urine and methane in non-lactating and lactating cows. *Z. Tierphysiol. Tierernahr. Futtermittelkd.* 44:181–189.
- Muñoz, C., T. Yan, D. A. Wills, S. Murray, and A. W. Gordon. 2012. Comparison of the sulfur hexafluoride tracer and respiration chamber techniques for estimating methane emissions and correction for rectum methane output from dairy cows. *J. Dairy Sci.* 95:3139–3148.
- Murray, R. M., A. M. Bryant, and R. A. Leng. 1976. Rates of production of methane in the rumen and large intestine of sheep. *Br. J. Nutr.* 36:1–14.
- Nagaraja, T. G., C. J. Newbold, C. J. Van Nevel, and D. I. Demeyer. 1997. Manipulation of ruminal fermentation. In: P. N. Hobson, and C. S. Stewart, editors, *The Rumen microbial ecosystem*. Blackie Academic and Professional, London, UK. p. 523–623.

- Newbold, C. J., B. Lassalas, and J. P. Jouany. 1995. The importance of methanogens associated with ciliate protozoa in ruminal methane production in vitro. *Lett. Appl. Microbiol.* 21:230–234.
- Newbold, C. J., and L. M. Rode. 2006. Dietary additives to control methanogenesis in the rumen. *Inter. Cong. Ser.* 1293:138–147.
- Niezen, J. H., H. A. Robertson, G. C. Waghorn, and W. A. G. Charleston. 1998a. Production, faecal egg counts and worm burdens of ewe lambs which grazed six contrasting forages. *Vet. Parasitol.* 80:15–27.
- Niezen, J. H., G. C. Waghorn, and W. A. G. Charleston. 1998b. Establishment and fecundity of *Ostertagia circumcincta* and *Trichostrongylus colubriformis* in lambs fed lotus (*Lotus pedunculatus*) or perennial ryegrass (*Lolium perenne*). *Vet. Parasitol.* 78:13–21.
- Niezen, J. H., T. S. Waghorn, W. A. G. Charleston, and G. C. Waghorn. 1995. Growth and gastrointestinal nematode parasitism in lambs grazing either lucerne (*Medicago sativa*) or sulla (*Hedysarum coronarium*) which contains condensed tannins. *J. Agric. Sci.* 125:281–289.
- Nishida, T., B. Eruden, K. Hosoda, H. Matsuyama, C. Xu, and S. Shioya. 2007. Digestibility, methane production and chewing activity of steers fed whole-crop round bale corn silage preserved at three maturities. *Anim. Feed Sci. Technol.* 135:42–51.
- Nocek, J. E., and D. G. Braund. 1985. Effect of feeding frequency on diurnal dry matter and water consumption, liquid dilution rate, and milk yield in first lactation. *J. Dairy Sci.* 68:2238–2247.
- Nocek, J. E., R. L. Steele, and D. G. Braund. 1986. Performance of dairy cows fed forage and grain separately versus a total mixed ration. *J. Dairy Sci.* 69:2140–2147.
- Nolan, J. V., R. S. Hegarty, J. Hegarty, I. R. Godwin, and R. Woodgate. 2010. Effects of dietary nitrate on fermentation, methane production and digesta kinetics in sheep. *Anim. Prod. Sci.* 50:801–806.
- Nousiainen, J., M. Rinne, and P. Huhtanen. 2009. A meta-analysis of feed digestion in dairy cows. 1. The effects of forage and concentrate factors on total diet digestibility. *J. Dairy Sci.* 92:5019–5030.
- NRC. 2001. Nutrient requirements of dairy cattle. 7th rev. ed. Natl. Acad. Press, Washington, DC.
- Odongo, N. E., R. Bagg, G. Vessie, P. Dick, M. M. Or-Rashid, S. E. Hook, J. T. Gray, E. Kebreab, J. France, and B. W. McBride. 2007. Long-term effects of feeding monensin on methane production in lactating dairy cows. *J. Dairy Sci.* 90:1781–1788.
- Palmquist, D. L., and T. C. Jenkins. 1980. Review Fat in lactation rations. *J. Dairy Sci.* 63:1–14.
- Parsons, A. J., J. S. Rowarth, and S. Rasmussen. 2011. High-sugar grasses. *CAB Rev.* 6:1–12.
- Patra, A. K. 2010. Meta-analyses of effects of phytochemicals on digestibility and rumen fermentation characteristics associated with methanogenesis. *J. Sci. Food Agric.* 90:2700–2708.
- Phillips, C. J. C., and M. I. Rind. 2001. The effects of frequency of feeding a total mixed ration on the production and behavior of dairy cows. *J. Dairy Sci.* 84:1979–1987.
- Pinares-Patiño, C. S., R. Baumont, and C. Martin. 2003. Methane emissions by Charolais cows grazing a monospecific pasture of timothy at four stages of maturity. *Can. J. Anim. Sci.* 83:769–777.
- Pinares-Patiño, C. S., P. D'hour, J. P. Jouany, and C. Martin. 2007. Effects of stocking rate on methane and carbon dioxide emissions from grazing cattle. *Agric. Ecosyst. Environ.* 121:30–46.
- Popova, M., C. Martin, M. Eugène, M. M. Mialon, M. Doreau, and D. P. Morgavi. 2011. Effect of fibre- and starch-rich finishing diets on methanogenic Archaea diversity and activity in the rumen of feedlot bulls. *Anim. Feed Sci. Technol.* 166:113–121.
- Poppy, G. D., A. R. Rabiee, I. J. Lean, W. K. Sanchez, K. L. Dorton, and P. S. Morley. 2012. A meta-analysis of the effects of feeding yeast culture produced by anaerobic fermentation of *Saccharomyces cerevisiae* on milk production of lactating dairy cows. *J. Dairy Sci.* 95:6027–6041.
- Potter, E. L., R. D. Muller, M. I. Wray, L. H. Carroll, and R. M. Meyer. 1986. Effect of monensin on the performance of cattle on pasture or fed harvested forages in confinement. *J. Anim. Sci.* 62:583–592.
- Poulsen, M., C. Schwab, B. B. Jensen, R. M. Engberg, A. Spang, N. Canibe, O. Hølbetg, G. Milinovich, L. Fragner, C. Schleper, W. Weckwerth, P. Lund, A. Schramm, and T. Ulrich. 2012. Methylophilic methanogenic Thermoplasmata implicated in reduced methane emissions from bovine rumen. *Nat. Commun.* 4:1428.
- Rabiee, A. R., K. Breinhild, W. Scott, H. M. Golder, E. Block, and I. J. Lean. 2012. Effect of fat additions to diets of dairy cattle on milk production and components: A meta-analysis and meta-regression. *J. Dairy Sci.* 95:3225–3247.
- Ramin, M., and P. Huhtanen. 2013. Development of equations for predicting methane emissions from ruminants. *J. Dairy Sci.* 96:2476–2493.
- Reynolds, C. K., D. J. Humphries, P. Kirton, M. Kinderman, S. Duval, and W. Steinberg. 2013. Effect of incremental doses of 3-nitrooxypropanol on methane production, digestion, and rumen parameters in lactating dairy cows. *Adv. Anim. Biosci.* 4(2):261.
- Robinson, P. H., and L. J. Erasmus. 2009. Effects of analyzable diet components on responses of lactating dairy cows to *Saccharomyces cerevisiae* based yeast products: A systematic review of the literature. *Anim. Feed Sci. Technol.* 149:185–198.
- Röhrmoser, G., H. L. Müller, and M. Kirchgesner. 1983. Energy balance and energy utilization of lactating cows with restricted protein supply and subsequent refeeding. *Z. Tierphysiol. Tierernähr. Futtermittelkd.* 50:216–224.
- Russell, J. B., and A. J. Houlihan. 2003. Ionophore resistance of ruminal bacteria and its potential impact on human health. *FEMS Microbiol. Rev.* 27:65–74.
- Sar, C., B. Santoso, B. Mwenya, Y. Gamo, T. Kobayashi, R. Morikawa, K. Kimura, H. Mizukoshi, and J. Takahashi. 2004. Manipulation of rumen methanogenesis by the combination of nitrate with β 1-4 galacto-oligosaccharides or nisin in sheep. *Anim. Feed Sci. Technol.* 115:129–142.
- Sauer, F. D., V. Fellner, R. Kinsman, J. K. Kramer, H. A. Jackson, A. J. Lee, and S. Chen. 1998. Methane output and lactation response in Holstein cattle with monensin or unsaturated fat added to the diet. *J. Anim. Sci.* 76:906–914.
- Sauvant, D., and S. Giger-Reverdin. 2009. Modélisation des interactions digestives et de la production de méthane chez les ruminants. (In French.) *INRA Prod. Anim.* 22:375–384.
- Sauvant, D., S. Giger-Reverdin, A. Serment, and I. Broudiscou. 2011. Influences des régimes et de leur fermentation dans le rumen sur la production de méthane par les ruminants. In: *Gaz à effet de serre en élevage bovin: Le méthane.* (In French.) M. Doreau, R. Baumont, and J. M. Perez, editors. *INRA Prod. Anim.* 24:433–446.
- Sawyer, M. S., W. H. Hoover, and C. J. Sniffen. 1974. Effects of a ruminal methane inhibitor on growth and energy metabolism in the ovine. *J. Anim. Sci.* 38:908–914.
- Schingoethe, D. J., K. F. Kalscheur, A. R. Hippen, and A. D. Garcia. 2009. The use of distillers products in dairy cattle diets. *J. Dairy Sci.* 92:5802–5813.
- Schoonmaker, J. P., and D. C. Beitz. 2012. Hydrogen sulphide: Synthesis, physiology, roles and pathology associated with feeding cattle maize co-products of the ethanol industry. In: H. P. S. Makkar, editor, *Biofuel co-products as livestock feed: Opportunities and challenges.* Food and Agriculture Organization of the United Nations, Rome, Italy. p. 101–113.
- Shewmaker, G. E., H. F. Mayland, C. A. Roberts, P. A. Harrison, N. J. Chatterton, and D. A. Sleper. 2006. Daily carbohydrate accumulation in eight tall fescue cultivars. *Grass Forage Sci.* 61:413–421.

- Sliwinski, B. J., M. Kreuzer, H. R. Wettstein, and A. Machmuller. 2002. Rumen fermentation and nitrogen balance of lambs fed diets containing plant extracts rich in tannins and saponins and associated emissions of nitrogen and methane. *Arch. Anim. Nutr.* 56:379–392.
- Spiehs, M. J., and V. H. Varel. 2009. Nutrient excretion and odorant production in manure from cattle fed corn wet distillers grains with soluble. *J. Anim. Sci.* 87:2977–2984.
- Spiehs, M. J., M. H. Whitney, and G. C. Shurson. 2002. Nutrient database for distiller's dried grains with solubles produced from new ethanol plants in Minnesota and South Dakota. *J. Anim. Sci.* 80:2639–2645.
- Staerfl, S. M., S. L. Amelchanka, T. Kälber, C. R. Soliva, M. Kreuzer, and J. O. Zeitz. 2012. Effect of feeding dried high-sugar ryegrass ('AberMagic') on methane and urinary nitrogen emissions of primiparous cows. *Livest. Sci.* 150:293–301.
- Steinfeld, H., P. Gerber, T. Wassenaar, V. Castel, M. Rosales, and C. de Haan. 2006. *Livestock's long shadow – Environmental issues and options.* Food and Agriculture Organization of the United Nations, Rome, Italy.
- Storm, I. M. L. D., A. L. F. Hellwing, N. I. Nielsen, and J. Madsen. 2012. Methods for measuring and estimating methane emission from ruminants. *Animals* 2:160–183.
- Sun, X. Z., S. O. Hoskin, S. Muetzel, G. Molano, and H. Clark. 2011. Effect of chicory (*Cichorium intybus*) and perennial ryegrass (*Lolium perenne*) on methane emissions in vitro and from sheep. *Anim. Feed Sci. Technol.* 166–167:391–397.
- Sun, X. Z., G. C. Waghorn, S. O. Hoskin, S. J. Harrison, S. Muetzel, and D. Pacheco. 2012. Methane emissions from sheep fed fresh brassicas (*Brassica* spp.) compared to perennial ryegrass (*Lolium perenne*). *Anim. Feed Sci. Technol.* 176:107–116.
- Sutton, J. D., R. Knight, A. B. McAllan, and R. H. Smith. 1983. Digestion and synthesis in the rumen of sheep given diets supplemented with free and protected oils. *Br. J. Nutr.* 49:419–432.
- Takahashi, J. 2011. Some prophylactic options to mitigate methane emission from animal agriculture in Japan. *Asian-Aust. J. Anim. Sci.* 24:285–294.
- Takahashi, J., M. Ikeda, S. Matsuoka, and H. Fujita. 1998. Prophylactic effect of L-cysteine to acute and subclinical nitrate toxicity in sheep. *Anim. Feed Sci. Technol.* 74:273–280.
- Tekippe, J. A., A. N. Hristov, K. S. Heyler, T. W. Cassidy, V. D. Zheljzkov, J. F. S. Ferreira, S. K. Karnati, and G. A. Varga. 2011. Rumen fermentation and production effects of *Origanum vulgare* L. in lactating dairy cows. *J. Dairy Sci.* 94:5065–5079.
- Terrill, T. H., G. B. Douglas, A. G. Foote, R. W. Purchas, G. F. Wilson, and T. N. Barry. 1992. Effect of condensed tannins upon body growth, wool growth and rumen metabolism in sheep grazing sulla (*Hedysarum coronarium*) and perennial pasture. *J. Agric. Sci.* 119:265–273.
- Tomkins, N. W., S. M. Colegate, and R. A. Hunter. 2009. A bromochloromethane formulation reduces enteric methanogenesis in cattle fed grain-based diets. *Anim. Prod. Sci.* 49:1053–1058.
- Tyrell, H. F., and P. W. Moe. 1972. Net energy value for lactation of a high and low concentrate ration containing corn silage. *J. Dairy Sci.* 55:1106–1112.
- Ungerfeld, E. M., R. A. Kohn, R. J. Wallace, and C. J. Newbold. 2007. A meta-analysis of fumarate effects on methane production in ruminal batch cultures. *J. Anim. Sci.* 85:2556–2563.
- U.S. Environmental Protection Agency (USEPA). 2006. *Global anthropogenic mon-CO₂ greenhouse gas emissions: 1990–2020.* USEPA, Washington, DC.
- U.S. Environmental Protection Agency (USEPA). 2011. *Inventory of U.S. greenhouse gas emissions and sinks: 1990–2009.* USEPA, Washington, DC. www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2011-Executive-Summary.pdf (accessed 21 July 2011).
- Van Middelaar, C. E., P. B. M. Berentsen, J. Dijkstra, and I. J. M. De Boer. 2012. Evaluation of a feeding strategy to reduce greenhouse gas emissions from milk production: The level of analysis matters. *J. Anim. Sci.* 90(Suppl. 3):707.
- Van Soest, P. J. 1994. *Nutritional ecology of the ruminant.* Cornell Univ. Press, Ithaca, NY.
- Van Vugt, S. J., G. C. Waghorn, D. A. Clark, and S. L. Woodward. 2005. Impact of monensin on methane production and performance of cows fed forage diets. *Proc. N.Z. Soc. Anim. Prod.* 65:362–366.
- Van Vuuren, A. M. 2003. Effect of live yeast on the performance of dairy cows. In: A. M. van Vuuren, editor, *The role of probiotics in animal nutrition and their link to the demands of European consumers.* TNO Publications, Lelystad, The Netherlands.
- Van Zijderveld, S. M., J. Dijkstra, H. B. Perdok, J. R. Newbold, and W. J. J. Gerrits. 2011a. Dietary inclusion of diallyl disulfide, yucca powder, calcium fumarate, an extruded linseed product, or medium-chain fatty acids does not affect methane production in lactating dairy cows. *J. Dairy Sci.* 94:3094–3104.
- Van Zijderveld, S. M., B. Fonken, J. Dijkstra, W. J. J. Gerrits, H. B. Perdok, W. Fokkink, and J. R. Newbold. 2011b. Effects of a combination of feed additives on methane production, diet digestibility, and animal performance in lactating dairy cows. *J. Dairy Sci.* 94:1445–1454.
- Van Zijderveld, S. M., W. J. J. Gerrits, J. A. Apajalahti, J. R. Newbold, J. Dijkstra, R. A. Leng, and H. B. Perdok. 2010. Nitrate and sulfate: Effective alternative hydrogen sinks for mitigation of ruminal methane production in sheep. *J. Dairy Sci.* 93:5856–5866.
- Van Zijderveld, S. M., W. J. J. Gerrits, J. Dijkstra, J. R. Newbold, R. B. A. Hulshof, and H. B. Perdok. 2011c. Persistency of methane mitigation by dietary nitrate supplementation in dairy cows. *J. Dairy Sci.* 94:4028–4038.
- Vellinga, T. V., and I. E. Hoving. 2011. Maize silage for dairy cows: Mitigation of methane emissions can be offset by land use change. *Nutr. Cycling Agroecosyst.* 89:413–426.
- Vogels, G. D., W. F. Hoppe, and C. K. Stumm. 1980. Association of methanogenic bacteria with rumen ciliates. *Appl. Environ. Microbiol.* 40:608–612.
- Waghorn, G. C. 2008. Beneficial and detrimental effects of dietary condensed tannins for sustainable sheep and goat production – Progress and challenges. *Anim. Feed Sci. Technol.* 147:116–139.
- Waghorn, G. C., H. Clark, V. Taufaa, and A. Cavanagh. 2008. Monensin controlled-release capsules for methane mitigation in pasture-fed dairy cows. *Aust. J. Exp. Agric.* 48:65–68.
- Waghorn, G. C., M. H. Tavendale, and D. R. Woodfield. 2002. Methanogenesis from forages fed to sheep. *Proc. N. Z. Grassland Assoc.* 64:167–171.
- Wallace, R. J., N. R. McEwan, F. M. McIntosh, B. Teferedegne, and C. J. Newbold. 2002. Natural products as manipulators of rumen fermentation. *Asian-Aust. J. Anim. Sci.* 15:1458–1468.
- Wang, J., J. Ye, and J. Liu. 2012. Effects of tea saponins on rumen microbiota, rumen fermentation, methane production and growth performance—A review. *Trop. Anim. Health Prod.* 44:697–706.
- Wattiaux, M. A., and K. L. Karg. 2004. Protein level for alfalfa and corn silage based diets. II. Nitrogen balance and manure characteristics. *J. Dairy Sci.* 87:3492–3502.
- Wedlock, D. N., G. Pedersen, M. Denis, D. Dey, P. H. Janssen, and B. M. Buddle. 2010. Development of a vaccine to mitigate greenhouse gas emissions in agriculture; vaccination of sheep with methanogen fractions induces antibodies that block methane production in vitro. *N. Z. Vet. J.* 58:29–36.
- Weinberg, Z. G., R. E. Muck, and P. J. Weimer. 2003. The survival of silage inoculant lactic acid bacteria in rumen fluid. *J. Appl. Microbiol.* 94:1066–1071.

- Williams, S. R. O., P. J. Moate, M. C. Hannah, B. E. Ribaux, W. J. Wales, and R. J. Eckard. 2011. Background matters with the SF₆ tracer method for estimating enteric methane emissions from dairy cows: A critical evaluation of the SF₆ procedure. *Anim. Feed Sci. Technol.* 170:265–276.
- Williams, Y. J., S. Popovski, S. M. Rea, L. C. Skillman, A. F. Toovey, K. S. Northwood, and A. D. G. Wright. 2009. A vaccine against rumen methanogens can alter the composition of archaeal populations. *Appl. Environ. Microbiol.* 75:1860–1866.
- Wolin, M. J. 1960. A theoretical rumen fermentation balance. *J. Dairy Sci.* 43:1452–1459.
- Wood, T. A., R. J. Wallace, A. Rowe, J. Price, D. R. Yáñez-Ruiz, P. Murray, and C. J. Newbold. 2009. Encapsulated fumaric acid as a feed ingredient to decrease ruminal methane emissions. *Anim. Feed Sci. Technol.* 152:62–71.
- Woodward, S. L., G. C. Waghorn, and N. A. Thomson. 2006. Supplementing dairy cows with oils to improve performance and reduce methane – Does it work? *Proc. N.Z. Soc. Anim. Prod.* 66:176–181.
- Woodward, S. L., G. C. Waghorn, M. J. Ulyatt, and K. R. Lassey. 2001. Early indications that feeding Lotus will reduce methane emissions from ruminants. *Proc. N.Z. Soc. Anim. Prod.* 61:23–26.
- Wright, A. D. G., P. Kennedy, C. J. O’Neill, A. F. Toovey, S. Popovski, S. M. Rea, C. L. Pimma, and L. Klein. 2004. Reducing methane emissions in sheep by immunization against rumen methanogens. *Vaccine* 22:3976–3985.
- Wright, A. D. G., and A. V. Klieve. 2011. Does the complexity of the rumen microbial ecology preclude methane mitigation? *Anim. Feed Sci. Technol.* 166–167:248–253.
- Yan, T., R. E. Agnew, F. J. Gordon, and M. G. Porter. 2000. Prediction of methane energy output in dairy and beef cattle offered grass silage-based diets. *Livest. Prod. Sci.* 64:253–263.
- Yang, W. Z., M. Oba, and T. A. McAllister. 2012. Precision processing maximizes the feed value of barley grain for feedlot cattle. In: *Prairie Post Bull Breeders*. p. A12–13.
- Zhou, Y. Y., H. L. Mao, F. Jiang, J. K. Wang, J. X. Liu, and C. S. McSweeney. 2011. Inhibition of rumen methanogenesis by tea saponins with reference to fermentation pattern and microbial communities in Hu sheep. *Anim. Feed Sci. Technol.* 166–167:93–100.