

REDUCING METHANE EMISSIONS FROM DAIRY COWS

Karen A. Beauchemin¹, Sean M. McGinn¹ and Chris Grainger²

¹Agriculture and Agri-Food Canada, ²Department of Primary Industries, Ellinbank

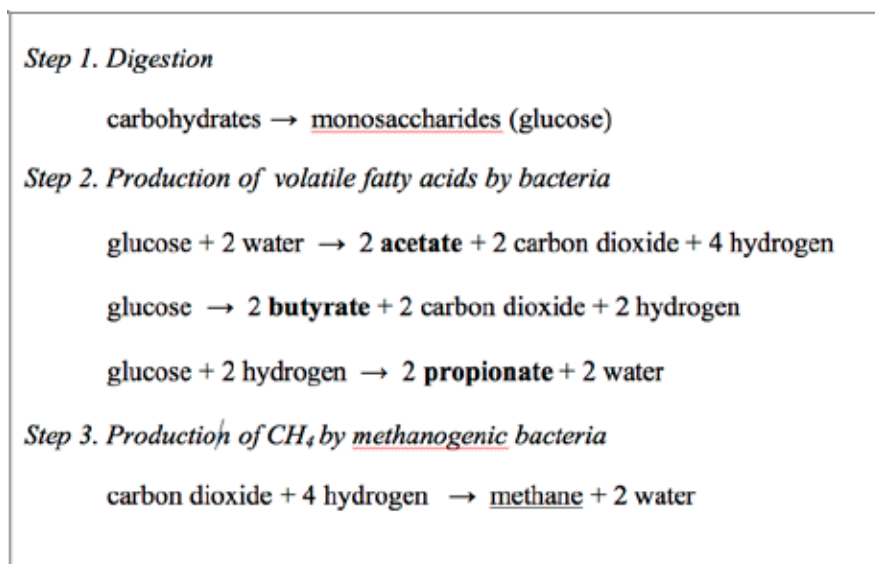
INTRODUCTION

Methane is produced in the rumen (called enteric methane, CH₄) as part of the normal process of feed digestion. Typically, about 6 to 10% of the total gross energy consumed by the dairy cow is converted to CH₄ and released via the breath. Thus, methane losses can be considered an inefficiency in converting feed energy to milk. In addition, CH₄ is a potent greenhouse gas (GHG) that contributes to global warming. Reducing CH₄ losses is an environmentally sound practice that can improve production efficiency. Our review presents some nutritional approaches that can reduce enteric CH₄ emissions from dairy cows.

ENTERIC METHANE PRODUCTION

Carbohydrates are converted in the rumen to volatile fatty acids (VFA) during the fermentation of feed. The most abundant VFA are acetate, propionate and butyrate. Hydrogen is also generated during this process (Fig. 1).

Figure 1. Production of methane in the rumen.



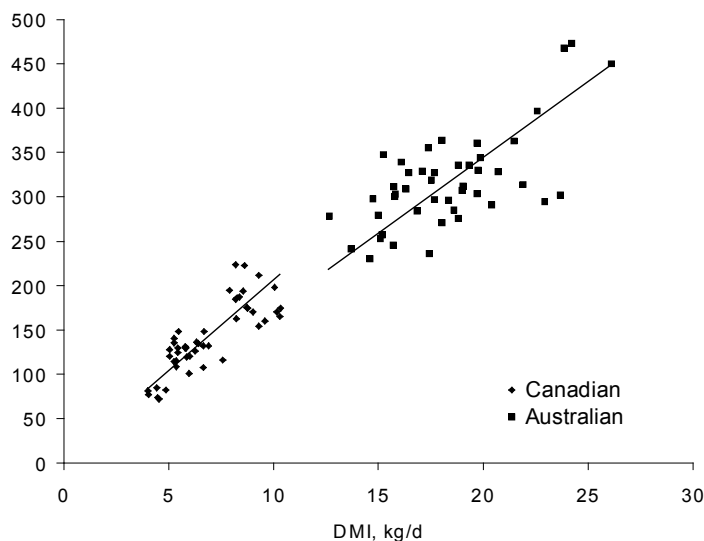
The formation of acetate generates twice the amount of hydrogen as does the formation of butyrate, whereas the formation of propionate actually uses hydrogen. Methane producing bacteria (known as methanogens) convert hydrogen and CO₂ into CH₄ and water. Thus, diets that favor lower acetate to propionate ratio usually decrease CH₄ production. Diets that restrict the hydrogen available in the rumen for methanogenic bacteria generate less enteric CH₄. Diet composition and the amount of feed consumed are the primary drivers of enteric CH₄ production (Fig 2).

Most of the enteric methane produced by cattle originates in the rumen. However, fermentation also occurs post-ruinally. About 13% of CH₄ is produced in the hind gut, with about 89% of it absorbed across the intestinal mucosa into the blood stream. Likewise, about 95% of CH₄ generated in the rumen is transferred to the lungs where the animal breathes it out. As a result, 99% of CH₄ emission is lost via the nostrils and mouth and only 1% of the total CH₄ emission is lost through the rectum (Murray 1976).

THE US CONTRIBUTION TO METHANE AND GREENHOUSE GAS EMISSIONS

The United Nations Framework Convention on Climate Change (UNFCCC) emissions inventory for 2005 identifies the US as a major source of GHG. The US is estimated

Figure 2. Relationship between methane [CH₄] emission determined in chambers and dry matter intake (DMI) for dairy cows [Australian study; Grainger et al. 2007] and beef cattle [Canadian study; McGinn et al. 2006]. Lines are through the origin and have slope estimates of 17.06 for the Australian data and 20.79 for the Canadian data [$P < 0.001$; SED = 0.928]. Graph is from Grainger et al. [2007].



to generate almost 40% of the global emissions, compared to about 23% for the European Community (EC; an aggregate of 15 countries within the European Union) and 4% for Canada (Table 1). In the US, agriculture accounts for 7.4% of its GHG, which is similar to Canada (7.6%) but lower than for the EC (9.2%).

In the US, the contribution of CH₄ accounts for 30% of all agricultural emissions, while the remaining 70% is attributed to nitrous oxide (N₂O). The division of CH₄ to N₂O in Canada is closer to 50:50, while in the EC it is 44:56.

The percentage of CH₄ generated by enteric fermentation, compared to all CH₄ sources, is similar between Canada and the US (22.5 and 21.2%), while the EC value is larger at 46.7%. On a global basis, enteric CH₄ production accounts for roughly 28% of all CH₄ emissions. Methane losses resulting from livestock manure are a much smaller than that from enteric losses, e.g., 7.8% for the US. Agriculture soils are the main source of N₂O losses in agriculture (Table 1).

In the US, beef cattle are responsible for 70.7% of the enteric CH₄ emission while dairy accounts for 24.7% of this emission (US EPA 2007). For CH₄ losses from livestock manure, beef cattle emissions are relatively lower (5.6%) than the emissions attributed to dairy cows (43.3%) due to the anaerobic state of dairy manure.

STRATEGIES FOR REDUCING METHANE EMISSIONS FROM DAIRY COWS

In the US, the Environmental Protection Agency calculates the enteric CH₄ emissions produced by the dairy sector as part of the national greenhouse gas inventory (US EPA

Table 1. A comparison of the percentage of methane (CH₄) and nitrous oxide (N₂O) emitted as determined from the 2005 emissions data reported by the United Nations Framework Convention on Climate Change (www.unfccc.int/2860.php) – data are for the exclusion of Land Use, Land Use Change and Forestry (LULUCF).

Region	% of Global Emission ¹	% Attributed to Agriculture ²	% of all CH ₄ Emission ³		% of all N ₂ O Emission ⁴	
			Enteric	Manure	Manure	Soils
Canada	4.1	7.6	22.5	2.9	12.2	53.5
EC5	23.1	9.2	46.7	16.6	9.8	72.9
USA	39.8	7.4	21.2	7.8	2.1	79.2
Global		7.9	27.7	6.7	6.7	68.0

¹ Percentage contribution by the region to all global GHG emissions.

² Percentage contribution of the regions agriculture relative to the whole region's GHG emission.

³ Percentage of the region's CH₄ emissions attributed to enteric production and manure management.

⁴ Percentage of the region's N₂O emissions attributed to manure management and agriculture soils: European Community.

2007). The calculation estimates gross energy intake of individual animals, applies a CH₄ conversion rate (fraction of gross energy intake converted to CH₄), and then sums the daily emissions by animal category (lactating cows, replacement heifers, calves). For lactating dairy cows, the conversion rates used range from 4.8% in California to 5.8% for many states. These values are lower than the conversion rates adopted by the International Panel on Climate Change (6.5%) and most other countries (IPCC 2006).

Using this method of calculation, CH₄ reduction can be achieved either by reducing the number of cows or by reducing the conversion rate. For example, the Canadian dairy industry has decreased its CH₄ emissions by about 20% in the past two decades because cow numbers have declined as a result of increased milk production per cow. The Supply Management System in Canada imposes quotas on production, thus increases in cow productivity have been accompanied by a decrease in cow numbers. Increasing animal productivity usually increases emissions per cow (due to higher feed intake), thus reductions are only achieved if product output is capped.

In the US, reductions in CH₄ emissions from dairy cows will likely only occur by reducing the conversion rate. Various research groups around the world are exploring the potential of strategically using feed ingredients and supplemental feed additives as a means of reducing conversion rates (Beauchemin et al. 2008). Other non-dietary approaches being examined include vaccination, biological controls (bacteriophage, bacteriocins), chemical inhibitors that directly target methanogens, and promotion of acetogenic populations in the rumen to lower the supply of metabolic hydrogen to methanogens (McAllister and Newbold 2008). While a number of strategies to reduce CH₄ have been proposed, the mitigant must meet the following criteria before it will be adopted on-farm: 1) documented effectiveness in reducing emissions, 2) profitable (or at least revenue neutral), and 3) feasible to implement on-farm.

ECONOMIC IMPLICATIONS OF REDUCING METHANE EMISSIONS

Enteric CH₄ formation in the rumen represents inefficiency in terms of converting feed energy to milk. For a high producing dairy cow, a 20% reduction in CH₄ emissions represents the same amount of energy needed to synthesize 0.6 kg/d of milk. In theory, implementing a dietary change to reduce CH₄ emissions could increase milk production simply by sparing energy. Revenue generated from increased milk yield could partially offset the cost of the dietary mitigant.

There may also be an opportunity in the future for dairy producers to benefit financially from carbon off-set programs. At the present time, the Agricultural Methane Emissions Offset Program under the Chicago Carbon Exchange does not recognize reductions in enteric CH₄ emissions. However, this will likely change in the near future as the technology for monitoring emissions on-farm becomes more readily available. Based on the current trading value of CH₄ on the Chicago Carbon Exchange (\$2.05/100 metric tonnes CO₂ equivalent), a 20% reduction in CH₄ from a dairy cow would generate a revenue of

\$0.03/cow/d ($350 \text{ g CH}_4/\text{cow/d} \times 0.20 = 0.07 \text{ tonnes CH}_4 \times 21 \text{ CO}_2/\text{CH}_4 = 1.47 \text{ tonnes CO}_2 \text{ equivalent} \times 0.0205 = \$0.03/\text{cow/d}$). Assuming a milk price of \$0.30/kg, the breakeven cost of feeding a cow to reduce CH₄ emissions by 20% is \$0.21/d ($0.6 \text{ kg milk} \times 0.30 = \$0.18 + \$0.03 = \$0.21/\text{d}$). These calculations are theoretical at best as very few studies have been conducted to look at the long-term effects of reducing CH₄ on the lactational performance of dairy cows.

NUTRITIONAL STRATEGIES THAT REDUCE ENTERIC CH₄ PRODUCTION

Some dietary strategies that reduce enteric CH₄ production are listed in Table 2. Diet modifications reduce CH₄ emissions by decreasing the fermentation of feed in the rumen, shifting the site of digestion from the rumen to the intestines, diverting H₂ away from CH₄ production during ruminal fermentation, or by inhibiting the formation of CH₄ by rumen bacteria.

Table 2. Dietary strategies that reduce enteric CH₄ production.

Strategy	Percentage Reduction in CH ₄ ¹	Comment
Strategies with higher certainty of reducing CH ₄ production		
Fats and oilseeds	5–25	Level dependant
Ionophores	0–10	Dose dependant, response may decline after several months
Higher grain diets	5–20	Level dependant, increases the risk of acidosis
Replacing barley with corn	0–7	Depends on grain processing
Use of cereal silage and corn silage	5–10	Depends on grain content of silage
Use of legumes	5–10	Response often confounded with stage of maturity
Tannin-containing forages	10–20	High potential, but production often limited by agronomics
Strategies that are experimental		
Condensed tannin extracts	0–15	Depends on source, high levels may decrease milk production
Saponins	0–10	Depends on source
Yeast	0–5	Depends on strain, commercial strains have not been tested for their effectiveness
Essential oils	0–20	Promising results with garlic, but further testing needed
Fiber-degrading enzymes	0–10	Commercial products have not been tested for their effectiveness

¹ Estimated by the authors based on a review of the literature.

The strategies in Table 2 have varying degrees of uncertainty associated with their estimated reduction in CH₄. A brief discussion of these strategies follows, but a more complete review of the impact of diet on CH₄ production can be found elsewhere (Johnson and Johnson 1995, Boadi et al. 2004, Monteny and Chadwick 2006, Beauchemin et al. 2008, McAllister and Newbold 2008). In addition, various models have been developed to predict CH₄ emissions based on diet composition (e.g. Blaxter and Clapperton 1969, Moe and Tyrrell 1979, Pelchen and Peters 1998).

Feeding Fats and Oilseeds

Adding fats to the diet reduces CH₄ emissions by decreasing organic matter fermentation in the rumen, reducing the activity of methanogens and protozoal numbers, and for lipids rich in unsaturated fatty acids, through hydrogenation of fatty acids (Johnson and Johnson 1995). The effectiveness of adding lipids to the diet to reduce CH₄ emissions depends on many factors including level of supplementation, fat source, fatty acid profile, form in which the fat is administered (i.e., either as refined oil or as full-fat oilseeds) and the type of diet. However, level of added fat is by far the most important factor. Figure 3 shows the relationship between level of added fat (% of DMI) and the reduction in CH₄ emissions (g/kg DMI) for a range of fat sources and diets (Beauchemin et al. 2008). Over a broad range of conditions, CH₄ (g/kg DMI) was reduced by 5.6% with each 1% addition of supplemental fat. In most cases, 2 to 3% fat can be added to dairy cow diets without negative effects. The total amount of fat in the diet (added fat plus fat in the basal diet) should not exceed 6 to 7% of the diet otherwise a depression in DMI may occur, negating the advantages of increased energy density of the diet.

There is considerable variation in the CH₄ reductions observed among fat sources. Higher reductions can be achieved with fats that contain medium chain fatty acids (i.e., C12:0 and C14:0). Examples of these types of oils are: coconut oil, myristic acid, palm kernel oil, high-laurate canola oil, and some genetically modified canola oils. However, refined oils containing medium chain fatty acids are unlikely to be used in North America because of their cost.

Sources of long-chain fatty acids that can be effective CH₄ suppressants include animal fats, oilseeds, and refined oils (Table 3). Pure oils are more effective against CH₄ than the same amount of lipid supplied via crushed oilseeds, but oilseeds are preferred because they have less adverse side-effects on feed intake and fiber digestibility. Oilseeds such as sunflower seed and cottonseed can be fed unprocessed, but others such as canola seed and flaxseed need to be processed before feeding because they are not substantially damaged during mastication. Byproducts from the ethanol and food processing industries can be less expensive sources of fat. In addition to reducing enteric CH₄, these fat sources also reduce net GHG emissions (net GHG emissions includes the GHG associated with crop growth, processing, transportation, etc.).

Fats increase the energy density of the diet, which can improve cow productivity

Figure 3. Summary of literature results for 33 treatment means showing the effect of added fat from various sources on the percentage reduction in methane (g/kg dry matter intake) relative to the control diet (added inert fat or no added fat). The solid line represents the regression accounting for the effect of study; $Y = 5.562$ (SE = 0.590) $\times$ percentage added fat; $r^2 = 0.67$; $P = 0.004$. Further details on the studies used in this analysis are given in Beauchemin et al. [2008].

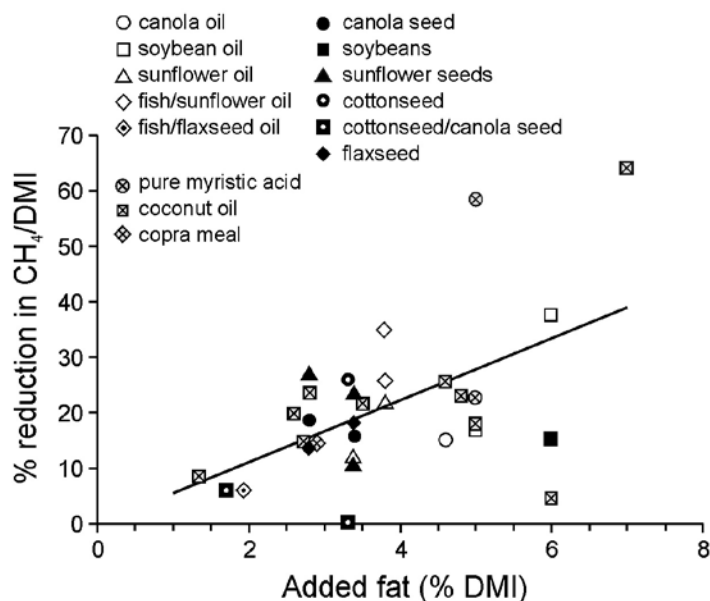


Table 3. Supplemental sources of fats for use in dairy diets.

Item	% Fat
Cottonseed (with lint)	23
Whole soybeans	19
Sunflower seeds	44
Crushed canola seeds	40
Cooked potato chips	18
Corn distillers dried grains	15
Brewers grains	10
Bakery waste (dried)	13
Citrus pulp (wet)	10
Naked oats	15
Tallow and animal fats	100

in some situations. However, high levels of added fat can reduce feed intake, fibre digestibility, and milk fat percentage, so care must be taken in choosing the appropriate level of supplementation.

Use of Ionophores

Ionophores such as monensin are antimicrobials typically used in dairy cattle diets to improve feed efficiency. Monensin decreases the proportion of acetate and increases the proportion of propionate in the rumen — an effect that decreases CH₄ output. At times, monensin may also lower rumen protozoal numbers. This is important, as a direct relationship exists between rumen protozoal numbers and CH₄ formation in the rumen. Rumen protozoa are estimated to provide a habitat for up to 20% of ruminal methanogens while methanogens living on and within protozoa are thought to be responsible for about a third of the CH₄ emissions from ruminants.

The effect of monensin on lowering CH₄ production appears to be dose-dependent. In recent studies, providing a dose of 10-15 ppm had no effect on CH₄ production (g/d or g/kg DMI) in dairy cows (Grainger et al. 2008; Waghorn et al. 2008) while a dose of 15-20 ppm either had no effect on CH₄ production or reduced total CH₄ but not CH₄ per kilogram of DMI in dairy cows (VanVugt et al. 2005). Higher doses (24 to 35 ppm), which are typically fed to dairy cows in North America, reduced CH₄ production (g/d by 4 to 13% and g/kg DMI by 0 to 10%) in beef cattle and dairy cows (Sauer et al. 1998, McGinn et al. 2004, VanVugt et al. 2005, Odongo et al. 2007), with short-term decreases in CH₄ of up to 30% being reported in beef cattle when 33 ppm of monensin was included in high or low forage diets (Guan et al. 2006).

Unfortunately, the inhibitory effects of ionophores on methanogenesis may not persist over time (Johnson and Johnson 1995). Guan et al. (2006) recently reported that monensin (33 mg/kg) lowered CH₄ emissions in beef cattle by up to 30%, but levels were restored within 2 months. In that study, the effect of ionophores on CH₄ production was related to protozoal populations, which adapted to ionophores over time. In contrast, Odongo et al. (2007) provides evidence that adaptation to ionophores may not always occur; in their study monensin lowered CH₄ production in dairy cows over a 6-month period. It is evident that the long-term effects of monensin on CH₄ emissions require further study.

Feeding Higher Concentrate Diets

Increasing the grain content of the TMR lowers the proportion of feed energy converted to CH₄ by decreasing the acetate:propionate ratio in the rumen fluid. Furthermore, methanogens are susceptible to the low pH conditions in the rumen that result from feeding high grain diets. However, the potential of using concentrates to lower CH₄ emissions from the dairy sector is limited because the increased incidence of rumen acidosis jeopardizes cow health and reduces milk fat content.

Replacing Barley Grain with Corn Grain

In addition to feeding more grain, CH₄ emissions are also lowered by feeding corn rather than barley grain. This difference is due to a partial shift in the site of digestion from the rumen to the intestines, as corn is typically less extensively digested in the rumen than is barley. Of course, the method used to process the grain is also an important consideration; high moisture grains, steam flaking of corn, and fine grinding increase ruminal digestion compared with dry rolling, steam rolling and coarse grinding.

Forage-Related Strategies

Several forage-related strategies that reduce CH₄ emissions have been identified, but the CH₄ response to implementing these strategies can be variable, as many interacting factors can arise. In general, replacing grass and legume forages with corn silage and whole crop small grain silages reduces CH₄ emissions because grain silages favor the production of propionate rather than acetate in the rumen. Improved forage quality typically results in greater CH₄ output per day because high-quality forages have a faster passage rate from the rumen, which leads to greater feed intake and more fermentable substrate in the rumen. The result is greater daily enteric CH₄ production per day. However, the amount of CH₄ produced per unit of energy consumed or per kilogram of milk typically decreases as the quality of forages increases. Feeding legumes compared to grasses tends to reduce CH₄, but this relationship is also influenced by the maturity of the forage at the time of consumption. Legumes produce less CH₄ because they have lower NDF content and pass more quickly through the rumen. Tannin-rich forages (e.g., sanfoin, birds' foot trefoil, big trefoil) can reduce emissions, but many of these forages are not agronomically suited to the geographical locations in the US.

Feed Additives

Condensed Tannin Extracts

Condensed tannins are phenolic compounds extracted from the bark of black wattle trees (*Acacia mearnsii*; grown in South Africa) and Quebracho-Colorado trees (grown in South America). Adding Acacia tannin extract powder to the diet of sheep at a rate of 2.5% of DMI decreased enteric CH₄ by about 12% with only a marginal decrease in fibre digestion (Carulla et al. 2005). However, Australian researchers used this same source of tannin extract in a dairy cow study and observed negative effects on milk production (Grainger et al., unpublished). In that study, the extract was mixed with water and provided to the cows twice daily as a drench at 1.5 and 3.0% of DMI. Within a few days, cows receiving the high dose dropped sharply in milk production (4 kg/d) and showed signs of ill health. Consequently, the high rate was reduced to 2.25% of DMI. Averaged over the 5-week experiment, the low and

high tannin levels reduced CH₄ emissions by 16 and 28%. However, the reduction in CH₄ was accompanied by a drop in the digestibility of the feed and a negative effect on milk yield (4.9 and 9.7% reduction in milk yield for the low and high tannin levels, respectively) and fat and protein yield (8 and 11% reductions in milk solids for the low and high tannin levels). At the Lethbridge Research Centre, we supplemented the diet of growing beef cattle with up to 1.8% condensed tannin extracted from Quebracho-Colorado trees and observed no effects on enteric CH₄ or digestibility of the dietary DM (Beauchemin et al. 2007).

These studies show that tannins hold some promise in terms of CH₄ abatement, but the source and optimum level of tannin need considerable refinement to ensure CH₄ is lowered without negatively affecting milk production. Tannins have an additional advantage in that they are also highly reactive with protein and can affect the partitioning of nitrogen within the cow shifting the route of excretion away from urine towards feces. Reduced urinary nitrogen excretion would result in reduced environmental losses through nitrate leaching, ammonia volatilisation and nitrous oxide emissions.

Yeast

Yeast cultures of *Saccharomyces cerevisiae* are widely used in ruminant diets to improve rumen function and milk production. Commercial products vary in the strain of yeast used and the number and viability of yeast cells present. Laboratory studies suggest that some live yeast strains can stimulate the use of hydrogen by acetogenic strains of ruminal bacteria, thereby enhancing the formation of acetate and decreasing the formation of CH₄. However, we conducted a study with growing beef cattle to evaluate two commercial yeast products, as commercial strains have not been selected for their effects on CH₄ (McGinn et al. 2004). One product caused a 3% decrease in CH₄ production (g/g DMI) while the other product increased CH₄ production (g/g DMI) by 8%. These results indicate that while it may be possible to select strains of yeast based on their anti-methanogenic effects, the commercially available strains of yeast likely have only minor, if any, effects on CH₄. Because yeast products are generally modestly priced and already widely used in ruminant production, acceptance of a CH₄-reducing yeast product would likely be high. However, considerable research and development would be needed to deliver such a product to the marketplace. To date, commercial manufacturers have been reluctant to invest in such products because animal performance, rather than CH₄ abatement, is the primary driver for product development.

Enzymes

Enzyme additives are concentrated fermentation products that contain fiber-digesting enzymes (e.g., cellulases, hemicellulases). The focus to date has been on developing enzyme additives that improve fiber digestion (Beauchemin et al. 2003), but it may also be possible to develop enzyme additives that reduce CH₄ emissions. In a recent in vitro study in our lab,

one particular enzyme candidate increased fiber degradation of corn silage by 58%, with 28% less CH₄ produced per unit of fiber degraded (Beauchemin et al, unpublished). Furthermore, feeding dairy cows a diet containing corn silage with added enzyme reduced CH₄ production (g/g DMI) by 9% (Beauchemin et al. unpublished). Enzymes that improve fiber degradation typically decrease the acetate:propionate ratio in rumen fluid (Eun and Beauchemin 2007), which is thought to be the primary mechanism whereby enzymes decrease CH₄ production. The potential of enzyme additives for CH₄ abatement warrants further research, because enzymes are likely to have positive effects both on milk production and CH₄ abatement.

CONCLUSIONS

There is an increasing body of research that demonstrates the potential of reducing CH₄ through diet manipulation. However, many of these approaches require further research to fully document long-term impact on CH₄ emissions, milk production, and profitability. While feeding diets that lower CH₄ emissions from the dairy industry is environmentally responsible, dairy producers are unlikely to adopt these measures unless there are also positive economic impacts.

REFERENCES

- Beauchemin K.A., Colombatto, D., Morgavi, D.P., and Yang, W.Z. 2003. Use of exogenous fibrolytic enzymes to improve feed utilization by ruminants. *J. Anim. Sc.* 81 (E. Suppl. 2), E37-E47.
- Beauchemin, K.A., McGinn, S.M., Martinez, T.F., and McAllister, T.A. 2007. Use of condensed tannin extract from quebracho trees to reduce methane emissions from cattle. *J. Anim. Sci.* 85:1990-1996.
- Beauchemin, K.A., Kreuzer, M., O'Mara, F., and McAllister, T. A. 2008. Nutritional management for enteric methane abatement: a review. *Australian J. Expt. Agric.* 48: (in press)
- Blaxter, K.L., and Clapperton, L. 1969. Prediction of the amount of methane produced by ruminants. *Br. J. Nutr.* 19:511-522.
- Boadi, D., Benchaar, C., Chiquette, J., and Masse, D. 2004. Mitigation strategies to reduce enteric methane emissions from dairy cows: update review. *Can. J. Anim..Sci.* 84: 319-335.
- Carulla, J.E., Kreuzer, M., Machmüller, A., and Hess, H.D. 2005. Supplementation of *Acacia mearnsii* tannins decreases methanogenesis and urinary nitrogen in forage-fed sheep. *Austr. J. Agric. Res.* 56:961-970.

Eun, J.-S., and Beauchemin, K.A. 2007. Assessment of the efficacy of varying experimental exogenous fibrolytic enzymes using in vitro fermentation characteristic. *Anim. Feed Sci. Technol.* 132:298–315.

Grainger, C., Clarke, T., McGinn, S.M., Auldist, M.J., Beauchemin, K.A., Hannah, M.C., Waghorn, G.C., Clark, H., and Eckard, R.J. 2007. Methane emissions from dairy cows measured using the sulfur hexafluoride (SF₆) tracer and chamber techniques. *J. Dairy Sci.* 90:2755–2766.

Grainger, C., Auldist, M.J., Clarke, T., Beauchemin, K.A., McGinn, S.M., Hannah, M.C., Eckard, R.J., and Lowe, L.B. 2008. Use of monensin controlled-release capsules to reduce methane emissions and improve milk production of dairy cows offered pasture supplemented with grain. *J. Dairy Sci.* (in press)

Guan, H., Wittenberg, K.M., Ominski, K.H., and Krause, D.O. 2006. Efficacy of ionophores in cattle diets for mitigation of enteric methane. *J. Anim. Sci.* 84:1896-1906.

Intergovernmental Panel on Climate Change (IPCC). 2006. Guidelines for National Greenhouse Inventories. Vol. 4. Agriculture, forestry and other land use. Ch. 10. Emissions from livestock and manure management pp. 10.1 – 10.87.

Johnson, K.A., and Johnson, D.E. 1995. Methane emissions from cattle. *J. Anim. Sci.* 73: 2483-2492.

McAllister, T.A., and Newbold, C.J. 2008. Redirecting rumen fermentation to reduce methanogenesis. *Austr. J. Expt. Agric.* 48: (in press)

McGinn, S.M., Beauchemin, K.A., Coates, T., and Colombatto, D. 2004. Methane emissions from beef cattle: effect of monensin, sunflower oil, enzymes, yeast and fumaric acid. *J. Anim. Sci.* 82:3346-3356.

McGinn, S. M., K. A. Beauchemin, A. D. Iwaasa, and T. A. McAllister. 2006. Assessment of the sulfur hexafluoride (SF₆) tracer technique for measuring enteric methane emissions from cattle. *J. Environ. Qual.* 35:1686–1691.

Moe, P.W., and Tyrrell, H.F. 1979. Methane production in dairy cows. *J. Dairy Sci.* 62: 1583-1586.

Monteny, G.J., and Chadwick, D. 2006. Greenhouse gas abatement strategies for animal husbandry. *Agric. Ecosys. Environ.* 112:163-170.

Murray, R.M., Bryant, A.M., and Leng, R.A. 1976. Rates of production of methane in the rumen and large intestine of sheep. *Br. J. Nutr.* 36:1-14.

Odongo, N.E., Bagg, R., Vessie, G., Dick, P., Or-Rashid, M.M., Hook, S., Gray, J. T., Kebreab, E., France, J., and McBride, B.W. 2007. Long-term effects of feeding monensin on methane production in lactating dairy cows. *J.Dairy Sci.* 90:1781–1788.

Pelchen, A., and Peters, K.J. 1998. Methane emissions from sheep. *Small Ruminant Res.* 27:137–150.

Sauer, F.D., Fellner, V., Kinsman, R., Kramer, J.K.G., Jackson, H.A., Lee, A.J., and Chen, S. 1998. Methane output and lactation response in Holstein cattle with monensin or unsaturated fat added to the diet. *J. Anim. Sci.* 76:906-914.

US Environmental Protection Agency (US EPA) 2007. Greenhouse gas emissions and sinks: 1990-2005. 6. Agriculture. USEPA #430-R-07-002. <http://epa.gov/climatechange/emissions/usinventoryreport.html> (Accessed December 17, 2007)

Van Vugt, S.J., Waghorn, G.C., Clark, D.A., and Woodward, S.L. 2005. Impact of monensin on methane production and performance of cows fed forage diets. *Proc. N. Z. Soc. Anim.Prod.* 65:362-366.

Waghorn, G. C., Clark, H., Tauf, V., and Cavanagh, A. 2008. Monensin controlled-release capsules for methane mitigation in dairy cows fed pasture. *Australian J. Expt. Agric.* 48: (in press).