Enteric methane emissions and mitigation opportunities for Canadian cattle production systems.

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■ Summary

Methane (CH_4) is a colorless, odorless gas generated as a by-product of microbial fermentation of feed in the gastrointestinal tract of ruminant animals. Methane producing bacteria, commonly referred to as methanogens, use the hydrogen and carbon dioxide produced as end products of microbial digestion to generate energy for growth, with CH_4 as an end product. Canadian estimates for enteric CH_4 emissions from ruminant animals show a 10.6 % increase from 1990 to 2000; 15,994 vs 17,696 kt carbon dioxide (CO_2) equivalents/yr respectively. As 1 g CH_4 is equivalent to 55.2 kJ of lost feed energy, mitigation strategies can result in improved feed utilization as well as contribute to Canada's commitment to reduce GHG emissions. Data collected from Canadian research indicate that energy losses associated with enteric CH_4 emissions range from 2 to 11.3 % of gross energy intake. Numerous mitigation strategies have been suggested in the literature, including: manipulation of rumen microfloral populations, diet manipulation to provide alternate hydrogen acceptors, diet manipulation to shift the fermentation pathway, management for improved productivity, and genetic selection for low methane emitting animals. Results from Canadian trials show that there are opportunities to reduce enteric methane emissions in commercial production systems. Many of these mitigation strategies will influence carbon sequestration opportunities and nitrous oxide emissions associated with manure handling and storage, and will require evaluation and validation at a systems level.

■ Emissions Estimates by Environment Canada

Estimates of greenhouse gas emissions in the agriculture sector are based upon two main categories (Environment Canada, 2002a). The livestock-related emissions are primarily from enteric fermentation in domestic animals (17,696 kt CO_2 equivalents as CH_4) and from manure management (9,400 kt CO_2 equivalents as CH_4 and N_2O), accounting for nearly 4 % of Canada's GHG emissions in 2000. The second category, soil management and cropping practices, contributes CO_2 and N_2O emissions which accounted for approximately 4.6% of total GHG emissions in 2000. General trends for the 1990 - 2000 accounting period show an 11.6 % increase in total livestock emissions while emissions from soils have decreased by 3.5 % (Figure 1, Environment Canada, 2002a). Most of the increase (about 95 %) in livestock-related emissions is attributed to increased cattle production (Figure 2).

Figure 1. Greenhouse Gas Emission Trends for Agriculture Soils and Livestock

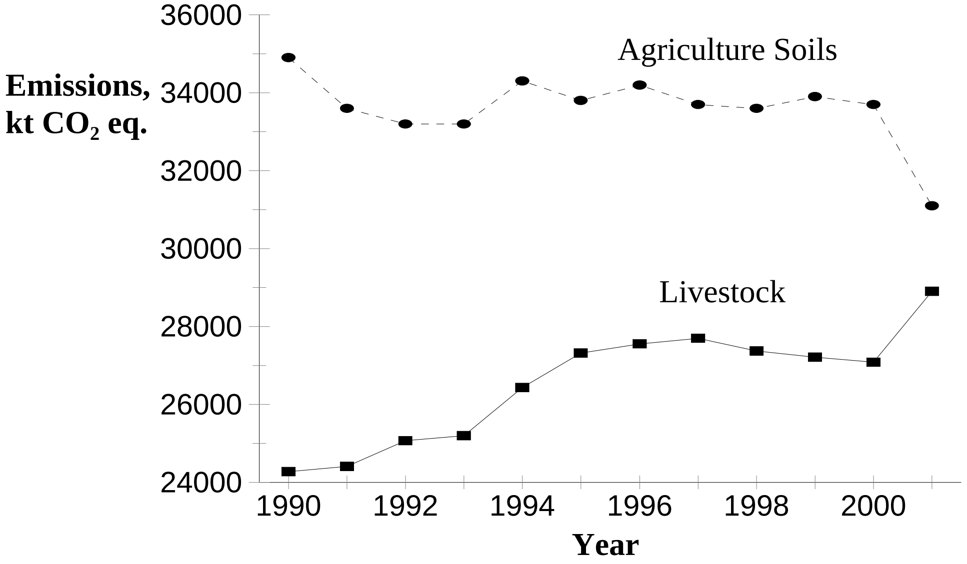
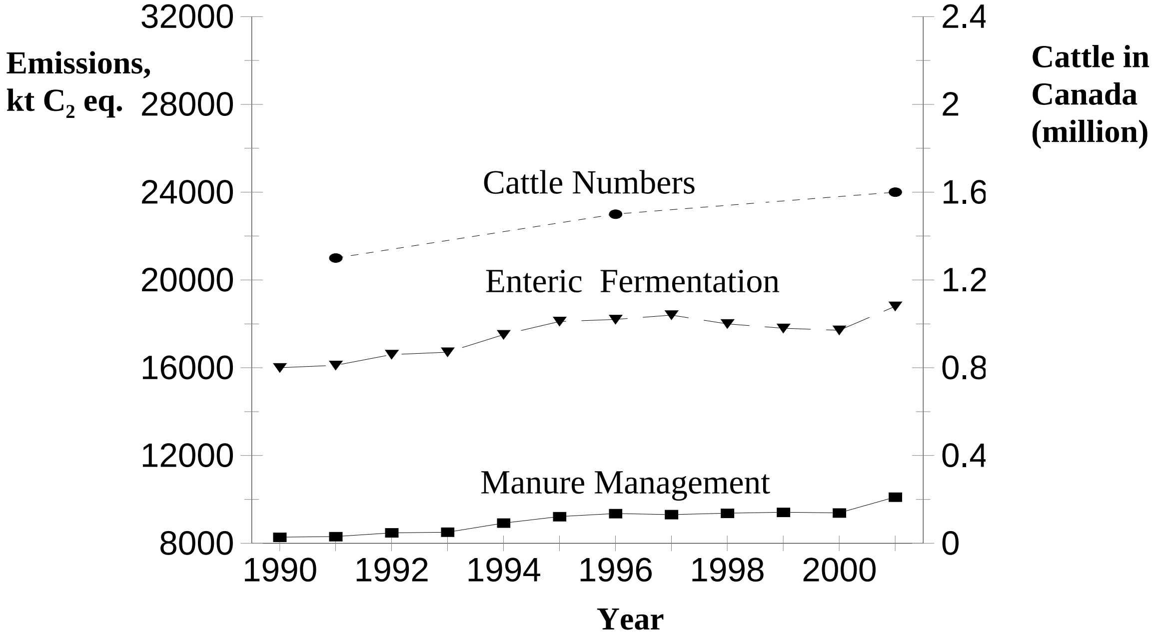


Figure 2. Greenhouse Gas Emission Trends for Enteric Fermentation and Manure Management



(Environment Canada, 2002b; Statistics Canada, 2002)

In Canada, CH_4 emissions from enteric fermentation are estimated by multiplying the population of various animal types by average emission rates (Environment Canada, 2002a). The emission rates used for cattle are listed in Table 1. At this time, Canadian estimates of GHG emissions from livestock operations do not reflect any changes in production practices or efficiencies between 1990 and today. Productivity gains have been significant in some sectors. For example, the production of milk in 2000 exceeds that of 1990, in spite of a 22 % decline in dairy cow numbers.

The cattle industry is unique relative to other livestock sectors because animals are managed in extensive as well as intensive production systems. As such, the industry gains no advantage by focusing on one particular GHG without regard for impact on the others, the coefficients currently used to generate emission rate may not properly reflect the combination of practices on a cattle operation. Kyoto specifies net emissions, hence carbon sequestration on grasslands is as effective as mitigation through altered feeding practices. Therefore, current databases for cattle emissions reflect trends based on animal numbers with little adjustment based on Canadian production practices.

Table 1. Methane Emission Factors for Livestock and Manure

Animal Types	Enteric Fermentation, kg CH4/head/year	Manure Management, kg CH4/head/year
Bulls	75	1
Dairy Cows	118	36
Beef Cows	72	1
Dairy heifers	56	36
Beef Heifers	56	1
Heifers for slaughter	47	1
Steers	47	1
Calves	47	1
Sheep	8	0.19
Goats	8	0.12
Horses	13	1.4

(Environment Canada, 2002a)

▪ Enteric Methane Production

Methane producing bacteria reside in the reticulo-rumen and large intestine of ruminant livestock.

These bacteria, commonly referred to as methanogens, use a range of substrates produced during the primary stages of fermentation to produce CH_4, thus creating generated energy required for their growth. Little work has been done to determine the relative amounts of CH_4 generated in the reticulo-rumen relative to the large intestine for the various ruminant species or for diets containing the range of feedstuffs that could potentially be fed to the animal. Studies conducted with forage-fed sheep approximate that 87 % of enteric CH_4 originates from the reticulo-rumen, the remainder being generated from the hindgut, Murray et al. (1976), Torrent and Johnson, 1994). Of the CH_4 produced in the hindgut, Murray et al.(1976) found the majority (89 %) to be absorbed and expired through the lungs. The remainder was excreted via the anus.

All methanogen species can utilize hydrogen ions (H_2) to reduce CO_2 in the production of CH_4 as this reaction is thermodynamically favorable to the organisms. Availability of H_2 in the rumen is determined by the proportion of end products resulting from fermentation of the ingested feed. Processes that yield propionate and cell dry matter act as net proton-using reactions, whereas a reaction that yields acetate results in a net proton increase (Hegarty, 1999). Other substrates available to methanogens include formate, acetate, methanol, methylamines, dimethyl sulfide and some alcohols, however, only formate has been documented as an alternative methane precursor in the rumen (Jones, 1991).

Symbiotic relationships are known to exist between methanogens and rumen microflora. The maintenance of a low ruminal partial pressure for H_2 can increase yield of acetate and increase the energy yield for methanogens as well as other microbes such as *Ruminococcus albus* (Wolin and Miller, 1988). Some methanogens are ingested by, and live within protozoa as metabolically active endosymbiots. Findlay et al. (1994) suggests that these endosymbiotic methanogens may generate 37 % of rumen CH_4 emissions. Further, Stumm et al. (1982) has estimated that 10 - 20 % of rumen methanogens may be attached to the outer surface of protozoa, with attachment increasing 10 to 100 fold after feeding as compared to before feeding. Thus, a wide range of factors can influence the enteric CH_4 emissions due to a direct or indirect impact on microbial populations and activity levels.

Diet composition and intake pattern are well known to affect enteric CH_4 emissions by cattle. Specific characteristics include; amount of digestible organic matter in the feed consumed, residence time of feed in the rumen, level of intake, source of carbon and pattern of fermentation. Approximately 5 % of the variation in the proportion of gross energy lost as CH_4 can be explained by the digestibility of dietary energy (Johnson and Johnson, 1995). Boadi and Wittenberg (2002) demonstrated that as forage invitro organic matter digestibility decreased from 61.5 to 38.5 %, there was a trend ($P < 0.14$) for CH_4 loss to increase from 6.0 to 7.0 % of gross energy intake (GEI) when animals were fed ad libitum, with no differences (7.1 to 7.6 % GEI) when intake was restricted to 2 % BW (Table 2). Dietary factors that reduce the residence time of feed in the rumen generally result in less CH_4 production because microbial digestion is reduced and a lower acetic : propionic acid ratio is favored. The limited work conducted in this area suggests that residence time in the rumen may account for as much as 28% of the variation in CH_4 emissions (Okine et al. 1989). A frequent consequence of increased organic matter digestibility or increased rate of passage is a change in dry matter intake. Increased dry matter intake is generally associated with increased CH_4 emissions per animal, but reduced emissions per unit feed consumed. The form and rate of fermentation of dietary carbohydrates influence the relative proportions of, and total volatile fatty acids produced during feed fermentation. Generally, diets rich in starch favor propionate production which results in lower CH_4 emissions as a % GEI than forage diets. Forage maturity and physical form will further influence fermentation and thus CH_4 production; emissions, % GEI being higher for mature forage vs. immature forage, coarse chopped vs. finely ground or pelleted low quality forage, hay vs. silage.

Table 2. Effect of forage organic matter digestibility on enteric methane emission

	Forage Quality			SE
	High	Medium	Low	
IVOMD, %	61.5	50.7	38.5	
Ad-libitum				
DMI, kg d^{-1}	9.7*a*	8.9*b*	6.3*c*	0.23
CH_4, L d^{-1}	281.7*a*	289.8*a*	203.5*b*	13.35
CH_4, % GEI	6.0	7.1	6.9	0.38
Restricted Intake				
DMI, kg d^{-1}	6.4	6.1	6.1	0.02
CH_4, L d^{-1}	224.6	193.3	195.6	16.19
CH_4, % GEI	7.6	7.1	7.1	0.53

(Boadi et al. 2002)

■ Mitigation Strategies

Genetic selection. Differences in the digestive anatomy or physiology of individual animals, or between breeds can result in differences in CH_4 production. Robertson and Waghorn (2002) recently completed a comparison of two dairy cow genotypes. The New Zealand Freisian, selected for high productivity on pasture, was compared to Holsteins derived from selection programs based on high concentrate diets in the Netherlands and North America. The data showed that cattle selected for high productivity on high concentrate diets produced 8 to 11 % less CH_4 as a percentage of GE than animals selected in a pasture system. These differences in feed utilization were apparent when animals were tested on either a pasture or high-concentrate total mixed ration diets. Differences between genotypes were most apparent during periods of high productivity. Boadi and Wittenberg (2002a) compared enteric CH_4 emissions from dairy (Holstein) and beef (Charolais x Simmental) heifers of similar body weight and age. Heifers were fed three qualities of forage under ad-libitum and restricted feeding conditions. Methane production was not different between Holstein (238.0 ± 6.9 L d^{-1}) and Charolais cross (228.6 ± 7.8 L d^{-1}) heifers. In North American dairy and beef cattle production systems, genetic selection for production traits is done using high concentrate diets. The literature published to date suggests that genetic selection using high concentrate diets is appropriate for mitigation of enteric CH_4 emissions in growing or lactating animals.

Trials conducted at the University of Manitoba suggest that as much as 27 % of the variation in CH_4 emission for cattle consuming forage diets is related to animal-to-animal variation (Boadi and Wittenberg 2002a). Work has not been done to determine whether these differences are related to intake behaviour, or to potential anatomical and physiological differences in the gastrointestinal tract of cattle or the heritability of this trait. However, the degree of variability suggests that there is potential to select for low methane emitting animals.

Forage selection and management. A high proportion of the Canadian cow herd is maintained on pasture from late spring to fall. As well, producers in traditional cow-calf producing regions are considering backgrounding programs which includes feeding forage-based diets after weaning, with calves entering feedlots or going to pasture as yearlings. Most of the conserved forage fed on Canadian beef and dairy cattle operations is produced on farm, however, production and management is changing. There is a trend toward increased use of annual vs perennial forage crops, increased silage vs. hay production, and increased incorporation of forage into total mixed rations. Therefore, forage selection and management are important to any greenhouse gas mitigation strategy.

Pasture management, including forage species selection, stocking rate and continuous vs. rotational grazing strategies have all been shown to influence enteric methane emissions in Canadian production systems. Perhaps the most promising pasture management strategy identified to date for mitigation of enteric emissions is the inclusion of legumes in the forage species mix. A cow-calf study at Brandon, Manitoba compared performance and enteric emissions of alfalfa-grass and grass only pastures over the course of a grazing season (McCaughey et al., 1999). Dry matter intake was greater for cows grazing alfalfa-grass pastures than for grass-only pastures (11.4 vs. 9.7 kg d^{-1}), however, methane production, adjusted for differences in body weight, was the opposite (0.53 vs 0.58 g kg BW d^{-1}, respectively). Energy lost as enteric methane emissions were 7.1 % of GEI for alfalfa-grass vs. 9.5 % of GEI for grass-only pastures. An 11 % increase for calf growth rates on the legume-grass pasture would serve as further incentive to consider legume incorporation as a mitigation strategy. The lowered methane loss observed with legumes is attributed to the lower proportion of structural carbohydrates and faster rate of passage of legumes, which will shift the fermentation pathway towards higher propionate production.

The extent to which forage species can influence enteric methane emissions of pastured ruminants is not known under Canadian conditions. In New Zealand, Waghorn et al. (2002) fed sheep a wide range of fresh cut, good quality forages and observed a two-fold range in methane emissions, from 11.5 g CH_4 kg^{-1} DMI with birdsfoot trefoil to 25.7 g CH_4 kg^{-1} DMI with a ryegrass, white clover pasture. All forages were delivered to the animal daily and had a DM digestibility of 70 % or greater. Animals grazing on pasture have the ability to be more selective than animals in this feeding trial, therefore the possibility exists that differences between forage species is even greater for pastured animals.

Condensed tannins, a constituent of some legumes, have been associated with reduced enteric CH_4 emissions. Waghorn et al. (2002) observed the impact of condensed tannins on rumen methanogenesis to be small but significant; a 16 % reduction. In addition to the beneficial impacts on methanogenisis, condensed tannins can reduce the incidence of bloat and lower the intestinal worm burdens (Waghorn et al 1998) and bind to plant protein complexes in the rumen (pH range of 3.5 - 7.0), reducing microbial degradation of soluble protein to ammonia. As these complexes dissociate below a pH of 3.5, condensed tannins can effectively increase absorption of plant amino acids at the small intestine. The mechanism of action of condensed tannins has not been established, however, Jones et al. (1994) did show that tannins reduced the ability of some bacterial species to colonize on plant particles. Condensed tannins are phenolic compounds that are wide spread in the plant kingdom and are found in a number of legumes grown in Canada including, red clover (*Trifolium pratense*), sainfoin (*Onobrychis viciifolia*), birdsfoot trefoil (*Lotus corniculatus*), and the flowers of white clover (*Trifolium repens*).

Less information is available about other forage characteristics or forage feeding strategies that can lead to reduced CH_4 emissions. Johnson et al. (1997) concluded that altering the dietary cation anion balance of a roughage diet could decrease ruminal CH_4 production without altering other aspects of rumen fermentation. For example, CH_4 loss for cattle fed a 65:35 ratio of alfalfa haylage and ryegrass screenings was 8.6, 8.2, 9.1 and 7.4 % of GEI for cation:anion balance of 10, 30, 50, and 70, respectively.

Matching pasture species with herd nutrient demand is another option. Olsen (1997) compared 5 forage stands on foothill rangeland in Utah. Treatments included native rangeland and pastures seeded to Hycrest crested wheat grass (*Agropyron desertorum* x *A. cristatum*), Nordan crested wheatgrass (*A. desertorum*), Vinall Russian wildrye (*Psathrostachys junceus*) and Syn-A Russian wildrye. There were three replicates of each forage, pastures being established in a complete block design. When nonlactating beef cows grazed these pastures in October, the native mixture compared favorably with improved species (Table 3). Methane emissions by lactating cows on these same pastures in the following spring again showed that native pasture resulted in the highest CH_4 emissions and was the least productive (Table 4). Olsen's work, although preliminary, suggests that variation does exist among grass species and that the choice of species may depend on the season of pasture use.

Whether using rotational or continuous grazing strategies, there is tremendous fluctuation in forage quality during the grazing season which affects fermentation efficiency and enteric methane emissions. Grain supplementation has been recommended as a means of improving the efficiency of fermentation for cattle when forage quality is poor. Results of a study recently completed by Boadi et al. (2002b) found grain supplementation for pastured yearling steers did result in increased DM intake and rates of gain, but there was no benefit relative to enteric emissions. That study clearly demonstrated forage quality to be the major factor influencing enteric emissions for pastured cattle. For example, the lowered quality and availability of forage from the time cattle entered a paddock to the time they were removed from that paddock in a rotational grazing system resulted in a 58 % reduction in forage DMI, but daily methane emissions remained the same.

Table 3. Methane emission and performance responses of non-lactating beef cows grazing dormant pastures during a 30-day grazing period in October.

Species	CH4 g hd^{-1} d^{-1}	CH4 g d^{-1} kg^{-1} BW	Weight change, kg
Native mixture	87	.150	- 40.6
Nordan crested wheatgrass	111	.204	- 42.5
Hycrest crested wheatgrass	124	.223	- 46.9
Vinall Russian wildrye	155	.282	- 10.6
Syn-A Russian wildrye	99	.179	- 20.6

(Olsen, 1997)

Table 4. Methane emission and performance responses of beef cows grazing forages during a 30-day grazing period in May.

Species	CH4, g hd^{-1} d^{-1}	CH4, g d^{-1} kg^{-1} BW	Cow weight change, kg	Calf weight change, kg
Native mixture	245	.510	- 19.0	18.5
Nordan crested wheatgrass	251	.491	- 8.6	23.2
Hycrest crested wheatgrass	227	.429	-5.0	.27.6
Vinall Russian wildrye	262	.502	-9.9	25.0
Syn-A Russian wildrye	259	.477	1.6	26.6

(Olsen, 1997)

A study with yearling steers at Brandon, Manitoba demonstrated that continuous grazing of improved pasture managed with a high stocking rate (2.2 steers ha^{-1}) resulted in 21 % lower daily CH_4 emissions as compared to the low stocking rate (1.1 steers ha^{-1}) when measured as emissions per animal per day, but these differences were not evident when measured as emissions per unit gain or as % GEI (McCaughey, 1997).

On the basis of work completed to date, forage species selection and pasture forage quality are critical elements to any mitigation strategy for pastured ruminants. Inclusion of legumes in the forage component of the diet and forage selection and harvest to increase forage DM digestibility will improve animal performance and reduce methane production. Further opportunities may be realized through the selection or development of forage species containing compounds that inhibit methanogenisis. European data (Moss, 1994) suggests that the trend towards more silage production may reduce methanogenisis for forage based diets. Much of that information is based on direct cut or high moisture silage, which differs from the material commonly produced in Western Canada.

Little effort has been made to challenge the current feeding practices of overwintering beef cows and weaned calves. In many cases the theoretical benefits of physical or chemical processing of forages, and supplementation of forage based diets have not been validated for Canadian production systems.

Methane inhibition. Ionophores cause a shift in the rumen bacterial population from gram positive to gram negative organisms, with a concurrent shift in fermentation from acetate to propionate. This fermentation shift is associated with a reduction in methanogenisis. Short-term *in vivo* trials suggest that the use of monensin can depress CH_4 production by 25 % (Van Nevel and Demeyer, 1995), however, data from longer term trials is much more variable, leading to speculation that an adaptive response may occur after 21 d of supplementation. For example, adult sheep fed a 75 % concentrate diet exhibited significant reductions in CH_4 emissions from the rumen and caecal contents for a 35 d period when given 50 g monensin per day (Mbanzamihigo et al. 1996). A study, conducted in Manitoba (McCaughey et al. 1997) compared enteric emissions of grazing steers with or without monensin controlled release boluses that delivered 270 mg d^{-1}. This study suggested that monensin supplementation had no impact on CH_4 emissions over an 80 day pasture period. Johnson et al (1997) showed monensin supplementation (250 mg d^{-1}) in yearling heifers resulted in a 15 % reduction in emissions when heifers were on an alfalfa diet for 28 days. Thereafter, heifers were moved to a smooth bromegrass pasture for a further 16 days. While on pasture, no differences were observed for emissions between control and monensin supplemented heifers. Monensin was also tested as a mitigation strategy in a lactating dairy herd, where whole barn emissions declined in the initial month after inclusion of monensin in the lactation ration, with emissions returning to previous levels thereafter (Kinsman et al. 1995). Further work is required to determine the mitigation potential of ionophores under feedlot and grazing conditions as this strategy is accepted by industry. As well, there is limited data relative to mitigation potential and adaptation to ionophores other than monensin. Addition of fat to the ruminant diet provides an alternate hydrogen acceptor in the rumen and can reduce enteric CH_4 production while providing an alternate source of energy to the animal. Unsaturated fatty acids serve as electron acceptors during biohydrogenation, causing this depression in CH_4 production. Several studies have demonstrated mitigation potential under commercial production conditions. Mathison (1997) reported that daily enteric CH_4 emissions were reduced by 33 % when canola oil was added to an 85 % concentrate feedlot diet. A Manitoba study (Boadi et al. in preparation) demonstrated a 30 % reduction in daily CH_4 emissions when comparing a typical 88.5 % concentrate feedlot diet with an alternate ration of equal energy density containing a 44:42:14 ratio of concentrate, silage and whole sunflower seed. Fat supplementation can serve as an important energy source in diets of high producing ruminants, however, excessive fat addition will depress fiber degradation in the rumen. For example, although diets were isocaloric in the

Manitoba study, dry matter intake was 1.7 kg lower and average daily gain was depressed by 0.3 kg for the whole sunflower seed diet. Therefore, the net reduction in CH_4 production was 23 % from the time cattle were placed on feed to the time they were finished.

Other mechanisms for methane inhibition include feed additives causing a direct inhibition of methanogenesis (Van Nevel and Demeyer 1995), feeding of dicarboxylic organic acids to enhance propionate production (Lopez et al. 1999b), use of acetogens as a daily feed additive to provide hydrogen (Lopez et al. 1999a), enhanced CH_4 oxidizing bacterial populations in the rumen (Valdes et al. 1996), rumen defaunation (Hegarty 1999), and immunization of ruminants against their own rumen methanogens (Baker, 1995). Issues regarding toxicity, product residue and insufficient in vivo testing and high cost of implementation limit assessment of these strategies as mitigation options in Canadian production systems.

Animal management. There are a wide range of management practices that improve animal productivity, resulting in reduced CH_4 emissions per unit animal product. Animal selection for increased production, management for improved reproductive performance, use of growth promoting agents, and application of more refined ration balancing technologies are examples of strategies that will reduce maintenance costs, and thereby CH_4 emissions, per unit of animal product. Some will argue that these strategies will not result in mitigation as improved productivity will lead to industry expansion.

■ Conclusion

This review has identified a number of strategies that will result in reduced CH_4 emissions when implemented at a commercial scale. These strategies include the feeding of highly digestible forages for grazing and confined cattle, inclusion of legumes in forage mixtures, inclusion of supplemental fats in diets. Many recommended on-farm practices, such as genetic selection for production traits, feed testing and ration balancing, pregnancy testing will reduce enteric CH_4 emissions by reducing feed costs associated with animal maintenance. Industry accepted practices such as the use of ionophores or probiotics need further evaluation to determine mitigation potential. Areas that require long term research support include the potential for selection of low methane emitting animals and the development of products to inhibit methanogenesis, provide alternate electron acceptors, or reduce rumen protozoa populations.

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