Chapter 16
Global Climate Change: Enteric Methane Reduction Strategies in Livestock

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Abstract The greenhouse gas (GHG) emission from the agricultural sector is considered to be a key contributor to the climate change, accounting for about 25.5% of total global anthropogenic emission. While carbon dioxide (CO_2) receives the most attention as a factor, which causes global warming, methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons (CFCs), also cause significant radiative forcing. With the relative global warming potential of 25 compared with CO_2, CH_4 is one of the most important GHGs. This chapter reviews the prediction models, estimation methodologies, and strategies for reducing enteric CH_4 emissions. Emission of CH_4 in ruminants differs between developed and developing countries, depending on factors like animal species, breed, pH of rumen fluid, ratio of acetate: propionate, methanogen population, composition of diet, and amount of concentrate fed. Among ruminants, cattle contribute the most toward greenhouse effect through methane emission, followed by sheep, goat and buffalo, respectively. The estimated CH_4 emission rate per cattle, buffalo, sheep, and goat in developed countries are 150.7, 137, 21.9, and 13.7 (g/animal/day) respectively. However, the estimated rates in

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V. Sejian et al. (eds.), *Environmental Stress and Amelioration in Livestock Production*, DOI: 10.1007/978-3-642-29205-7_16,

developing countries are significantly lower, at 95.9 and 13.7 (g/animal/day) per cattle and sheep, respectively. There is a strong interest in developing new and improving existing CH_4 prediction models that are effective in identifying mitigation strategies for reducing the overall CH_4 emissions. A careful examination of the literature suggests that the mechanistic models are superior to empirical models in accurately predicting the CH_4 emission from dairy farms. The latest development in prediction model is the integrated farm system model, which is a process-based whole farm simulation technique. Several techniques are used to quantify enteric CH_4 emissions starting from whole animal chambers to sulfur hexafluoride (SF_6) tracer techniques. The latest technology developed to estimate CH_4 more accurately is the micrometeorological mass difference technique. Understanding this basic information about enteric methane is very vital for formulating suitable mitigation strategies to curtail methane production. There are varieties of mitigation strategies available, which can be grouped under managemental, nutritional, and advanced molecular technologies. Strategies that are cost-effective, improve productivity, with potentially limited negative effects on livestock production are likely to be adopted by producers.

Keywords Enteric methane · Climate change · Global warming potential · Prediction models for enteric CH_4 · Respiratory chamber · SF_6 · Whole farm model · Defaunation · Immunization

Contents

16.1 Introduction

There is a growing interest in reducing the emission of greenhouse gases (GHGs) into the atmosphere, because of its potential effect on global warming (Moss et al. 2000). Agricultural activities contribute significantly to global GHG emissions. Examples include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ammonia (NH_3), which are major GHGs contributing to global warming (IPCC 2001). Increasing awareness of environmental problems associated with global warming has brought significant attention to the need to mitigate global warming and protect the environment (Meadows et al. 1992). Minimizing the contamination of air with CO_2, CH_4, NH_3, and N_2O and other GHGs that contribute to radiative forcing has been promoted as a possible route for mitigating global warming (Tamminga 1996). The consequences of increasing the atmospheric concentration of GHGs responsible for the radiative forcing are gradual elevation of average global temperatures, altered viability of plants, animals, insects, and microbes with numerous adverse consequences to human well-being. The degree to which these changes are projected to occur is dependent upon reliable GHG policy models with a range of scenarios for the levels of GHG emissions (Moss et al. 2000).

The scientific evidence of anthropogenic interference with the climate system through GHG emissions has led to worldwide research on assessing impacts that could result from potential climate change associated with GHG accumulation (Sejian 2012). As ecosystems are sensitive to climatic changes, it is necessary to examine the likely impacts of climate change on various components within ecosystems to develop a comprehensive understanding of these effects on climate change. While CO_2 receives the most attention, methane with the global warming potential of 25 and longer residence time in the atmosphere, is an important GHG (Wuebbles and Hayhoe 2002; Forster et al. 2007). The rising concentration of CH_4 is strongly correlated with increasing populations, and currently about 70% of its production arises from anthropogenic sources (Moss et al. 2000; IPCC 2007).

Increase in the global release of CH_4 from agricultural sources can be ascribed to growing rice paddies, fermentation of feed by ruminants (enteric CH_4), biomass burning, and animal wastes (Sejian et al. 2011). In recent times, CH_4 production has been aggravated by large-scale ruminant production (Beauchemin and McGinn 2005). Globally, ruminant livestock are responsible for about 85 Tg ($1\ Tg = 10^{12}\ g = 1$ million metric ton) of the 550 Tg CH_4 released annually (McGinn et al. 2006). Ruminant animals, particularly cattle (*Bos taurus*), buffalo (*Bubalus bubalis*), sheep (*Ovis aris*), goat (*Capra hircus*), and camels (*Camalus camalis*) produce significant amounts of CH_4 via anaerobic digestion. This microbial fermentation process, referred to as 'enteric fermentation', produces CH_4 as a by-product, which is released through eructation, normal respiration, and small quantities as flatus (Lassey 2007; Chhabra et al. 2009).

Measurement of CH_4 production in animals requires complex and often expensive equipment. Some models have been developed to specifically predict CH_4 emissions from animals (Ellis et al. 2007). At present, mathematical models are used to estimate CH_4 emissions from enteric fermentation at a national and global level, based on the guidelines of the intergovernmental panel on climate change (IPCC 2006). However, the accuracy of these models has been widely challenged (Kebreab et al. 2006).

Understanding the relationship of diet to enteric CH_4 production is essential to reduce uncertainty in GHG emission inventories and to identify viable reduction strategies. As a result, quantifying and reducing emissions from livestock farms is important in reducing overall CH_4 emission. This article reviews the sensitivity of livestock production to climate change in general, while attempting to highlight some important progresses made in predicting accurately the enteric CH_4 emissions. As animal production systems are vulnerable to climate change, while also contributing to potential global warming through CH_4 and N_2O emissions, this review also collates and synthesises the literature on prediction models, estimation methodology, and strategies for reducing CH_4 emission from ruminants.

16.2 The Contribution of CH_4 to Global Warming/Climate Change

Increasing concentrations of GHGs in the atmosphere have contributed to an increase in the earth's atmospheric temperature, an occurrence known as global warming (FAO 2006). Indeed, average global temperatures have risen considerably, and the IPCC (2007) predicts increases of 1.8–3.9°C (3.2–7.1°F) by 2100. Based on the current trends, the earth's temperature may rise by 1.4–5.8°C by the end of this century. With rare unanimity, the scientific community warns of a more abrupt and greater climatic change in the future (Moss et al. 2000; Gleik et al. 2010).

The GHG emissions from the agriculture sector account for about 25.5% of the total global radiative forcing and over 60% of anthropogenic sources (FAO 2009). Animal husbandry accounts for 18% of GHG emissions that cause global warming. Emission of CH_4 is responsible for nearly as much radiative forcing as all other non-CO_2 GHG gases combined. While atmospheric concentrations of GHGs have risen by about 39% since the pre-industrial era, CH_4 concentration has more than doubled during this period (WHO 2009). Reducing the increase of GHG emissions from agriculture, especially livestock production, should therefore be a top priority, because it could curb warming considerably (McMichael et al. 2007).

The major global warming potential (GWP) of livestock production worldwide comes from the natural life processes of the animals. In fact, CH_4 is considered to be the largest potential contributor to the global warming phenomenon (Johnson et al. 2002; Steinfeld et al. 2006). It is an important component of GHG in the atmosphere (Leng 1993; Moss et al. 2000). The development of management strategies to mitigate CH_4 emissions from cattle is possible and desirable. Not only can the enhanced utilization of dietary carbon (C) improve feed efficiency and

Table 16.1 Global domesticated ruminant population (10^6) and their respective distribution across major continents (Adapted from FAO 2008)

Animal type	World	Africa	North America	South America	Asia	Europe	Oceania
Cattle	1347	270	111	315	431	127	38
Buffalo	181	5	–	1	174	0.33	0.0002
Sheep	1078	288	7	73	452	134	113
Goat	862	291	3	21	514	18	1

animal productivity, but a decrease in CH_4 emissions may also reduce the contribution of ruminant livestock to the global CH_4 inventory.

16.3 Sources of CH_4 Emission

CH_4 is emitted from a variety of anthropogenic and natural sources (Wuebbles and Hayhoe 2002; Rotz et al. 2010). The anthropogenic sources include fossil fuel production and exploitation, animal husbandry, including manure storage (Chianese et al. 2009), paddy rice cultivation, biomass burning, and waste management (Kumaraswamy et al. 2000; Mosier et al. 2004). Other sources of methane emission are predominantly natural sources, including wetlands, gas hydrates, permafrost, termites, oceans, freshwater bodies, non-wetland soils, volcanos, and wildfires (Breas et al. 2001).

16.4 Enteric Emission of CH_4 by Livestock

Domestic animal production increased sharply since the 1990s due to policies encouraging large-scale livestock production, improvements in feeding technology, and market requirements (Yang et al. 2003; Sejian and Saumya 2011). Improved animal feeding techniques have had a marked impact on livestock production over the past few decades. In ruminants, a significant amount of fermentation takes place in the rumen, resulting in relatively large CH_4 emissions per unit of feed energy consumed. Capturing and burning methane produced by methanogens in manure lagoons, and regulation of dairy diet to reduce enteric CH_4 emission are among effective strategies that could be employed to reduce enteric CH_4 production. Pseudo-ruminants (e.g. horses) and monogastric animals (e.g. pigs) do not support the same level of feed fermentation, and consequently emissions from these animals are relatively low. Synthesis in Table 16.1 depicts world ruminant livestock population.

Among farm animals, cattle population contributes the most toward enteric CH_4 production (Johnson and Johnson 1995). Enteric fermentation emissions for cattle are estimated by multiplying the emission factor for each species by the relevant cattle populations. The emission factors are an estimate of the amount of CH_4 produced (kg) per animal, and are based on animal and feed characteristics, average energy requirement of the animal, the average feed intake, and the quality of the feed consumed (Sejian et al. 2011a). The district on county level emission from enteric fermentation is computed as a product of the livestock population under each category and its emission coefficient (Chhabra et al. 2009; Sejian and Naqvi 2011a). However, emission coefficients are country-specific, and should conform to IPCC guidelines (IPCC 2007).

16.4.1 Enteric Fermentation: Process Description

Enteric fermentation is the digestive process in herbivore animals by which carbohydrates are broken down by microorganisms into simple molecules for absorption into the bloodstream (Sejian and Saumya 2011). CH_4 is produced as a waste product of this fermentation process. CH_4 production through enteric fermentation is of concern worldwide for its contribution to the accumulation of greenhouse gases in the atmosphere, as well as its waste of fed energy for the animal. CH_4 is produced in the rumen and hindgut of animals by a group of *Archaea* known collectively as methanogens, which belong to the phylum *Euryarcheota*. Among livestock, CH_4 production is greatest in ruminants, as methanogens are able to produce CH_4 freely through the normal process of feed digestion. Ruminant animals are the principal source of emissions, because they produce the maximum CH_4 per unit of feed consumed. What makes ruminant animals unique is their 'fore-stomach' or rumen, a large, muscular organ. The rumen is characterized as a large fermentation vat where approximately 200 species and strains of microorganisms are present. The microbes ferment the plant material consumed by the animal through a process known as enteric fermentation. Figure 16.1 describes the enteric CH_4 emission from different feed components by the various rumen methanogen species. The products of this fermentation provide the animal with the nutrients it needs for survival, enabling them to subsist on coarse plant material. CH_4 is produced as a byproduct of the fermentation and is expelled. Monogastric animals produce small amounts of CH_4 as the result of incidental fermentation that takes place during the digestion process. Non-ruminant herbivores produce CH_4 at a rate that is of between monogastric and ruminant animals. Although these animals do not have a rumen, significant fermentation takes place in the large intestine, allowing significant digestion and use of plant material.

CH_4 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. 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

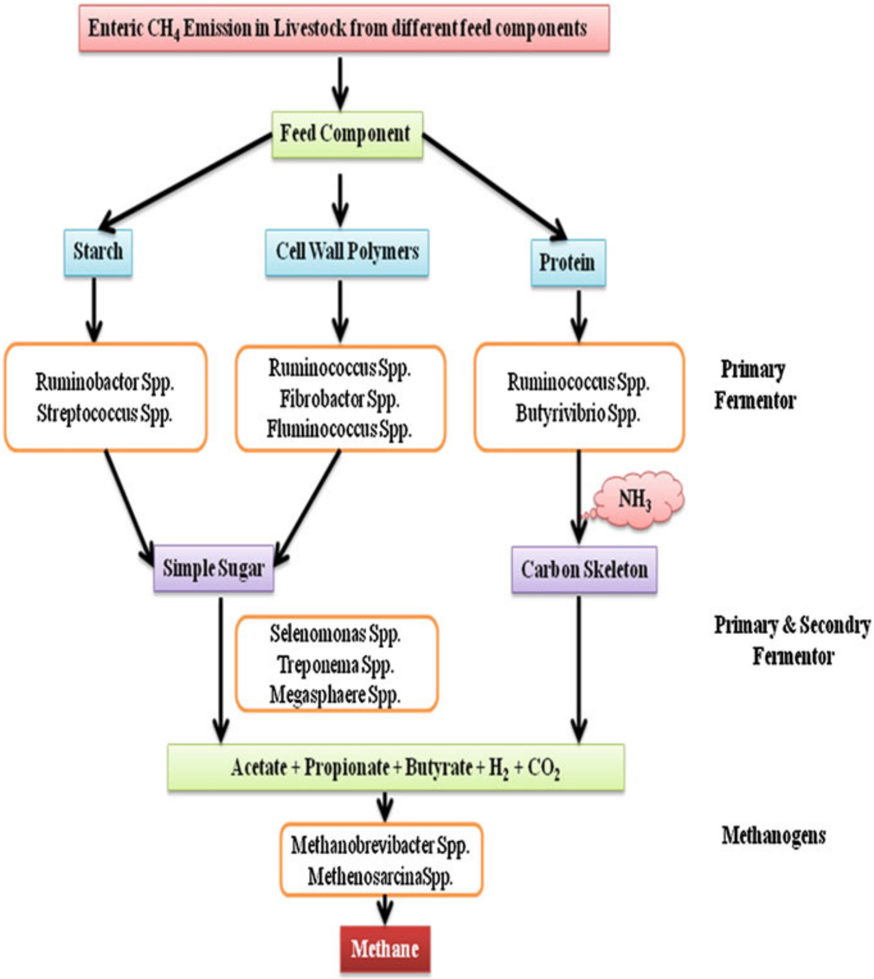

Fig. 16.1 Enteric methane emission from different feed components. Different feed components, such as starch, cell wall polymers, and proteins, are broken down to simpler sugars and carbon skeleton by primary fermentor microbes in the rumen. These simpler sugars are converted into volatile fatty acids by both primary and secondary fermentor microbes. This VFAs are acted upon by methanogen microbes in the rumen to produce methane

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. Other substrates available to methanogens include formate, acetate, methanol, methylamines, dimethyl sulfide, and some alcohols; however, only formate has been documented as an alternative CH_4 precursor in the rumen. Figure 16.2 describes the mechanism of CH_4 production during digestion process in the rumen.

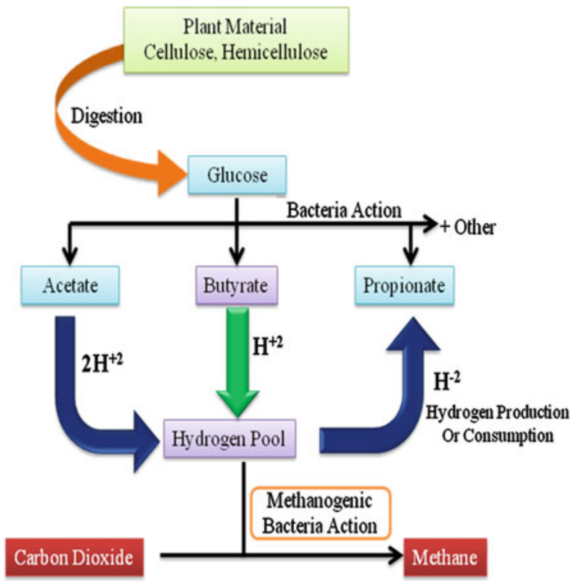

Fig. 16.2 Mechanism of enteric CH_4 production during digestion in the rumen. This figure describes the process of methane production in the rumen. From feed components, initially glucose is produced and from glucose VFAs are produced. Acetate and butyrate are hydrogen providers while propionate is hydrogen consumer. Based on the proportion of end product of digestion methane is produced in the rumen

The principal methanogens in the bovine rumen utilize hydrogen and carbon dioxide, but there is a group of methanogens of the genus *Methanosarcina* that grows slowly on H_2 and CO_2 and therefore maintains a distinct niche by utilizing methanol and methylamines to produce CH_4 (Sejian and Naqvi 2011a). Formate, which is formed in the production of acetate, can also be used as a substrate for methanogenesis, although it is often converted quickly into H_2 and CO_2 instead. Volatile fatty acids (VFA) are not commonly used as substrates for methanogenesis as their conversion into H_2 and CO_2 is a lengthy process, which is inhibited by rumen turnover. Therefore, methanogenesis often uses the C and CO_2 produced by carbohydrate fermentation, as VFAs are formed. By removing H_2 from the ruminal environment as a terminal step of carbohydrate fermentation, methanogens allow the microorganisms involved in fermentation to function optimally and support the complete oxidation of substrates (Sejian and Naqvi 2011a). The fermentation of carbohydrates results in the production of H_2 and if this end product is not removed, it can inhibit metabolism of rumen microorganisms.

16.5 CH_4 Emission in Developed and Developing Countries

The global production and consumption of farm animals and their products are increasing significantly and are predicted to continue up until ~2050. This increase comes at a time when it is recognized that the world is facing a crisis about the impact of humans on the planet's climate (Sejian et al. 2011a). Animal products have a high

GWP per kg compared to most plant-derived foods (FAO 2008). In addition to enteric fermentation, which is the major source of CH_4 emission, meat and dairy production and consumption also contribute significantly to the emission of GHGs in developed countries (Eshel and Martin 2006; Ogino et al. 2007 Comparatively, due to intensive animal production, developed countries tend to record higher CH_4 emission than their developing counterparts do.

Thus, developed countries have the highest emissions factors per animal while Asia, North, and Sub-Saharan Africa have the lowest (USEPA 1994). Among dairy cows, the temperate mixed farming production system has the highest emissions factors, reflecting higher levels of milk production. In light of this, emissions per unit of product can be used to identify opportunities for reducing CH_4 emissions from enteric fermentation.

The emission of CH_4 is quantified by its conversion rate, which differs among developed and developing countries. The conversion rate in developed countries is 4% for feedlot cattle and 6% for other cattle (Lassey et al. 1997). Better-digested feeds with higher energy value result in lower conversion rates. The CH_4 conversion rate in developing countries is also 6% for dairy cows and young cattle, and 7% for non-dairy cattle with the exception of stall-fed animals (Lassey et al. 1997). Grazing cattle have a conversion rate of 6%, except for grazing cattle in tropical Africa, which have a rate of 7% because of the poor quality forage. These estimates are based on the general feed characteristics and production practices observed in many developed and developing countries.

The data on GHG emissions from animal production depend on the natural life processes of the animals. However, these processes are difficult to control without reducing productivity. Hence, overproduction of livestock is likely to have a negatively impact on overall food production given the accompanying damages to the environment, such as more frequent droughts, floods, storms, and harvest failures. This calls for better-planned and well-managed reduction in worldwide production and consumption of meat and milk products to mitigate global warming. Global trends indicate that overproduction and consumption of animal products (meat, milk, and eggs) in high-income, developed countries may be nearing its peak and further increase in production may be unsustainable due to population growth and environmental concerns (Gold and Porritt 2004). While low-income countries and some fast-developing countries are expected to continue their rapid growth in animal production and consumption, it is essential that emission of livestock-related GHGs is monitored and controlled in the short-term.

16.6 Factors Influencing CH_4 Production

Factors that influence enteric methane production outlined in Fig. 16.3 indicate that CH_4 production varies with microbial species and livestock breed. Consequently, breeding of livestock on the basis of CH_4 production in an effort to reduce enteric CH_4 emissions without compromising animal productivity is possible

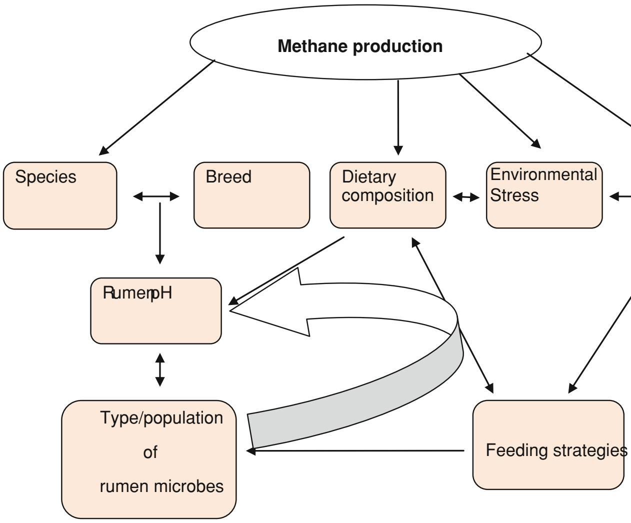

Fig. 16.3 Factors influencing methane output from enteric fermentation. These factors can be broadly categorized into animal, feed, rumen, and environmental factors

(Hegarty et al. 2007). Rumen pH plays a major role in determining the predominant microbial population, which has a direct bearing on CH_4 gas emission (Erfle et al. 1982). Reduction of ruminal pH can decrease ruminal CH_4, which can improve feed utilization in the ruminant animals (Lana et al. 1998). The ratio of ruminal acetate: propionate in vivo is highly influenced by the capacity of the bacteria to produce CH_4 in vitro. Cattle with low acetate: propionate ratios also have low ruminal pH values, and in vitro experiments corroborate the concept that pH has a major impact on CH_4 production and acetate: propionate ratio (Lana et al. 1998; Sejian et al. 2011a).

Methanogens that thrive on and within rumen ciliate protozoa may account for up to 37% of the rumen CH_4 emissions (Hegarty et al. 2007). In the absence of protozoa, rumen CH_4 emissions are reduced by up to 13% on the average depending on the diet. Decreased CH_4 emissions from protozoa-free rumen may be a consequence of reduced ruminal dry matter digestion, decreased methanogen population, altered pattern of volatile fatty acid production, decreased hydrogen availability, and increased partial pressure of oxygen in the rumen (Yoon and Stern 1995). Decline in methanogenesis associated with removal of protozoa is strung on high concentrate diets, because protozoa are relatively more important sources of hydrogen on starch diets, and many starch-fermenting bacteria do not produce hydrogen. Because protozoa also decrease the supply of protein available to the host animal, their elimination offers benefits in both decreasing GHG emissions and potentially increasing feed conversion ratio in livestock production (Hegarty 1999; Sejian et al. 2011a).

The composition of diet fed to the livestock is another important factor, which influences CH_4 emission (McCrabb et al. 1997), especially from enteric fermentation in lactating dairy cows. For instance, the proportion of forage in livestock diet and the source of grain influence enteric CH_4 production by ruminants (Beauchemin and McGinn 2005). The amounts of digestible nutrients especially the carbohydrate fraction is used to estimate CH_4 emission from livestock with high precision. Conversely, a diet rich in fat reduces CH_4 formation in the rumen (Jentsch et al. 2007). Puchala et al. (2005) identified the potential of condensed tannins in forages to reduce CH_4 emission by ruminants. The level of CH_4 emission is positively correlated with live weight, dry matter intake (DMI), milk yield (MY), and feeding level (Yan et al. 2006). To enhance productivity, manipulation of dietary composition of cattle feed is a nutritional management strategy with potential to reduce CH_4 production by dairy cows (Yan et al. 2006).

There are several feed supplements, which significantly alter the level of CH_4 emission (Leng 1991; Moss et al. 1995). However, additional feed supplement should be used with caution as they can reduce animal productivity when the wrong dosage is administered (Beauchemin and McGinn 2006; Foley et al. 2009). Incremental inclusion of malic acid in beef cattle diets results in linear reductions of both the total daily emission of CH_4 and its emissions expressed per unit of DMI. Nevertheless, the dietary inclusion of malate is also associated with a decline in DMI in both studies (Martin and Streeter 1995). This could potentially decrease animal performance, with consequent increases in lifetime CH_4 emission owing to extended slaughter age. Therefore, further in vivo research is required to clarify the long-term effects of malate supplementation on CH_4 emission, animal performance, and productivity (Foley et al. 2009). Beauchemin and McGinn (2006) demonstrated that canola oil (*Brassica campestris L*) can be used to reduce CH_4 emissions from cattle, but animal performance may be compromised due to lower feed intake and decreased fiber digestibility. Essential oils have no effect on CH_4 emissions, whereas fumaric acid causes potentially beneficial changes in ruminal fermentation although with no measurable reductions in its emissions. Certain fats and oils are potential natural CH_4 reducing feed compounds, and are effective even at common dietary proportions (Machmuller et al. 1998). McGinn et al. (2004) demonstrated that sunflower (*Helianthus annuus L*) oil, ionophores, and possibly some yeast products can be used to decrease the gross energy loss as CH_4 from cattle, however, fiber digestibility is impaired with oil supplementation.

Research involving in vitro and in vivo experiments indicates that high grain feeding reduces CH_4 emission in farm animals. (Lana et al. 1998; Hristov et al. 2001). There are two possible reasons for this viz., reduced methanogenesis and lower acetate: propionate ratio (Christophersen et al. 2008). Not only enhanced utilization of dietary C can improve feed utilization efficiency and animal productivity, but also a decrease in CH_4 emissions can reduce the contribution of ruminant livestock to the global CH_4 inventory (Johnson and Johnson 1995). Using best management practices (BMPs), the emission of CH_4 per unit of animal weight gain reduces significantly. Management-intensive grazing (MIG) is a BMP that offers the potential for more efficient utilization of grazed forage crops via controlled rotational grazing and more efficient conversion of forage into meat and milk (DeRamus et al. 2003).

As highlighted above, there are several factors, which play important roles in influencing enteric fermentation, hence CH_4 emission. There is an urgent need to understand these factors better, with a view to decreasing GHG emissions (Beauchemin and McGinn 2005).

16.7 Prediction of CH_4 Emission by Emission Models

CH_4 production is generally predicted on the basis of equations involving DMI, intake of carbohydrates, digestibility and intake of dietary energy, animal size, milk components, and digestibility of dietary components (Sejian et al. 2011b). The models developed for the prediction of CH_4 emission can be classified into two principal groups: (i) empirical (statistical) models, which directly relate nutrient intake to CH_4 output, and (ii) dynamic mechanistic models that attempt to simulate CH_4 emissions based on a mathematical description of ruminal fermentation biochemistry (Kebreab et al. 2006). Synthesis in Table 16.2 depicts the merits and demerits of the empirical and mechanistic models.

16.7.1 Empirical Models

Although many statistical models have been fairly successful in predicting CH_4 production, many variables in these models are not commonly measured, which may lead to difficulties in predicting CH_4 production outside the range of values used for model development (Johnson et al. 1996; Sejian and Rajni 2011). These problems may be addressed by using equations with common input variables and by developing models with minimum input variables from multiple sources. The limitation of using some of the extant models, such as the equation of Moe and Tyrrell (1979), is the difficulty in obtaining reliable model input variables, which might have compromised the predictive ability of the model in the study. Ellis et al. (2007) formulated the most widely accepted equations, which could be useful to the livestock industry for accurately predicting CH_4 production from a minimum set of inputs. Although the extant models evaluated performed well, the new equations developed in the study were more user-friendly and reliable than the extant models, as a result, it is a preferable model for generating national CH_4 emissions inventory. Synthesis in Table 16.3 depicts different types of regression/prediction equations for enteric methane emission.

Table 16.2 The merits and demerits of empirical and mechanistic prediction models for methane emission

Type of prediction models	Empirical models	Mechanistic models
Description	Statistical models that relate nutrient intake to CH_4 output directly	Dynamic models that attempt to simulate CH_4 emissions based on a mathematical description of ruminal fermentation biochemistry
Models	IPCC (2006) tier II model Moe and Tyrrell (1979) model	MOLLY (Baldwin (1995) and its current version MOLLY 2007), COWPOLL (rumen model of Dijkstra et al. 1992)
Merits	1. Simple uncomplicated regression equation based on feed characteristics	1. Predict CH_4 production from cattle without undertaking extensive and costly experiments
		2. The advantage over empirical models is that mitigation options implemented at a farm or national level can be evaluated for effectiveness
		3. Climate and management informations are included in these models
		4. Take into account the methanogenic bacterial population and their methane production efficiency
Demerits	1. Predict CH_4 production from livestock by undertaking extensive and costly experiments	1. For effective application, these models should possess accurate values for input parameters, such as the chemical composition of the diet, degradation rates of feed components, and passage rates
	2. Do not take into account the influence of environmental effect and rumen microbial population on methane production	2. One of the main limitations of mechanistic models is its lack of detailed and accurate data, in light of, the complexity of the system
	3. Cannot accurately predict CH_4 production under all perturbation conditions as it is based only on feed characteristics, and do not take other factors into account	3. Similarly, the rapid dynamic changes in metabolic flux during lactation, especially in late pregnancy and early lactation pose another major limitation
	4. Empirical models lack the biologic basis necessary to evaluate mitigation strategies and cannot be used to predict changes in methane emissions outside the range they were developed for	

Source Sejian et al. (2011a)

Table 16.3 Examples of regression/prediction equations for methane emission

Prediction equations	Reference
Methane (McaI/d) = (18 + 22.5 × DM1 (kg/d)) × .013184 (Mcal/g of methane)	Kriss (1930)
Methane (Mcal/d) = (17.68 + .04012 × digested carbohydrate (g/d)) × .013184 (Mcal/g of methane)	Bratzler and Forbes (1940)
Methane (Mcal/d) = −0.494 + 0.629 × DMI (kg/d) − 0.025 × DMI^2 (kg/d)	Axelsson (1949)
CH_4 (%GE) = 1.30 + .122 *D* + *L* (2.37 .05 *D*) GE—gross energy; *D*—digestibility of energy; *L*—intake relative to maintenance	Blaxter and Clapperton (1965)
Methane (MJ/d) = 3.41 + 0.51 NFC + 1.74 HC + 2.65 *C* For intake of carbohydrate fractions Methane (Mcal/d) = .814 + .122 × NFC (kg/d) + .415 × HC (kgId) + .633 × *C* (kg/d) NFC—non fiber carbohydrate; HC—hemicellulose; *C*—Cellulose	Moe and Tyrrell (1979)
F_{CH4} = 9.77 + .87 × CF F_{CH4} is methane emissions as a percentage of digestible energy and CF is crude fiber	Giger-Reverdin et al. (1992)
CH_4 (g/d) = SF_6 permeation rate (g/d) × $[CH_4]/[SF_6]$	Johnson et al. (1995)
CH_4 (g/d) = 55 + 4.5**M* + 1.2**W* (grass) CH_4 (g/d) = 26 + 5.1**M* + 1.8**W* (corn silage) *M* = milk yield; *W* = live weight	Kirchgessner et al. (1991)
CH_4 (g/d) = 63 + 79 CF + 10 NFE + 26 CP − 212 EE (all nutrients in kg/d) CF—crude fiber; NFE—nitrogen free extract; EE—ether extract	Kirchgessner et al. (1995)
CH_4 (MJ/d) = 1.36 + 1.21*Dm − 0.825*Dmc + 12.8*Nd (all) CH_4 (MJ/d) = −35.5 + 0.0216*N + 27.6*Sdm + 1.63*Gdm (silage) Dm = dry matter intake (kg); Dmc = dry matter concentrates (kg); Nd = ratio of NDF/Dm; *N* = *N* intake; Sdm = ratio of silage Dm/Dm; Gdm = ratio of gross energy/Dm	Yates et al. (2000)
CH_4 (MJ/d) = *E*max – *E*max*exp(−*c**MEI) *E*max = maximum value of CH_4 production; *c* = shape parameter; MEI = metabolizable energy intake	Mills et al. (2003)
Based on dry matter intake $Y = 164.18(\pm 39.39).\ X_1 + 8427.54(\pm 603.20)$ $Y = 82.3418(\pm 8.41).\ X_2 + 5227.35(\pm 596.12)$ where $y = CH_4$ energy (kJ); $x1$ = dry matter intake (g feed/kg BW) and $x2$ = dry matter intake (g feed/kg $W^{0.75}$)	Jentsch et al. (2007)

Source Sejian et al. (2011a)

16.7.2 Mechanistic Models

Synthesis in Table 16.4 describes the various emission models available to predict enteric methane emission for farm households. Yan et al. (2000) improved on the earlier representation of methanogenesis in the mechanistic model, and outlined some likely reasons for the differences between observed and predicted values for

Table 16.4 Examples of prediction models for methane emission

Prediction models	References
Statistical models/empirical model	Blaxter and Clapperton (1965)
Statistical models/empirical model	Moe and Tyrrell (1979)
Dynamic/mechanistic model	Dijkstra et al. (1992)
Dynamic/mechanistic model	Baldwin (1995)
MOLLY (mechanistic model)	Baldwin (1995)
Dynamic/mechanistic model	Benchaar et al. (1998)
Farm system simulation framework (whole farm model)	Neil et al. (1997), Sherlock et al. (1997), Sherlock and Bright (1999), Bright et al. (2000)
Mechanistic model refined with knowledge of the dietary components	Yan et al. (2000), Mills et al. (2003)
COWPOLL (mechanistic model)	Kebreab et al. (2004)
Tier II model (empirical model)	IPCC (2006)
Dynamic/mechanistic model	Ellis et al. (2007)
Integrated farm system model	Rotz et al. (2007)
Diet specific nonlinear mechanistic models	Kebreab et al. (2008)
Integrated farm system model refined with process-based whole farm simulation	Rotz et al. (2009)

Source Sejian et al. (2011a)

CH_4 production. One of these is the error attributable to dietary composition, not only in the analysis, but also due to variation in nutrient composition between samples of the same feedstock. This knowledge of the dietary components is a prerequisite for successful use of the models to compare the effect of different feeds on CH_4 production (Palliser and Woodward 2002). Nonlinear mechanistic model of CH_4 production provides a significant opportunity to enhance scientific capacity to estimate CH_4 emissions from cattle (Mills et al. 2003; Kebreab et al. 2008). In addition, researchers have identified that mechanistic models can be used to generate Ym values, which can be applied in national CH_4 emission inventory models. It was suggested that if incentives were introduced to mitigate CH_4 emissions at a farm level, mechanistic models would be excellent tools to make reliable estimates of enteric CH_4 emissions. The advantage of mechanistic models compared with empirical models is that mitigation options implemented at a farm or national level can be assessed for their effectiveness.

16.7.3 Whole Farm Model

Computer simulation can provide a cost-effective and efficient method of estimating CH_4 emissions from dairy farms and analyzing effects of management strategies on emissions. Invariably all whole farm models (WFM) are mechanistic models. A commonly used simulation is that proposed by Rotz et al. (2007). The model is an integrated farm system model (IFSM), which is a potential tool for simulating whole farm emissions of CH_4 and evaluating the overall impact of management strategies used to reduce CH_4 emissions. The IFSM was further refined into a process-based whole farm simulation including major components for soil processes, crop growth, tillage, planting, and harvest operations, feed storage, feeding, herd production, manure storage, and economics (Rotz et al. 2009). Incorporation of the CH_4 module with IFSM in addition to modules simulating N_2O emissions, provides an important tool for evaluating the overall impact of management strategies used to reduce GHG emissions in dairy farms.

Farm system simulation framework (FSSF) is another type of WFM, which uses pasture growth and cow metabolism for predicting CH_4 emissions in dairy farms. Also included in the WFM is climate and management information. Other examples of WFMs include those developed by Neil et al. (1997), Sherlock et al. (1997), Sherlock and Bright (1999), and Bright et al. (2000); however, these models are adequate only for predicting CH_4 production by non-lactating Holstein cows. Prediction rates for lactating cows are less accurate and WFMs currently described in the literature seem inappropriate (IPCC 1997). Hence, development of WFMs is required for the prediction of nutrient and GHG emissions and to get better estimate of enteric CH_4 production (Sejian and Singh 2011). Currently available WFMs may incorrectly estimate CH_4 emission levels, because they cannot broadly predict enteric CH_4 emissions as affected by DMI and diet. The low prediction accuracy of CH_4 equations in current WFMs may introduce substantial errors in the calculation of GHG emissions, thereby leading to incorrect mitigation recommendations. If regression equations examined here and elsewhere continue to explain only a small fraction of the variations in observed values, moving toward regression equations including more nutritional informations and details on a subanimal level, or toward a dynamic mechanistic description of enteric CH_4 emission, will improve predictions (Ellis et al. 2010; Sejian et al. 2011b).

16.8 Estimation Methodologies for Enteric CH_4 Emission

There is a growing interest in changing the management strategies to reduce enteric CH_4 production without negatively influencing animal productivity. This theme has been the focus of much research to improve environmental sustainability from an agricultural standpoint. However, accurate CH_4 measurements are required for identifying mitigation strategies that can discriminate among treatments relevant to on-farm conditions (Lassey 2008). Several techniques are used to quantify enteric CH_4 emissions including whole animal chambers (Grainger et al. 2007), and SF_6 tracer technique (Pinares-Patiño et al. 2008; McGinn et al. 2009).

Measurement of CH_4 emissions from individual animals has traditionally been made with open-circuit respiration chambers, which are highly accurate and reliable for animals offered indoor diets (Sejian and Saumya 2011). However, these chambers are not as suitable for evaluating emissions for grazing animals. A new technique that makes use of an inert gas (SF_6) has recently been developed for determining CH_4 emissions from cattle and sheep under grazing conditions. The SF_6 tracer technique enables the determination of enteric CH_4 emissions from both individual as well as on a large number of animals (Vlaming et al. 2007). This technique is based on the use of a controlled release bolus containing SF_6 gas, which is inserted into the animal's rumen (DeRamus et al. 2003). This technique slowly samples the mixed eructated and respired air from the animal, generally over a 24-h period. This air sample is then analyzed for the ratio of CH_4:SF_6 concentration, and the ratio is multiplied by the known release rate of SF_6 emitted from a permeation tube placed in the rumen (Pinares-Patiño et al. 2008). This technique is extremely useful for examining grazing management influences on enteric CH_4 emissions (Pinares-Patiño et al. 2007). In addition, the authors concluded that the SF_6 tracer technique can be used with a reasonable degree of accuracy for inventory purposes and for evaluating the effects of mitigation strategies on CH_4 emissions.

A more flexible technique for quantifying emissions is to model the dispersion of a target gas from the source (Flesch et al. 2004), so that a downwind concentration of gas can establish the emission rate. This "inverse-dispersion" technique has the advantage of simplicity, as it requires only a single gas concentration measurement and basic wind information (McGinn et al. 2006). However, several important factors must be considered to get accurate results from this technique. These factors include: (1) ambient conditions including landscape with clearly defined wind regime as well as not having other nearby emission sources; (2) duration of measurement; (3) period specific measurements (while ignoring periods known to be problematic for inverse-dispersion calculations), and (4) lactation specific concentration measurement.

A micrometeorological mass difference technique is used to measure CH_4 production by cattle in pasture and feedlot conditions (Harper et al. 1999). Measurements are made continuously under field conditions, semiautomatically for several days. The method permits a relatively large number of cattle to be sampled. These techniques do not infringe on the measurement being made, and are generally nonintrusive (Laubach and Kelliher 2004). Limitations include light winds, rapid wind direction changes, and high precision CH_4 gas concentration measurement. The mass difference method provides a useful tool for 'undisturbed' measurements on the influence of feedstuffs and nutritional management practices on CH_4 production from animals and for developing improved management practices for enhanced environmental quality (Harper et al. 1999).

McGinn et al. (2006) used a backward Lagrangian Stochastic (bLS) dispersion technique where plume gas concentrations are measured several hundred meters downwind of a dairy farm. The bLS dispersion technique is a useful approach for measuring whole farm emissions (e.g., dairies and feedlots) and emissions from well-defined point sources within the farm. In addition, this technique is useful in evaluating mitigation strategies, is nonintrusive, less labor-intensive, and is much easier to implement than most techniques. Furthermore, using the bLS dispersion technique in conjunction with global positioning system (GPS) may have application for monitoring enteric CH_4 emissions from grazing cattle herds in large pad docks (McGinn et al. 2009).

16.9 Mitigation Strategies for Reducing CH_4 Production

Any reduction strategies must be confined to the following general framework viz., development priority, product demand, infrastructure, livestock resource, and local resources (Sejian et al. 2011a). The most attractive emissions mitigation projects must balance the needs in all of these areas, so that, no one factor creates a constraint on continued improvement in production efficiency, and the resulting CH_4 emissions reductions. Within this framework, CH_4 emissions mitigation options for enteric fermentation can encompass a wide range of activities across these areas (Sejian and Indu 2011). However, underlying these activities must be specific options for improving the production efficiency of the livestock. Without these options, CH_4 emissions cannot be reduced. A range of reduction strategies to reduce enteric methane production outlined in Fig. 16.4 are briefly discussed below.

16.9.1 Reduction of Livestock Numbers

Reducing livestock numbers may be the best possible way for countries that hold large livestock population and are committed to reducing GHG emission from animal sources. Nevertheless, countries, which are heavily dependent on their livestock industries for generation of national income, imposition of regulations aimed at reducing livestock numbers would be economically unacceptable. Reducing livestock numbers through normal market processes can be effective. For example, in New Zealand, sheep farming has become less profitable since ~1990, and farmers have reduced sheep numbers and used the land for alternative enterprises, such as forestry (Ulyatt and Lassey 2001). Sheep populations have been reduced from 57.9 million in 1990 to 45.2 million in 2000, while dairy cattle and beef cattle population have increased slightly. The net outcome was a decline in ruminant CH_4 emission from 1.45 to 1.31 Tg/year from 1990 to 2000. This change in stock numbers, predominantly a reflection of the profitability of sheep farming, implies that New Zealand is in a position to meet its commitments to the UNFCCC. However, livestock population may respond positively to improved economic conditions. However, if sheep farming become more profitable an increase in stock numbers and thus CH_4 emission become most probable.

16.9.2 Management Strategies

Adoption of the basic livestock management principles offers the best opportunity for improving production efficiency while also reducing emissions (Sejian and Naqvi 2011b). Within the context of these livestock management principles, specific techniques for improving production efficiency and reducing CH_4

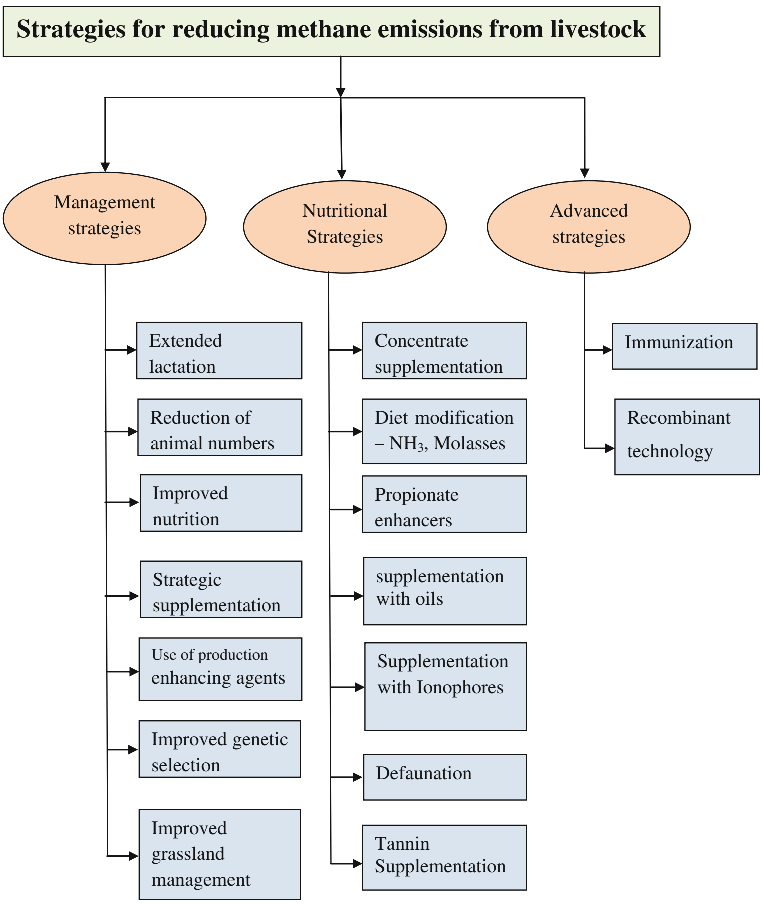

Fig. 16.4 Various strategies to reduce enteric methane production. These mitigation strategies can be grouped into three broader category-managemental, nutritional and advanced strategies (*Source* Sejian et al. 2011b)

emissions include the following: (1) enhanced nutrition through mechanical and chemical feed processing, (2) balanced nutrition through strategic supplementation, (3) intake of production enhancing agents, (4) improved production through enhanced genetic characteristics, (5) increased production efficiency through improved reproduction, and (6) improved grassland and rangeland management (USEPA 1993).

There is a wide range of management practices that improve animal productivity, with concomitant reduction in CH_4 emission per unit animal product (Naqvi and Sejian 2011). Genetic selection of animals that consume less feed or produce less CH_4 per unit of feed is a management strategy that may be used to reduce enteric CH_4 emissions. Improving the efficiency of ruminant animal performance will generally lead to a reduction of CH_4 emitted per unit of animal product. There are two aspects of this practice: genetic improvement of the animals to achieve more products per unit of feed intake and dietary manipulation via increased feed intake and appropriate feed composition (Ulyatt and Lassey 2001). These authors also suggested that increasing feed intake decreases the CH_4 emission per unit of feed intake. Increased intake of the same diet to a cow increases milk production, but decreases CH_4 emitted per unit of milk (Kirchgessner et al. 1995). The probable reason for this could be that as intake increases, the CH_4 emission associated with the essential but non-productive requirements for maintenance is diluted. Dietary manipulations aimed at reducing CH_4 emission include decreasing dietary fiber and increasing starch and lipid (Beauchemin and McGinn 2006). Generally, diets of higher digestibility have these characteristics (Johnson et al. 2002). Treatment of animals with growth promoting substances can increase production efficiency. Examples of such substances are bovine somatotrophin (bST), ionophores, and anabolic steroids. All these techniques use dilution of maintenance requirements to achieve reduced CH_4 emission. Their maximum effectiveness in terms of reducing CH_4 emission would be in maintaining present levels of animal production with fewer animals, or in increasing animal production with the same number of animals. This would provide the farmer with options for land use that should improve productivity.

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). The natural variation among animals in the quantity of feed eaten per unit of liveweight gain can be exploited to breed animals that consume less feed than the unselected population while achieving a desired rate of growth (Hegarty 2001). Thus, the concept of residual feed intake (RFI) was developed and used by Boadi et al. (2004a). In addition, there are large differences in emission per unit of feed intake between animals. Such differences between animals are real and can persist for some time (Lassey et al. 1997). Implementing proper grazing management practises to improve the quality of pastures increases animal productivity and has a significant effect on reducing CH_4 emission from fermentation in the rumen. Management-intensive grazing (MIG) is an effective form of grazing BMPs. As a result, the CH_4 emissions per unit of product as well as total emissions into the atmosphere are reduced (DeRamus et al. 2003; Naqvi and Sejian 2011).

There are many potential opportunities for mitigating CH_4 through microbial intervention in the rumen, such as: targeting methanogens with antibiotics, bacteriocins, or phage; removing protozoa from the rumen; development of alternative sinks for H_2 such as reductive acetogenesis (Ulyatt and Lassey 2001). There is considerable evidence that the rumen can function satisfactorily in the absence of methanogens (Joblin 1999). Given that CH_4 results from microbial activity, the animal can only have an impact on this variation through interactions with the microbes directly, through the diet selected, or through control of the fermenter (rumen) conditions (Ulyatt and Lassey 2001). Animal effects on fermentation could include saliva, feed processing, or flow rate through the rumen. It is possible that the animal impact on fermentation is genetically determined and if this is the case, it may be possible to create market opportunities that can be used to select low CH_4 emitters. Several CH_4 oxidizing bacteria have been isolated from the rumen and when added to the rumen fluid in vitro, decrease CH_4 accumulation in the rumen (Boadi et al. 2004a). In the long term, however, CH_4 oxidizers from gut sources could be screened for their activity in the rumen to reduce the proportion of CH_4.

16.9.3 Nutritional Strategies

Diet modification is one way in which the cattle industry can reduce its contribution to GHG emissions (Beauchemin and McGinn 2006; Sejian et al. 2011c). It has been accepted generally that digestibility is maximized when optimum levels of NH_3 is maintained in the rumen (Bowman et al. 1992). Supplying NH_3 can, therefore, greatly increase digestive efficiency and utilization of available energy. NH_3 can be supplied via urea, chicken manure, or soluble protein that degrades in the rumen. In addition to NH_3, there are some nutrients that must be present in the diet to support the microbe population in the rumen. The most common nutrients required are sulfur (S) and phosphorus (P), although this may vary greatly with region. In addition, molasses provides the energy needed to realize the improved microbial growth that can result from enhanced ammonia levels. Molasses nutrient blocks (MNBs) have been used as a supplement in many countries with encouraging results of increased milk yield by 20–30%; increased growth rate of 80–200% and increased reproductive efficiency. Based on these results, CH_4 emissions per unit product are expected to be reduced by up to 40% (Leng 1991). Bowman et al. (1992) reported that strategic supplementation of dairy animals with MNBs may reduce CH_4 emissions by 25%.

Improving the nutritive value of the feed given to grazing animals by balancing the diet with concentrates, or by breeding improved pasture plants, may reduce CH_4 emission. The proportion of concentrate within the diet is negatively correlated with CH_4 emissions (Yan et al. 2000; Lovett et al. 2005). Increased concentrate supplementation decreases enteric CH_4 production, increases proportion of propionate in rumen VFA and therefore reduces hydrogen for CH_4 synthesis. Indeed increasing the digestibility of pasture for grazing ruminants is the most practical means of reducing their CH_4 emissions (Hegarty 1999). If animal numbers do not decrease in response to the improved productivity, however, then emissions from the sector may increase rather than decrease (Hegarty 2002). Waghorn et al. (2002) observed that the impact of condensed tannins on rumen methanogenesis is small, although significant. Furthermore, legumes reduce CH_4 emissions when fed at comparable intake levels (Beever et al. 1985).

16.9.4 Chemical Inhibitors of Methanogenesis

Several mechanisms influence the availability of H_2 in the rumen and subsequent production of enteric CH_4 emissions by cattle. Processes that yield propionate act as net proton-using reactions while those that yield acetate result in a net increase in protons. That is, the proportion of volatile fatty acids, specifically acetate, propionate; produced as a consequence of microbial fermentation in the rumen has a significant influence on CH_4 production. If precursors of propionate are added to the diet, they should reduce CH_4 production by removing some of the H_2 produced during ruminal fermentation (O'Mara 2004). Another mechanism by which CH_4 production may be reduced during the rumen fermentation process is through the provision of alternative hydrogen acceptors or sinks.

A wide range of chemicals are available that may reduce rumen methanogenesis (Johnson and Johnson 1995; Mathison 1997). Organic acids, such as malate, fumarate, citrate, succinate, etc., are propionate precursors. Experiments conducted in vitro (Martin and Streeter 1995; Ulyatt and Lassey 2001) and in vivo (Newbold et al. 2002) show that addition of organic acids to the diet reduces CH_4 production, in a dose dependent manner (Martin and Streeter 1995). Thus, a feed additive or ingredient that reduces CH_4 emissions from cattle fed high-forage diets could have an important impact on reducing the emissions from the livestock sector (Beauchemin and McGinn 2006). Adding 4.6% of canola oil, a source of unsaturated fat, to a high-forage diet is an effective suppressant of CH_4, with daily emissions decreased by 32% and emissions as a percentage of gross energy intake decreased by 21%. McGinn et al. (2004) also reported reduced CH_4 production after supplementing the feed with sunflower oil and monensin. Halogenated CH_4 analogs, such as, chloroform, CCl_4, chloral hydrate, bromochloromethane, and bromoethanesulphonic acid are potent CH_4 inhibitors (McCrabb et al. 1997).

There is an increasing interest in exploiting natural products as feed additives to manipulate enteric fermentation and possibly reduce CH_4 emissions from livestock (Wenk 2003). Essential oils can interact with microbial cell membranes and inhibit the growth of some gram-positive and gram-negative bacteria. As a result of such inhibition, the addition of some plant extracts to the rumen results in an inhibition of deamination and methanogenesis, resulting in lower ammonia N, CH_4, and acetate, and in higher propionate and butyrate concentrations (Boadi et al. 2004b; Calsamiglia et al. 2007). Data from in vitro and in vivo experiments involving essential oil indicate that these are antimethanogenic agents leading to reduction in CH_4 production (Busquet et al. 2006; Castillejos et al. 2006). Supply of lipids from linseed (*Linum usitatissimum*) significantly decreased the amount of CH_4 emitted by dairy cows. Linseed fatty acid offers a promising dietary means to depress ruminal methanogenesis. The form of linseed fatty acid greatly influences CH_4 output from dairy cows (Martin et al. 2008). Polyunsaturated fatty acid decreases CH_4 through a toxic effect on microorganisms involved in fiber digestion and hydrogen production, such as protozoa (Doreau and Ferlay 1995) and cellulolytic bacteria (Nagaraja et al. 1997).

Ionophores, such as monensin and lasalocid also reduce CH_4 emission (Johnson and Johnson 1995). In the rumen, ionophores increase the proportion of gram-positive bacteria, resulting in a shift in fermentation acids from acetate and butyrate to propionate, consequently CH_4 production is reduced (NRC 2001). However, the rumen microbes adapt to the additives within two weeks (Saa et al. 1993; O'Mara 2004). Monensin supplementation can reduce CH_4 production by 25% (Tedeschi et al. 2003).

Defaunating agents, like manoxol, teric, alkanate $3SL_3$ and sulphosuccinate can reduce CH_4 emission (Mathison et al. 1998). They act by disrupting the close symbiotic relationship between methanogenic bacteria and protozoa. One method by which defaunation can be brought about is the addition of certain oils/fats (Machmuller et al. 1998; Hegarty 1999). The magnitude of reduction in CH_4 output following dietary supplementation of fats/oils is source-dependent, with coconut (*Cocos nucifera*) oil identified as being very effective (Lovett et al. 2005; Jordan et al. 2004). However, the use of defaunation to decrease CH_4 production from ruminants would have to be balanced against the effects on fiber and protein metabolism in the rumen (Gworgwor et al. 2006).

The main problems with chemical additives are the following: (i) some are toxic to the animal and rumen microflora thereby reducing digestion and food intake, (ii) some have short-lived effects, because the rumen microbes adapt, they are mainly volatile hence, difficult to administer, and (iii) some are expensive, and may not meet consumer product acceptance.

16.9.5 Immunization

The most noteworthy achievement with regards to reducing CH_4 production in livestock is the development of a vaccine containing an antigen derived from methanogenic bacteria (Gworgwor et al. 2006) and an immunogenic preparation which reduces the activity of rumen protozoa (Baker et al. 1997). Such vaccines are potent in providing a cost-effective treatment for reducing CH_4 emission and enhancing animal production. In light of these, Baker (1995) and Shu et al. (1999) proposed that it may be possible to immunize ruminants against their own methanogens with associated decrease in CH_4 output and that such an approach could reduce the members of streptococci and lactobacilli in the rumen.

16.10 Conclusions

This chapter addresses enteric CH_4 production from livestock and its mitigation strategies. It describes factors influencing CH_4 production, prediction models, and estimation methodologies for identifying different strategies to reduce such emissions. There are urgent needs to understand the various factors affecting variability in enteric CH_4 production to decrease GHG emission inventories and to identify viable GHG reduction strategies. Considerable progress has been made in the design of simulation models for predicting CH_4 emissions and the latest integrated farm system models offer greater capacity to predict more accurately GHG emissions with the incorporation of climatic and management information. Although the reduction in GHG emissions from livestock industries is of high priority, strategies for reducing emissions should not reduce the economic viability of the livestock industry.

The reduction of enteric CH_4 emissions from livestock by the selection of more feed-efficient animals based on their estimated breeding value offers a novel way of reducing the CH_4 emissions without compromising animal growth rate. Decreasing feed losses to CH_4 emission in the cattle industry can represent an improvement in feed efficiency. Therefore, mitigating CH_4 losses from cattle have both environmental and economic benefits. Improved knowledge of quantitative nutrition provides powerful tools to develop concepts to undertake a wide range of problem-oriented research with the goal of curbing emissions by livestock farms. Many authors have recommended on-farm practises, such as genetic selection for production traits, feed testing, and ration balancing, using CH_4 inhibitors to reduce enteric CH_4 emissions with concomitant reduction in feed costs. Several other CH_4 reduction strategies are at various stages of investigation, such as the use of feed additives, ionophores, defaunation, and vaccination. Pending an improved understanding of the global impact of these mitigation strategies on livestock, there are grounds for optimism that in the medium term, more effective strategies may become available to supplement those presently available. Finally, more consideration must be given to total farm GHG emissions from enteric fermentation. As low-income countries and some fast-developing countries are expected to continue their rapid growth in animal production, it is essential that the growth of global livestock-related GHG emissions is restricted in the short term to reduce the effects of CH_4 on global temperatures.

16.11 The Scope of Future Research

There is new need for further concerted research on methane emission by livestock and its mitigation. For instance, there are several new and more advanced CH_4 mitigation options, including the addition of probiotics, acetogens, bacteriocins, archaeal viruses, organic acids, and plant extracts to the diet, as well as immunization and genetic selection of animals. Although these new strategies are promising, more research is needed for validation purposes and to assess in vivo their effectiveness in reducing CH_4 production in dairy animals. In addition, there is a need to improve the efficacy of current strategies both economically, for livestock production and increasing their capacity to limit emissions. Vaccine development against methanogens is promising and calls for concerted research efforts if this strategy is to become a reality. The development of biomarkers to identify low CH_4 emission animals or low CH_4-producing bacteria also merits further investigation. Future developments in the area of modeling must accompany any improved understating of the underlying rumen biology. Furthermore, the need to develop simpler and more accurate models compatible with current trends in computer technology cannot be overemphasized.

References

Axelsson J (1949) The amount of produced methane energy in the European metabolic experiments with adult cattle. Ann R Agric Coll Sweden 16:404–419

Baker SK (1995) Method of improving utilization of nutrients by ruminants or ruminant like animals. International patent, WO9511041, USA

Baker SK, Gnanasampanthan G, Purser DB, Hoskinson RM (1997) Immunogenic preparation and method for improving the productivity of ruminant animals. Patent Application WO 97/00086

Baldwin RL (1995) Modeling ruminant digestion and metabolism. Chapman and Hall, London

Beauchemin KA, McGinn SM (2005) Methane emissions from feedlot cattle fed barley or corn diets. J Anim Sci 83:653–661

Beauchemin KA, McGinn SM (2006) Methane emissions from beef cattle: effects of fumaric acid, essential oil, and canola oil. J Anim Sci 84:1489–1496

Beever DE, Thomson DJ, Ulyatt MJ, Camell SB, Spooner MC (1985) The digestion of fresh perennial ryegrass (Lolium perenne L. cv.Melle) and white clover (Trifolium repens L. cv. Blanca) by growing cattle fed indoors. Br J Nutr 54:763–775

Benchaar C, Rivest J, Pomar C, Chiquette J (1998) Prediction of methane production from dairy cows using existing mechanistic models and regression equations. J Anim Sci 76:617–627

Blaxter KL, Clapperton JL (1965) Prediction of the amount of methane produced by ruminants. Br J Nutr 19:511–522

Boadi D, Benchaar C, Chiquette J, Massé D (2004a) Mitigation strategies to reduce enteric methane emissions from dairy cows: update review. Can J Anim Sci 84:319–335

Boadi D, Wittenburg KM, Scott SL, Burton D, Buckley K, Small JA, Ominski KH (2004b) Effect of low and high forage diets on enteric and manure pack GHG emissions from a feedlot. Can J Anim Sci 84:445

Bowman RL, Croucher JC, Picard MT (1992) Assessment of the prefeasibility of strategic supplementation as an opportunity for reducing methane emissions in Gujarat, India, A.T, International, prepared for the Global Change Division, U.S. Environmental protection agency, Washington DC

Bratzler JW, Forbes EB (1940) The estimation of methane production by cattle. J Nutr 19(6):611–613

Breas O, Guillou C, Reniero F, Wada E (2001) The global methane cycle: isotopes and mixing ratios, sources and sinks. Isot Environ Health Stud 37(4):257–379

Bright KP, Sherlock RA, Lile J, Wastney ME (2000) Development and use of a whole farm model for dairying, applied complexity: from neural nets to managed landscapes. NZ Institute for Crop and Food Research, Christchurch, pp 382–389

Busquet M, Calsamiglia S, Ferret A, Kamel C (2006) Plant extracts affect in vitro rumen microbial fermentation. J Dairy Sci 89:761–771

Calsamiglia S, Busquet M, Cardozo PW, Castillejos L, Ferret A (2007) Invited review: essential oils as modifiers of rumen microbial fermentation. J Dairy Sci 90:2580–2595

Castillejos L, Calsamiglia S, Ferret A (2006) Effect of essential oils active compounds on rumen microbial fermentation and nutrient flow in vitro systems. J Dairy Sci 89:2649–2658

Chhabra A, Manjunath KR, Panigrahy S, Parihar JS (2009) Spatial pattern of methane emissions from Indian livestock. Curr Sci 96(5):683–689

Chianese DS, Rotz CA, Richard TL (2009) Whole farm GHG emissions: a review with application to a Pennsylvania dairy farm. Appl Eng Agric 25(3):431–442

Christophersen CT, Wright ADG, Vercoe PE (2008) In vitro methane emission and acetate: propionate ratio are decreased when artificial stimulation of the rumen wall is combined with increasing grain diets in sheep. J Anim Sci 86:384–389

DeRamus HA, Clement TC, Giampola DD, Dickison PC (2003) Methane emissions of beef cattle on forages: efficiency of grazing management systems. J Environ Qual 32:269–277

Dijkstra J, Neal HD, Beever DE, France J (1992) Simulation of nutrient digestion, absorption and outflow in the rumen: model description. J Nutr 122:2239–2256

Doreau M, Ferlay A (1995) Effect of dietary lipids on nitrogen metabolism in the rumen: a review. Livest Prod Sci 43:97–110

Ellis JL, Kebreab E, Odongo NE, McBride BW, Okine EK, France J (2007) Prediction of methane production from dairy and beef cattle. J Dairy Sci 90:3456–3467

Ellis JL, Bannink A, France J, Kebreabz E, Dijkstra J (2010) Evaluation of enteric methane prediction equations for dairy cows used in whole farm models. Glob Change Biol. doi:10.1111/j.1365-2486.2010.02188.x

Erfle JD, Boila RJ, Teather RM, Mahadevan S, Sauer FD (1982) Effect of pH on fermentation and protein degradation by rumen microorganism in vitro. J Dairy Sci 65:1457–1464

Eshel G, Martin PA (2006) Diet, energy and global warming. Earth Interact 10:1–17

Food and Agriculture Organization of the United Nations (2006) Livestock a major threat to the environment: remedies urgently needed. Available: http://www.fao.org/newsroom/en/news/2006/1000448/index.html

Food and Agriculture Organization of the United Nations (2008) Accessed 24 Mar 2008. FAOSTAT

Food and Agriculture Organization of the United Nations (2009) Submission to UNFCCC AWG LCA, enabling agriculture to contribute to climate change. Available: http://unfccc.int/resource/docs/2008/smsn/igo/036.pdf).

Flesch TK, Wilson JD, Harper LA, Crenna BP, Sharpe RR (2004) Deducing ground-to-air emissions from observed trace gas concentrations: a field trial. J Appl Meteorol 43:487–502

Foley PA, Kenny DA, Callan JJ, Boland TM, O'Mara FP (2009) Effect of DL-malic acid supplementation on feed intake, methane emission, and rumen fermentation in beef cattle. J Anim Sci 87:1048–1057

Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW, Haywood J, Lean J, Lowe DC, Myhre G, Nganga J, Prinn R, Raga GMS, Van Dorland R (2007) Changes in atmospheric constituents and in radiative forcing. In: Solomon S et al (eds) Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Giger-Reverdin S, Vermorel M, Sauvant D (1992) Factors of variation of methane energy-loss in ruminants given compound feeds. Ann Zootech 41:37–38

Gleik PH, Adams RM, Amasino RM (2010) Climate change and the integrity of science. Science 328:689–691

Gold M, Porritt J (2004) The global benefits of eating less meat. A report for compassion in world farming trust, CIWF Trust, Petersfield, Hampshire, GU32 3EH, UK pp 1–76

Grainger C, Clarke T, McGinn SM, Auldist MJ, Beauchemin KA, Hannah MC, Waghorn GC, Clark H, Eckard RJ (2007) Methane emissions from dairy cows measured using the sulfur hexafluoride (SF_6) tracer and chamber techniques. J Dairy Sci 90:2755–2766

Gworgwor ZA, Mbahi TF, Yakubu B (2006) Environmental implications of methane production by ruminants: a review. J Sustain Dev Agr Env 2(1):1–14

Harper LA, Denmead OT, Freney JR, Byers FM (1999) Direct measurements of methane emissions from grazing and feedlot cattle. J Anim Sci 77:1392–1401

Hegarty RS (1999) Reducing rumen methane emissions through elimination of rumen protozoa. Aust J Agric Res 50:1321–1327

Hegarty RS (2001) Strategies for mitigating methane emissions from livestock—Australian options and opportunities. In: Proceeding of the 1st international conference on GHGes and animal agriculture. Obihiro, Hokkaido, pp 31–34

Hegarty RS (2002) Strategies for mitigating methane emissions from livestock—Australian options and opportunities. In: Takahashi J, Young BA (eds) GHGes and animal agriculture. Elsevier Science

Hegarty RS, Goopy JP, Herd RM, McCorkell B (2007) Cattle selected for lower residual feed intake have reduced daily methane production. J Anim Sci 85:1479–1486

Hristov AN, Ivan M, Rode LM, McAllister TA (2001) Fermentation characteristics and ruminal ciliate protozoal populations in cattle fed medium- or high-concentrate barley-based diets. J Anim Sci 79:515–524

Intergovernmental Panel on Climate Change (1997) Guidelines for national GHG inventories: workbook and reference manual. Agriculture (Chapter 4) and Waste (Chapter 6). OECD, Paris

Intergovernmental Panel on Climate Change (2001) Climate change 2001: the scientific basis. Cambridge University Press, Cambridge

Intergovernmental Panel on Climate Change (2006) IPCC guidelines for national GHG inventories. IGES, Hayama. http://www.ipccnggip.iges.or.jp

Intergovernmental Panel on Climate Change (2007) Climate change: synthesis report; summary for policymakers. Available: http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf

Jentsch W, Schweigel M, Weissbach F, Scholze H, Pitroff W, Derno M (2007) Methane production in cattle calculated by the nutrient composition of the diet. Arch Anim Nutr 61(1):10–19

Joblin KN (1999) Ruminal acetogens and their potential to lower ruminant methane emissions. Aust J Agric Res 50:1307–1313

Johnson KA, Johnson DE (1995) Methane emissions from cattle. J Anim Sci 73:2483–2492

Johnson DE, Ward GW, Ramsey JJ (1996) Livestock methane: current emissions and mitigation potential. Lewis Publishers, New York

Johnson DE, Phetteplace HW, Seidl AF (2002) Methane, nitrous oxide and carbon dioxide emissions from ruminant livestock production systems. In: Takahashi J, Young BA (eds) GHGes and animal agriculture. Proceeding of the 1st international conference on GHGes and animal agriculture, Obihiro, November 2001, pp 77–85

Jordan E, Lovett DK, Hawkins M, O'Mara FP (2004) The effect of varying levels of coconut oil on methane output from continental cross beef heifers. In: Proceeding of GHG emissions from agriculture—mitigation options and strategies, Leipzig

Kebreab E, Mills JAN, Crompton LA, Bannink A, Dijkstra J, Gerrits WJJ, France J (2004) An integrated mathematical model to evaluate nutrient partition in dairy cattle between animal and environment. Anim Feed Sci Technol 112:131–154

Kebreab E, Clarke K, Wagner-Riddle C, France J (2006) Methane and nitrous oxide emissions from Canadian animal agriculture—a review. Can J Anim Sci 86:135–158

Kebreab E, Johnson KA, Archibeque SL, Pape D, Wirth T (2008) Model for estimating enteric methane emissions from United States dairy and feedlot cattle. J Anim Sci 86:2738–2748

Kirchgessner M, Windisch W, Muller HL (1995) Nutritional factors for the quantification of methane production. In: Von Engelhardt W, Leonhard-Marek S, Breves G, Giesecke D (eds) Ruminant physiology: digestion, metabolism, growth and reproduction proceedings of the eighth international symposium on ruminant physiology. Stuttgart Ferdinand Enke Verlag, pp 333–348

Kirchgessner M, Windisch HJ, Muller HL, Kreuzer M (1991) Release of methane and of carbon-dioxide by dairy-cattle. Agribiol Res Agrarbiol Agrikulturchemie Okol 44:91–102

Kriss M (1930) Quantitative relations of the dry matter of the food consumed, the heat production, the gaseous outgo and the insensible loss in body weight of cattle. J Agric Res 40:283–295

Kumaraswamy S, Rath AK, Ramakrishnan B, Sethunathan N (2000) Wetland rice soils as sources and sinks of methane: a review and prospects for research. Biol Fertil Soils 31:449–461

Lana RP, Russell JB, Van Amburgh ME (1998) The role of pH in regulating ruminal methane and ammonia production. J Anim Sci 76:2190–2196

Lassey KR, Ulyatt MJ, Martin JR, Walker CF, Shelton DI (1997) Methane emissions measured directly from grazing livestock in New Zealand. Atmos Environ 31:2905–2914

Lassey KR (2007) Livestock methane emission: from the individual grazing animal through national inventories to the global methane cycle. Agric For Meteorol 142:120–132

Lassey KR (2008) Livestock methane emission and its perspective in the global methane cycle. Aust J Exp Agric 48:114–118

Laubach J, Kelliher FM (2004) Measuring methane emission rates of a dairy cow herd by two micrometeorological techniques. Agric For Meteorol 125:279–303

Leng RA (1991) Improving ruminant production and reducing methane emissions from ruminants by strategic supplementation, United States Environmental Protection Agency, Office of Air and Radiation, Washington DC, p 105

Leng RA (1993) Quantitative ruminant nutrition—a green house science. Aust J Agri Res 44:363–380

Lovett DK, Stack LJ, Lovell S, Callan J, Flynn B, Hawkins M, O'Mara FP (2005) Manipulating enteric methane emissions and animal performance of late-lactation dairy cows through concentrate supplementation at pasture. J Dairy Sci 88:2836–2842

Machmuller A, Ossowski DA, Wanner M, Kreuzer M (1998) Potential of various fatty feeds to reduce methane release from rumen fermentation in vitro (Rusitec). Anim Feed Sci Technol 77:117–130

Martin C, Rouel J, Jouany JP, Doreau M, Chilliard Y (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

Martin SA, Streeter MN (1995) Effect of malate on in vitro mixed ruminal microorganism fermentation. J Anim Sci 73:2141–2145

Mathison G (1997) Effect of canola oil on methane production in steers. Can J Anim Sci 77:545–546

Mathison GW, Okine EK, McAllister TA, Dong Y, Galbraith J, Dmytruk OIN (1998) Reducing methane emission from ruminant animals. J Appl Anim Res 14:1–28

Meadows DH, Meadows DL, Randers J (1992) Beyond the limits. Earthscan Publications Ltd, London

McCrabb GJ, Berger KT, Magner T, May C, Hunte RA (1997) Inhibiting methane production in Brahman cattle by dietary supplementation with a novel compound and the effects on growth. Austr J Agric Res 48:323–329

McGinn SM, Beauchemin KA, Coates T, Colombatto D (2004) Methane emissions from beef cattle: effects of monensin, sunflower oil, enzymes, yeast, and fumaric acid. J Anim Sci 82:3346–3356

McGinn SM, Flesch TK, Harper LA, Beauchemin KA (2006) An approach for measuring methane emissions from whole farms. J Environ Qual 35:14–20

McGinn SM, Beauchemin KA, Flesch TK, Coates T (2009) Performance of a dispersion model to estimate methane loss from cattle in pens. J Environ Qual 38:1796–1802

McMichael AJ, Powles JW, Butler CD, Uauy R (2007) Food, livestock production, energy, climate change, and health. The Lancet 370(9594):1253–1263

Mills JAN, Kebreab E, Yates CM, Crompton LA, Cammell SB, Dhanoa MS, Agnew RE, France J (2003) Alternative approaches to predicting methane emissions from dairy cows. J Anim Sci 81:3141–3150

Moe PW, Tyrrell HF (1979) Methane production in dairy cows. J Dairy Sci 62:1583–1586

Mosier A, Wassmann R, Verchot L, King J, Palm C (2004) Methane and nitrogen oxide fluxes in tropical agricultural soils: sources, sinks and mechanisms. Environ Dev Sustain 6:11–49

Moss AR, Givens DI, Garnsworthy PC (1995) The effect of supplementing grass silage with barley on digestibility, in sacco degradability, rumen fermentation and methane production in sheep at two levels of intake. Anim Feed Sci Tech 55:9–33

Moss AR, Jounany JP, Neevbold J (2000) Methane production by ruminants: its contribution to global warming. Ann Zootech 49:231–253

Nagaraja TG, Newbold CJ, Van Nevel CJ, Demeyer DI (1997) Manipulation of rumen fermentation. In: Hobson PN, Stewart CS (eds) The rumen microbial ecosystem. Blackie Academic and Professional Press, London, pp 523–632

Naqvi SMK, Sejian V (2011) Managemental strategies to reduce enteric methane emission. In: Sejian V, Naqvi SMK, Bhatt RS, Karim SA (eds) NAIP sponsored national training manual on carbon sequestration, carbon trading and climate change., Division of physiology and biochemistryCentral Sheep and Wool Research Institute, Avikanagar, pp 248–256

National Research Council (2001) Nutrient requirements of dairy cattle, 7th revised edn. National Academy Press, Washington

Neil PG, Bright KP, Sherlock RA (1997) Integrating legacy subsystem components into an object-oriented model, MODSIM 97—Proceedings of the international conference on modelling and simulation, modelling and simulation society of Australia, Hobart, pp 1133–1138

Newbold CJ, Ouda JO, Lopez S, Nelson N, Omed H, Wallace RJ, Moss AR (2002) Propionate precursors as possible alternative electron acceptors to menthane in ruminal fermentation. In: Takahashi J, Young BA (eds) GHGes and animal agriculture. Proceeding of the 1st international conference on GHGes and animal agriculture, Obihiro, November 2001, pp 151–154

Ogino A, Orito H, Shimada K, Hirooka H (2007) Evaluating environmental impacts of the Japanese beef cow–calf system by the life cycle assessment method. Anim Sci J 78(4):424–432

O'Mara F (2004) GHG production from dairying: reducing methane production. Adv Dairy Technol 16:295–309

Palliser CC, Woodward SL (2002) Using models to predict methane reduction in pasture fed dairy cows. Proceedings integrating management and decision support. Coordinated by Susan M. Cuddy (CSIRO, Australia) 482(1):162–167

Pinares-Patiño CS, Hour PD, Jouany JP, Martin C (2007) Effects of stocking rate on methane and carbon dioxide emissions from grazing cattle. Agric Ecosyst Environ 121:30–46

Pinares-Patiño CS, Machmüller A, Molano G, Smith A, Vlaming JB, Clark H (2008) The SF_6 tracer technique for measurements of methane emission from cattle—effects of tracer permeation rate. Can J Anim Sci 88:309–320

Puchala R, Min BR, Goetsch AL, Sahlu T (2005) The effect of a condensed tannin-containing forage on methane emission by goats. J Anim Sci 83:182–186

Robertson LJ, Waghorn GC (2002) Dairy industry perspectives on methane emissions and production from cattle fed pasture or total mixed rations in New Zealand. Proc NZ Soc Anim Prod 62:213–218

Rotz CA, Corson MS, Coiner CU (2007) Integrated farm system model: reference manual. Pasture systems and watershed management research unit, USDA Agricultural Research Service. University Park, PA. Available: http://www.ars.usda.gov/Main/docs.html?docid=8519

Rotz CA, Corson MS, Chianese DS, Coiner CU (2009) The integrated farm system model: reference manual. USDA-ARS Pasture Systems and Watershed Management Research Unit. University Park, PA. Available: www.ars.usda.gov/SP2UserFiles/Place/19020000/ifsmreference

Rotz CA, Montes F, Chianese DS (2010) The carbon footprint of dairy production systems through partial life cycle assessment. J Dairy Sci 93(3):1266–1282

Saa CF, Hill TM, Johnson DE (1993) Persistance of methane suppression by ionophore and glycopeptide in steers fed a brome hay diet. CSU Beef Programe Report

Sejian V (2012) Climate change, green house gas emission and sheep production. In: Shinde AK, Swarnkar CP, Prince LLL (eds) Status papers on future research in sheep production and production development, 50 years research contributions (1962–2012). Director, Central Sheep and Wool Research Institute, Avikanagar, pp 155–178

Sejian V, Saumya B (2011) Enteric methane emissions in livestock: contributors, prediction, estimations and repercussion. In: Sejian V, Naqvi SMK, Bhatt RS, Karim SA (eds) NAIP sponsored national training manual on “Carbon sequestration, carbon trading and climate change”., Division of physiology and biochemistryCentral Sheep and Wool Research Institute, Avikanagar, pp 68–80
Sejian V, Rajni C (2011) Modeling of green house gases in livestock farms. In: Sejian V, Naqvi SMK, Bhatt RS, Karim SA (eds) NAIP sponsored national training manual on “Carbon sequestration, carbon trading and climate change”., Division of physiology and biochemistryCentral Sheep and Wool Research Institute, Avikanagar, pp 178–190
Sejian V, Singh AK (2011) In vitro gas production model (bioreactor model) and dairy GHG model to predict GHG emission from livestock farm. In: Sejian V, Naqvi SMK, Bhatt RS, Karim SA (eds) NAIP sponsored national training manual on “Carbon sequestration, carbon trading and climate change”., Division of physiology and biochemistryCentral Sheep and Wool Research Institute, Avikanagar, pp 295–301
Sejian V, Naqvi SMK (2011a) Enteric methane emissions. In: Training manual on NAIP national training on “Climate change carbon sequestration and carbon credits” at Indian Institute of Soil Science (ICAR), Nabi Bagh, Bhopal, pp 73–89
Sejian V, Naqvi SMK (2011b) Mitigation strategies to reduce methane production from livestock. In: Training manual on NAIP national training on “Climate change carbon sequestration and carbon credits” at Indian Institute of Soil Science (ICAR), Nabi Bagh, Bhopal, pp 90–105
Sejian V, Indu S (2011) Salient mitigation strategies to reduce enteric methane emission from livestock. In: Sejian V, Naqvi SMK, Bhatt RS, Karim SA (eds) NAIP sponsored national training manual on “Carbon sequestration, carbon trading and climate change”., Division of physiology and biochemistryCentral Sheep and Wool Research Institute, Avikanagar, pp 118–131
Sejian V, Naqvi SMK, Bhatt RS, Karim SA (2011a) Carbon sequestration, carbon trading and climate change. Director, Central Sheep and Wool Research Institute, Avikanagar, pp 1–324
Sejian V, Lal R, Lakritz J, Ezeji T (2011b) Measurement and prediction of enteric methane emission. Inter J Biometeorol 55:1–16
Sejian V, Rotz A, Lakritz J, Ezeji T, Lal R (2011c) Modeling of green house gas emissions in dairy farms. J Anim Sci Adv 1(1):12–20
Sejian V, Lakritz J, Ezeji T, Lal R (2011d) Forage and flax seed impact on enteric methane emission in dairy cows. Res J Vet Sci 4(1):1–8
Sherlock RA, Bright KP, Neil PG (1997) An object-oriented simulation model of a complete pastoral dairy farm, MODSIM 97—Proceedings of the international conference on modelling and simulation, Modelling and Simulation Society of Australia, Hobart, pp 1154–1159
Sherlock RA, Bright KP (1999) An object-oriented framework for farm system simulation, MODSIM 99—Proceedings of the international conference on modelling and simulation, Modelling and Simulation Society of Australia and New Zealand, Hamilton, pp 783–788
Shu Q, Gill HS, Hennessy DW, Leng RA, Bird SH, Rowe JB (1999) Immunisation against lactic acidosis in cattle. Res Vet Sci 67:65–71
Steinfeld H, Gerber P, Wassenaar T, Castel V, Rosales M, de Haan C (2006) Livestock’s long shadow: environmental issues and options. Food and Agriculture Organization of the United Nations, Rome
Tamminga S (1996) A review on environmental impacts of nutritional strategies in ruminants. J Anim Sci 74:3112–3124
Tedeschi LO, Fox DG, Tylutki TP (2003) Potential environmental benefits of ionophores in ruminant diets. J Environ Qual 32:1591–1602
Ulyatt MJ, Lassey KR (2001) Methane emissions from pastoral systems: the situation in New Zealand. Arch Latinoam Prod Anim 9(1):118–126
United States Environmental Protection Agency (1993) Anthropogenic methane emissions in the United States. Estimates for 1990: report to congress. Atmospheric Pollustatestion Prevention Division, Office of Air and Radiation, Washington DC

United States Environmental Protection Agency (1994) International anthropogenic methane emissions: estimates for 1990, office of policy planning and evaluation, Washington DC, EPA 230-R-93-010.94

Vlaming JB, Brookes IM, Hoskin SO, Pinares-Patiño CS, Clark H (2007) The possible influence of intra-ruminal sulfur hexafluoride release rates on calculated methane emissions from cattle. Can J Anim Sci 87:269–275

Waghorn GC, Tavendale MH, Woodfield DR (2002) Methanogenesis from forages fed to sheep. Proc NZ Grassl Assoc 64:167–171

Wenk C (2003) Herbs and botanicals as feed additives in monogastric animals. Asian Austral J Anim Sci 16:282–289

World Health Organization (2009) Department of health statistics and health information systems, world health statistics

Wuebbles DJ, Hayhoe K (2002) Atmospheric methane and global change. Earth Sci Rev 57:117–210

Yan T, Agnew RE, Gordon FJ, Porter MG (2000) Prediction of methane energy output in dairy and beef cattle offered grass silage based diets. Livest Prod Sci 64:253–263

Yan T, Mayne S, Porter MG (2006) Effects of dietary and animal factors on methane production in dairy cows offered grass silage-based diets. Int Cong Ser 1293:123–126

Yang SS, Liu CM, Liu YL (2003) Estimation of methane and nitrous oxide emission from animal production sector in Taiwan during 1990–2000. Chemosphere 52:1381–1388

Yates CM, Cammell SB, France J, Beever DE (2000) Prediction of methane emissions from dairy cows using multiple regression analysis. Proc Br Soc Anim Sci 2000:94

Yoon IK, Stern MD (1995) Influence of direct-fed microbials on ruminal fermentation and performance of ruminants: a review. Asian Austral J Anim Sci 8:533–555