Published December 11, 2014

Methane Emissions from Cattle

K. A. Johnson* and D. E. Johnson†

Departments of Animal Science, *Washington State University, Pullman 99164 and †Colorado State University Fort Collins, 48824

ABSTRACT: Increasing atmospheric concentrations of methane have led scientists to examine its sources of origin. Ruminant livestock can produce 250 to 500 L of methane per day. This level of production results in estimates of the contribution by cattle to global warming that may occur in the next 50 to 100 yr to be a little less than 2%. Many factors influence methane emissions from cattle and include the following: level of feed intake, type of carbohydrate in the diet, feed processing, addition of lipids or ionophores to the diet, and alterations in the ruminal microflora. Manipulation of these factors can reduce methane emissions from cattle. Many techniques exist to quantify methane emissions from individual or groups of animals. Enclosure techniques are precise but require trained animals and may limit animal movement. Isotopic and nonisotopic tracer techniques may also be used effectively. Prediction equations based on fermentation balance or feed characteristics have been used to estimate methane production. These equations are useful, but the assumptions and conditions that must be met for each equation limit their ability to accurately predict methane production. Methane production from groups of animals can be measured by mass balance, micrometeorological, or tracer methods. These techniques can measure methane emissions from animals in either indoor or outdoor enclosures. Use of these techniques and knowledge of the factors that impact methane production can result in the development of mitigation strategies to reduce methane losses by cattle. Implementation of these strategies should result in enhanced animal productivity and decreased contributions by cattle to the atmospheric methane budget.

Key Words: Cattle, Methane, Global Warming

J. Anim. Sci. 1995. 73:2483–2492

Introduction

Cattle typically lose 6% of their ingested energy as eructated methane. Animal science nutrition research has focused on finding methods to reduce methane emissions because of its inefficiency not because of the role of methane in global warming. However, because methane can affect climate directly through its interaction with long-wave infrared energy and indirectly through atmospheric oxidation reactions that produce CO_2, a potent greenhouse gas, more recent attention has been given to its potential contribution to climatic change and global warming. Recent measurements of methane trapped in polar ice showed atmospheric concentrations of methane remained relatively stable at approximately 750 ppb until nearly 100 yr ago when concentrations began to rise to present levels of approximately 1,800 ppb (Khalil et al., 1993). The more than 500 Tg (1 Tg = 1 million metric tons) of methane that enters the atmosphere annually exceeds its atmospheric and terrestrial oxidation (IPCC, 1992). At this rate, methane is expected to cause 15 to 17% of the global warming over the next 50 yr (IPCC, 1992). This excess methane has led to several examinations of its sources.

Methane sources are fairly well established (Table 1), but the relative and absolute sizes of the various sources are open to question (Cicerone and Oremland, 1988). Very recent radiocarbon [^{14}C–] isotope measurements on atmospheric methane indicate that between 20 and 30% is of fossil origin. Sources contributing old carbon include 1) gas drilling, venting, and distribution; 2) mining; and 3) wetland emissions that contain carbon that has been stored for several thousand years. The remaining 70 to 80% of atmospheric carbon is derived from sources that yield contemporary carbon: enteric fermentation (animals and insects), natural wetlands, biomass burning, oceans and lakes, rice production, and waste treatment (landfills, sewage, etc.). The world's 1.3 billion

[1]Presented at a symposium entitled "Impact of Methane Emissions from Beef Cattle on the Environment" at the 1994 ASAS/ADSA Annu. Mtg., Minneapolis, MN. Washington State University, Pullman, Agric. Res. Sta., project no. 0918; paper no. 8101.

Received October 20, 1994.

Accepted March 9, 1995.

Table 1. Recent estimates of the principal natural and anthropogenic global methane sources, Tg/yr[a]

Natural		Energy/refuse		Agricultural	
Wetlands	115	Gas and Oil	50	Rice	60
Oceans	15	Coal	40	Livestock	80
Termites	20	Charcoal	10	Manure	10
Burning	10	Landfills	30	Burning	5
		Wastewater	25		
	160		155		165

[a]Adapted from IPCC (1992). Most authorities estimate total global production to be between 500 and 550 Tg/yr. These estimates reflect entry into the atmosphere. Tg = 1 million metric tons.

cattle account for some 73% of the 80 Tg of methane produced by livestock worldwide each year (Gibbs and Johnson, 1994). Within each of these categories, the range of estimates for a specific source can easily vary by a factor of two and in some cases by as much as 10.

The contribution by cattle to any global warming that may occur in the next 50 to 100 yr has been estimated to be a little less than 2%. Very different views of the importance of the contribution of ruminants to global warming are offered by groups espousing different political, economic and ecological philosophies. The Clinton administration has directed the USDA and the United States EPA to return United States greenhouse gases to 1990 levels by the year 2000 (Clinton and Gore, 1993). This mandate translates into a 6% reduction in methane emissions from ruminant sources. It is thought that reductions in methane emissions are possible and desirable because methane has a major warming capacity, a short atmospheric half-life, and distinct and concentrated sources.

The collateral environmental and economic benefits to the livestock industry and to society of decreasing livestock methane emissions make examination of the factors impacting methane production important. The development and implementation of feeding and management strategies to reduce methane emissions and increase the efficiency of dietary energy use will not only reduce the contribution of livestock to the atmospheric methane budget but will also enhance production efficiency.

Discussion

Variation in Cattle Methane Emissions

Eructation of methane by cattle begins approximately 4 wk after birth when solid feeds are retained in the reticulorumen (Anderson et al., 1987). Fermentation and methane production rates rise rapidly during reticulorumen development. Estimates of yearly methane production of the typical beef and dairy cow range from 60 to 71 kg and 109 to 126 kg, respectively (EPA, 1993). Measurements made by indirect respiration calorimetry (Figure 1) show methane losses vary from approximately 2 to nearly 12% of GE intake (Johnson et al., 1993b). Generally, as diet digestibility increases, variability in methane loss also increases. There are two primary mechanisms that cause this variation in methane production.

The first is the amount of dietary carbohydrate fermented in the reticulorumen. This mechanism has many diet-animal interactions that affect the balance between the rates of carbohydrate fermentation and passage. A second mechanism regulates the available hydrogen supply and subsequent methane production through the ratio of VFA produced. Principally, the fraction of propionic acid that is produced relative to acetic acid has a major impact on methane production. If the acetic:propionic acid is .5, the loss of substrate energy as methane would be 0%. If all carbohydrate is fermented to acetic acid and no propionic acid is produced, energy loss as methane would be 33% (Wolin and Miller, 1988). Because acetic:propionic acid typically varies from approximately .9 to 4, corresponding methane losses vary widely as well. Methane production can also be affected when there are significant alternative hydrogen sinks. These alternative sinks are usually relatively minor but can include oxygen, unsaturated fatty acids, nitrates, sulfates, and microbial growth.

Published research on animal methane losses describe many factors that have their effects through one or more of these mechanisms. These factors include feed intake, type of carbohydrate, forage processing, lipid addition, and manipulation of ruminal microflora including the use of ionophores.

Level of Intake. As the daily feed eaten by any given animal increases, the percentage of dietary GE lost as methane decreases by an average of 1.6% per level of intake (Johnson et al., 1993b). Efforts to use statistical relationships to predict this decline in methane production with increased intake have largely failed (e.g., Blaxter and Clapperton, 1965) and limit extrapolations from laboratory to field situations. When highly available carbohydrates are fed at limited intakes, high fractional methane losses occur. At high intakes of highly digestible diets, low fractional methane losses occur.

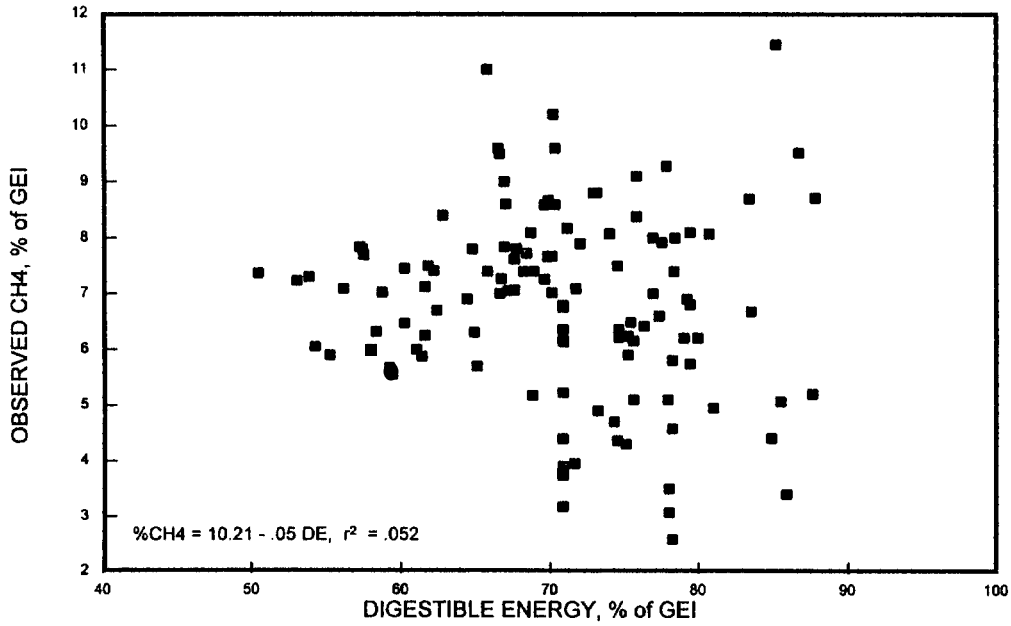

Figure 1. Methane production, percentage of gross energy (GE) intake, vs digestible energy, percentage of GE intake. (Treatment means, n = 118; Johnson et al., 1992). Reprinted with permission of Springer-Verlag New York.

Carbohydrate Type. The type of carbohydrate fermented influences methane production most likely through impacts on ruminal pH and the microbial population. Fermentation of cell wall fiber yields higher acetic:propionic acid and higher methane losses (Moe and Tyrrell, 1979; Beever et al., 1989). Moe and Tyrrell (1979) found fermentation of soluble carbohydrate to be less methanogenic than cell wall carbohydrates. Our recent regression analysis of literature data with beef cattle agrees with the idea that digested cell wall leads to higher methane loss, but suggests that non-cell wall components should be further separated into soluble sugars, which are more methanogenic than starch (Torrent et al., unpublished data). Additionally, as a greater amount of any carbohydrate fraction is fermented per day, whether it is fiber or starch, methane production is decreased. This observation was confirmed by direct measurements of methane production by steers fed beetpulp, a highly digestible fiber source. Methane losses with high intakes of beetpulp fell to 4 to 5% of GE intake (Kujawa, 1994). Additionally, the fermentation of brewery and distillery products containing relatively available fiber results in a surprisingly low methane production, generally one-half to one-third of that seen with common feedstuffs of comparable digestibility (Wainman et al., 1984).

The very high grain diets (90+ % concentrate) commonly fed in U.S. feedlots result in strikingly different methane loss rates than are commonly predicted. Considerable variation is found among diets, but typical losses frequently fall between 2 to 3% of GE (Abo-Omar, 1989; Carmean, 1991; Hutcheson, 1994). This loss rate is approximately one-half of the commonly predicted 6% of diet GE lost as methane.

Forage Processing. Grinding and pelleting of forages can markedly decrease methane production (Blaxter, 1989). These effects are not apparent when intakes of these diets are restricted, however. At high intakes, methane loss/unit of diet can be reduced 20 to 40%. Increased rate of passage of the ground or pelleted forage likely contributes to the reduced methane production. Okine et al. (1989) reported a significant reduction in methane production (29%) when weights were added to the rumen. Methane production was reduced from 189 to 135 L/d with no change in digestibility. When regression equations were fitted to the data, 28 and 25% of the variation in methane production were related to ruminal particulate passage rate and fluid dilution rates, respectively. Ammoniation (Birkelo et al., 1986) or protein supplementation of low-quality forages will increase the methane losses proportional to the improvement in digestibility. It should be noted, however, that overall methane losses per unit of product (maintenance, lactation, or growth) would be decreased.

Lipid Additions. Fat additions to ruminant diets impact methane losses by several mechanisms, including biohydrogenation of unsaturated fatty acids, enhanced propionic acid production, and protozoal inhibition. Czerkawski et al. (1966) demonstrated that addition of long-chain polyunsaturated fatty acids decreased methanogenesis by providing an alternative metabolic hydrogen acceptor to reduction of CO_2. However, the amount of total metabolic hydrogen used

in the biohydrogenation process of endogenous unsaturated fatty acids is small (1%) compared with that used for reduction of CO_2 to methane (48%), VFA synthesis (33%), and bacterial cell synthesis (12%; Czerkawski, 1986). Sheep or cattle fed supplemental fat sources such as animal tallow or soybean oil had decreased methane production compared with controls fed isocaloric diets (Swift et al., 1948; Haaland, 1978; Van der Honing et al., 1981). The reduction in methane production in these studies was attributed to decreased fermentable substrate rather than to a direct effect on methanogenesis. The methane reduction effects are likely to be dramatic only when basal digestion is inhibited, such as the 29% reduction in methane found by Park et al. (1994). In this experiment, the addition of 6% of a dry powdered fatty-acid supplement to a 60% concentrate diet also marginally decreased organic matter digestion.

Ionophore Addition. Ionophore additions to beef cattle diets, particularly monensin, reduces feed intake 5 to 6%, decreases acetic:propionic acid and decreases methane losses (Goodrich et al., 1984). The decrease in methane production ranges from slight to approximately 25% (Benz and Johnson, 1982; Garrett, 1982; Wedegaertner and Johnson, 1983). However, recent investigations indicate that the decrease in methane production is short-lived (Rumpler et al., 1986; Abo-Omar, 1989; Carmean, 1991; Saa et al., 1993). Methane production per unit of diet by cattle fed either grain or forage diets returned to initial levels within 2 wk. The ability of the ruminal microflora to adapt to feed additives was seen in earlier examinations of methane suppression by addition of chloralhydrate to sheep diets. Initially, methane production was reduced by 64%, but within 30 d the methane production returned to near control levels (Johnson, 1974). Therefore, the reduction seen in methane production by ionophore supplemented cattle is likely to be related to the reduction in feed intake and not a direct effect on methanogenesis.

Microbial Flora Alterations. Ruminal protozoa may also play an important role in methane production, particularly when cattle are fed high-concentrate diets. Ruminal methanogens have been observed attached to protozoal species suggesting possible interspecies hydrogen transfer (Stumm et al., 1982). Defaunation of the rumen of cattle fed a barley diet decreased methane production by approximately one-half (Whitelaw et al., 1984). However, defaunation of animals receiving high-forage diets (Itabashi et al., 1984) did not reduce methane losses.

An alternative to methanogenesis is autotrophic acetogenesis, a hydrogen disposal mechanism that occurs in the gut of some termites, rodents, and humans (Lajoie et al., 1988; Breznak and Kane, 1990). At least three different acetogenic bacterial species have been isolated from the rumen of cattle (Greening and Leedle, 1989). Although these species possess the ability to reduce CO_2 to acetate, they also have the ability to utilize other substrates including formate, glucose, cellobiose, and fructose (Greening and Leedle, 1989; Dore and Bryant, 1990). Despite the presence of these organisms in the rumen, little autotrophic acetogenic activity can be found in fresh ruminal contents. There is evidence however, that autotrophic acetogenesis occurs in the lower gut of some individual ruminants (Torrent, 1994).

In spite of the variability in the amount of methane lost (as a percentage of dietary GE intake) that has been documented to occur in beef cattle, common commercial situations may not deviate much from 6% methane losses. Extrapolation from chamber measurements to typical diets at common levels of intake that occur across U.S. beef cattle herds (Table 2) suggest methane losses vary from approximately 5.8 to 6.5% of GE for all categories and classes except for the unique high grain feedlot situation in which typical methane loss may drop to approximately 3% (Johnson et al., 1993a). The implication for most of the world is that the best strategy for mitigation of cattle methane is likely to be enhancing the efficiency of feed energy use. Assuming a constant percentage of methane loss, this strategy will decrease methane loss per unit of product and likely decrease methane emissions by cattle over the long term.

Measurement of Methane

To develop strategies to mitigate livestock methane emissions, it must be possible to quantify cattle emissions under a wide range of circumstances. This objective may be accomplished using many different techniques ranging from short-term expired air samples to more elaborate chamber systems. Incumbent with any of these techniques is the need to determine methane concentrations. Methane may be measured using infrared spectroscopy, gas chromatography, mass spectroscopy, and tunable laser diode techniques.

In general, infrared analyzers measure methane in the 0- to 500-ppm range, although most manufacturers can customize the analyzer to either attenuate or extend this range. These analyzers measure methane concentration in a steady gas stream. A detailed discussion of the analytical principles involved with infrared analyzers may be found in McLean and Tobin (1987).

Methane may be measured using gas chromatographs equipped with thermal conductivity or flame ionization detectors (Steele et al., 1987). In both cases, quantification of methane is accomplished by comparing the peak height and retention time of the sample to standards of known concentration. Gas chromatography is highly accurate and precise.

Mass spectrometers may also be used to measure methane concentrations. These instruments have very rapid response times and can detect many gases at

Table 2. Projected methane emissions from the 1992 U.S. cattle herd by class[a]

Class	Avg. no.[b] million	Loss %	Liveweight In	Liveweight Out	Days	DMI[c], kg/d	Methane loss %	Methane loss Tg/yr
Beef								
Cows	33.83	0	450	450	365	8.9	6.2	2.29
Births	30.87	22	—	—	—	—	—	—
Calves	29.33	10	36	215	210	1.2	6	.15
Stocker	27.51	2	215	315	150	6.2	6.5	.56
Replacement hfr[d]	5.93	6	315	410	365	7.8	6.5	.37
Bulls	2.28	0	700	700	365	11.8	6	.20
Fed-hfr	6.97	1.5	300	480	140	8.2	3.5	.09
Fed-str	12.48	1.5	330	525	140	8.8	3.5	.18
Fed-import	1.94	—	—	—	140	8.8	3.5	.03
Not fed[e]	.94	—	—	—	—	—	—	—
							Total beef	3.87
Dairy								
Cows	9.85	0	700	650	365	17.1	5.8	1.2
Replacement hfr	4.35	5	330	500	365	8.7	6.5	.30
Stocker Repl. hfr	4.48	1	220	330	150	6.3	6.5	.09
Calf Replacement	4.90	15	45	220	210	3.8	6	.08
							Total dairy	1.67
Dairy beef								
Calf-str	4.23	15	45	230	210	3.8	6	.07
Calf-hfr	.70	15	42	210	210	3.8	6	.01
Stocker-str	3.87	1	230	345	150	6.4	6.5	.08
Stocker-hfr	.64	1	210	315	150	6.3	6.5	.01
Fed-str	3.82	1.5	345	535	140	9.8	3.5	.06
Fed-hfr	.63	1.5	315	490	140	9.2	3.5	.01
							Total dairy beef	.24
							U.S. Total	5.78

[a]Adapted from Johnson, 1992.
[b]Average number in millions, calculated as follows: (Beginning and ending numbers in class)/2.
[c]DMI = Dry matter intake.
[d]Yearling replacement heifers, 17% for beef and 43% for dairy.
[e]Deleted from inventory after stocker phase.

one time. They exhibit linear responses over a wide range of concentrations and are very accurate and stable (McLean and Tobin, 1987). However, mass spectrometers are expensive and in many cases exceed the cost of other adequate analyzers. Methane may also be measured using a tunable laser diode but as with mass spectroscopy expense may limit their usefulness for measurement of ruminal methane (Harper et al., 1993).

Methane Sampling. There are many options available by which methane emissions from ruminants may be measured. Sampling of individual or group gaseous emissions may be accomplished using enclosure techniques or tracer methods. Selection of a technique is dependent on the question asked as each technique has its strengths and weaknesses. Screening of mitigation strategies may be best evaluated using individual animals before large scale tests on herds of animals are conducted.

Individual Animal Techniques

Enclosure Techniques. Respiration calorimetry techniques such as whole animal chambers, head boxes, or ventilated hoods and face masks have been used effectively to collect most of the available information concerning methane emissions from cattle. The principle behind open-circuit indirect-respiration techniques is that outside air is circulated around the animal's head, mouth, and nose and expired air collected (McLean and Tobin, 1987). Methane emissions are determined by measuring the total air flow through the system and the difference in concentration between inspired and expired air.

Whole animal open-circuit indirect-respiration chamber systems may be elaborate, highly computerized systems, although simple systems work just as well. The chamber itself must be well sealed and capable of a slight negative pressure. The negative pressure ensures that all leaks will be inward and not result in a net loss of methane. Some degree of animal restraint is necessary within the chamber but animal movement and normal behavior should be provided for as much as possible. In order to create a comfortable environment within the chamber, air conditioning, dehumidification, feeders, waterers, and a method by which feces and urine can be removed are necessary. Descriptions of various types and designs of whole animal chamber systems are found throughout the literature (Flatt et al., 1958; Kleiber, 1958a; McLean

and Tobin, 1987; Cammell et al., 1980; Johnson, 1986; Miller and Koes, 1988). Major advantages to the use of whole animal chambers include the ability to make accurate measurements of emissions from cattle including methane from ruminal and hindgut fermentation. Disadvantages to this technique include the expense associated with construction and maintenance of the chambers, the restriction of animal movement and the high labor input for animal training that may limit the number of animals that can be measured.

A ventilated hood, or headbox, can also be used to quantify methane emissions using the same principles. This technique involves the use of an air-tight box that surrounds the animal's head. The box is big enough to allow the animal to move its head in an unrestricted manner and allows access to feed and water. A sleeve or drape is placed around the neck of the animal to minimize air leakage. The relatively lower cost of the headbox system as compared to a whole animal chamber is the primary advantage to this technique. As with the chamber, use of a hood also requires a restrained and trained animal. Another disadvantage is the inability to measure all hindgut methane. Descriptions of hood systems may be found in Young et al. (1975), McLean and Tobin (1987), and Kelly et al. (1994).

Face masks may also be used to quantify methane production (Kleiber, 1958b; Liang et al., 1989). The principle behind the use of the face mask is the same as that of the chamber and hood. The disadvantages of this method are numerous because it requires subject cooperation and eliminates the animal's ability to eat and drink. The latter disadvantage precludes making meaningful methane emission measurements because of the normal daily variation in emissions. Short-term measurements should be avoided as much as possible. The face mask, compared with chamber methods, underestimates heat production and likely methane as well by an average of 9% (Liang et al., 1989).

Tracer Techniques. Both isotopic and non-isotopic tracer techniques are available to determine methane production from ruminants. Isotopic methods involve the use of [^{3}H–] methane or [^{14}C–] methane and ruminally cannulated animals (Murray et al., 1975, 1976). Using the continuous infusion technique, infusion lines deliver the labeled gas to the ventral rumen and sampling of gas takes place in the dorsal rumen. Alternatively total expired methane can be collected using the enclosure techniques mentioned previously. After determination of the specific activity of the radiolabeled methane gas, total methane production can be calculated. It is also possible to measure methane production from a single dose injection of tracer (France et al., 1993). Depending on the degree of description desired, various mathematical models are available to estimate methanogenesis in various compartments of the rumen. France et al. (1993) describes models for up to three and higher methane pools. Isotopic tracer techniques generally require straightforward simple experimental designs and relatively straightforward calculations, at least for the lower number pools. The major limitation when using isotopic tracers is the difficulty in preparation of the infusion solution because of the low solubility of methane gas.

Non-isotopic tracer techniques are also available for measurement of methane production. Johnson et al. (1994) described a technique using sulfur hexafluoride (SF_6), an inert gas tracer, placed in the rumen. The release rate of the gas from a permeation tube is known before its insertion into the rumen. A halter fitted with a capillary tube is placed on the animal's head and connected to an evacuated sampling canister. As the vacuum in the sampling canister slowly dissipates a steady sample of the air around the mouth and nose of the animal is taken. By varying the length and diameter of the capillary tube the duration of sampling may be regulated. After collection of a sample the canister is pressurized with nitrogen, and methane and SF_6 concentrations are determined by gas chromatography. Methane emission rate is calculated as follows: $QCH_4 = QSF_6 \times [CH_4]/[SF_6]$; where QCH_4 is the emission rate of methane in liters/hour, QSF_6 is the known release rate of SF_6 from the permeation tube, $[CH_4]$ and $[SF_6]$ are the measured concentrations in the canister.

This technique eliminates the necessity to restrain or enclose the animal, thus allowing the animal to move about and graze. It is also not necessary to sample directly from the animal's rumen or throat because the use of the tracer accounts for changes in dilution associated with head or air movement. However, it is necessary to train the animal to wear a halter and collection canister. This tracer technique does not measure all of the hindgut methane. Any methane from the hindgut that is absorbed into the blood stream will be expired and collected but any methane that escapes absorption and is released from the rectum is not collected.

Prediction Equations. There are essentially three major methods by which methane production may be estimated that do not rely on individual animals. In vitro incubation is one of these methods (Hoover et al., 1976; Czerkawski and Breckenridge, 1977; Merry et al., 1987). However, despite the value of using in vitro techniques as screening devices, it is difficult to extrapolate in vitro methane production rates to the cow.

Wolin (1960) derived a method by which methane emissions may be calculated from the molar distribution of VFA. The fermentation balance has been used extensively to predict methane production from the conversion of dietary carbohydrate to VFA (Czerkawski, 1986). These relationships are very useful for comparing different diets as long as the assumptions implicit within the equations are understood. These

assumptions are as follows: all excess hydrogen is found in methane, there is no hydrogen associated with microbial cell synthesis, and no VFA results from the fermentation of non-carbohydrate substrate. Certainly these assumptions are open to criticism as Wolin discussed; however, fermentation balance is a useful technique for comparative purposes.

Feed characteristics may also be used to calculate methane production. The Blaxter and Clapperton (1965) equation is the basis from which most all estimates of methane production from ruminants have been derived. The relationship was derived from a series of methane production measurements from mature sheep fed a range of diets. Methane, in kcal/100 kcal of GE, is predicted from the digestibility of GE and intake relative to maintenance. Figure 2 illustrates a comparison of actual methane measurements and those predicted by the Blaxter and Clapperton equation (Johnson et al., 1993b). As illustrated, Blaxter and Clapperton predict methane to range from 6 to 10% with most points in the 6 to 8% range. Actual methane measurements ranged from 2 to 11%. Therefore, some care should be taken in using this relationship.

Moe and Tyrrell (1979) proposed another equation that incorporated actual feed characteristics, which is an improvement on the Blaxter and Clapperton equation. The relationship was derived from measurements made from cattle fed high-quality dairy rations and relates soluble residue, hemicellulose, and cellulose to methane production. CH_4 = 3.406 + .510 (soluble residue) + 1.736 (hemicellulose) + 2.648 (cellulose): where CH_4 is in megajoules/day and soluble residue, hemicellulose, and cellulose in kilogram fed/day (R^2 = .67). The accuracies of seven published equations for predicting methane production from dairy cattle were recently examined (Wilkerson et al., 1994) and indicate the Moe and Tyrrell (1979) equation containing descriptors of dietary carbohydrate intake resulted in the lowest absolute error of prediction within their range of dairy cattle diets. The variables most effective in accurately predicting methane production include the digestibilities of fiber components such as cellulose, hemicellulose, and neutral detergent solubles (Holter and Young, 1992; Kirchgessner et al., 1994; Wilkerson et al., 1994). These equations may become useful tools because the feed characteristics needed to predict methane are measurable in some production situations. However, it is unlikely that a simple equation based on feed characteristics will accurately predict methane production under all perturbation conditions.

Groups of Animals

Group dynamics can impact animal dietary consumption or selection and thus methane production under common production situations. Measurements of methane emissions from groups of animals may be made using mass balance, micrometeorological, or tracer methods.

Mass Balance Techniques. This approach involves measuring the difference in methane concentration

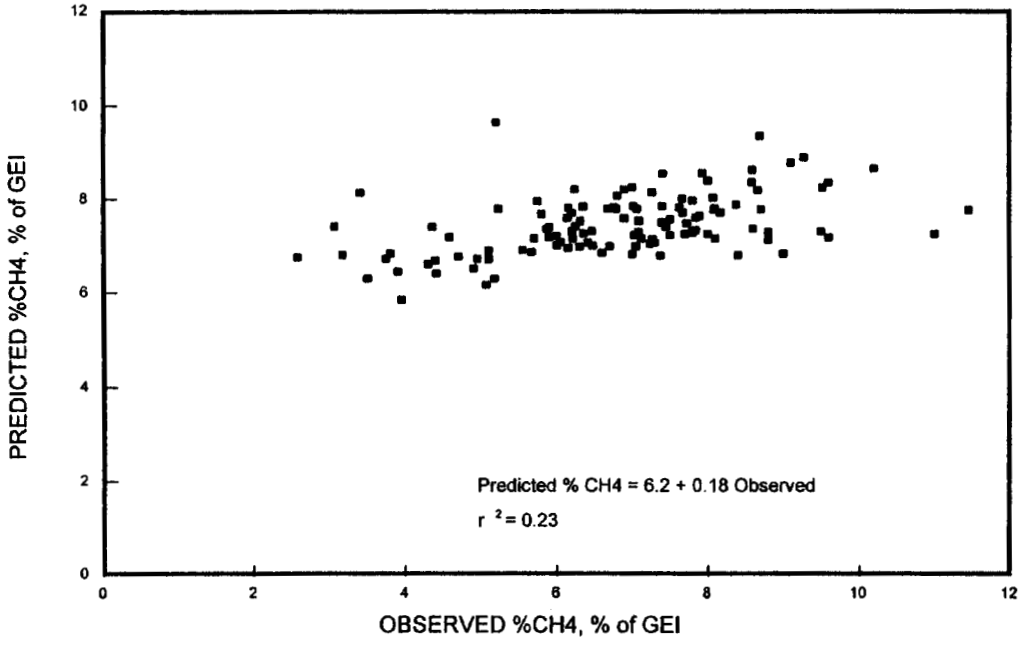

Figure 2. Observed methane production, percentage of gross energy (GE) intake, vs methane production predicted using the Blaxter and Clapperton equation (1965), percentage of GE intake. (Treatment means, n = 452; Johnson et al., 1993b).

coming into and exiting from a group of cattle. The enclosure can be a building or fenced pen. Emissions of methane are calculated from the volume of the air flow through the enclosure and net concentration of methane.

In building studies, air flow is quantified by either measuring the air flow rate through exhaust vents using anemometers or by employing a tracer gas (Persily, 1988; Howard, 1991). The total air flow through a building can be measured by releasing the tracer at a constant known rate and allowing the concentration to build to a steady state. When the tracer is well mixed, the amount leaving the building is equal to the amount being released and the air flow through the building can be calculated. Measurements of methane and carbon dioxide from indoor cattle, swine, and poultry production facilities have been made using the methods outlined above (Westberg et al., 1990).

Mass balance procedures can be used in outdoor enclosures if certain measurement constraints are met. Cattle must be placed in an enclosure that allows integration of methane concentrations across the vertical planes for incoming and outgoing air. Enclosure methane cannot escape out the top of the enclosure box. Thus, downwind boundary measurements must be made to heights approximately 20% the horizontal length of the pasture. In this case, the air flow term is determined by conventional meteorological methods. Recently, Harper et al. (1993) reported a new methodology to measure CH_4 emissions using a mass balance approach.

Micrometerological Methods. Eddy correlation, eddy accumulation, and gradient methods can be employed to measure methane emissions from cattle in a pasture (Lenshaw and Hicks, 1987; Andreae and Schimel, 1989). Eddy correlation techniques for methane require expensive equipment, a sonic anemometer, and a fast-response methane sensor (laser). A sonic anemometer is needed for relaxed eddy accumulation measurements but the methane analysis device could be a conventional gas chromatograph. The gradient method uses meteorological sensors to derive a vertical diffusitivity constant and the measurement of methane at two vertical levels in the emission plume. All of these meteorological methods require tower based measurements in the plume emanating from the pasture. Ensuring that the tower's sphere of influence include all cattle in the pasture, as well as other logistical constraints, limit the usefulness of these methods for monitoring methane emissions from cattle in an outdoor environment.

Tracer Method. The tracer method employs an inert gas such as SF_6 to quantify atmospheric dilution as the methane plume disperses downwind of a feedlot or pasture. The tracer is released in a way that simulates the methane emissions. For example, 5 to 10 release points may be used that are spread throughout the area inhabited by the cattle. The tracer gas and methane concentrations are measured at several points downwind. It is important to quantify the background concentrations of both gases, as well. A description of this methodology is provided in Lamb et al. (1986).

Potential for Mitigation of Methane Emissions

Modest reductions in methane emissions are possible with current technologies, while maintaining or enhancing productivity. Of most general use, but with particular application to developing countries, is to enhance productivity by improving diet quality, eliminating nutrient deficiencies, and using growth promotants and appropriate genotypes. Enhancing level of productivity decreases the maintenance subsidy and, thus, decreases the obligatory methane emissions from fermentation of the feed associated with animal maintenance. Other additional strategies are available including the increased use of ionophores that will reduce total feed fermented and decreased methane per unit of product. Methane can be reduced with diets containing higher levels of nonstructural carbohydrates through earlier harvesting of higher quality forages or the inclusion of starchy feeds that act to enhance propionic acid and dilute maintenance subsidy. Methane production per unit of animal product formed will also be reduced by any method that will reduce the excess lipid content of meat or milk products. Longer term future technologies may develop methods to alter the microbial population in a way that would provide a hydrogen sink of more usefulness to the animal and less damage to the environment.

Implications

The development of management strategies to mitigate methane emissions from cattle are possible and desirable. Not only will enhanced utilization of dietary carbon improve feed efficiency and animal productivity, but a decrease in methane emissions will reduce the contribution of ruminant livestock to the global methane inventory.

Literature Cited

Abo-Omar, J. M. 1989. Methane losses by steers fed ionophores singly or alternatively. Ph.D. Dissertation. Colorado State Univ., Fort Collins.

Anderson, K. L., T. G. Nagaraja, J. L. Morrill, T. B. Avery, S. J. Galitzer, and J. E. Boyer. 1987. Ruminal microbial development in conventionally or early-weaned calves. J. Anim. Sci. 64:1215.

Andreae, M. O.., and D. S. Schimel (Ed.). 1989. Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere. John Wiley and Sons, New York.

Beever, D. E., S. B. Cammell, J. D. Sutton, M. C. Spooner, M. J.

Haines, and J. I. Harland. 1989. The effect of concentrate type on energy utilization in lactating cows. Proc. 11th Symp. on Energy Metabolism EAAP Publication No. 43:33.

Benz, D. A., and D. E. Johnson. 1982. The effect of monensin on energy partitioning by forage fed steers. Proc. West. Sect. Amer. Soc. Anim. Sci. 33:60.

Birkelo, C. P., D. E. Johnson, and G. M. Ward. 1986. Net energy value of ammoniated wheat straw. J. Anim. Sci. 63:2044.

Blaxter, K. L. 1989. Energy Metabolism in Animals and Man. Cambridge University Press, New York.

Blaxter, K. L., and J. L. Clapperton. 1965. Prediction of the amount of methane produced by ruminants. Br. J. Nutr. 19:511.

Breznak, J. A., and M. D. Kane. 1990. Microbial H_2-CO_2 acetogenesis in animal guts: Nature and nutritional significance. FEMS Microbiol. Rev. 87:309.

Cammell, S. B., D. E. Beever, K. V. Skelton, and M. C. Spooner. 1980. The construction of open circuit chambers for measuring gaseous exchange and heat production in sheep and young cattle. Lab. Pract. 30:115.

Carmean, B. R. 1991. Persistence of monensin effects on nutrient flux in steers. M.S. Thesis. Colorado State Univ., Fort Collins.

Cicerone, R. J., and R. S. Oremland. 1988. Biogeochemical aspects of atmospheric methane. Global Biogeochem. Cycles 2:299.

Clinton, W. J., and A. Gore, Jr., 1993. The Climate Change Action Plan. The White House, Washington, DC.

Czerkawski, J. W. 1986. An Introduction to Rumen Studies. Pergamon Press, New York.

Czerkawski, J. W., K. L. Blaxter, and F. W. Wainman. 1966. The metabolism of oleic, linoleic, and linolenic acids by sheep with reference to their effects on methane production. Br. J. Nutr. 20:349.

Czerkawski, J. W., and G. Breckenridge. 1977. Design and development of a long-term rumen simulation technique (Rusitec). Br. J. Nutr. 38:371.

Dore, J., and M. P. Bryant. 1990. Metabolism of one-carbon compounds by the ruminal acetogen *Syntrophococcus sucromutans*. Appl. Environ. Microbiol. 56:984.

EPA. 1993. Anthropogenic methane emissions in the United States: Estimates for 1990. Report to Congress. EPA 430-R-93-003.

Flatt, W. P., P. J. Van Soest, J. F. Sykes, and L. A. Moore. 1958. A description of the energy metabolism laboratory at the U.S. Department of Agriculture, Agricultural Research Center in Beltsville Maryland. In: G. Torbek and H. Aersoe (Ed.) 1. Symposium on energy metabolism: Principles, methods and general aspects. Statens Husdyrbrugsudvalg, Copenhagen, Denmark. 53.

France, J., D. E. Beever, and R. C. Siddons. 1993. Compartmental schemes for estimating methanogenesis in ruminants from isotope dilution data. J. Theor. Biol. 164:207.

Garrett, W. N. 1982. Influence of monensin on the efficiency of energy utilization by cattle. In: A. Ekern and F. Sundstol (Ed.). Energy Metabolism of Farm Animals In: Proc. 9th Symp. EAAP Publication No. 29:104.

Gibbs, M., and D. E. Johnson. 1994. Methane emissions from the digestive processes of livestock. In: Int. Anthropogenic Methane Emissions Estimates for 1990. U.S. EPA 230-R-93-010. Jan. 1994.

Goodrich, R. D., J. E. Garrett, D. R. Gast, M. A. Kirick, D. A. Larson, and J. C. Mieske. 1984. Influence of monensin on the performance of cattle. J. Anim. Sci. 58:1484.

Greening, R. C., and J.A.Z. Leedle. 1989. Enrichment and isolation of Actetomaculum ruminis, gen. nov., sp. nov.: Acetogenic bacteria from the rumen. Arch. Microbiol. 151:399.

Haaland, G. L. 1978. Protected fat in bovine rations. Ph.D. Dissertation. Colorado State University, Fort Collins.

Harper, L. A., O. T. Denhead, and J. R. Freney. 1993. Micrometeorological determination of methane production by grazing and feedlot cattle. Proc. Am. Soc. Agron. (Abstr.) 13.

Holter, J. B., and A. J. Young. 1992. Methane prediction in dry and lactating Holstein cows. J. Dairy Sci. 75:2165.

Hoover, W. H., P. M. Knowlton, M. D. Stern, and C. J. Sniffen. 1976. Effects of differential solid-liquid removal rates on fermentation parameters in continuous cultures of rumen contents. J. Anim. Sci. 43:535.

Howard, H. 1991. Measurement of fugative hydrocarbon emissions from BP operations in Prudhoe Bay, Alaska. Final report to British Petroleum Research, Cleveland, OH.

Hutcheson, J. P. 1994. Anabolic implant effects on body composition, visceral organ mass and energetics of beef steers. Ph.D. Dissertation. Colorado State Univ., Fort Collins.

IPCC. 1992. Intergovernmental panel on climate change. Climate Change 1992. The supplementary report to the IPCC Scientific Assessment. Cambridge University Press, New York.

Itabashi, H., T. Kobayashi, and M. Matsumoto. 1984. The effects of rumen ciliate protozoa on energy metabolism in some constituents in rumen fluid and blood plasma of goats. Jpn. J. Zoo Tech. Sci. 55:248.

Johnson, D. E. 1974. Adaptational responses in nitrogen and energy balance of lambs fed a methane inhibitor. J. Anim. Sci. 38:154.

Johnson, D. E. 1986. Fundamentals of whole animal calorimetry: Use in monitoring body tissue deposition. J. Anim. Sci. 63(Suppl. 2):111.

Johnson, D. E., T. M. Hill, B. R. Carmean, M. E. Branine, D. W. Lodman, and G. M. Ward. 1993a. Perspectives on ruminant methane emission. 1993 Beef Program Report. Dept. of Anim. Sci., Colorado State University, Fort Collins.

Johnson, D. E., T. M. Hill, G. M. Ward, K. A. Johnson, M. E. Branine, B. R. Carmean, and D. W. Lodman. 1993b. Principle factors varying methane emissions from ruminants and other animals. In: M.A.K. Khalil (Ed.). Atmospheric Methane: Sources, Sinks, and Role in Global Change. NATO ADI Series Vol 113, Springer-Verlag, Berlin, Germany.

Johnson, K. A., M. T. Huyler, H. H. Westberg, B. K. Lamb, and P. Zimmerman. 1994. Measurement of methane emissions from ruminant livestock using a SF_6 tracer technique. Environ. Sci. & Technol. 28:359.

Kelly, J. M., B. Kerrigan, L. P. Milligan, and B. W. McBride. 1994. Development of a mobile, open-circuit indirect calorimetry system. Can. J. Anim. Sci. 74:65.

Khalil, N.A.K., R. A. Rasmussen, and F. Moraes. 1993. Atmospheric methane at Cape Meares: analysis of a high-resolution data base and its environmental implications. J. Geophys. Res. 98: 14753.

Kirchgessner, M., W. Windisch, and H.-L. Muller. 1994. Methane release from dairy cows and pigs. In: J. F. Aguilera (Ed.) Proc. 13th Symp. on Energy Metabolism of Farm Animals. Mojacar, Spain. EAAP Publ. 76.

Kleiber, M. 1958a. Some special features of the California apparatus for respiration trials with large animals. In: G. Torbek and H. Aersoe (Ed.) 1. Symp. on energy metabolism: Principles, methods and general aspects. Statens Husdyrbrugsudvalg, Copenhagen, Denmark.

Kleiber, M. 1958b. A respiration apparatus for tracer trials with radiocarbon on cows, sows and sheep. In: G. Torbek and H. Aersoe (Ed.) 1. Symp. on energy metabolism: principles, methods and general aspects. Statens Husdyrbrugsudvalg, Copenhagen, Denmark.

Kujawa, M. A. 1994. Energy partitioning in steers fed cottonseed hulls and beet pulp. Ph.D. Dissertation. Colorado State Univ., Fort Collins.

Lajoie, S. F., S. Bank, T. L. Miller, and M. J. Wollen. 1988. Acetate production from hydrogen and ^{13}C carbon dioxide by the microflora of human feces. Appl. Environ. Microbiol. 54:2723.

Lamb, B. K., H. H. Westberg, and G. Allwine. 1986. Isoprene emission fluxes determined by an atmospheric tracer technique. Atmos. Environ. 20:1.

Lenshow, D. H., and B. B. Hicks (Ed.). 1987. Global Tropespheric Chemistry: Chemical Fluxes in the Global Atmosphere. National Center for Atmospheric Research, Boulder, CO.

Liang, J. B., F. Terada, and I. Hamaguchi. 1989. Efficacy of using

the face mask technique for the estimation of daily heat production of cattle. In: Y. Van Der Honing and W. H. Close (Ed.). Energy Metabolism of Farm Animals. Pudoc, Waginingen, The Netherlands.

McLean, J. A., and G. Tobin. 1987. Animal and Human Calorimetry. Cambridge University Press, New York.

Merry, J., R. M. Smith, and A. B. Mc Allan. 1987. Studies of rumen function in an in vitro continouous culture system. Arch. Anim. Nutr. 6:475.

Miller, W. H., and R. M. Koes. 1988. Construction and operation of an open-circuit indirect calorimetry system for small ruminants. J. Anim. Sci. 66:1042.

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

Murray, R. M., A. M. Bryant, and R. A. Leng. 1975. Measurement of methane production in sheep. In: Tracer Studies on Non-Protein Nitrogen for Ruminants II. International Atomic Energy Agency, Vienna, Austria.

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

Okine, E. K., G. W. Mathison, and R. T. Hardin. 1989. Effects of changes in frequency of reticular contractions on fluid and particulate passage rates in cattle. J. Anim. Sci. 67:3388.

Park, H. S., J. J. Ramsey, J. Torrent, and D. E. Johnson. 1994. Nutritional evaluation of an experimental fat supplement for cattle. Metabolic Laboratory Report, Colorado State University, Fort Collins.

Persily, A. 1988. Tracer techniques for measuring ventilation rates in building. National Institute of Standards and Technology, Washington, DC.

Rumpler, W. V., D. E. Johnson, and D. B. Bates. 1986. The effect of high dietary cation concentration on methanogenesis by steers fed diets with and without ionophores. J. Anim. Sci. 62:1737.

Saa, C. F., T. M. Hill, and D. E. Johnson. 1993. Persistence of methane suppression by ionophore and glycopeptide in steers fed a brome hay diet. CSU Beef Program Report.

Steele, P., P. Fraser, R. Rasmussen, M. Khalil, T. Conway, A. Crawford, R. Gammon, K. Masarie, and K. Thoning. 1987. The global distribution of methane in the troposphere. J. Atmos. Chem. 5:125.

Stumm, C. K., H. J. Gijzen, and G. D. Vogels. 1982. Association of methanogenic bacteria with ovine ciliates. Br. J. Nutr. 47:95.

Swift, R. W., J. W. Bratzler, W. H. James, A. D. Tillman, and D. C. Meek. 1948. The effect of dietary fat on utilization of the energy and protein of rations by sheep. J. Anim. Sci. 7:475.

Torrent, J. 1994. Autotrophic acetogenesis in ruminants. Ph.D. Dissertation. Colorado State Univ., Fort Collins.

Torrent, J., D. E. Johnson and A. Reverter. 1994. Prediction of methane production using rates of digestion and passage. J. Anim. Sci. 72 (Suppl.1):189.

Van der Honing, Y., B. J. Wieman, A, Steig, B. van Donselaar. 1981. The effect of fat supplementation of concentrates on digestion and utilization of energy by productive dairy cattle. Neth. J. Agric. Sci. 29:79.

Wainman, F. W., P.J.S. Dewey, and A. C. Brewer. 1984. Feedstuffs evaluation unit. Fourth Report. Rowett Research Institute, Aberdeen, Scotland.

Wedegaertner, T. C., and D. E. Johnson. 1983. Monensin effects on digestibility, methanogenesis and heat increment of a cracked corn- silage diet fed to steers. J. Anim. Sci. 57:168.

Westberg, C., P., P. Zimmerman, and B. K. Lamb. 1990. Preliminary measurements of CH_4 and CO_2 emission rates from cattle, swine and poultry production facilities. Final report to U.S. EPA (EPA #68-02-4601).

Whitelaw, F. G., W. J. Eadie, L. A. Bruce, and W. A. Shand. 1984. Methane formation in faunated and ciliate-free cattle and its relationship with rumen volatile fatty acid proportions. Br. J. Nutr. 52:261.

Wilkerson, V. A., D. P. Casper, D. R. Mertens, and H. F. Tyrrell. 1994. Evaluation of several methane prediction equations for dairy cows. In: J. F. Aguilera (Ed.) Proc. 13th Symp. on Energy Metabolism of Farm Animals. Mojacar, Spain. EAAP Publ. 76.

Wolin, M. J. 1960. A theoretical rumen fermentation balance. J. Dairy Sci. 40:1452.

Wolin, M. J., and T. L. Miller. 1988. Microbe interactions in the rumen microbial ecosystem. In: P. N. Hobson (Ed.). The Rumen Ecosystem. Elsevier Applied Science, New York.

Young, B. A., B. Kerrigan, and R. J. Christopherson. 1975. A versatile respiratory pattern analyzer for studies of energy metabolism of livestock. Can. J. Anim. Sci. 55:17.