FINAL REPORT

Report to NASA

Modelling Global Methane Emissions from Livestock: Biological and Nutritional Controls

Contract NAGW-1829

Prepared by:
Donald E. Johnson
Metabolic Laboratory
Department of Animal Sciences
Colorado State University
Fort Collins, CO 80523

Contributing Personnel:

Dr. G.M. Ward, Emeritus Professor
Dr. W.C. Miller, Adjunct Professor
Dr. T.M. Hill, Postdoctoral
Dr. M.E. Branine, Postdoctoral
B.R. Carmean, Postgraduate Research Assistant
D.W. Lodman, Research Associate
J. Torrent, Research Associate
Colorado State University
Fort Collins, Colorado 80523

P. Zimmerman, Research Scientist
National Center for Atmospheric Research
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FINAL REPORT

To:
NASA Interdisciplinary Research Program in Earth Sciences,
Terrestrial Ecology Projects

PROJECT: Modelling Global Methane Emissions from Livestock: Biological and Nutritional Controls

CONTRACT: NAGW-1829

REPORTING PERIOD: Last six months: 12/31/91-6/30/92
Overall project: 7/1/89-6/30/92

EXECUTIVE SUMMARY:

The available observations of methane production from the literature have been compiled into a ruminant methane data base. This data base includes 400 treatment mean observations of methane losses from cattle and sheep, and minor numbers of measurements from other species. Methane loss varied from 2.0 to 11.6% of dietary gross energy. Measurements included describe the many different weights and physiological states of the animals fed and diets ranging from all forage to all concentrate diets or mixtures thereof. An auxiliary spreadsheet lists approximately 1000 individual animal observations.

Many important concepts have emerged from our query and analysis of this data set. The majority of the world's cattle, sheep and goats under normal husbandry circumstances likely produce methane very close to 6% of their daily diets gross energy (2% of the diet by weight). Although individual animals or losses from specific dietary research circumstances can vary considerably, the average for the vast majority of groups of ruminant livestock are likely to fall between 5.5 to 6.5%. We must caution, however, that little experimental data is available for two-thirds of the world's ruminants in developing countries. Available evidence suggests similar percentage of emissions, but this supposition needs confirmation. More importantly, data is skimpy or unavailable to describe diet consumption, animal weight and class distribution.

One exception to this 6% rule is where cattle or sheep are fed very high concentrate diets (> 80% grain and/or supplement). When fed these diets, likely methane emissions will be 3.5% of gross energy. Frequently, they fall as low as 2%. Such dietary circumstances occur almost exclusively in the U.S. feedlot operations. Globally it has little reducing effect on emissions, since it only applies to approximately 27 million head of cattle fed for 140 days per year, with current emissions of about .4 Tg/year.

Another finding is the transitory effect of ionophores on reduction of methane emissions. Ionophores are a class of antibiotic feed additives of wide use primarily in the U.S. feedlot industry which have been considered to suppress methane losses by 20-30%.

This degree of suppression persists for some two weeks or less. Therefore, the methane reduction effect of ionophores is more modest and primarily results from a 6 to 7% reduced total feed requirements for production.

Another surprising finding was the uniqueness of one class of feedstuffs. Brewery and distillery byproduct feeds produce about half as much methane as other common feeds fed to ruminants. While of little impact globally because of the limited amounts of such feed supplies, it could provide a clue to control of methanogenesis.

An important principle influencing methane emissions from ruminant systems is the inverse relationship between rate of productivity and methane losses, especially when expressed per unit of animal product. Methane losses are closely related to the amount of feed resource used to produce an animal product. An increase in rate of production commonly decreases the feed/product by decreasing the maintenance feed subsidy. The supplementation of a moderate to low quality forage diet as might be employed in extensive grazing areas, could increase the daily average gain from .35 kg up to .7 kg. This increased rate of productivity would reduce the methane emissions per lifetime of the steer from 170 to 100 kg, again without changing product. Likewise, stimulating the rate of milk production by using bovine somatotropin in the dairy cattle industry in the United States is expected to reduce methane production by the industry some 9%, essentially producing the same amount of milk with less feed and less methane losses.

An additional source of methane indirectly emanating from the livestock industry is that from manure disposal systems. The potential production is huge, considerably larger than that coming directly from livestock, however, measurements made in our laboratory and in Australia show a very small production rate from manure disposed under simulated or actual range or pasture situations. Thus, the major global disposition of manure on pasture likely produces little methane. The critical question then becomes what fraction of manure is disposed of by anaerobic lagoons a figure which is not known very accurately. Our present best estimate of global manure methane adjusts the disposal method data from a recent EPA report to our estimates of range or pasture production. With these suppositions, the estimate of global methane entry from manure disposal approximates 10 Tg annually.

CHAPTER I

METHANE EMISSIONS FROM U.S. BEEF AND DAIRY CATTLE HERDS FOR 1990 AND 1992

D.E. Johnson and G.M. Ward
Department of Animal Sciences
Colorado State University
Fort Collins, CO 80523

The U.S. beef and dairy cattle herds were divided into 17 class groups by age, sex and physiological stage for 1990 and 1992. The diet composition, diet consumption and typical methane production was then estimated for each group. The beginning points for the characterization of numbers within each class were January 1 beef and dairy cow numbers and their replacement rates (Table 1) garnered from USDA-ERS publications in 1991 and 1992. The offspring were assumed to go through three or more of the production classes. Adjustments were made for calf/veal slaughter, imports (assumed to be fed) and nonfed heifer and steer slaughter. The reproductive and death loss in each category was based on expert opinion and adjusted to result in a number of fed cattle slaughtered within 1% of USDA figures, i.e., Table 1. The reproductive rate for January 1 beef cows, plus their replacements, was set at 80%, and dairy at 88%. Death loss of calves from birth to 210 days at weaning were 8 and 15% in the 1990 synthesis for beef and dairy. Additional losses in the various classes ranged from 1 to 5%, as shown in Tables 2 and 3. One-fourth of the bulls were replaced each year from the beef stocker class.

The feed intake for each production class was estimated from NRC Beef (1984) and/or NRC Dairy (1991) nutrient requirement tables. The average weight of each animal within its class, their level of productivity and diet composition used in commercial practice were estimated from expert opinion to determine the average daily dry matter intake. For calves nursing cows, i.e., beef calves, the assumption was made that .33 $g/Wt^{.75}/d$, about 1/3 of the total, intake was dry feed and thus subjected to fermentation, losing 6% of its gross energy as methane. For dairy calves, the assumption was that all of the feed past one month of age would be fermented. Methane losses as a percentage of dietary gross energy as shown in (Tables 2 and 3) were derived from respiration calorimetric measurements of animals fed a similar diet and in a similar production class (Branine et al., Cattle Methane Database) after adjusting for experimental vs. industry level of intake differences according to Hill et al. (1992).

The majority of cattle methane emissions are produced by the cow herds (> 4 Tg/yr). In contrast, the short time span and low fractional methane loss of cattle in the feedlot phase yield relatively low annual emissions (< .4 Tg). These estimates include a 150-d stocker/grower phase prior to a 140-d yearling feedlot phase. A shift to more direct placement of calves into the feedlot, as has been occurring in the industry, would reduce this even further.

Total cattle emissions are expected to change very little from 1990 to 1992. Dairy cattle numbers are down, their milk production up and beef cows up slightly. The weighted (by days in class) average cattle inventory is estimated to be 104.1 and 103.6 million head. The USDA/ERS (1992) report 98.2 and 100.1 on January 1 of these years and higher numbers for July counts. Since the January 1 numbers are usually reported by FAO, global summaries, i.e., Crutzen et al. and Lerner et al. (1989) likely reflect this slightly lower inventory.

Beef cattle emissions were unchanged in 1992 vs 1990 in spite of a small increase in cow numbers and imports. Increases in these categories were affected by an increased calf death loss imposed to yield estimated slaughter numbers (based on 1991 figures). Dairy cattle milk production increased about 2 kg per cow and more than offset the decreased cow numbers between 1990 and 1992. A slight total methane increase from dairy reflects the extra diet required for the extra milk. However, total methane/kg milk is projected to decrease slightly.

If the estimated annual U.S. methane emissions from livestock other than cattle (.27 Tg) and from livestock manure (1.5 Tg) are added to beef and dairy cattle emissions, the total reaches 7.54 Tg/yr (Table 4). About 55% is estimated to result from beef cattle eructations and 22% from dairy cattle. The 20% coming from manure is about half from cattle and half from other species, most notably swine. The higher incidence of anaerobic lagoon use for swine manure disposal along with the high population results in estimates of over 40% of U.S. livestock manure methane, produced from this species (Table 5).

Table 1. Statistical characterization of U.S. beef and dairy cattle in 1990 and 1992 (USDA-ERS,91,92)

Class	1990 Herd	1992 Herd[a]
Beef cows, mill. hd	33.7	33.8
Replacement %	16	17
Bulls, mill. hd	2.2	2.28
Dairy cows, mill. hd	10.1	9.85
Replacement %	42	43
Milk production, kg/d	21	23
Imports, mill. hd	1.3	1.94
Calf slaughter, mill. hd	1.74	1.41
Nonfed slaughter, mill. hd	.99	.94
Fed cattle slaughter, mill. hd	26.2	25.5

[a]Imports and slaughter numbers based on 1991 figures.

Table 2. Estimated methane emissions from the 1990 U.S. cattle herd

Class	Avg #[a]	Loss	Live weight In	Live weight Out	Days	Dry matter intake	Methane loss %	Methane loss Tg/yr
Beef:	Mill.	%	kg	kg		kg/d	%	Tg/yr
Cows	33.70	0	450	450	365	8.9	6.2	2.28
Births	31.27	20						
Calves	30.02	8	36	215	210	1.2[d]	6	0.15
Stocker	28.48	2	215	315	150	6.2	6.5	0.58
Replacements[b]	5.56	6	315	410	365	7.8	6.5	0.35
Bulls	2.20	0	700	700	365	11.8	6	0.19
Fed-hfr	7.81	1.5	300	480	140	8.2	3.5	0.11
Fed-str	12.96	1.5	330	525	140	8.8	3.5	0.19
Fed-imports	1.30				140	8.8	3.5	0.02
Not fed[c]	0.99							
						Total beef:		3.87
Dairy:	21.2 kg 3.5% milk							
Calves born	12.62	14						
Veal	1.74	5						
Cows	10.1	0	700	650	365	16.4	5.8	1.18
Replac.	4.35	5	330	500	365	8.7	6.5	0.30
Stock. Rep.	4.49	1	220	330	150	6.3	6.5	0.09
Calf Rep.	4.91	15	45	220	210	3.8	6	0.08
						Total dairy		1.65
Dairy Beef:								
Calf-str	4.14	15	45	230	210	3.8	6	0.07
Calf-hfr	0.93	15	42	210	210	3.8	6	0.01
Stocker-str	3.79	1	230	345	150	6.4	6.5	0.08
Stocker-hfr	0.85	1	210	315	150	6.3	6.5	0.02
Fed-str	3.74	1.5	345	535	140	9.8	3.5	0,06
Fed-hfr	0.84	1.5	315	490	140	9.2	3.5	0.01
						Total dairy beef		0.25
Total fed	26.39						US TOTAL:	5.76
Calves weaned	37.77 (43.69 born)							
U.S. herd	104.1							

[a](Beginning and ending #s in class) ÷ 2.

[b]Yearling replacement heifers, 16% for beef and 42% for dairy.

[c]Deleted from inventory after stocker phase.

[d]Dry feed consumed and fermented estimated at .33 $g/Wt^{.75}/d$.

Table 3. Projected methane emissions from the 1992 U.S. cattle herd by class

Class	Avg #[a]	Loss	Live weight In	Live weight Out	Days	Dry matter intake	Methane loss %	Methane loss Tg/yr
Beef:	Mill.	%	kg	kg		kg/d	%	Tg/yr
Cows	33.83	0	450	450	365	8.9	6.2	2.289
Births	30.87	22						
Calves	29.33	10	36	215	210	1.2	6	0.15
Stocker	27.51	2	215	315	150	6.2	6.5	0.56
Replacements[b]	5.93	6	315	410	365	7.8	6.5	0.37
Bulls	2.28	0	700	700	365	11.8	6	0.20
Fed-hfr	6.97	1.5	300	480	140	8.2	3.5	0.09
Fed-str	12.48	1.5	330	525	140	8.8	3.5	0.18
Fed-import	1.94				140	8.8	3.5	0.03
Not fed[c]	0.94							
						Total beef:		3.87
Dairy:	43% repl. 23 kg 3.5% milk							
Cows	9.85	0	700	650	365	17.1	5.8	1.20
Replac.	4.35	5	330	500	365	8.7	6.5	0.30
Stock. Rep.	4.48	1	220	330	150	6.3	6.5	0.09
Calf Rep.	4.90	15	45	220	210	3.8	6	0.08
						Total dairy		1.67
Calves born	12.11	14						
Veal	1.41	5						
Dairy Beef:								
Calf-str	4.23	15	45	230	210	3.8	6	0.07
Calf-hfr	0.70	15	42	210	210	3.8	6	0.01
Stocker-str	3.87	1	230	345	150	6.4	6.5	0.08
Stocker-hfr	0.64	1	210	315	150	6.3	6.5	0.01
Fed-str	3.82	1.5	345	535	140	9.8	3.5	0.06
Fed-hfr	0.63	1.5	315	490	140	9.2	3.5	0.01
						Total dairy beef:		0.24
Total fed	25.66						U.S. Total:	5.78
Calves weaned	36.82							
U.S. count	103.6							

[a](Beginning and ending #s in class) ÷ 2.

[b]Yearling replacement heifers, 17% for beef and 43% for dairy.

[c]Deleted from inventory after stocker phase.

Table 4. Summary estimate of overall 1992 U.S. livestock and livestock manure methane

Source	Tg/yr	%
Beef breeding herd	3.00	40
Feeders and feedlot	1.12	15
Dairy herd	1.67	22
Other livestock[a]	0.27	3
Manure[b]	1.48	20
Total Livestock Industry	7.54	100

[a]Extrapolated from Crutzen et al. (1986); sheep, swine, horses, etc.

[b]Based on Safley et al. (1992) manure disposal survey with methane loss rates adjusted to Lodman et al. (1992) findings.

Table 5. U.S. manure methane by species[a]

Species/dose	Tg/yr	% of U.S.
Swine	.67	43
Dairy	.60	39
Beef	.19	12
Poultry	.07	5
Other	.01	1
Total	1.5	100

[a]Extrapolated from Safley et al. (1992) estimates adjusted to Lodman et al. (1992) measurements.

CHAPTER II

MATHEMATICAL MODELING OF METHANE PRODUCTION FROM U.S. BEEF CATTLE BY REGION

W.C. Miller*, D.E. Johnson and G.M. Ward
Department of Animal Sciences
Colorado State University
Fort Collins, CO 80523

A mathematical model of the beef cattle production of the United States developed by Miller et al. (1980), was expanded to evaluate beef cattle production of methane by all classes of cattle. Methane production from cattle is a function of the animal's diet, physiological state and metabolic size. United States beef cattle were classified as cow/calf, bulls, replacement cows, replacement bulls, weanling steer and heifer calves, stocker steers and heifers, grass-fed steers and heifers and feedlot steers and heifers. The United States was modeled as nine regions (Figure 1), such that environment affected diet and management of cattle in a region. All classes of cattle that were raised in any region were modeled for the region. Where there was a "real world" movement of cattle between regions, this movement was also modeled. Feed resources were contained within regions except for concentrates which were considered unlimited. Those resources were used to feed cattle classes of cows, bulls, calves, replacements, stockers and feedlot. The three quality grades of beef produced were choice grade, good grade and standard grades. Cow numbers, feed resources or quality grade constraints controlled the model parameters to determine optimal feeding practices, beef production or herd sizes.

New constraints and equations were added to the model to determine methane production, depending on cattle class and feeding practice. The northeast region of the U.S. was added as the ninth region which was not in the original model because of small cattle numbers in this region.

The model was exercised for three beef production modes: 1) typical U.S. production where about 40% of the production is graded choice, 2) no feedlot feeding with grass resources allowed to expand in private sector and 3) no feedlot feeding, but grass resources held at current levels. Methane emissions by region were also generated for Model 1, the typical U.S. system.

Results

Exercise 1 indicates 9 x 10^6 tons of total beef production and 3.889 Tg of methane per year distributed by regions as shown in Table 1. Exercise 2 gives 7.2 x 10^6 tons of total beef production and 3.869 Tg of methane. To support the same cow herd size and grazing of their offspring, 151 x 10^6 tons of total TDN of additional grazing were required. Exercise 3 indicates 6.9 x 10^6 tons of total beef production and 3.690 Tg of methane. Because grazing was constrained from expansion, the cow herd decreased from 33.70 to 32.35 beef cows per year.

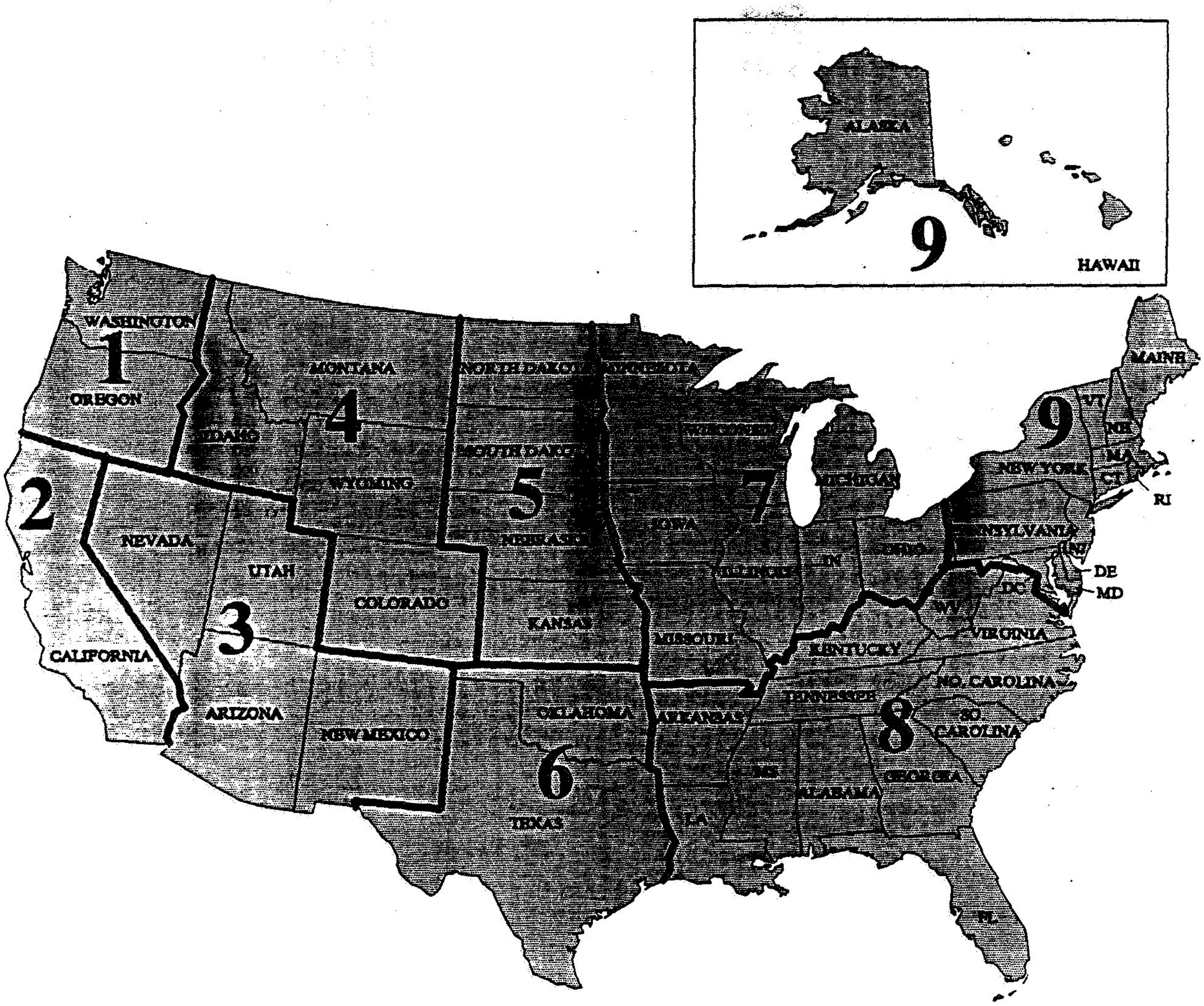

Figure 1. Map of regions incorporated in the model.

Regions

1 Pacific Northwest
2 Pacific Southwest
3 Southwest and Intermountain
4 Northern Rock Mountains
5 Northern Plains
6 Southern Plains
7 Corn Belt
8 Southeast
9 Northeast

Table 1. Methane emission estimates from Beef Model (Miller, 1979) for regions of the U.S. based upon 1990 beef cow numbers of 33.7 million head

Regions (see Figure 1)	Cow #s/million head	CH_4 production Tg/yr
1		0.114
2		0.142
3		0.327
4		0.449
5		0.721
6		0.456
7		0.773
8		0.854
9		0.053
Total		3.889

The two regions with the largest emissions are the southeast and cornbelt, producing nearly half of U.S. beef cattle methane (1.62 Tg). The next largest emissions are from the northern and southern plains regions. The total for 98 million cows predicted by this independent assessment of feed resource allocation (3.89 Tg) compares favorably to what is predicted by a recent separate exercise, 3.87 Tg (Johnson et al., 1992).

Using the national beef production model to study methane production by beef cattle indicates a minor change in methane production by changes from the feedlot system to all forage diets. The bulk of the U.S. beef cattle emissions occur from the southeast and central U.S. regions.

References

Miller, W.C., G.M. Ward, T.P. Yorks, D.L. Rossiter and J.J. Combs. 1980. A mathematical model of the United States beef production system. Agric. Systems 5:295-307.

CHAPTER III

STRATEGY TO ESTIMATE METHANE EMISSIONS FROM LIVESTOCK IN DEVELOPING COUNTRIES WITH SOME EXAMPLES

Dr. Gerald M. Ward
Department of Animal Sciences
Colorado State University
Fort Collins, CO 80523

Abstract

A comprehensive assessment of methane emissions by livestock in developing countries is basically dependent upon FAO statistics of cattle numbers and average carcass weights which can be used to approximate mature body weights and probable feed intake. For individual countries or regions, more specific data may be available on animal weights, feed intake and feed type.

Example calculations are presented for cattle from India and China and the tropical African countries. Estimates for 197 million cattle in India are 4.7 Tg/yr based upon the feed intakes measured by Odend'hal (1968-69). Estimates for 72 million cattle in China are 3.2 Tg/yr and for the 167 million cattle in tropical Africa 7.3 Tg/yr. These estimates can be compared to 5.8 Tg/yr calculated for about 100 million cattle in the U.S.

Introduction

Calculation of methane emissions by animals requires knowledge of feed dry matter intake and the type or composition of feed. Methane emission is some fraction of the gross energy of feed consumed. The gross energy of feeds varies little from 4.4 Mcal/kg unless the feed contains a high level of fat. Factors that affect methane as a percentage of gross energy intake have been reviewed in detail by Johnson et al. (1992). Calculations of methane emissions for U.S. cattle and the methodology for calculations have also been presented (Johnson et al., 1990). The method uses USDA statistics for cattle numbers by age group and production classes (i.e., replacements, feeders, milking cows, etc.). Mean weights are assigned to each class, feed type and intakes estimated from which daily methane output per animal type is calculated and then summed for the population. It should be pointed out that neither in the U.S. nor any other countries are specific data available on a country-wide basis for average body weights, feed intake or diet composition of cattle or other livestock. The data can only be synthesized from masses of experimental data and finally from expert opinion.

The method is the same for calculating methane emissions from the large numbers of livestock in the developing countries, but the data base is more sparse and often the data have a higher degree of uncertainty. According to FAO (1990), there are 1,280 million cattle in the world, of which 880 million or about 60% are found in developing countries.

The only inclusive data source on the world's livestock is found in the annual publication FAO Production Yearbook and the only data provided for cattle are total numbers (with no breakdown by age, sex or type, except milking cows), total head slaughtered per year and their average carcass weight at slaughter. Any calculations of methane emissions must begin with this data base and then incorporate any other information that can be obtained for a country, region or continent. A large body of information on cattle and less for other species is available in the literature. Much of this information has been summarized and synthesized to produce estimates of methane emissions by domestic ruminants of the world. These estimates were made by making numerous assumptions about feed intakes and body weights by regions of the world (Reuss et al., 1990).

This paper provides methane estimates to the extent possible, based upon the FAO data. For example, these data indicate that in Africa, 11% of the cattle inventory is slaughtered per year. This means that nine head are maintained per year for every one slaughtered. This ratio equates well with what is known about general production practices in Africa. Cattle are slaughtered at five to seven years of age, which means a cow, calf and 1- through 5- or 6-year-old cattle plus several replacement females are being supported for each slaughter animal. The average weight of these cattle can be inferred from the slaughter weight. The average for cattle in Africa in 1990 was 156 kg. If the dressing percentage was 50%, then the mature weight was 312 kg and probably would be similar for mature weights of cows. Estimates can then be worked out for body weights of animals for each age for males and females. These estimates can be verified to some extent against limited research reports available from various sites. With body weight estimates and estimates of yearly growth increments it is possible to estimate digestible energy (DE) requirements from which DM intake can be estimated based upon information on the general types of feeds available in a region. Our analysis of world-wide data indicates that attempts to predict DM intake from DM digestibility are of little value (Johnson et al., 1992).

Livestock numbers and meat production data are also presented in the FAO Production Yearbooks for buffalo, sheep and goats from which similar calculations of methane may be derived. Numbers of milking cows, but not buffalo and goats are listed by country and average milk production for cows. Calculations of methane emissions for milking animals are more difficult. Feed intake is related to level of milk production as well as body weight, and although body weight generally increases with level of milk production, there is no close relation between the two. Other data will be necessary to calculate body weights of milking animals as well as characteristic feed types and feed intake.

Estimates of Methane Production by Cattle in the Sahel Region of Africa

It is difficult to find hard data on body weights and feed intake to support calculations of methane emissions by cattle in Africa. However, two important papers by Wilson (1986, 1987) provide such data for Mali and it is his opinion that this can be applied to the six countries of the Sahel (Senegal, Mauritania, Mali, Niger, Chad and Sudan). These countries have a total of 38 million cattle, of which 55% are in Sudan. Wilson (1986) provides data on herd structure, body weights by ages and reproduction rates, weight gains and milk production. The average body weight of a mature cow was 230 kg at five years of age and bullocks averaged 297 kg at six years, which would be in line with FAO carcass weights. These weights agree with weights recorded for similar cattle in Gambia (Spencer and Eckert, 1988), while in northeast Kenya, cows averaged 184-210 kg (Coppock et al., 1986).

Wilson (1986) estimates that the 38 million cattle in the Sahel, of which sixty percent are less than five years old, average 0.73 TLU (tropical livestock unit). A TLU is defined as a mature cow weighing 250 kg. So thirty-eight million head x 0.73 = 24.8 million head equivalent at 250 kg. McDowell (1981) estimates that the average cow in Africa consumes an average of 1.2 x the maintenance requirement over the year. The maintenance requirement of 250 kg of mature cattle would be 4.9 kg/d of dry matter if it is 50% DE (or 4.9 x 1.2 = 5.9 kg/d). This equates to 43.6 kg CH_4/yr for a TLU (250 kg). The total for the 38 million head in the Sahel then would be 1,656 x 10^6 kg methane. For the 167 million head of cattle in tropical Africa, the methane estimate would be 728 x 10^6 kg/yr. or 7.3 tg/year. These are cattle excluding North and South Africa. This compares to 5.8 Tg/yr estimated for the 100 million cattle in the U.S. (Johnson et al., 1992) and 3.2 Tg estimated for 72 million head in China (Ward and Johnson, 1990) and our estimate of 4.7 Tg for Indian cattle (see below, also Table 3).

Estimations of Methane Emissions by Indian Cattle

Crutzen et al. (1986) used data from a study in India as the basis to calculate methane output by cattle for all the developing countries. The data is from Odend'hal (1972), who conducted three surveys over an 18-month period in 1968-69 in an area of West Bengal (near Calcutta) that covered an area of 5.8 square miles. The area contained an average of 3,770 cattle and 16,445 people. He determined weights of feed consumed by cattle and calculated from tables the daily energy intake of three classes of cattle: mature cows, bullocks and young cattle (under four years of age). The average daily intake for all cattle was estimated to be 14.4 Mcal (60.3 MJ).

Thus, an intensive study (25 years ago) of a small area (about 6 sections of land) in Eastern India became the basis for estimating the methane emissions of over one-half of the world's cattle (Crutzen et al., 1986). Crutzen calculated that 9% of feed energy was converted to methane, but our (Johnson et al., 1992) literature survey would indicate 6% to be a more accurate estimate.

There are numerous uncertainties concerning the application of this data on such a wide scale. First is the question of the size of these animals. Odend'hal did not provide weights or weight estimates. However, estimates of digestible energy intake indicates that the feed intake would support maintenance for only about a 150-kg mature cow with no energy for lactation or pregnancy. The feed intake of bullocks would support maintenance for a 235-kg body weight. The average carcass weight for cattle in India in 1990 was 80 kg (FAO, 1991). This includes some unknown percentage of calves which might translate to about 160-kg live weight. The Province of West Bengal is one of the poorer in India and the cattle are probably smaller than those in the northern provinces. Bengal borders Bangladesh, where the average slaughter weight is 60 kg (FAO, 1991). In 25 years, the average weight of cattle has increased in India as well as milk production per cow, while according to Odend'hal (1988), the number of working bullocks in Bengal declined 19% in the past two decades. Of the 197 million head of cattle in India, 29.5 million in 1990 were milk cows that produced an average of 905 kg per year or perhaps 3-4 kg of milk per day as compared to 1.5 reported by Odend'hal (1972).

Using the energy intakes of Odend'hal and 6% of energy as methane, we calculate methane from 197 million cattle to be 4.68 tg. Lerner et al. (1988) estimated 6.38 for 182 million head using Crutzen's calculations. The India Leather Institute made estimates based upon 201 million cattle of 3.95 Tg/yr based upon body weights of 130 kg for mature cattle and 100 kg for younger cattle.

Buffalo. India has about 50% of the world's buffalo. Carcass weight is reported to be 138 kg per animal or 1.7 times the weight of cattle. Neither milking buffalo nor milk production per buffalo is listed in FAO reports, but almost one-half of the national milk supply is from buffalo and the fat percentage of their milk is substantially higher, which requires more feed energy. Thus, judging from carcass weights and estimates of milk production, feed intake by India's 75 million buffalo is perhaps two times that for cattle. There are no reliable estimates of CH_4 per unit of feed energy for buffalo, but they are probably similar to cattle, although buffalo generally digest poor quality feeds more efficiently than cattle. As a first approximation, buffalo emissions of methane in India may approach that from cattle. The India Leather Institute estimated 2.19 Tg/yr of methane from 76 million buffaloes.

Goats. India has 41 million goats and goat milk production is more than half that from cattle. Average slaughter weight of goats is 10 kg. Another estimate for India's goats and sheep was 0.81 Tg/yr of methane (India Leather Institute report).

Calculation of Methane Emission Estimates for Cattle in China

A considerable body of information on livestock production systems was available to the from four scientific visits to China and from discussions with Chinese scientists, especially at the Beijing Agriculture University and the Gansu Grassland Ecological Research Institute at Lanzhou and from reports by DeBoer (1984) and Tuan (1987).

As an illustration of our methodology, an analysis is presented for the People's Republic of China, where we use the following stepwise procedure:

1. Classify animals by age and sex.
2. Assign weights to these groups.
3. Determine principal feed types.
4. Estimate average daily dry matter intake (DMI) and gross energy intake (GEI).
5. Assign a % of CH_4 from GEI and calculate daily CH_4 output.

6. Aggregate groups and sexes for national or regional output.

Livestock Production Systems of China

China historically has been divided into a farming region and a grazing or pastoral region as elegantly described in the historical context by Lattimore (1951). Table 1 shows agricultural and livestock distribution between the two regions. The grazing region includes Inner Mongolia and Ningxia, and the four very large provinces of Western China: Gansu, Qinghai, Xinjiang and Xizang (Tibet). Within the farming area, there is also some rough or poor quality land used for grazing, but the animals mostly belong to farming villages or communes. Grazing areas are found within some other farming provinces, especially Hebei, Shaanxi and Sichuan, which may be offset by agricultural areas found within the grazing region. Within the pastoral areas, small areas of irrigated land with intensive farming are found, but associated animal numbers are small.

Table 1. Features of livestock regions, 1979 (Ren, 1983)

Item	Grazing Region	Farming Region
	Percent of National Total	
Land area	54.5	45.5
Area sown to crops	8.8	91.2
Total population	6.1	93.9
Cattle	25.0	75.0
Horses	36.7	63.3
Mules	41.6	58.4
Donkeys	20.5	79.5
Camels	99.7	0.3
Sheep	69.8	30.2
Goats	28.9	71.1
Beef output	41.4	58.6
Mutton output	51.5	48.5

Grazing Region. Grazing in these provinces provides nearly all the feed for cattle, sheep, goats, camels and yaks. Transhumance is common in those areas near mountains with summer grazing at the higher elevations. Often a surplus of forage is available in the summer. Hay is harvested in many areas, but not in adequate amounts and mostly of poor quality. Some winter grazing on crop residues is available in the irrigated valleys and also some from dry land cereal crops grown at high elevations (Ward et al., 1986). Winter death losses are estimated at 5-6%, but weight losses during winter are estimated at 4 to 6 times the losses from death. Severe winters are reported to result in 30% death losses from lambs (Ren et al., 1983). All native cattle are called yellow cattle and those in the pastoral region are nearly all milked and their average production is probably about 300 kg per lactation (Cheng, 1979).

Yaks which are found above 8000 ft elevation appear to have many of the characteristics of the American bison. They mature later than cattle. Milk production is about 2 kg per day for 3 or 4 summer months. The body weight of mature cows is similar to cattle or 300-400 kg. Cattle yak hybrids are common at intermediate elevations (Wen, 1988).

Farming Region. Yellow cattle are the major livestock of the farming region. The cattle are larger than those in the pastoral areas. Females average 350 kg and males 550. However, cattle get progressively smaller in size as one goes south of the Yellow River. For this reason, we have divided the farming region into North and South China with the division being the Changjiang (Yangtze) River. Cattle are reared for draft and historically have not been milked. Mostly beef is produced only from old animals unable to work, but some beef is fed for market (Qui Huai et al., 1983). The recent demand for milk has led to milking some yellow cattle and to crossing with imported dairy breeds. Milk production is mostly provided by less than one million black and white (Friesian) cattle located near urban centers (Simpson, 1988). Total goat milk production has been about 25% of the volume produced by cows. Shaanxi Province has the largest number of milk goats.

The basic feed for all ruminants in the farming region is straw (wheat, rice, sorghum or millet) and other crop residues. Grazing of waste, roadside, forests, etc. provides some nutrients. A variety of concentrates are sometimes fed to supplement forage for working or milking animals (Ji Yu-Lun et al., 1983; De Boer, 1984).

<u>Structure of Chinese Cattle Population</u>

As a national average, it is reported that 36% of cattle population are fertile females which is interpreted to mean females of breeding age (China Ag. Yearbook, 1985). The average age of first calving is between 3.0 and 3.5 years (Zhu, Personal Communication). Calves born in the year represent 14% of the cattle population (calving rate of 40%). The slaughter rate in 1984 was 6.3% of the total cattle. These are the only statistics available for estimating herd structure. If it is assumed that slaughter animals are disproportionately male, then there may be 32% of mature males. The sum of 32, 36 and 14% (for calves) is 82% of the population, which would mean 18% in the category of two- and three-year-olds. This percentage may seem small, but the mortality rate is especially high for cattle in the second winter of life.

Once the two coefficients, DMI as a percentage of body weight and CH_4 as a percentage of GEI, are selected, estimates of total CH_4 output by cattle in China can be calculated with a reasonable degree of certainty. A first approximation of dry matter intake is 2% (range 1.0-2.5%) of body weight for mature animals and 1.0% for cattle less than one year because they are partially dependent upon milk. One estimate of CH_4 produced by cattle fed wheat straw (a common feed in China) in our laboratory indicated CH_4 to be 6.0% of GEI (Birkelo et al., 1983) and this value was used for all categories of animals.

Table 2 presents a summary of age distribution of cattle estimates of body weight and feed intake for each age group in the three subdivisions of China. The total CH_4 output for the 72 million Chinese cattle using these data is 3.2 Tg per year or about 7% of the global total for cattle as estimated by Crutzen et al. (1986). Other estimates for Chinese cattle emissions range from 2.51 to 3.17 Tg/yr when adjusted to 72 million head (Table 3).

Possible Future Trends

Long range plans in China call for increases in livestock productivity, especially milk and meat output from their large ruminant animal population. Greater integration of crop and livestock is seen as a means of reducing mortality and winter weight losses and also as a means to increase fertility of females (Ward et al., 1986). A large research effort is underway to accomplish these objectives. This strategy may reduce the CH_4 output per kg of feed consumed and will certainly reduce CH_4 emissions per unit of milk, meat and wool.

A tremendous gap in productivity between the U.S. and China is indicative of the potential for improvement. Beef production per head of cattle is 8.0 kg in China (FAO Yearbook, 1990) and about 100 kg in the U.S. Part of the discrepancy can be explained by the fact that many cattle in China are kept for work and not for beef. Farm mechanization will change this factor, but at what rate is difficult to predict. Milk production per year for cattle classified as milk cows is about 1500 kg (Simpson, 1988) in China and 5800 kg in the U.S., which also illustrates a large potential for improvement. The most important requirement for increasing animal productivity and reducing CH_4 per unit of animal product is a greater supply and better quality animal feedstuffs.

However, the demands for additional feed from crop land will require additional fertilizer, irrigation water and probably greater mechanization. Inputs dependent upon fossil fuels have the potential to contribute in their way to global warming. Options for reducing methane must be evaluated within the context of impacts from the overall agricultural system.

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References

Birkelo, C.P., D.E. Johnson and G.M. Ward. 1983. Net energy value of ammoniated wheat straw. J. Anim Sci. 62:2044-2052.

Cheng, Pi-liu. 1979. The livestock industry of China. In: Dairy Science Handbook. M.E. Ensminger (Ed.). Agriservices Foundation, Inc. pp. 1-10.

China Agricultural Yearbook. 1985. Agricultural Publishing House, Beijing.

Coppock, D. Layne, D.M. Swift, J.E. Ellis and K. Galvin. 1986. Seasonal patterns of energy allocation to basal metabolism activity and production for livestock in a nomadic pastoral ecosystem. J. Agric. Sci. Canb. 107:357-365.

Crutzen, P.J., I. Asselman and W. Seiler. 1986. Methane production by domestic animals, world ruminants, other herbivorous fauna and humans. Tellus 271-284.

DeBoer, A.J. (Ed.). 1984. Ruminant livestock in intensive agricultural areas of Sichuan Province, China: Current status and development prospects. Winrock International, Morrilton, AR. 137 pp.

FAO Production Yearbook. 1990. Food and Agriculture Organization of the United Nations, Rome.

ICF. 1992. Personal communication, M. Gibbs, Unpublished Document, ICF, Inc.

Ji Yi-lun et al. 1983. Some aspects of ingestion behaviours and feed requirements of the draft cattle in Shanxi province: Ingestion behaviors and rate of passage of feeds through the digestive tract of draft cattle. In: Proceedings of First China - U.S. Symposium on Ruminant Animal Productivity, Beijing, China, September.

Johnson, D.E., T.M. Hill, G.M. Ward, M.E. Branine, K.A. Johnson, B.R. Carmean and D.W. Lodman. 1992. IV. Ruminants. In: Atmospheric Methane, NATO, Springer-Verlag.

Johnson, D.E., M. Branine and G.M. Ward. 1990. Methane emissions from Livestock. AFMI. Nutrition Symposium, November, 1990, St. Louis, p. 33.

Lattimore, Owen. 1951. Inner Asian frontiers of China. Beacon Press, Boston, MA.

Leather Institute Report. Unpublished Document, ICF, Inc.

Lerner, J., E. Matthews and I. Fung. 1988. Methane emissions from animals: A global high-resolution data base. Global Biogeochem. Cycles 2:139-156.

McDowell, R.E. 1981. The need to know about animals. Paper on World Food Issues. Cornell University, Ithaca, NY.

Odend'hal, S. 1972. Energetics of Indian cattle in their environment. Human Ecol. 1:3-22.

Odend'hal, S. 1988. Human and cattle population changes in Deltaic West Bengal, India 1977-1987. Human Ecol. 16:23-32.

Qiu Huai et al. September, 1983. A study on the beef performance of Quinchuan cattle. In: Proceedings of First China - U.S. Symposium on Ruminant Animal Productivity. Beijing, China.

Ren Jizhou et al. 1983. The grasslands of China and their problems. In: Proceedings of First China - U.S. Symposium on Ruminant Animal Productivity. Beijing, China.

Reuss, S., J.P. Ellis, G.M. Ward and D.W. Swift. 1990. Global ruminant production systems. Report to EPA - unpublished.

Simpson, J.R. 1988. China dairy industry: Economic analysis and implications. Feedstuffs (October 3).

Spencer, W.P. and J.B. Eckert. 1988. Estimating live weight and carcass weight in Gambian N'Dama cattle. World Animal Review 65:18-23.

Tuan, Francis C. 1987. China's livestock sector. USDA Foreign Agricultural Economic Report #226. USDA Economic Research Service, Washington, D.C. 82 pp.

Ward, G.M., R. Oltjen, R. Temple and D. Gates. 1986. New technologies needed to improve animal production in China. Feedstuffs (January 6).

Wen Zen Zhong. 1988. Structure and Age Distribution in Yak herds in Qinghai Province, China. J. Livestock Ecology 2:41-44.

Wilson, R.T. 1986. Livestock production in central Mali: Long term studies in cattle and small ruminants in the agropastoral system. ILCA Research No. 14. ILCA. December, 1986.

Wilson, R.T. 1987. Livestock production in central Mali: Environmental factors affecting weight in traditionally managed goats and sheep. Animal Prod. 45:223-232.

Table 2. Methane emissions from cattle in China

	Female			Male		
Age Group	> 3	103	< 1	> 3	1-3	< 1
% in each group	36	21	6	32	9	6
NORTH CHINA						
No. of cattle (10^6)	10.2	3.4	1.7	9.1	2.5	1.7
Live wt (kg)	350	250	75	500	300	100
*DMI (%)	2	2	1	2	2	1
DMI (kg/da)	7	5	0.75	10	6	1
CH_4 (% DMI)	6	6	6	6	6	6
CH_4, L/d	198	141	21	283	170	28
kg/animal/yr	51	37	6	73	44	7
MT X 10^3/yr	525	125	9	667	113	13
Total						1452
SOUTH CHINA						
No. of cattle (10^6)	8.1	2.7	1.3	7.2	2.0	1.3
Live wt (kg)	250	175	60	350	250	70
*DMI (%)	2	2	1	2	2	1
DMI (kg/da)	5	3.5	0.6	7	5	0.7
CH_4 (% DMI)	6	6	6	6	6	6
CH_4, L/d	141	99	17	198	141	20
kg/animal/yr	37	26	4	51	37	5
MT X 10^3/yr	299	70	6	372	75	7
Total						828
GRAZING REGION						
No. of cattle (10^6)	7.4	2.4	1.2	6.6	1.8	1.2
Live wt (kg)	300	200	70	450	300	80
*DMI (%)	2	2	1	2	2	1
DMI (kg/da)	6	4	0.7	9	6	0.8
CH_4 (% DMI)	6	6	6	6	6	6
CH_4, L/d	170	113	20	254	170	23
kg/animal/yr	44	29	5	66	44	6
MT X 10^3/yr	328	73	6	438	82	7
Total						935
Grand Total						**3215**

*DMI; dry matter intake as % of body weight.

Table 3. **Estimates of methane emissions for specific countries and regions**

Country/ Species	This Report No's (10^6)[a]	This Report CH_4 (Tg/yr[b]	Reuss (1990) No's	Reuss (1990) CH_4	Lerner (1988) No's	Lerner (1988) CH_4	Leather Inst. No's	Leather Inst. CH_4	ICF (1992) No's	ICF (1992) CH_4
<u>USA</u>										
Cattle	98	5.8	98	7.74	114	6.62			98	5.3
<u>India</u>										
Cattle	197	4.68	197	5.28	182	6.38	201	3.95	197	5.6
Buffalo	75	4.70	75	6.12	64	3.20	76	2.19	77	4.1
<u>China</u>										
Cattle	72	3.20	75	4.35	58.5	2.05			77	3.4
Buffalo	---	---	21	1.44	19.2	0.96			26	1.5
<u>Africa</u>										
Subsaharan Africa	167	7.3	162	6.5					188	6.1

[a]Million head.

[b]Tg/yr.

CHAPTER IV

PERSISTENCE OF METHANE SUPPRESSION BY AN IONOPHORE AND A GLYCOPEPTIDE IN STEERS FED A BROME HAY DIET

C.F. Saa, T.M. Hill and D.E. Johnson
Department of Animal Sciences
Colorado State University
Fort Collins, CO 80523

Introduction

Foraging animals do not achieve maximum gains because of suboptimal energy intakes associated with forages and/or suboptimal protein nutrition related to ruminal degradation of forage protein. Supplementation of ionophores may serve to improve the animal energy status (Byers, 1980; Wedegaertner and Johnson, 1983) and these and glycopeptides may reduce the wasteful ruminal degradation of forage protein (Schelling, 1984; Ysunza et al., 1991a). Ionophores have been reported to reduce energy losses as methane and VFA shifts noted from the glycopeptides and ardacin also predict lower methane losses. Methane is not only an energy loss to the animal, but also contributes to the warming of our atmosphere (Johnson et al., 1990). Thus, reduction in methane production would benefit the energy status of the animal and possibly help the environment.

Ardacin is a complex glycopeptide antibiotic which possesses an inhibitory effect against Gram positive bacteria. Preliminary *in vitro* studies suggest that ardacin modifies ruminal fermentation primarily by increasing propionate, total VFA production and it reduces methane production (SmithKline Beecham, personal communication), thus improving metabolizable energy available to the animal for production.

The objective of this study was to evaluate the effects of ardacin and monensin on ruminal fermentation, methanogenesis, total tract digestibility and energy partitioning in beef steers fed bromegrass hay.

Materials and Methods

Twelve mixed British breed steers averaging 260 kg were used for the experiment. The animals were dewormed with Ivermectin (Ivomec, 5 cc/head) and intramuscularly injected with a vitamin mixture containing 1,000,000 IU vitamin A; 150,000 IU vitamin D-2; and 2000 IU vitamin E upon arrival to the laboratory. Each animal was housed outdoors, halter broken, gentled and then adapted to indoor laboratory facilities by feeding them in the digestion stalls and the calorimetric chambers for three weeks prior to the beginning of the experiment.

Throughout the experiment, the steers were fed a basal diet composed of 94% bromegrass hay and 6% supplement based on ground corn, a mineral and vitamin mix (Table 1) and the test compound. The diet was formulated to meet NRC (1984) nutrient requirements. The feed offered to each steer was 85% of *ad libitum* intake. This intake was established by averaging the intake of two weeks feeding during the adaptation phase. Eighty-five percent of *ad libitum* intake was offered for three days prior to and during the chamber measurements and during the total tract collection periods.

Table 1. Basal diet composition

Ingredient	% (as-fed)
Bromegrass hay	94.00
Supplement:	
Ground corn	4.27
Sweet 45 lite (dried molasses)	0.46
Vitamin premix[a]	0.93
Mineral premix[a]	0.17
Limestone	0.11
Biofos	0.06
Monensin, 33 mg/kg	±[b]
Ardacin, 33 mg/kg	±[b]

[a]Vitamin premix, Ranch-Way Feeds, Fort Collins, CO. Mineral mix, Ranch-Way Feeds, Fort Collins, CO. Vitamin and contents of the supplement fraction: 1.01% Ca; 0.44% P; 0.06% NaCl; 0.46% K; 0.17% Mg; 444.3 mg/kg Mn; 789.5 mg/kg Zn; 1028.9 mg/kg Fe; 72.6 mg/kg Cu; 57.73 mg/kg I; 28.79 mg/kg Co; 0.26 mg/kg Se; 224,581 IU/kg vitamin A; 149,427 IU/kg vitamin D-3; 13,064 IU/kg vitamin E.

[b]Treatment compounds, not fed in combination. Control group received no treatment compound in the diet.

The steers were offered monensin at 33 mg/kg of diet, ardacin at 33 mg/kg of diet, or no treatment compound (control) in the diet. The desired dose was obtained by diluting monensin or ardacin with the concentrate supplement.

The dilution was 4.10 grams of monensin premix[1] per kg of the supplement mix and 2.17 g of ardacin premix[2] per kg of the supplement premix. The experimental drugs were fed along with the diet twice daily, with half given in the morning and half with the evening meal. The same concentration of supplement +/- treatment compound in the diet was maintained throughout the experiment.

[1]Rumensin premix (60 g active monensin/lb premix).

[2]Ardacin premix (250 mg active ardacin/kg premix).

The design of the experiment is illustrated in Table 2. The twelve steers were stratified according to baseline methane emissions as a percentage of gross energy intake and subsequently paired into four groups identified as high, medium high, medium low and low methane production. One steer from each pair was then randomly assigned to one of three treatment groups designated ardacin, monensin and control.

Table 2. Experimental design for investigation of adaptation and persistence of response to ardacin- or monensin-fed steers

	Treatment											
	Ardacin				Monensin				Control			
	Animal											
Day of trt.	1	4	7	10	2	5	8	11	3	6	9	12
-15	y[a]	y	y	y	y	y	y	y	y	y	y	y
2	x[b]	x	x	x	x	x	x	x	x	x	x	x
3	v[c]	v	v	v	v	v	v	v	v	v	v	v
9	x	x	x	x	x	x	x	x	x	x	x	x
10	v	v	v	v	v	v	v	v	v	v	v	v
16	x	x	x	x	x	x	x	x	x	x	x	x
17	v	v	v	v	v	v	v	v	v	v	v	v
34	x	x	x	x	x	x	x	x	x	x	x	x
35	v	v	v	v	v	v	v	v	v	v	v	v
36	d[d]	d			d	d			d	d		
45	x	x	x	x	x	x	x	x	x	x	x	x
46	v	v	v	v	v	v	v	v	v	v	v	v
50			d	d			d	d			d	d
82	p[e]	p	p	p	p	p	p	p	p	p	p	p
83	v	v	v	v	v	v	v	v	v	v	v	v
92	q[f]	q	q	q	q	q	q	q	q	q	q	q

[a]Each y indicates 2 consecutive 22-hr gas exchange measurements on basal diet.

[b]Each x indicates a 22-hr gas exchange measurement.

[c]Each v indicates a rumen fluid collection.

[d]Each d indicates the beginning of a 7-d digestion trial.

[e]Each p indicates a 22-hr gas exchange measurement at low level of intake.

[f]Each q indicates a 22-hr gas exchange measurement at low level of intake on basal diet after withdrawal of treatment.

Gaseous exchange measurements were made on each steer by indirect respiration calorimetry beginning on day -15, 2, 9, 16, 32, 45, 82 and 92. Wedegaertner and Johnson (1983) provided a description of the calorimetric chamber system utilized. Two consecutive 22-hr measurements were made at d 15 and 22-hr measurements were made at each of the other aforementioned time periods. Feed offered to the animals was changed to a low level of intake (LOI), approximately 1XM after day 82 of the experiment. Measurement at day 92 was performed 10 days after monensin and ardacin were withdrawn from the diet. Heat production (HP) was calculated according to the formula adopted by the EAAP (Brouwer, 1965):

$$HP = 3.866(O_2) + 1.2(CO_2) - 0.518(CH_4) - 1.43(N)$$

where O_2, CO_2 and CH_4 are liters of oxygen consumed, carbon dioxide and methane produced and N is grams of urinary nitrogen. Energy loss as methane was calculated using 9.45 kcal/liter of methane produced (Blaxter and Clapperton, 1965).

The calorimetry chambers were calibrated for oxygen consumed and carbon dioxide produced by the burning of absolute ethanol in alcohol lamps. Three alcohol recoveries were conducted prior to and during chamber measurements.

Feed refusals, if any, were weighed at the end of each chamber measurement. Orts were dried at 60°C, air-equilibrated for two days, and ground in a Wiley mill to pass a 2-mm screen. Approximately 100 grams of ground orts were saved per time period and composited across all time periods.

Two 7-d conventional total collection digestion trials were conducted with six steers during each trial, two steers from each treatment group. Eighteen meals were weighed and presacked for each steer prior to the collection period. Daily rations were stored at 10°C for twice-daily feeding prior to and during the 7-d digestion trials. Grab samples from each of the feedstuffs were obtained during the weighing and sacking process and stored separate for later analysis.

Before the digestion trial, hair around the tail region was clipped to minimize hair contamination. The animals were individually weighed twice before the beginning of the digestion trial and after the completion of the digestion trial.

Feces were collected into a collection pan using a vinyl chute which was attached to the animals by a harness. A 10% aliquot of homogenized feces was collected daily from each steer and stored frozen. Orts were collected daily and refrigerated until the end of the digestion trial. Composited orts were homogenized and dried at 60°C, air-equilibrated for 2 days and ground in a Wiley mill to pass a 2-mm screen. Dried orts were stored for later analysis. Following the seven days of collection, feces were defrosted and homogenized by steer. Approximately 1000 g of homogenized feces were weighed, dried in a 60°C oven, air equilibrated for 2 days, and weighed again for 60°C dry matter (DM) determination. Dried feces were ground in a Wiley mill to pass a 2-mm screen, and approximately 200 g was stored in a tightly capped plastic bottle for later analysis.

Urine was not collected for any of the digestion trials, values for urine output and urinary energy were estimated from the data presented by Benz and Johnson (1982) using a similar diet.

Rumen samples were taken on days 3, 10, 17, 35, 46 and 83 of treatment immediately following chamber measurements of heat and methane 9 hours after feeding. Rumen contents (approximately 300 ml) were collected via vacuum stomach tube. Rumen contents were strained through four layers of cheesecloth and the pH was immediately determined on the fluid. Strained ruminal fluid (50 ml) was acidified with 2 ml of 25% hydrochloric acid per sample and stored frozen for later analysis.

Ground feedstuffs and feces were analyzed individually. Dry matter and ash (AOAC, 1984) were determined sequentially. Gross energy was determined by adiabatic bomb calorimetry[3] (AOAC, 1980). Nitrogen was determined by micro-Kjeldahl (AOAC, 1984). Acid detergent fiber (ADF) was determined as described by Goering and Van Soest (1970).

Concentrated sulfuric acid (1 ml) was added to the hydrochloric acid treated rumen fluid and centrifuged at approximately 2000 x g for 20 minutes. The supernatant analyzed for volatile fatty acids (VFA). Volatile fatty acids were determined by gas chromatography[4] (Erwin et al., 1961). This method of separation involves the physical separation of moving gas phases by the difference of absorption onto a non-volatile liquid. A commercial standard[5] of VFA was used for peak area determination.

Data were analyzed utilizing General Linear Models procedure in SAS (1988). The study was designed to study the treatment by time interaction in a repeated measure design. The statistical analysis has examined time effect, treatment and treatment by pair interaction. Gross energy intake was used as a covariate, and the treatment by pair interaction was used as the error term for the analysis of variance.

Results

Methane losses for steers fed ardacin were reduced ($P < .05$) 9, 14 and 8% relative to the control on days 2, 8 and 16, respectively (Table 3). Methane losses for steers fed monensin were reduced ($P < .05$) 19 and 14% relative to the control on days 2 and 9, respectively. However, by d 34 (ardacin) and as early as d 16 (ardacin), methane production was no longer significantly decreased ($P > .05$) from the control. Ardacin vs monensin treatments did not differ ($P > .05$) from each other in methane production. These gaseous losses ranged from 6 to 8% of diet gross energy.

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[3]Parr Instrument Co., Inc., Moline, IL.

[4]Shimadzu gas chromatograph, Model GC-8A.

[5]Standard, Supelco VFA rumen standard.

Table 3. Methane emissions, methane/GEI

Treatment	-15	2	9	16	34	45	82	92
	Day of treatment							
Ardacin	7.56	7.07	7.38	6.44	6.70	6.05	7.91	7.47
Monensin	7.96	6.17	6.89	6.99	6.37	5.79	7.11	7.34
Control	7.62	7.85	8.03	7.44	6.64	6.53	7.51	7.49

Ruminal pH ranged from 6.9 to 7.1 in nearly all cases and did not differ ($P > .05$) among treatments, however, there was a trend for ardacin-treated steers to maintain higher ruminal pH than control or monensin-treated steers. Ruminal acetate-to-propionate ratios also did not differ ($P > .05$) among treatments (Table 4), but tended to be lower than the control for both ardacin- and monensin-treated steers.

Table 4. Ruminal Acetate/Propionate

Treatment	3	10	17	35	46	83
	Day of treatment					
Ardacin	1.67	2.20	2.43	2.84	2.62	2.97
Monensin	1.85	2.00	2.21	2.47	2.75	2.95
Control	2.45	2.70	2.62	3.21	3.06	3.25

Digestibilities of DM (63%), OM (64%), energy (64%), CP (67%) or ADF (51%) did not differ ($P > .05$) among treatments. Neither did ME, HP or RE differ ($P > .05$) due to treatment, however, there was a trend for both to be greater than the control for ardacin- and monensin-treated steers (Tables 7-9). Maintenance requirements were 19% lower ($P < .05$) for ardacin-treated steers and 11% lower ($P < .05$) for monensin-treated steers compared to the control, but ardacin-treated steers were not different ($P > .05$) from monensin-treated steers. The efficiency of energy use above maintenance did not differ ($P > .05$) due to treatment and averaged .59.

Table 7. Heat production (HP) kcal/MBS

Treatment	-15	2	9	16	34	45	82	92
	Day of treatment							
Ardacin	177.4	179.3	179.8	169.8	157.1	153.9	110.7	108.1
Monensin	174.4	172.4	173.8	170.5	168.5	152.4	112.4	107.9
Control	163.4	173.8	181.1	171.0	158.4	154.4	119.2	110.0

Table 8. Metabolizable energy (ME), kcal/MBS

	Day of treatment							
Treatment	-15	2	9	16	34	45	82	92
Ardacin	188.9	215.6	200.1	221.3	207.6	216.0	100.0	100.5
Monensin	186.6	208.2	201.8	200.4	202.4	202.6	103.4	101.2
Control	183.3	191.4	195.8	201.4	206.8	197.8	99.7	100.0

Table 9. Retained energy (RE), kcal/MBS

	Day of treatment							
Treatment	-15	2	9	16	34	45	82	92
Ardacin	11.48	36.36	20.31	52.47	37.81	62.01	-10.67	-7.55
Monensin	12.15	35.84	28.04	28.92	46.64	50.19	-9.38	-6.66
Control	19.85	17.54	14.78	30.36	48.33	43.34	-19.47	-10.05

Discussion

The lack of persistence in methane suppression in the current experiment with either ardacin or monensin is consistent with data of Omar et al. (1992) and Carmean (1991) with monensin-treated steers consuming greater than 85% concentrate diets. Methane suppression did persist longer with ardacin (16 d) than with monensin treatment.

There was a time effect ($P < .05$) on methane production for all treatments, making it difficult to clearly interpret these data. Methane production declined ($P < .05$) for all treatments with time. Gross energy intake (kcal/d) was increasing with time, however, energy intake per BW was declining with time, negating any level on intake depression on methane production over time.

Consistent with literature data for monensin (Richardson et al., 1976; Bergen and Bates; 1984; Schelling, 1984), acetate-to-propionate ratios were lower than the control for monensin-treated steers. Similarly, the ratio was lower than controls for ardacin-treated steers. However, as with methane production, the acetate-to-propionate ratio changed with time ($P < .05$) for all treatments. Interestingly, the acetate-to-propionate ratio increased with time as methane production decreased with time for all treatments. This phenomenon is inconsistent with the stoichiometric transfer of H_2 described by Czerkawski (1972) that negatively related methane production to propionate concentration in ruminal fluid.

Reductions in maintenance requirements for monensin-treated animals have been reported by Byers (1980) and Wedegaertner and Johnson (1983). Maintenance requirements were reduced relative to the control by 11% for monensin-treated steers and 19% for ardacin-treated steers in the current study.

Lack of differences in digestibility measurements, metabolizable energy and retained energy may have been due to the design of restricted intake. Both monensin and avoparcin, a glycopeptide similar to ardacin, have been reported to alter ruminal kinetics at *ad libitum* intakes. Delany and Ellis (1983) reported increased ruminal fractional turnover of solid, liquid and microbial phases with 100 mg/head daily of monensin supplemented to cows grazing bermudagrass resulting in modest depressions in digestibility. Similarly, Chapula et al. (1981) reported an increase in fractional turnover of the liquid phase in heifers fed a 75% concentrate diet with avoparcin. Ysunza et al. (1991a) reported a linear increase in forage OM digestibility (OMD) with daily doses of up to 120 mg/head of ardacin to calves grazing bermudagrass (15% CP, 56% OMD with no ardacin). However, Ysunza et al. (1991b) observed no differences in digestibility to titrated doses of ardacin up to 240 mg/head daily as supplemented to either calves grazing lower quality (14% CP, 49% OMD) or higher quality forage (16% CP, 61% OMD). Ardacin depressed ruminal OMD at the 60 mg/head daily doses, but increased ruminal OMD at the 120 mg/head daily doses relative to no ardacin (Ysunza et al., 1991a), suggesting that ardacin affects ruminal digestibility and hindgut compensation occurs.

Ruminal digestion of protein was not examined in this study. However, both monensin (Schelling, 1984) and ardacin (Ysunza et al., 1991a) have been reported to spare catabolism of forage protein by ruminal microbes. Ysunza et al. (1991b) reported gain responses to ardacin carried by a 34% protein supplement to calves grazing lower quality pasture (14% CP, 49% OMD), but not when grazing higher quality pasture (16% CP, 61% OMD). However, when ardacin was carried in a corn-based supplement (8% CP), a gain response to ardacin was observed on the higher quality pasture (16% CP, 61% OMD). Gains of calves receiving the .45 kg daily of the low protein supplement with 60 mg/head of ardacin had gains equal to calves receiving .45 kg daily of the 34% CP supplement with no ardacin. Thus, the protein sparing effect of ardacin was improving daily gain.

Implications

Gain responses to monensin or ardacin supplemented to foraging cattle can be attributed to a reduction in maintenance requirements of the animal as observed in this study and to a ruminal protein sparing effect as observed in other literature citations. Reductions in methane production of monensin- and ardacin-treated cattle consuming forage can be expected only in the first two weeks of treatment. Beyond two weeks, no reduction in methane production can be expected from either monensin or ardacin.

Literature Cited

AOAC. 1980. Official Methods of Analysis. (13th Ed.) Association of Official Analytical Chemists, Washington, D.C.

AOAC. 1984. Official Methods of Analysis. (14th Ed.) Association of Official Analytical Chemists, Washington, D.C.

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

Bergen, W.G. and D.B. Bates. 1984. Ionophores: Their effect on production efficiency and mode of action. J. Anim. Sci. 58:1456.

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

Brouwer, E. 1965. Report of subcommittee on Constraints and Factors. Proc. of 3rd Inter. Symp. on Energy Met. EAAP. Pub. No. 11:441.

Byers, F.M. 1980. Determining effects of monensin on energy value of corn silage diets for beef cattle by linear or semi-log methods. J. Anim. Sci. 51:158.

Carmean, B.R. 1991. The persistence of monensin effects. M.S. Thesis. Colorado State University, Fort Collins.

Chapula, W., C. Oppegard, H.C. Williams, B. Bloch and G. Perkins. 1981. Effect of avoparcin on rumen environment and fermentation. J. Anim. Sci. 53(Suppl. 1):387 (Abstr.).

Czerkawski, J.W. 1972. Fate of metabolic hydrogen in the rumen. Proc. Nat. Soc. 31:141.

Delaney, D.S. and W.C. Ellis. 1983. Intraruminal responses to monensin in grazing cattle. J. Anim. Sci. 57(Suppl. 1):428 (Abstr.).

Erwin, E.S., G.L. Marco and E.M. Emery. 1961. Volatile fatty acid analysis of blood and rumen fluid by gas chromatography. J. Dairy Sci. 44:1768.

Goering, H.K. and P.J. Van Soest. 1970. Forage fiber analyses (apparatus, reagents, procedures and some applications). Agric. Handbook 379. ARS, USDA.

Johnson, D.E., M. Branine and G.M. Ward. 1990. Methane emissions from livestock. Proc. Nutr. Symp. Amer. Feed Ind. Assoc., Arlington, VA.

NRC. 1984. Nutrient Requirement of Domestic Animals, Revised 6th Ed. Nutrient Requirements of Beef Cattle. National Academy of Sciences, Washington, D.C.

Omar, J.A., D.E. Johnson, K.A. Johnson, B.R. Carmean and T.M. Hill. 1992. Methane losses by steers fed ionophores singly or alternatively. J. Anim. Sci. (submitted).

Richardson, L.F., A.P. Raun, E.L. Potter and C.O. Cooley. 1976. Effect of monensin in rumen fermentation *in vitro* and *in vivo*. J. Anim. Sci. 43:657.

SAS. 1988. SAS User's Guide: Statistics. Version 6th Ed. SAS Institute, Inc., Cary, NC.

Schelling, G.T. 1984. Monensin mode of action in rumen. J. Anim. Sci. 58:1518.

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.

Ysunza, F., T.M. Hill, W.C. Ellis and T. Lindsey. 1991a. Effect of level of Ardacin on digestibility and duodenal protein flow in calves grazing bermudagrass pasture. J. Anim. Sci. 69(Suppl. 1):66 (Abstr.).

Ysunza, F., W.C. Ellis, C.B. Madden and T. Lindsey. 1991b. Effects of Ardacin upon growth of cattle grazing pastures of varying nutritional content. J. Anim. Sci. 69(Suppl. 1):265 (Abstr.).

CHAPTER V

INTAKE LEVEL AND DIGESTIBILITY EFFECTS ON METHANE LOSSES BY CATTLE[1]

T.M. Hill, D.E. Johnson, M.E. Branine[2] and G.M. Ward
Metabolic Laboratory
Department of Animal Sciences
Colorado State University
Fort Collins, CO 80523

Abstract

Observations of direct measurements of methane emissions by beef cattle were collected from the literature and entered into a spreadsheet to reexamine its predictability from consumption and general diet descriptions. Methane production as a percentage of gross energy intake was negatively correlated ($P < .05$) to level of intake as a multiple of maintenance (LOI), gross energy intake per metabolic body size (GEI, Mcal) and digestible energy intake per metabolic body size (DEI, Mcal). Methane production also appeared related ($P < .1$) to percentage of concentrate in the diet. Empirical equations using multiple regression were developed that had a greater R^2 than predictions using the classical equation of Blaxter and Clapperton ($R^2 = .23$). The relationship between methane and digestible energy ($R^2 = .01$) was not as strong as that between methane and LOI ($R^2 = .27$). Relating methane to three descriptors of level of intake produced similar R^2. Equations for methane prediction from gross energy intake and digestible energy for groupings 0 to 20, > 20 to 80 and > 80% dietary concentrate were: 7.38 - 9.14 GEI + .0218 DE, 10.52 - 8.81 GEI - .0119 DE and 12.22 - 9.45 GEI - .0505 DE, respectively. The coefficient adjusting for intake is relatively constant for low and high concentrate diets (-8.8 to -9.5) while the coefficient adjusting for digestible energy changes from positive .02 with low concentrates diets to negative .05 with high concentrate diets. Empirical approaches that are presently available to predict methane production from cattle are not very accurate. Methane production as a percentage of gross energy intake characteristically declines approximately two percentage units for each multiple of maintenance that intake increases.

Key Words: Methane, Beef Cattle, Prediction, Energy

Introduction

Characterization of energy availability to ruminants from their diets requires quantitation of methane losses. Because methane is a gaseous loss its measurement requires specialized equipment, uncommon to most nutrition laboratories. Therefore a

[1]Supported in part by NASA, Terrestrial Ecosystems Div.

[2]Present address, SmithKline Beecham, Animal Health Div., West Chester, PA 19380

calculated methane production provides the basis for most feedstuff metabolizable energy values and to a degree, other energy values derived from them (i.e., NEm and NEg). Prediction of methane losses from ruminants also has recently become important because of methane's contribution to global warming (IPCC, 1990).

The equation of Blaxter and Clapperton (1965), which relates methane loss to the dietary digestible energy and level of intake relative to maintenance, is often used to calculate methane production in cattle and sheep. This equation predicts methane yield, methane energy as a percentage of dietary gross energy, and is based on data from both cattle and sheep. Early research related methane production to dry matter intake in cattle (Kriss, 1930) or carbohydrate digested in cattle (Bratzler and Forbes, 1940) and sheep (Swift et al., 1948). Later, Moe and Tyrrell (1979) related methane loss to hemicellulose, cellulose and cell solubles consumed and digested in dairy cattle. With the exception of the work of Moe and Tyrrell (1979), all of these equations were based on a narrow range of intakes and frequently lower intakes than are found in commercial practice.

The objective of this research was to test the accuracy and applicability of the Blaxter and Clapperton (1965) equation for contemporary diets and to develop other prediction equations for methane production as a percentage of gross energy intake for a wide range of diets and levels of intake. Multiple regression was used to relate various nutritional factors to methane production as a percentage of gross energy intake.

Materials and Methods

Treatment means for methane as a percentage of gross energy intake (CH4) were collected from the literature (Table 1). Other variables included were percentage of concentrate in the diet (CON), BW (kg), DMI (kg/d), DE (%), gross energy intake (Mcal/d) per $BW^{.75}$ (GEI), digestible energy intake (Mcal/d) per $BW^{.75}$ (DEI) and level of intake as a multiple of maintenance (LOI).

Calculations of LOI were made in a manner attempting to most similarly reproduce those of Blaxter and Clapperton (1965). Since animal age was often not available to select Blaxter's "preferred" fasting heat production (ARC, 1965), animal weight was used to predict the animal's fasting heat production (FHP) according to MAFF (1976). The equation used was:

$$LOI = MEI / (FHP / k_m)$$

where MEI was metabolizable energy intake (Mcal/d)

$$FHP, (Mcal/d) = 1.36 + (.0146\ BW)$$
$$k_m = .35\ ME + .503)$$

where ME = Mcal ME of diet ÷ diet gross energy.

Note: The ME of the diet as measured at one times maintenance was used, as intended, when possible.

All variables were used to identify the optimum prediction of CH4 using FORWARD, BACKWARD, MAXR, MINR and STEPWISE selection methods in the REG procedure of SAS (1986). Based on maximum R^2 and minimum C_{press} statistics, the best model was chosen. Alternative models with poorer statistics are presented, along with simple linear regressions of CH4 vs LOI, DE and CON.

The equation of Blaxter and Clapperton (1965; B/C) was used to predict CH4 from the variables LOI and DE and compared to observed values in the database. Additionally, a group of references, not included in the presently developed equations were used to evaluate equation reliability.

From those references where individual observations were available and minimum LOI was .75 or less of maximum LOI, simple regressions of CH4 vs LOI were made to compare variability within experiments to variability across experiments.

Results

Respiration calorimetry observations of methane production (Table 1) from 118 treatment group means reported in 25 cattle experiments ranged from 2.6 to 11.5% of diet gross energy. The range was broader, from 3.3 to 16.7% if expressed as percentage of DE. Treatment groups receiving methane inhibitors other than ionophores were excluded. Both the lowest and highest percentage methane losses occurred when cattle were fed high concentrate diets. The higher percentage losses only occurred when measurements were made at restricted intakes of some of these diets.

The diets evaluated in these experiments ranged from 0 to 100% concentrate reflecting a digestibility range from 50 to 88% DE (Table 2). The diet intakes ranged from 2 to 11 kg DM/d, resulting in an LOI range of .4 to 2.9 times maintenance.

An evaluation of methane predictability revealed several equations (Table 3) that were significant (P < .05). Animal body weight, DMI and percentage of diet concentrate were not significant (P > .05). Diet concentrate percentage, however, neared significance (P < .1) in some equations. Thus, equations in Table 3 and 4 are presented separately for each range of diet concentrate. Within most concentrate groupings, DE in addition to LOI in equations predicting methane yield improved the R^2 value. However, for regressions encompassing CON levels, DE did little to improve the R^2 when compared to predictions using only a measure of intake level. The R^2 for all predictive relationships were moderate to low. The best relationships (R^2 = .40 to .57) were found within the low concentrate-high forage dietary groupings.

Without DE in the model, the slopes for LOI differed (P < .05) and were -1.71, -1.84 and -2.14 for CON divisions of 0 to 20, 20 to 80 and 80 to 100, respectively. The overall slope (0 to 100 CON) was -1.84. The effect of DE on CH4 was +.06, -.02 and

-.01 when added to LOI for 0 to 20, 20 to 80 and 80 to 100 CON groupings, respectively. The effect of LOI on CH4 was greater ($P < .05$) than the effect of DE on CH4.

The effect of LOI on CH4 within individual experiments where LOI changed by at least 25% and individual observations were available and regression was highly variable (Table 5). Slopes of CH4 vs LOI ranged from -4.75 to -.95. The average slope of these experiments was -2.03.

Where either GEI or DEI were used in place of LOI in methane prediction equations, the R^2 values were similar. Simple regression coefficients predicting CH4 losses where all negatives ranging from -8 to -9 when related to GEI and from -9 to -12 for DEI, respectively.

When utilizing equation selection procedures in SAS, the best one parameter model was CH4 = 9.49 - 1.84 LOI. The best two parameter model was CH4 = 10.32 - 1.79 LOI - .0112 DE. Additional parameters were not significant ($P > .10$).

Discussion

The complexity of factors affecting methane loss is illustrated by the lack of relationship ($R^2 = .03$) of methane yield and diet DE (Figure 1) and the generally negative but moderate correlation ($R^2 = .31$) to amount or level of diet consumed daily (Figure 2). The use of both DE and LOI as independent variables in a multiple regression to predict methane loss was of little value over LOI alone, considering the overall data set. The R^2 of regressions was improved within subclass of some concentrate groupings, particularly for low CON groups of diets. Generally, DE was positively related to CH4 loss within zero or low CON groups and negatively related to methane within high CON groups.

In light of the poor relationship of CH4 to DE and the variation associated with the negative relationship of CH4 to LOI, it is not surprising that there was a poor relationship ($R^2 = .23$) between CH4 predicted with B/C equation and observed methane (Figure 3). The appearance of a changing CH4 to DE relationship from positive to negative with increasing CON may lead to poor fit with a single equation, especially if the equation was based on a narrow range of dietary conditions as was the case with the B/C equation. Our best equation across all diets (#5, Table 3) was of similar accuracy.

Prediction of CH4 vs observed values for the equation CH4 = 10.32 - 1.79 LOI - .0012 DE yielded a very poor fit ($R^2 = .27$). The range of predicted values was considerably smaller than the range (approximately 4.5 to 10%) of observed values (2.6 to 11.5). A better, yet still poor, fit was observed when a series of equations (#10, #15, #20, Table 3) for CH4 vs DE and GEI were used for CON groupings of 0 to 20, 20 to 80 and 80 to 100% CON ($R^2 = .32$).

The ability of equation 10, 15 and 20 to predict CH4 was examined by comparison to observed percentage of CH4 from randomly selected references not used in developing the equations. The R^2 of predicted to observed was .37, similar to that of the original equation suggesting at least some repeatability when applied to other data.

Poor fit associated with all equations using LOI, DE and sometimes including CON, suggests other variables, besides these three, affect CH4. Moe and Tyrrell (1979) found that methane production from dairy cattle was greatest from the digestion of cellulose, followed by hemicellulose and was least from digestion of cell solubles. This type of carbohydrate effect was much greater at high than at low levels of intake. However, Czerkawski and Breckenridge (1969) concluded from in vitro trials that methane production was not related to type of carbohydrate but rather the quantity fermented. Moe and Tyrrell (1979) further suggested that the type of carbohydrate effect might be partially explained by site of digestion differences (ruminal fermentation vs intestinal enzymatic digestion). The possibility exists that a greater turnover at higher intakes increases the ruminal escape, thus reducing the ruminal fermentation, of concentrates (cell solubles) more than fiber fractions (Hill et al., 1991). High intakes of rapidly fermentable carbohydrates may also influence pH and thus microbial species.

Possibly, factors such as the digestibility and site of digestion of various carbohydrate fractions should be included in prediction equations for methane production. However, measurements of this nature combined in the same experiments with methane measurements are very limited.

When a series of prediction equations for partitions of CON were used for either LOI or LOI and DE or the B/C equation and used to predict CH4 for different beef cattle classes, CH4 appeared to differ by class (Table 6). Fattening cattle were projected to produce 4.2% CH4 compared to growing cattle (6.5% CH4) using equations containing both LOI and DE. The B/C equation projected a narrower range of CH4 across classes of cattle than our equations.

The variable CON may be an inappropriate variable to use since methane production among concentrates may be related to fermentable sugar or starch content. Data of Wainman et al. (1984) would suggest that CH4 may be greater with highly fermentable feeds, such as cassava and barley, and lower with low starch feeds, such as distiller's grains and corn gluten feed.

Additionally, the use of nonfermentable fractions of feeds may be an important consideration in predicting CH4. For example, Giger-Reverdin et al. (1990) has included ether extract as a variable affecting methane production. With their equation, feeds with a higher ether extract proportion are projected to have lower losses of energy as methane.

Similarity in R^2 values for equations using either LOI or GEI suggests there is little difference in these two means of expressing intake energy and relating intake energy to CH4. Considering the extreme variation in these data, either means of expressing intake energy would seem appropriate. Expressing intake energy in the manner of a multiple of maintenance is very tedious and subject to errors of interpretation because often the data needed to calculate LOI are not clearly available. Thus, a simple calculation of intake energy such as GEI is readily available and less confusing to apply.

Implications

The empirical approaches available to relate methane production by cattle to measures of diet type, digestibility and/or intake are not very accurate, reflecting the complex array of factors affecting microbial digestion. Certainly, level of intake and digestible energy are related to methane production, however, precise prediction awaits elucidation from simultaneous measurement of production and control factors. For the present, adjustments for level of intake should be made with the global factors of 1.8 times level of intake per multiple of maintenance or 9 times daily gross energy intake expressed in Mcal per $BW^{.75}$.

Literature Cited

ARC. 1965. The Nutrient Requirements of Farm Livestock. No. 2. Ruminants. H.M.S.O.

Abo Omar, A. 1989. Methane losses by steers fed ionophore singly or alternatively. Ph.D. Dissertation. Colorado State Univ., Fort Collins.

Armsby, H. P. and J. A. Fries. 1915. Net energy values of feeding stuffs for cattle. J. Agric. Res. 3:435.

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

Birkelo, C. P. 1988. Seasonal changes in energy metabolism of cattle in Colorado. Ph.D. Dissertation. Colorado State Univ., Fort Collins.

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

Blaxter, K. L. and F. W. Wainman. 1961. The utilization of food by sheep and cattle. J. Agric. Sci. (Camb.) 57:419.

Blaxter, K. L. and F. W. Wainman. 1964. The utilization of the energy of different rations by sheep and cattle for maintenance and for fattening. J. Agric. Sci. (Camb.) 63:113.

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

Bratzler, J. W. and E. B. Forbes. 1940. The estimation of methane production by cattle. J. Nutr. 19:611.

Byers, F. 1974. The importance of associative effects of feeds on corn silage and corn grain net energy values. Ph.D. Dissertation. Colorado State Univ., Fort Collins.

Cammell, S. B., D. J. Thomson, D. E. Beever, M. J. Haines, M. S. Dhanoa and M. C. Spooner. 1986. The efficiency of energy utilization on growing cattle consuming fresh perennial ryegrass or white clover. Br. J. Nutr. 55:669.

Carmean, B. R. 1991. The persistence of monensin effects on ruminal fermentation and nutrient digestion in steers. M.S. Thesis. Colorado State Univ., Fort Collins.

Colovus, N. F., J. B. Holter, R. M. Koes, W. E. Urban, Jr. and H. A. Davis. 1970. Digestibility, nutritive value and intake of ensiled corn plant (*Zea mays*) in cattle and sheep. J. Anim. Sci. 30:819.

Czerkawski, J. W. and G. Breckenridge. 1969. Fermentation of various soluble carbohydrates by rumen microorganisms with particular reference to methane production. Br. J. Nutr. 23:925.

Delfino, J., G. W. Mathison and M. W. Smith. 1988. Effect on lasalocid on feedlot performance and energy partitioning in cattle. J. Anim. Sci. 66:136.

Forbes, E. B., W. W. Braman, M. Kriss, J. A. Fries, C. D. Jeffries, R. W. Swift, R. B. French and J. V. Maucher. 1927. Net energy values of corn silage, soybean hay, alfalfa hay and oats. J. Agric. Res. 34:785.

Forbes, E. B., W. W. Braman, M. Kriss and R. W. Swift. 1933. The associative effects of feeds in relation to the utilization of feed energy. J. Agric. Res. 46:8.

Forbes, E. B., J. A. Fries and W. W. Braman. 1925. Net energy values of alfalfa hay and alfalfa meal. J. Agric. Res. 10:987.

Giger-Riveverdin, S., J. Aufrere, D. Sauvant, C. Demarquilly, M. Vermorel and S. Pochet. 1990. Prevision de la valeur energetique des alimets composes pour les ruminants. INRA Prod. Anim. 3:181.

Hashizume, T., H. Morimoto, T. Haryu, M. Itch and S. Tanabe. 1967. Utilization of the energy of fattening rations containing ground or steam-rolled barley by Japanese Black Breed cattle. Eur. Assoc. Anim. Proc. Publ. 12:261.

Hill, T. M., W. C. Ellis, J. H. Matis and F. M. Rouquette, Jr. 1991. Differential turnover of digesta entities. p. 190. Proc. 2nd Grazing Conf., Steamboat Springs, CO.

IPPC. 1990. Intergor Panel on Climate Change. Scientific Assesment of Climate Change. World Meteorological Org., Cambridge Univ. Press.

Johnson, D. E. 1966. Utilization of flaked corn by steers. Ph.D. Dissertation. Colorado State Univ., Fort Collins.

Kappelman, P. 1980. The effect of limestone on energy partitioning by feedlot steers. M.S. Thesis. Colorado State Univ., Fort Collins.

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.

Lapierre, H., H. F. Tyrrell, C. K. Reynolds, T. H. Elsasser, P. Gaudreau and P. Brazeau. 1992. Effect of growth hormone-releasing factor and intake on energy metabolism in growing beef steers: Whole body energy and nitrogen metabolism. J. Anim. Sci. 70:764.

MAFF. 1976. Energy allowances and feeding systems for ruminants. Technical Bulletin 33. Ministry of Agriculture, Fisheries and Food. London.

Mitchell, H. H., T. S. Hamilton and W. T. Haines. 1940. The utilization by calves of energy in rations containing different percentages of protein. J. Agric. Res. 61:847.

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

SAS. 1986. SAS User's Guide: Statistics, 6th Edition. SAS Inst., Inc., Cary, NC.

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.

Terada, F., K. Iwasaki, R. Tano, M. Itoh and K. Kameoka. 1985. Comparison of metabolizability and metabolizable energy contents among cattle, sheep, and goats fed the same diets. Eur. Assoc. Anim. Prod. Publ. 32:130.

Tyrrell, H. F. and C. K. Reynolds. 1989. Effect of stage of growth on utilization of energy by beef heifers. Eur. Assoc. Anim. Prod. Publ. 43:17.

Wainman, F. W., P. J. S. Dewey and A. C. Brewer. 1984. Feedingstuffs Evaluation Unit, 4th Report. Department of Agriculture and Fisheries for Scotland, Edinburgh.

Wainman, F. W., J. S. Smith and P. J. S. Dewey. 1979. The predicted and observed metabolizable energy values of mixtures of maize silage and barley fed to cattle. Eur. Assoc. Anim. Prod. Publ. 26:55.

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.

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

TABLE 1. OBSERVED RANGES IN METHANE PRODUCTION EXPRESSED AS A PERCENTAGE OF GROSS ENERGY INTAKE (GEI) AND DIGESTIBLE ENERGY INTAKE (DEI) FROM THE REFERENCES USED IN DEVELOPING THE REGRESSION EQUATIONS AND REFERENCES USED IN CHECKING THE EQUATIONS

Reference	Per GEI	Per DEI
Developing		
Johnson (1966)	3.07-4.35	3.93-5.85
Birkelo et al. (1986)	5.90-6.47	10.69-10.75
Byers (1974)	2.58-7.80	3.30-11.53
Birkelo (1988)	3.17-6.79	4.48-9.58
Wedegaertner and Johnson (1983)	3.95-6.36	5.52-8.52
Benz and Johnson (1982)	5.55-6.25	9.34-10.14
Whitelaw et al. (1984)	6.68-11.45	8.00-13.44
Blaxter and Wainman (1961)	7.67-8.67	10.90-12.40
Blaxter and Wainman (1964)	3.40-9.28	3.96-12.38
Kappelman (1980)	4.70-6.20	6.33-7.76
Armsby and Fries (1915)	5.99-9.52	9.92-13.71
Tyrrell and Reynolds (1989)	3.50-7.50	4.49-12.14
Hashizume et al. (1967)	8.40-11.00	12.04-16.72
Wainman et al. (1979)	7.50-8.10	10.07-10.20
Terada et al. (1985)	6.00-7.80	9.84-13.59
Abo Omar (1989)	4.41-5.06	5.19-6.11
Mitchell et al. (1940)	6.13-7.41	8.65-14.62
Delfino et al. (1988)	5.10-10.20	6.55-14.53
Cammell et al. (1986)	6.15-6.48	8.14-8.60
Forbes et al. (1933)	7.20-8.61	10.95-14.42
Checking		
Lapierre et al. (1992)	5.41-7.52	7.03-9.39
Forbes et al. (1925)	5.87-6.73	10.42-11.07
Forbes et al. (1927)	4.89-11.10	7.56-15.61
Colovus et al. (1970)	5.87-6.72	8.48-10.17
Carmean et al. (1991)	4.20-4.39	5.24-5.88

TABLE 2. MINIMUM, MAXIMUM AND MEAN VALUES FOR VARIABLES INCLUDED IN THE DATABASE

Variable	Minimum	Maximum	Mean
Concentrate, %	0	100	49
Body weight, kg	217	627	402
Metabolic body size, $kg^{.75}$	57	125	89
Dry matter intake, kg/d	2.1	10.9	5.4
Digestible energy, %	50.4	87.8	70.6
Gross energy intake, Daily Kcal/$BW^{.75}$	95	457	272
Digestible energy intake, Daily Kcal/$BW^{.75}$	63	323	193
Level of intake, multiple of maintenance	.4	2.9	1.5
Observed methane, % gross energy	2.6	11.5	6.8
Observed methane, % digestible energy	3.3	16.7	9.8

TABLE 3. PREDICTION EQUATIONS OF METHANE LOSS AT VARIOUS LEVELS OF CONCENTRATE IN BEEF CATTLE DIETS

Equation No.	% diet conc.	CH4 = Equation[a]	R^2
1	0-100	9.1 - 8.23 GEI	.18
2		9.1 - 11.97 DEI	.21
3		9.5 - 1.84 LOI	.31
4		11.0 - 8.35 GEI - .03 DE	.20
5		10.3 - 1.79 LOI - .01 DE	.31
6	0-20	9.1 - 8.55 GEI	.51
7		8.5 - 9.51 DEI	.40
8		9.1 - 1.71 LOI	.57
9		7.8 - 9.14 GEI + .02 DE	.54
10		5.5 - 2.25 LOI + .06 DE	.57
11	> 20-80	9.6 - 8.66 GEI	.21
12		9.8 - 13.10 DEI	.23
13		9.8 - 1.84 LOI	.27
14		10.5 - 8.81 GEI - .01 DE	.22
15		11.3 - 1.81 LOI - .02 DE	.27
16	> 80	7.9 - 8.01 GEI	.12
17		8.2 - 11.91 DEI	.13
18		8.9 - 2.14 LOI	.17
19		12.2 - 9.54 GEI - .05 DE	.14
20		9.9 - 1.54 LOI - .01 DE	.18

[a]GEI = daily gross energy intake (Mcal) per $BW^{.75}$, DEI = daily digestible energy intake (Mcal) per $BW^{.75}$, LOI = level of intake calculated as per Baxter and Clapperton (1965) but using MAFF (1976) linear equation to predict fasting heat production, DE = digestible energy (percent). For 0 to 100% CON, n = 118; for 0 to 20% CON, n = 32; for > 20 to 80% CON, n = 64; for > 80% CON, n = 22.

TABLE 4. RELATIONSHIP OF METHANE PRODUCTION PER GROSS ENERGY INTAKE (CH4) TO LEVEL OF INTAKE RELATIVE TO MAINTENANCE (LOI) WITHIN INDIVIDUAL EXPERIMENTS THAT LOI CHANGED BY AT LEAST 25%

		Equation[c]					
Reference[a]	CON[b]	Yint	Slope(b)	SE of b	P > F	CH4 at 1 M[d]	DE at 1 M[e]
7	60	9.73	-2.44	0.39	0.01	7.29	71
7	60	9.74	-2.80	0.63	0.01	6.94	72
7	60	7.95	-2.18	0.36	0.01	5.77	71
7	60	9.45	-2.71	0.44	0.01	6.74	72
7	60	9.81	-2.71	0.88	0.02	7.10	71
8	85	8.31	-1.29	0.49	0.02	7.02	77
9	10	7.64	-1.11	0.24	0.01	6.53	61
11	33	9.21	-1.04	0.27	0.01	8.17	65
12	0	8.51	-0.95	0.33	0.05	7.56	62
12	20	9.52	-1.25	0.60	0.10	8.27	68
12	40	9.74	-1.07	0.90	0.30	8.67	74
12	60	10.67	-1.79	0.12		8.88	76
12	80	12.58	-4.75	1.05	0.01	7.83	82
12	95	6.53	-1.88	1.26	0.21	4.65	87
41	80	9.36	-2.07	0.38	0.01	7.29	81
41	80	7.23	-0.95	0.51	0.09	6.28	76
86	50	9.92	-1.54	0.47	0.08	8.38	62
86	42	8.79	-0.95	1.33	0.55	7.84	62

[a]References: 7 = Birkelo (1988), 8 = Wedegaertner an Johnson (1983), 9 = Benz and Johnson (1982), 11 = Blaxter and Wainman (1961), 12 = Blaxter and Wainman (1964), 41 = Kappelman (1980), 86 = Forbes et al. (1933).

[b]Percentage of concentrate of the diet.

[c]Equation of percentage of CH4 vs LOI. Yint = y intercept, SE = standard error.

[d]Percentage of CH4 at one times maintenance.

[e]Digestible energy (%) at one times maintenance.

TABLE 5. PREDICTIONS OF METHANE LOSSES FROM TYPICAL CLASSES OF BEEF CATTLE USING EQUATIONS IN TABLE 3 AND EQUATIONS OF BLAXTER AND CLAPPERTON[a]

Class	Gain (lbs)	Daily ME intake (Mcal)	Diet DE (%)	LOI[b]	Percentage of CH4 predicted by: LOI	DE-LOI	B/C
Cow, maintenance	0	15.5	48	1.1	7.2(8)[c]	5.9(5)	6.6
Cow, lactation	0	20.3	56	1.5	6.5(8)	5.5(5)	6.9
Growing	.7	17.2	63	2.0	6.2(13)	6.5(15)	6.8
Fatten	1.4	21.1	84	2.6	4.4(18)	4.2(20)	5.0

[a]NRC (1984) requirements by class. Equation of Blaxter and Clapperton (1965; B/C) is percentage of CH4 = 1.30 + .112 DE + LOI (2.37 - .05 DE).

[b]Level of intake (LOI) calculated as per Blaxter and Clapperton (1965) but using the MAFF (1976) linear equation to predict fasting heat production.

[c]Equation number from Table 3 used in estimation of CH4.

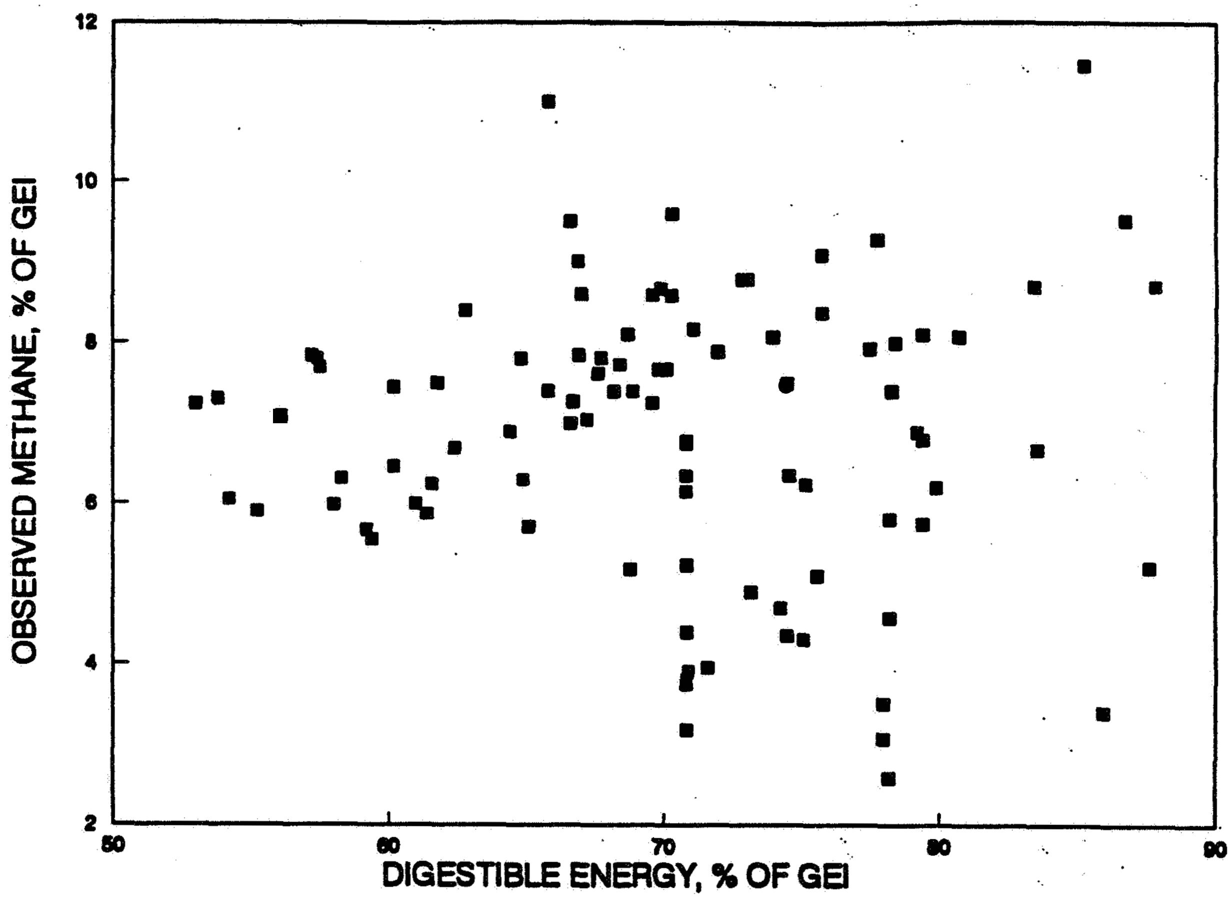

Figure 1. Observed production of methane versus digestible dietary energy. Methane = 9.6 - .038 digestible energy, R^2 = .03, P < .01.

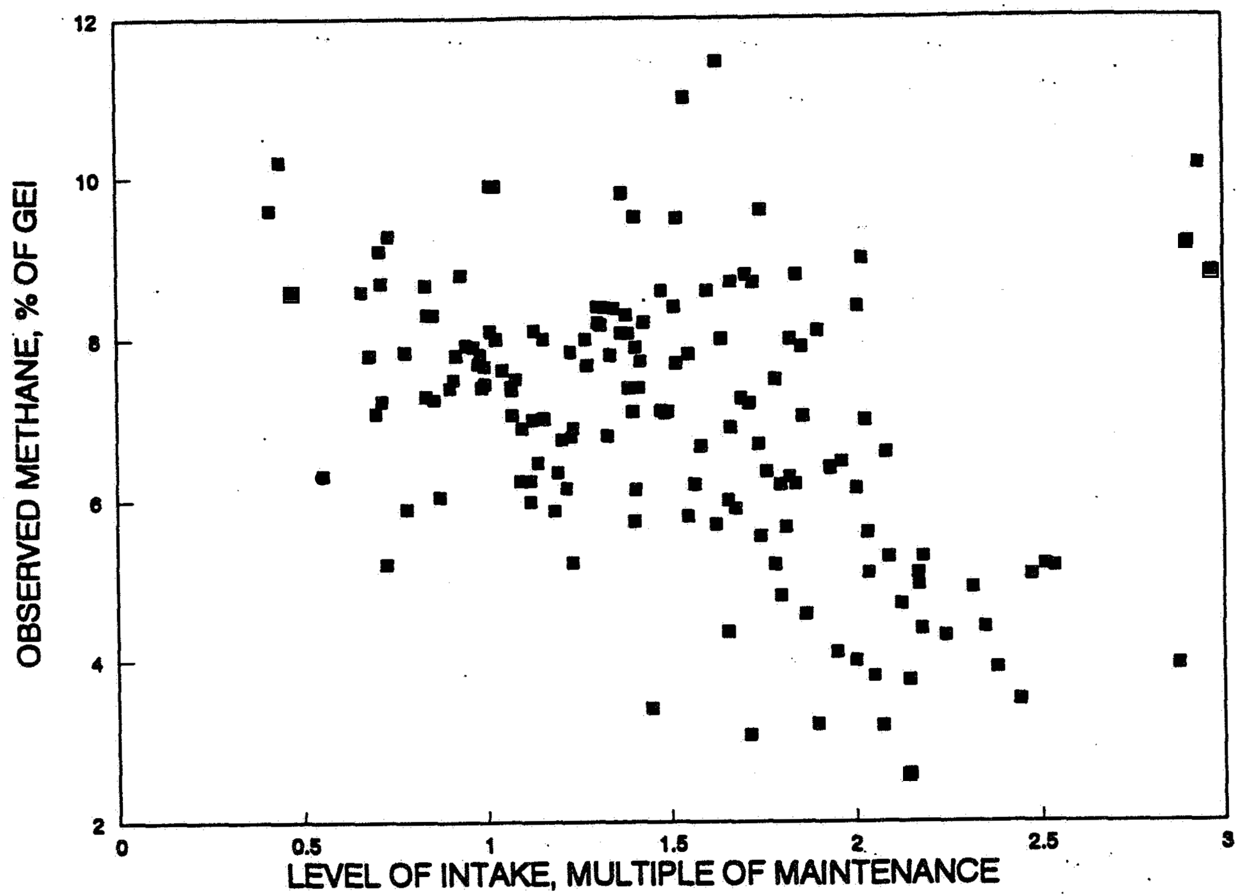

Figure 2. Observed production of methane versus level of intake as a multiple of maintenance. Methane = 9.5 - 1.84 level of intake, R^2 = .31, P < .01.

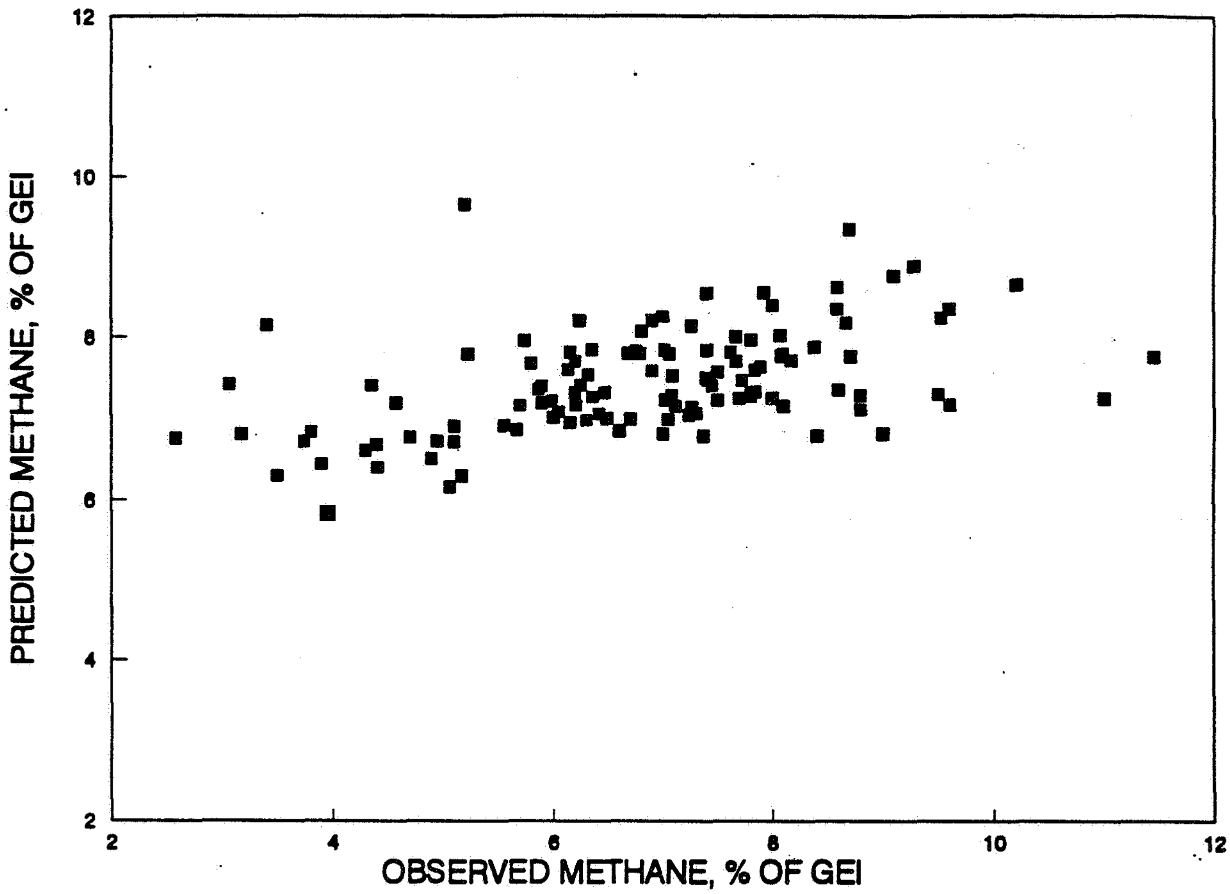

Figure 3. Methane production as predicted by the equation of Blaxter and Clapperton (1965) verses observed methane production. Predicted = 6.2 + .18 observed, R^2 = .23, P < .01.

TABLE 6. REGRESSION EQUATIONS RELATING METHANE PRODUCTION PER UNIT GROSS ENERGY INTAKE (CH4) TO LEVEL OF INTAKE RELATIVE TO MAINTENANCE (LOI) AND PERCENTAGE OF DIGESTIBLE ENERGY (DE) GROUPED BY PERCENTAGE OF CONCENTRATE IN THE DIET (CON)

Equation No.	% CON	Equation, percentage of CH4	R^2	n
21	0-10	8.6 - 1.45 LOI	.48	25
22		4.4 - 2.15 LOI + .02 DE	.70	25
23	> 10-20	7.9 - 1.58 LOI	.02	7
24		2.3 - 1.86 LOI + 0.98 DE	.42	7
25	> 20-30	8.2 - .88 LOI	.34	9
26		8.2 - .88 LOI - .01 DE	.34	9
27	> 30-40	9.6 - 1.30 LOI	.81	7
28		1.8 - .85 LOI + .10 DE	.95	7
29	> 40-50	6.8 - .68 LOI	.24	4
30		4.2 - .20 LOI + .05 DE	.95	4
31	> 50-60	9.7 - 2.07 LOI	.25	19
32		5.4 - 1.95 LOI - .06 DE	.27	19
33	> 60-70	6.3 + 1.35 LOI	.10	12
34		1.6 + 1.49 LOI + .06 DE	.23	12
35	> 70-80	10.9 - 2.25 LOI	.32	13
36		29.1 - 2.93 LOI - .23 DE	.64	13
37	> 80-90	8.6 - 2.59 LOI	.27	16
38		12.2 - 1.47 LOI - .05 DE	.31	16
39	> 90-100	6.9 - .70 LOI	.01	6
40		-3.6 - .35 LOI + .12 DE	.04	6
41	0-100	9.5 - 1.84 LOI	.31	118
42	0-100	10.4 - 1.79 LOI - .01 DE	.31	118

CHAPTER VI

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LIVESTOCK METHANE: SOURCES AND MANAGEMENT IMPACTS

Donald E. Johnson, T. Mark Hill and G.M. Ward
Metabolic Laboratory
Department of Animal Sciences
Colorado State University
Ft. Collins, CO 80523

Abstract

Herbivorous animals, particularly ruminants, have a digestive tract that facilitates extensive symbiotic microbial digestion of dietary structural plant carbohydrates. A byproduct of this symbiotic microbial process is an estimated 70 Tg of methane globally per year, primarily from cattle and buffalo. Cattle methane emissions equal 6 ± 0.5% of their diet energy (2% by wt) for most global conditions studied. Emissions by U.S. feedlot cattle are uniquely lower at about 3.5% of diet energy. A major lack of information on size, diet, class distribution and percentage loss from developing country livestock precludes accurate definition of this source, which is about 2/3 of global. Manure disposal from livestock may produce an additional 10 Tg globally, primarily through anaerobic lagoons. Possible ameliorative strategies include the decreased use of lagoon disposal or the capture of this methane. General efforts should concentrate on improving productivity of beef and dairy cattle production systems, which will secondarily reduce methane.

Methane Emissions: A Byproduct of Animal Microbial Symbiosis

Digestive secretions by the gastrointestinal tract of animals, per se, can digest no structural components of plants. They can only digest the soluble and/or starchy components. The only digestive enzymes that can unlock the cellulose base of the structural components of plants are those produced by microorganisms. Since about 75% of the photosynthetically fixed plant material is cellulosic or structural, it perhaps is not surprising that many herbivorous animals developed a symbiotic relationship with microorganisms in their gastrointestinal tract to assist in utilizing these materials. All animals have some microbial action in their gut, however, it is very extensive only in the herbivores, particularly the ruminant herbivores. This fortuitous symbiotic relationship between animal and microbe allows the utilization of vast tonnages of cellulosic materials, i.e., grass, which would otherwise be left to decompose on the earth's surface.

The microbes that function in the gastrointestinal tract, particularly the carbohydrate utilizing anaerobes, require a sink to dispose of excess hydrogen other than oxygen. Several species of the archebacteria fill this niche nicely. These methanogens reduce CO_2 with the available hydrogen to produce methane. In doing so, they doubly enhance the symbiotic relationship. First, they facilitate the cellulolytic function of other bacteria and secondly, they increase the supply of amino acids and vitamins to the host animal.

In general, the more extensive the gut microbial digestion of an animal species, the higher the fraction of dietary loss as methane. Ruminant animals (i.e., cattle, sheep and goats) with their large foregut fermentation vat, the rumen, eructate or belch approximately 95% of the emissions from all animals. Cattle in particular, because of their large numbers (1.2 billion), their large size and appetites, coupled with this extensive symbiotic microbial fermentation in their gastrointestinal tract account for some 71% of the approximately 70 Tg of methane produced globally by animals each year. Another approximately 8% is contributed by buffalo, with sheep and goats producing approximately 12%.

We have compiled the available observations of methane production (i.e., Table 1, cattle data) from the literature into a ruminant methane data base. This data base includes 400 treatment mean observations of methane losses from cattle and sheep, and minor numbers of measurements from other species. Methane loss varied from 2.0 to 11.6% of dietary gross energy. Measurements included describe the many different weights and physiological states of the animals fed and diets ranging from all forage to all concentrate diets or mixtures thereof. An auxiliary spreadsheet lists approximately 1000 individual animal observations.

Many important concepts have emerged from our query and analysis of this data set. The majority of the world's cattle, sheep and goats under normal husbandry circumstances likely produce methane very close to 6% of their daily diet's gross energy (2% of the diet by weight). Although individual animals or losses from specific dietary research circumstances can vary considerably, the average for the vast majority of groups of ruminant livestock are likely to fall between 5.5 to 6.5%. We must caution, however, that little experimental data is available for two-thirds of the world's ruminants in developing countries. Available evidence suggests similar percentage of emissions, but this supposition needs confirmation. More importantly, data is skimpy or unavailable to describe diet consumption, animal weight and class distribution.

TABLE 1. SUMMARIZED VARIABLES FOR BEEF CATTLE FROM RUMINANT METHANE DATABASE

Variable	Minimum	Maximum	Mean
Observed methane, % gross energy	2.6	11.5	6.8
Observed methane, % digestible energy	3.3	16.7	9.8
Animal weight, kg	217	627	402
Dry matter intake, kg/d	2.1	10.9	5.4
Digestible energy, %	50.4	87.8	70.6
Level of intake, multiple of maintenance	0.4	2.9	1.5

One exception to this 6% rule is where cattle or sheep are fed very high concentrate diets (> 80% grain and/or supplement). When fed these diets, likely methane emissions will be 3.5% of gross energy. Frequently, they fall as low as 2%. Such dietary circumstances occur almost exclusively in the U.S. feedlot operations. Globally it has little reducing effect on emissions, approximately 27 million head of cattle fed for 140 days per year, with current emissions of about .4 Tg/year.

Another important finding is the transitory effect of ionophores on reduction of methane emissions. Ionophores are a class of antibiotic feed additives which have been considered to suppress methane losses by 20-30%. This degree of suppression persists for some two weeks or less. Therefore, the methane reduction effect of ionophores is more modest and primarily results from a 6 to 7% reduced total feed requirement for production.

Another surprising finding was the uniqueness of one class of feedstuffs. Brewery and distillery byproduct feeds produce about half as much methane as other common feeds fed to ruminants (1). While of little impact globally because of the limited amounts of such feed supplies, it could provide a clue to control of methanogenesis.

An important principle influencing methane emissions from ruminant systems is the inverse relationship between rate of productivity and methane losses, especially when expressed per unit of animal product. Methane losses are closely related to the amount of feed resource used to produce an animal product. An increase in rate of production commonly decreases the feed/product by decreasing the maintenance feed subsidy. Placing a beef calf directly into the feedlot in the United States rather than the slower growth stocker phase preceding the feedlot is expected to reduce the methane per lifetime of a steer by some 34% while producing the same amount of product (2). Perhaps more dramatically, the supplementation of a moderate to low quality forage diet as might be employed in Australia or South America, could increase the daily average gain from .35 kg up to .7 kg. This increased rate of productivity would reduce methane emissions per lifetime of the steer from 170 to 100 kg, again without changing product. Likewise, stimulating the rate of milk production by using bovine somatotropin in the dairy cattle industry in the United States is expected to reduce methane production by the industry some 9%, essentially producing the same amount of milk with less feed and less methane losses (3).

One important additional source of methane indirectly emanating from the livestock industry is that from manure disposal systems. The potential production is huge, considerably larger than that coming directly from livestock, however, measurements made in our laboratory (4) and in Australia (5) show a very small production rate from manure disposed under simulated or actual range or pasture situations. Thus, the major global disposition of manure on pasture likely produces little methane. The critical question then becomes what fraction of manure is disposed of by anaerobic lagoons, a figure which is not known very accurately. Our present best estimate of global manure methane adjusts the disposal method data of Saffley et al. (6) to our estimates of range or pasture production. With these suppositions, the estimate of global methane entry from manure disposal approximates 10 Tg annually.

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References

1. Wainman, F.W., Dewey, P.J., and Brewer, H.C. Feedingstuffs Evaluation Unit, 4th Report, Rowett Research Institute, Aberdeen, 1984.

2. Johnson, D.E., Hill, T.M., and Ward, G.M. Methane emissions from cattle: Global warming and management issues. Proc. Minn. Nutr. Conf. 1992 (in press).

3. Johnson, D.E., Ward, G.M., and Torrent, J. The environmental impact of bovine somatotropin use in dairy cattle. J. Envir. Qual. 21:157.

4. Lodman, D.W., Carmean, B.A., and Johnson, D.E. Estimates of methane emissions from manure of U.S. cattle. Chemos. (in press), 1992.

5. Williams, D.J. Methane production from manure from free-range cows. Chemos. (in press) 1992.

6. Saffley, L.M., Jr., Casada, M.E., Woodbury, J.W., and Roos, K.F. Global methane emissions from livestock and poultry manure. US-EPA Report, 1992.

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METHANE EMISSIONS FROM CATTLE: GLOBAL WARMING AND MANAGEMENT ISSUES

D.E. Johnson, T.M. Hill and G.M. Ward[1]
Metabolic Laboratory
Department of Animal Sciences
Colorado State University
Fort Collins, CO 80523

The concentration of several trace gases in the earth's atmosphere have increased dramatically in the last one to two centuries. Several national and international groups of scientists (Kerr, 1992) conclude that these increases will lead to significant climatic shifts. Included is an increasing average global temperature from 1.5-4.5°C (3-8°F). The amount of warming is a function of the increased gas concentrations, their infrared absorbing ability and their half-life in the atmosphere. The major "greenhouse" gas causing about half of the warming is carbon dioxide, arising primarily from fossil fuel and rain forest combustions. Methane increases will likely cause about 15% and nitrous oxide, an additional 7% of the warming.

Methane concentration in the atmosphere was around 750 ppb for thousands of years, up to 200 years ago. It is presently increasing at 1% per year (Khalil and Rasmussen, 1990). The projected 1992 global concentration average is 1751 ppb. About 550 Tg (1 Tg = 1,000,000 metric tons) of methane is estimated to enter the atmosphere yearly, while about 460 Tg are consumed in the atmosphere and by soils (Table 1).

The largest single source of methane is from natural wetlands (Table 1), where organic matter decays anaerobically, producing an estimated 125 Tg annually. Although considerable uncertainty remains (i.e., termites), most authorities put modest estimates on amounts from other natural sources. About one-third of all methane is from natural sources.

The other two-thirds of methane is termed anthropogenic, or related to human activity. Approximately 145 Tg originates from energy production activities (coal, gas industries, or from landfills. Note: Fossil fuels have a triple-whammy effect on warming; CO_2, NOx and CH_4). The remaining sources relate to agricultural activity accounting for approximately 250 Tg or 40% of all methane.

The largest agricultural source is associated with rice production (110 Tg) with a smaller amount (15 Tg) arising from biomass burning. Present best estimates suggest that the enteric or "gut" methane from livestock amounts to 75 Tg annually. Another 15 Tg may

[1]Professor, Postdoc, Professor Emeritus, respectively.

arise during manure disposal from farm animals, principally through the use of anaerobic lagoons. Livestock, thus, probably contribute about 16% of the methane entering the atmosphere. Please note, however, the rather large uncertainty range of estimates for most methane sources.

Table 1. Global sources and sinks of atmospheric methane[a]

Sources	Tg/yr	(range)[b]	Sinks	Tg/yr
Wetlands	125	(100-200)	Hydroxyl (OH)	420
Oceans, hydrates	35	(10-80)	Soils	30
Termites	20	(10-100)	Cl and O	10
Burning and other	10	(5-15)		
Natural sources total	190		**Total**	460
Rice	110	(25-150)		
Livestock	75	(50-110)		
Manure	15	(10-35)		
Biomass burning	15	(10-30)		
Agricultural total	215			
Gas and oil industries	70	(25-85)		
Coal mines	40	(20-43)		
Charcoal/wood	10	(5-30)		
Landfills	25	(15-70)		
Energy and waste total	145			
All sources total	550			

[a]Compiled from Cicerone and Oremland, 1988; Crutzen, 1991; and NATO Workshop Proceedings, 1991 (in press).

[b]Tg = Teragram = 10^{12}g = million metric ton, range = range of estimates.

The origin of methane produced by animals is microbial action in their gastrointestinal tracts, which occurs to varying degrees in all animals. Major fermentative digestion allowing utilization of fibrous dietary components occurs in herbivores, particularly ruminants, which have an accentuated microbial activity. Their gut structures and diets, coupled with large body size, appetites and animal numbers results in 95% of animal methane arising from ruminants, about 80% from the bovidae family alone. Sheep and goats account for another 12%, while horses and pigs are next on the list, contributing approximately 2 and 1%. Stoichiometry of the fermentation of carbohydrate to common ratios of volatile fatty acid products results in the compulsory production of hydrogen as an intermediary byproduct. If hydrogen were allowed to accumulate, it would interfere with the thermodynamic favorability of the hydrogen production reactions and interfere with the growth of corresponding organisms, many cellulolytic species. Thus, the presence of methanogenic bacteria improves the growth and efficiency of other organisms and captures ATP from the reduction of CO_2 to CH_4, thus furthering the amount of bacterial matter presented to the animal to improve its protein nutrition. The amount of hydrogen presented to methanogens for methane production depends on several factors. First is the amount of carbohydrate fermented, which in turn depends on a host of diet animal interactions, including amount and type consumed, rates of carbohydrate digestion and passage, etc. The second primary factor regulating the hydrogen supply to methane is the ratio of volatile fatty acids produced, primarily the ratio of acetic acid to propionic acid. If all acetic acid would be produced, then 33% of the energy of the substrate would be given off as methane gas, whereas if the ratio of acetate to propionate is 0.5, the methane production would be zero. Since A:P ratios typically vary from approximately 4 to .9, the corresponding methane loss varies widely. Alternate hydrogen sinks, i.e., microbial growth, unsaturated fatty acids, nitrates, etc., also can have some effect on methane production.

The extremes of methane loss found in the literature from sheep and cattle with functional rumens show wide variations ranging from under 2 to nearly 12% of the gross energy of the diet. As Figure 1 illustrates, lower digestibility or all forage diets are more consistent in fraction of methane loss. The extremes of both high and low losses occur with higher digestibility and higher concentrate diets. Further examination reveals that the very high fractional methane losses only occur when highly available carbohydrates are fed at limited intake. Also, the very low amounts of methane loss will only occur at very high intakes of very highly digestible diets. Only the latter commonly occurs in commercial practice, i.e., the U.S. feedlot cattle industry.

Figure 1. Observed production of methane versus digestible dietary energy. Methane = 9.6 - 0.038 digestible energy, $R^2 = 0.03$, $P < 0.01$.

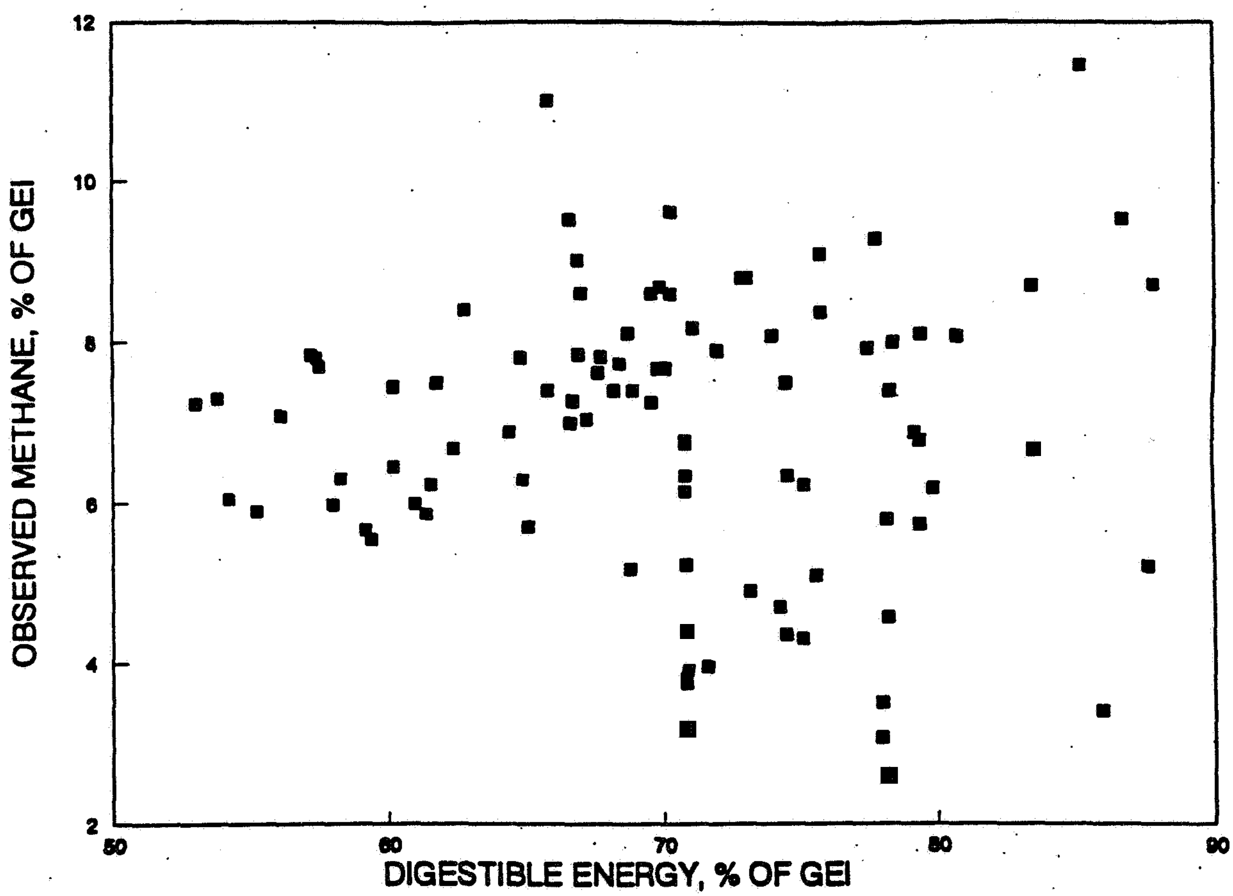

Table 2. Prediction equations of methane loss at various levels of concentrate in beef cattle diets

% Diet Conc.	CH4 = Equation[a]	R^2
0-20	7.8 - 9.14 GEI + .02 DE	.54
	5.5 - 2.25 LOI + .06 DE	.57
> 20-80	10.5 - 8.81 GEI - .01 DE	.22
	11.3 - 1.81 LOI - .02 DE	.27
> 80	12.2 - 9.54 GEI - .05 DE	.14
	9.9 - 1.54 LOI - .01 DE	.18
All diets	9.1 - 8.23 GEI	.18
	9.1 - 11.97 DEI	.21
	9.5 - 1.84 LOI	.31
	11.0 - 8.35 GEI - .03 DE	.20
	10.3 - 1.79 LOI - .01 DE	.31

[a]GEI = daily gross energy intake (Mcal) per $BW^{.75}$, DEI = daily digestible energy intake (Mcal) per $BW^{.75}$, LOI = level of intake calculated as per Blaxter and Clapperton (1965) but using MAFF (1976) linear equation to predict fasting heat production, DE = digestible energy (percent). For all diets, n = 118; for 0 to 20% CON, n = 32; for > 20 to 80% CON, n = 64; for > 80% CON, n = 22.

Several dietary intake descriptors and digestibility were related to methane production in beef cattle using 118 treatment means from the literature. The relationship between methane and level of intake (R^2 = .31) was greater than the relationship between methane and digestible energy (R^2 = .01). Increasing digestibility positively affected methane losses from high forage diets, but negatively for mixtures or high grain diets. Level of energy intake was consistently negatively related to % methane loss (Table 2). Percentage losses decline about 1.8 units per increased intake expressed as multiples of maintenance or 9 units per Mcal increase in $GE/W^{.75}$. Considering the difficulty in calculating level of intake as a multiple of maintenance, intake energy per unit metabolic body size seems appropriate and is less confusing to apply.

The fermentability of feeds should possibly be considered in prediction equations, however, data in the literature that simultaneously quantitate ruminal fermentation fractions of feeds and methane production are virtually non-existent. Data of Wainman et al. (1984) would suggest that methane production may be greater with highly fermentable feeds, such as cassava and barley, and lower with low starch feeds, such as distiller's grains and corn gluten feed. Comparisons of beet pulp to barley, however, suggest the opposite (Beever et al., 1989). Giger-Reverdin et al. (1990) developed a prediction equation with ether extract as a variable that was negatively correlated to methane losses from feeds, consistent with data of Swift et al. (1948), Czerkawski et al. (1966), Haaland (1978) and Van der Honing et al. (1981).

Feed additives such as monensin (Joyner et al., 1979; Thorton and Owens, 1981; Benz and Johnson, 1982) and lasalocid (Delfino et al., 1988) have been demonstrated to suppress methane production, possibly through selection, against certain strains of ruminal microorganisms and altering the ruminal fermentation patterns in short term experiments. This suppression in methane production did not persist beyond 16 days in 45-day persistence experiments with feedlot cattle given monensin, lasalocid and daily rotations of the two as reported by Abo-Omar (1989) or monensin as reported by Carmean et al. (1992) when these ionophores were given as additives to 90% concentrate diets.

Utilizing these prediction equations, methane as a percentage of gross energy intake from various classes of animals fed typical diets was calculated (Table 3). Fattening cattle were projected to lose about 3.5% of diet energy as methane compared to around 6% for other classes of cattle.

Table 3. Prediction of methane loss from typical diets fed to different classes of beef cattle using various prediction equations[a]

					% CH_4 predicted by equation[c]	
Class	Daily Gain (kg)	Daily ME intake (Mcal)	Diet DE (%)	ARC LOI[b]	LOI	DE-LOI
Cow, maint.	0	16	48	1.1	7.2	5.9
Cow, lact.	0	20	56	1.5	6.5	5.5
Growing	.7	15	63	2.0	6.2	6.5
Fatten	1.4	26	84	2.6	4.4	4.2

[a]NRC (1989) requirements by class. B-C equation is percentage of CH_4 = 1.30 + .112 DE + LOI (2.37 - .05 DE).

[b]Level of intake as a multiple of maintenance calculated as per Blaxter and Clapperton (1965), but using the MAFF (1975) linear equation to predict fasting heat production.

[c]Equation from Table 2 to calculate CH_4 as a percent of gross energy intake.

Methane production per slaughter steer was projected for various management scenarios (Table 4). Scenarios 1 and 2 compared two typical management systems for growing and fattening cattle in the U.S. Considerably less methane per lifetime is projected for calves weaned and placed directly in the feedlot (28 kg) compared to a stocker phase preceding a feedlot phase (41 kg). Scenario 3 represents the typical Australian system (Howden, 1991) of calves finished on a 1051-day grazing period (169 kg of methane per lifetime). Scenario 4 doubles rate of gain by improving dietary energy quality from 57 to 63% digestible energy by supplementing concentrates. The results are a reduction of 43% in methane production per lifetime compared to Scenario 3. Considering these scenarios, large reductions in methane per slaughtered animal's lifetime apparently can be achieved through management strategies that improve animal performance.

Table 4. Various management scenarios and estimated methane production per animal lifetime

Class	Days	Daily gain (kg)	Daily ME intake (Mcal)	Diet DE (%)	%CH_4	CH_4 l/d	CH_4/ kg
Scenario 1							
Calf	210	---	1.2	---	6.0	34	5
Stocker	150	.7	6.5	63	6.5	199	21
Feedlot	140	1.4	8.8	84	3.5	145	14
						Total	40
Scenario 2							
Calf	210	---	1.2	---	6.0	34	5
Feedlot	251	1.2	7.9	84	3.5	130	23
						Total	28
Scenario 3							
Calf	180	---	1.2	---	6.0	34	4
Stocker	1051	.35	7.5	57	6.2	220	165
						Total	169
Scenario 4							
Calf	180	---	1.2	---	6.0	34	4
Stocker	514	.7	8.2	63	6.5	249	92
						Total	96

In conclusion, the contribution of livestock methane emissions to global warming is small, about 2% of all greenhouse gas effects. Strategies to reduce methane losses from cattle should probably focus on improved production efficiency. These strategies are also likely to make a contribution to reduce future warming.

Literature Cited

Abo-Omar, J., 1989. Methane losses by steers fed ionophores singly or alternatively. Ph.D. Dissertation. Colorado State University, Fort Collins, Colorado 80523.

Beever, D.E., S.B. Cammell, J.D. Sutton, M.C. Spooner, M.J. Haines and J.I. Harland, 1989. Effect of concentrate type on energy utilization in lactating dairy cows. In: 11th Symposium on Energy Metab. EAAP 43:33.

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

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

Carmean, B.R., D.E. Johnson, M.A. Ward and G.M. Trotter, 1992. The persistence of monensin effects on ruminal fermentation and nutrient digestion in steers. Beef Prog. Report, Colorado State University, p. 39.

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

Crutzen, P.J., I. Aselmann and W. Seiler, 1986. Methane production by domestic animals, wild ruminants and other fauna. Tellus 38B:271.

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. Brit. J. Nutr. 20:349.

Delfino, J., G.W. Mathison and M.W. Smith, 1988. Effect of lasalocid on feedlot performance and energy partitioning in cattle. J. Anim. Sci. 66:136.

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

Howden, S.M., 1991. Personal communication. Bureau of Rural Resources, Canberra, Australia.

Joyner, A.E., L.J. Brown, T.J. Fogg and R.T. Rossi, 1979. Effect of monensin on growth, feed efficiency and energy metabolism of lambs. J. Anim. Sci. 48:1065.

Kerr, R.A., 1992. Greenhouse science survives skeptics. Sci. 256:1138.

Khalil, M.A.K. and R.A. Rasmussen, 1990. Atmospheric methane: Recent global trends. Envir. Sci. and Tech. 24:549.

MAFF, 1975. Energy Allowances and Feeding Systems for Ruminants. Tech. Bull. No. 33, HMSO. London.

NATO Workshop Proceedings, 1991. The Global Methane Cycle. Edit. Khalil et al. (in press).

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.

Thorton, J.H. and F.N. Owens, 1981. Monensin supplementation and in vivo methane production by steers. J. Anim. Sci. 52:628.

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

Wainman, F.W. and P.J.S. Dewey, 1984. Feedingstuffs Eval. Unit Rep. 14-18, Rowett Res. Inst., Aberdeen.

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The Environmental Impact of Bovine Somatotropin Use in Dairy Cattle

Donald E. Johnson, Gerald M. Ward,* and Joan Torrent

ABSTRACT

The environmental impact of bovine somatotropin (bST) use in dairy cattle (*Bos taurus*) was analyzed with the following assumptions: base herd (1989) of 10.1 × 10⁶ cows, milk production 6475 kg of 3.5% fat per 305 d; bST herd of 8.96 × 10⁶ cows, 3.8 kg/d increase during 215 d treatment period; 100% adoption rate, 60 d dry period, 40% replacement rate; all formulated diets from: alfalfa (*Medicago sativa* L.) hay, corn (*Zea mays* L.) silage, cracked corn, soybean [*Glycine max* (L.) Merr.] meal, and supplement to satisfy level of production. Using these assumptions, the analysis indicates that the current U.S. milk supply could be produced by 11% fewer cows fed 9% less feed produced on 6% less land, and soil loss would be 5% less. Fossil fuel requirements would be 6% less and irrigation water use would be reduced by 9%. Output of the greenhouse gas methane would be decreased 9%; manure production and outputs of N and P declined by 10, 8, and 10%, respectively.

RECOMBONINANTLY DERIVED bovine somatotropin (bST) offers a new technology that will enable increased milk production per cow (*Bos taurus*), as is clearly documented by extensive, large-scale experiments by universities and private firms.

The environmental impact of any new technology is a matter of public concern. The introduction of new technologies often creates a new set of environmental impacts that may be considered positive or negative. The Food and Drug Administration (Juskevich and Guyer, 1990) has concluded from a review of many research projects that bST represents no increased health risk to the milk consumers. The environmental or ecological concerns related to milk production can be described in terms of: (i) animal manure, (ii) production of methane, (iii) fossil fuel requirements, (iv) water use, and (v) soil loss. This report considers only biologically important environmental impacts. We have not addressed social, political, or economic implications of bST use. These issues have been considered by U.S. Congress (1991) and Fallert et al. (1987).

Animal waste consists primarily of urine and feces. The principal components that may contribute to environmental problems are N and P (Van Horn, 1990; Ward et al., 1978). Both of these elements, of course, are also basic requirements for plant nutrition. Nitrogen is consumed by cows in the form of protein or nonprotein. Approximately 25% of the N consumed by dairy cows is recovered in milk and a small amount in body tissue. The remaining dietary N is excreted primarily as urea in the urine, undigested feed protein, and bacterial cells in the feces. Microbial processes in storage or in the soil can convert both urine and fecal N to ammonia (NH_3), some of which may be released to the atmosphere. Dutch estimates are 36 kg of NH_3 per dairy cow per year (de Haan, 1990). Ammonia in most soils is stable, but oxidation to nitrates produces a form of N that is mobile in soils and can contaminate groundwater. Denitrification of nitrates to N_2 produces an environmentally innocuous product, but denitrification also produces N_2O and NO, which, if released to the atmosphere, can destroy ozone (O_3) and contribute to global warming (IPCC, 1990). Thus, N in animal waste, although a valuable resource, can have a variety of unfavorable effects on the environment. The situation in this country has been reviewed

Department of Animal Sciences, Colorado State Univ., Ft. Collins, CO 80523. Received 8 July 1991. *Corresponding author.

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by Schepers (1988) and the much more serious problems in the Netherlands by de Haan (1990).

Phosphorus, like N, is rather inefficiently used by animals, including dairy cows. Phosphorus can have serious ecological effects in surface water by stimulating algal blooms that reduce the oxygen content of the water. The result can be death of fish. Factors known to affect P digestibility would not suggest any response to bST or level of intake.

Methane is a greenhouse gas that contributes to global warming. Increases in atmospheric methane are expected to cause 15 to 18% of future global warming (IPCC, 1990). The world cattle contribute about 10% of global methane production and U.S. cattle produce about 11% of global methane from cattle (Johnson et al., 1990). The percentage from U.S. dairy animals was estimated to be 30% of U.S. cattle emissions (Johnson et al., 1990).

Even though feed consumption per bST-treated cow would be increased, total feed consumption for bST-treated cows in the USA would be reduced, and this represents reduced requirements for all the resources used in feed production and dairy farm management. Many of these resources can be integrated into fossil fuel requirements because each has its own rather well-defined requirements for fuel energy. Conservation of fossil fuels is a long-term environmental issue. Public interest in the issue waxes and wanes with the price of oil. Feed production in the western states is principally dependent upon irrigation water where water conservation and water use priorities are of great importance. Lastly, reduction in soil loss from reduced feed requirements for milk production will have positive environmental consequences.

METHODS

Analysis of the environmental impact of adoption of bST by milk producers requires a large and diverse series of data and many assumptions. The first and basic assumption for calculation is the average increase in milk production per cow to be expected from the use of bST. An extensive review of many trials comparing controls and bST treatment (Johnson et al., 1991), indicates that great variability in response (2.2 to 35.5% or 0.6 to 10.7 kg/milk per day) has been observed, even when excluding observations from treatments of ≤10 mg bST/d. Factors such as age, milk yield, dosage, length of treatment, feeding level and others varied from trial to trial. The type of diet infrequently influenced the bST stimulation of milk yield. Grain source exerted no significant effect on production parameters and efficacy of bST, although milk production tended to be higher with corn compared to barley (*Hordeum vulgare* L.) (Eisenbeisz et al., 1990). Nevertheless, the increase of milk production may be limited in high-producing cows by the amount of protein available at the small intestine (McGuffey et al., 1990). On the other hand, bST did not interact with feeding frequency (French et al., 1990).

The response to bST between different genetic groups has not differed (McDaniel and Hayes, 1988; Nytes et al., 1990). In one recent experiment, phenotypic potential for production was significant in explaining variation in response to treatment; cows of low and medium production potentials responded more to treatments than their counterparts with higher production potential (predicted performance > 8000 kg). In contrast, the cow's genetic potential for production was not significant in explaining response to treatment (Leitch et al., 1990).

Choosing a mean response to bST requires a judgment based on experiments conducted under varying conditions. We found an increase of 19% (Fallert et al., 1987), or 3.8 kg/d for the last 215 d of the 305-d lactation period to be reasonable. This equals a 12.6% increase in milk produced by the average cow over a 305-d lactation period. Others who have made analyses similar to ours are Elam (1991), who estimated an increase of 10.3%, a study for the National Milk Producers Federation (1990) with an increase of 727 kg of milk per year (10.5%) for cows averaging 6913 kg (15210 lbs) per year. Bauman (1990), on the other hand, chose an average of 12% increase in milk yield.

The rate of adoption and extent of use by producers is highly speculative. For simplicity, our calculations are based on 100% adoption. Although the assumption is unrealistic in near term, there is no agreement on any other percentage. Interpolation from our results can be easily made for any percentage adoption that one chooses.

The total number of milk cows in 1989 was 10.1 million (ERS, 1989) with an average yield of 6475 kg (14244 lbs) for a total milk production in the USA of 65.4 billion kg. To produce the same volume of milk (because there is currently no market for additional milk), producing 12.5% more milk per year would require 8.96 million cows instead of the 10.1 milked in 1989.

It was assumed that all milk cows were dry for 60 d. Replacement heifers, 1 to 2 yr old, were estimated to be 40% of the number of milking cows, the average percentage in 1989 (ERS, 1989). Calf and yearling numbers were increased to account for mortality rates prior to entering the milking herd (Table 1). Replacements and dry cow numbers for bST treatment were reduced in proportion to the milk cow numbers.

Feed intake for bST-treated cows was increased and diet net energy (NE) increased slightly (Table 1) to support the additional milk production for the last 215 d of lactation. Feed intake for the first 90 d of lactation was the same as controls, and maintenance requirements were considered to be the same for both groups. Generic daily rations were calculated for control cows, bST-treated cows (last 215 d of lactation), and for dry cows, replacement heifers, and calves (Table 1) to meet requirements (NRC, 1989). Feeds are considered to be from only four sources: alfalfa hay, corn silage, cracked corn, and soybean meal together with supplemental minerals and vitamins. Milk replacer for calves was also expressed as corn and soybean meal. This is, of course, a gross oversimplification of dairy feeding, but there is no practical way to include the dozens of important feed ingredients or the hundred or more minor components.

The amount of feces produced by the two treatments was calculated by using the digestion coefficients (NRC, 1989) for each class of cattle as indicated in Table 1. Urine volumes for other classes were estimated from data of experiments at the CSU Metabolic Laboratory.

Methane emission estimates for the control situation are adapted from Johnson et al. (1990), and assume no change per unit of feed for output of the bST-treated group.

Nitrogen excretion for cows was calculated by deducting the N in milk based on 3.2% protein (Chase, 1990) from N intake based on the crude protein content of the ration. Crude protein of feed and tissue was assumed to be 6.25 and milk to be 6.38% N. The weight gain of calves and heifers was assumed to be 18% protein. Dry cows and milking cows were assumed to be in N and P equilibrium. Phosphorous excretion was calculated in the same way. Milk was assumed to be 0.1% P and weight gains to be 0.74% P (Maynard and Loosli, 1969). Phosphorus in milk has not been shown to be affected by bST (Eppard et al., 1985; Peel and Bauman, 1987).

Fossil fuel energy requirements (Table 2) were based on fuel requirements for feeds (Ward, 1980) and for dairy op-

Table 1. U.S. dairy industry data base used for calculations.

Cattle classes	Milking cows			Dry cows	Heifers	Calves	
	First 90 d	Last 215 d					
		Base	bST			Milk fed	Dry feed
Number (10^6)							
Base	10.10	10.1	0.0	10.10	4.10	4.70	4.20
bST	8.96	0	8.96	8.96	3.58	4.10	3.67
Days/year	90	215	215	60	365	42	323
Milk (kg/d)	24.2	20	23.8	0	0	0	0
Avg. wt. (kg)	675	650	650	700	418	50	77
Diets, %							
Alfalfa	28	30	27	35.7	50.1	3.8	40
Corn silage	28	30	27	57.9	47.6	0	0
Cracked corn	29	28	32.5	0	0	68.9	50
Soybean meal	13	10	11.5	5.1	0	26.4	7.5
Supplement	2.0	2.0	2.0	1.3	2.3	0.9	2.5
CP (%)	15.3	14.2	14.7	12.0	12.9	20.7	16.2
P (%)	0.45	0.45	0.45	0.26	0.23	0.5	0.31
DMI† (kg/d)	18.9	18.1	19.4	11.8	8.9	1.4	4.3
DMD‡ (%)	67	66	67	56	62	85	68
CH_4 (% GEI)§	5.6	5.7	5.7	6.2	6.5	2.0	6.0
Urine volume (L/d)	20	20	21	15	8	2	5

† DMI, dry matter intake.
‡ DMD, dry matter digestibility.
§ GEI, gross energy intake assumed to be 4.45 Mcal/kg DMI for all diets.

erations (Oltenacu and Allen, 1980). The latter represented 35% of the total and feed 65%, of which the largest input is represented by fertilizer and other chemicals.

The amount of farm land required was determined from the total feed use divided by the average yields for the four feed types (Table 2). Topsoil losses were calculated by assigning a loss of 1–2 t/ha to alfalfa hay land and 1–6 t/ha to crop land (Miller and Donahue, 1990). Consumptive use of irrigation water was calculated from data (Table 2) based on Colorado farms (Ward, 1991) and applied to the number of dairy cattle (16%) that are in the Western states where most feed crops are irrigated although there are exceptions (i.e., Washington and Oregon). This estimate, however, is conservative because some irrigation is used in many other states.

We have made no adjustments in our calculations for possible effects of bST on reproduction. Results indicate a general increase in calving interval, a trend that is associated with increased milk production levels (Bauman et al., 1990; McGuffey et al., 1991; Weller et al., 1990).

EFFECT OF BOVINE SOMATOTROPIN ON DIGESTION AND METABOLISM

An evaluation of the effects of bST treatment on nutrient digestibility, metabolizability, partial efficiency, and requirements needs to consider the direct effects of bST and the indirect effect of increased intake of diet (approximately 0.25 × maintenance), which occurs following a few weeks after initiation of treatment. One short-term experiment (Moseley et al., 1982) reported a small but significant increase in diet energy digestibility by bST-treated steers. This result was not confirmed in any of the seven other experiments, which report digestibilities of bST vs. control growing or lactating animals over short or long terms. However, in nearly all of these experiments, feed intake was not allowed to increase, either because of short-term durations or experimental limitations.

Increased feed intake of the magnitude expected to occur with bST-treated cows is generally expected to depress dietary energy digestibility by one percentage

Table 2. Data for calculating fuel and water consumption.

Feed	Yield† t/ha	Fossil fuel‡	Irrigation water§
		Mcal/kg	m^3/t
Alfalfa	5.9	0.5	866
Corn silage	33.0	0.8	372
Corn grain	7.5	1.3	571
Soybean meal	1.8	1.5	¶

† Elam, 1990, personal communication.
‡ Ward, 1980.
§ Ward, 1990.
¶ Soybean is not normally produced under irrigation.

unit (NRC, 1989), although considerable variation has been experienced in the degree of depression (Tyrrell and Moe, 1975). Recent data of Bines et al. (1988) also suggest that depression within levels of intake by lactating cows may not be as great as prior experiments predict. Most of the prior experiments looked at changes between nonlactating and lactating animals. It is possible that increased gut volumes associated with genetically set higher milk productions or those that have resulted from bST treatment in growing (Early et al., 1990) or in lactating (Brown et al., 1989) animals may at least partially ameliorate the depressing effects of intake on digestibility.

Reports concerning the effect of bST on methane loss have been mixed. Short-term measurements with lactating cows have shown (in one case) a 9% increase in methane (Tyrrell et al., 1988) and in another, a 14% decrease in methane losses (Sechen et al., 1989). Long-term measurements repeated four times over an approximately 6-mo period (Kirchgeßner et al., 1989) reported virtually identical methane productions on control- and bST-treated cows. An experiment by Eisemann et al., 1986, with growing heifers reported the sum of gaseous and urinary losses unchanged by bST. Potential interactions of changing feed intake and gut volume as discussed for energy digestibility may also impact methane losses.

Only very small, statistically nonsignificant changes in urinary energy have been reported, ranging from $+0.12$ to -0.1 percentage units. Changes in dietary energy metabolizability reflect those previously discussed as fecal, urinary, and gaseous losses. One short-term experiment with lactating cows reported a small 1.8 percentage depression ($P < 0.05$) of ME, and one of the four measurement periods in a long-term experiment reported a 1.5% depression in ME. Other periods of the latter experiment (Kirchgeßner et al., 1989) and other experiments, however, reported insignificant changes ranging from -0.7 to $+0.6$ percentage units.

The digestibility of protein evaluated simultaneous to energy in most of these experiments has shown bST to have no effect on digestibility. Effects on urinary N excretion or efficiency of absorbed amino acid utilization have been mixed and likely depend on the interactions with mobilized tissue protein. In cows adequately fed to prevent mobilization of body protein, the efficiency of absorbed amino acids from milk production has been enhanced (McGuffey et al., 1990).

Three experiments have examined the partial efficiency of metabolizable energy use for milk production (Tyrrell et al., 1988; Sechen et al., 1989; Kirchgeßner et al., 1989). All experiments have reported identical partial efficiencies for bST-treated and control cows. For example, in the long-term Kirchgeßner experiment, partial efficiency of ME use for control and bST-treated cows averaged 0.71 and 0.72, respectively. Additionally, these experiments have found that bST does not affect the basal metabolic rate or metabolizable energy requirement for maintenance of the lactating cow. Heat productions from maintenance and/or milk production varied in a manner predictable by standard diet and body tissue utilization efficiencies.

We concur with other summaries of the 900 plus experiments investigating bST effects, that bST-treated animals have increased nutrient requirements, which are very likely those predicted from NRC (1989) nutrient requirement tables as given for each observed level of milk production (Bauman, 1990; Chalupa and Galligan, 1989, 1990). With only a few reservations as discussed previously, there is little evidence that diet energy or protein digestibility, metabolizability, partial efficiency of nutrient use for maintenance or for milk production or nutrient requirements for maintenance or per unit of milk produced are changed. Thus, only increased milk production and the extra diet to produce that milk need be considered in altering feed requirements for the bST-treated cows similarly to increasing feed allowances to genetically superior cows.

Cows producing more than 35 kg of milk per day will likely need special dietary considerations to enhance dietary energy concentration and flow of amino acids to the small intestine (Chalupa and Galligan, 1989). This will be true for these high producing cows regardless of bST treatment. Inasmuch as bST will increase the percentage of cows in the herd that will fall into this higher producing class, bST will, to this degree, increase special dietary concerns.

We estimate that cattle will eat 1.3 kg of dry matter per day more on the average over the 215 = d period of treatment with bST than they will without treatment. Long-term experiments (more than 120 d) with cows treated with bST (> 10 mg/d) and averaging about 1.4 kg of dry matter per day (Johnson et al., 1991). The magnitude of increases in intake is what would be expected for these cows in response to the noted higher milk yields (NRC, 1989; Marsh et al., 1988; NRC, 1987).

RESULTS

This analysis of bST adoption is presented for seven categories of environmental stress: (i) manure, (ii) N, (iii) P, (iv) methane, (v) fossil fuel, (vi) water use, and (vii) soil loss.

Feed intake or feed energy and protein intake must be increased proportionately to support the additional milk production. However, the maintenance requirement for the cow remains the same. Because maintenance requirements for energy and protein represent a substantial percentage of total requirements, feed efficiency per kilogram of milk increases with increased production. This response is commonly called *maintenance dilution*. Further efficiency of milk production will be achieved because fewer cows will be required to produce the same volume of milk. Fewer cows means a reduction in waste output nationally and less demand for feed with its embodied requirements for fossil fuel and water. A reduction in cow numbers will also translate to a need for fewer replacement heifers with a consequent saving in feed and other resources. The response to bST results in the same trends that have been occurring because of increased production per cow over many decades.

The impact of bST adoption is summarized in Table 3 for each of the factors analyzed in this study. Feed intake per cow while they are milking increases with bST from 5592 to 5872 kg/yr. The feed requirement per kilogram of milk declines by 7% from 0.86 to 0.80 kg of feed. Total feed consumption with 100% adoption of bST is estimated to decline by 6.8×10^9 kg (Table 3). Alfalfa hay use would be reduced by 12% and corn silage by 13%. A small increase in corn grain and soybean meal may be required.

Urine volume was calculated to be reduced by 4.7 $\times$ 10^9 L and fresh weight feces by 9.3×10^{10} kg as a result of 100% application of bST technology. Total

Table 3. Summary of decreases (or increases) in resource use and environmental impact between the base herd and the 100% bST adoption herd.

Resources	Amount/yr	%
Total feedstuffs (kg)	-7.1×10^9	−9
Alfalfa (kg)	-3.6×10^9	−13
Corn silage (kg)	-3.4×10^9	13
Corn (kg)	1.9×10^8	1
Soybean meal (kg)	1.0×10^7	0.1
Urine volume (L)	-8.5×10^9	−9
Manure production (kg)	-1.5×10^{10}	−10
Total N (kg)	-1.4×10^8	−8
Total P (kg)	-2.2×107	−10
Methane (kg)	-1.4×10^8	−9
Cropland for feed (ha)	-6.9×10^5	−6
Soil loss (t)	-5.3×10^6	−5
Irrigation water (m^3)	-6.8×10^8	−9
Fossil fuel energy (Mcal)	-6.8×10^9	−6

N losses in animal waste would be reduced by 2.2 × 10^7 kg/yr and P by 1.4 × 10^8 kg. These two elements are considered important potential pollutants of water supplies. The reductions indicated could have a significant positive effect on the environment. On the other hand, soil fertility is reduced to the extent that these elements would be efficiently used for fertilizer on crop land.

Methane production by dairy cows and their support herd would be reduced by 1.3 × 10^8 kg/yr, which would represent a decline of 9% of production by dairy cows in the USA.

The crop land required to produce the feed to support the dairy operation would decline by 688000 ha (1.7 million acres). Assuming that this land was not cropped, but returned to grassland, soil loss nationally would be reduced 7.11 × 10^6 t/yr.

The amount of irrigation water that would be saved by the reduced feed requirements for bST-treated dairy cattle is estimated to be 6.8 × 10^8 m^3 (55100 acre feet). By way of comparison, the average suburban family in Colorado is estimated to use 1233.5 m^3 of water.

Fossil fuel energy requirements would be reduced by 6.80 × 10^9 Mcal, which at 34.22 MJ/L, translates to 8.29 × 10^8 L of gasoline. The average personal car travels 24135 km/yr at 8.5 km/L. The fuel savings from bST adoption thus equates to fuel to supply 292000 personal automobiles.

DISCUSSION

All of the environmental impacts of bST adoption that were analyzed were positive. The impact of bST is found to be favorable for all categories except beef production. Beef is a different category from the other seven evaluated above. Beef from salvage dairy animals and fed beef resulting from male dairy calves represents about 25% of the beef supply. We estimate the number of cows and replacements to be reduced by 11%, which means that beef output would be reduced by about 3%. An increase of 3% in the national beef herd would be necessary, which may have accompanying environmental costs. The impact would be greater in Europe where dual purpose cattle are still an important source of beef (Mochet, 1987).

The data presented here provide an indication of the degree of environmental change that can be expected. It must be recognized that the values presented have a degree of uncertainty, because of the many assumptions that are necessary for the calculations. First, there is the question of extent to which bST might be adopted, assumptions made for other studies are far below 100%, which is the basis of the calculations presented here. Additionally, the milk production response that will result under field conditions cannot be predicted with certainty.

The generic diets for milking cows obviously do not represent a weighted average of feed ingredients consumed by the average cow. Such data are not available, nor can they be reasonably simulated. For instance, dairy cows are fed a wide variety of by-products or waste products. We have used good quality alfalfa in our diets, which is not available in all parts of the country. Lower quality hay would mean a requirement for more protein supplement. Estimates of average daily feed intake and nutrients are based on NRC requirements for the assumed level of milk production and body weight. Body weights for the average cow must be assumed (i.e., 650 kg) and the assumption is implicit that cows will consume the dry matter provided in the ration. Predicting voluntary feed intake is one of the major uncertainties of animal nutrition. In the real world, many dairymen tend to overfeed protein, partly because of imprecise ration formulation and excess protein in legume forages, and partly because of the recognized need for rumen-bypass protein by milking cows. The P content of the average diet probably exceeds NRC requirements, because of questions of availability and because of a perceived value for improving reproduction.

The discussion above of the limitations on the absolute values presented should not be viewed as a disclaimer for conclusions drawn from the analysis. There is no evidence that the direction of environmental changes or their order of magnitude would be different if more perfect input data became available. The results presented here are in general agreement with those presented by Fallert et al. (1987), Elam (1991, personal communication), M. Kirchgeßner (1989, personal communication), U.S. Congress (1991), and the NMPF study (1990), although each analysis differs in the assumptions used.

REFERENCES

Bauman, D.E. 1990. Bovine somatotropin: Review of an emerging animal technology. Commissioned background paper prepared for the Official Technology Assessment, Washington, DC.

Bines, J.A., W.H. Broster, and J.D. Sutton. 1988. Effect of amount consumed and diet composition on the apparent digestibility of feed in cattle and sheep. J. Agric. Sci. 110:249–259.

Brown, D.L., S.J. Taylor, E.J. DePeters, and R.L. Baldwin. 1989. Influence of sometribove, USAN (recombinant methionyl bovine somatotropin) on the body composition of lactating cattle. J. Nutr. 119:633–638.

Chalupa, W., and D.T. Galligan. 1989. Nutritional implications of somatotropin for lactating cows. J. Dairy Sci. 72:2510–2524.

Chalupa, W., and D.T. Galligan. 1990. Metabolic modifiers and the nutritional requirements of lactating dairy cattle. p. 10–16. *In* Proc. 1990 Cornell Nutrition Conference for Feed Manufacturers. Cornell University, Ithaca, NY.

Chase, L.E. 1990. New concepts in protein nutrition for the high producing dairy cow. p. 93. *In* Proc. of the American Industry Association. Nutrition Symposium. Animal Agriculture for the 90's, St. Louis, MO. 5–6 Nov. 1990. Am. Feed Industry Assoc., Arlington, VA.

de Haan, F.A.M. 1990. Agronomic and environmental implications of soil enrichment with mineral elements originating from animal slurries. p. 6. *In* Proceedings of the American Feed Industry Association. Nutrition Symposium. Animal Agriculture for the 90's, St. Louis, MO. 5–6 Nov. 1990. Am. Feed Industry Assoc., Arlington, VA.

Early, R.J., B.W. McBride, and R.O. Ball. 1990. Growth and metabolism in somatotropin-treated steers: II. Carcass and noncarcass tissue components and chemical composition. J. Anim. Sci. 68:4144–4152.

Economic Research Service. 1989. Livestock and poultry situation and outlook LPS-37. USDA, Washington, DC.

Eisemann, J.H., H.F. Tyrrell, A.C. Hammond, P.J. Reynolds, D.E. Bauman, G.L. Haaland, J.P. McMurtry, and G.A. Varga. 1986. Effect of bovine growth hormone on metabolism of growing Hereford heifers: Dietary digestibility, energy and nitrogen balance. J. Nutr. 116:157–163.

Eisenbeisz, W.A., D.J. Schingoethe, D.P. Casper, R.D. Shaver, and R.M. Cleale. 1990. Lactational evaluation of recombinant bovine somatotropin with corn and barley diets. J. Dairy Sci. 73:1269–1279.

Eppard, P.J., D.E. Bauman, J. Bitman, D.L. Wood, R.M. Akers, and W.A. House. 1985. Effect of dose of bovine growth hor-

mone on milk composition: α-lactalbumin, fatty acids and mineral elements. J. Dairy Sci. 68:3047–3054.
Fallert, R., T. McGuckin, C. Belts, and G. Brunner. 1987. bST and the dairy industry: A national, regional and farm-level analysis. USDA, Economic Res. Services, Washington, DC.
French, N., G. de Boer, and J.J. Kennelly. 1990. Effects of feeding frequency and exogenous somatotropin on lipolysis, hormone profiles, and milk production in dairy cows. J. Dairy Sci. 73:1552–1559.
International Panel on Climate Change. 1990. Intergovernmental Panel on Climate Change on Methane Emissions and Opportunities for Control Workshop. USEPA, Washington, DC.
Johnson, D.E., M.E. Branine, and G.M. Ward. 1990. Methane emissions from livestock. p. 33. *In* Proc. of the American Feed Industry Association Nutrition Symposium. Animal Agriculture for the 90's, St. Louis, MO. 5–6 Nov. 1990. Am. Feed Industry Assoc., Arlington, VA.
Johnson, D.E., G.M. Ward, J. Torrent, and J.J. Ramsey. 1991. Milk production response, health and fertility of dairy cows treated with bST; a literature review. Misc. Rep. Dep. Animal Sci., Colorado State Univ., Ft. Collins.
Juskevich, J.C., and C.G. Guyer. 1990. Bovine growth hormone: Human food safety evaluation. Science (Washington, DC) 249:875–884.
Kirchgeßner, M., W. Schwab, and H.L. Müller. 1989. Effect of bovine growth hormone on energy metabolism of lactating cows in long term administration. p. 143–150. *In* Energy metabolism of farm animals. Proc. of the 11th Symp., Lunteren, the Netherlands. 18–24 Sept. 1988. EAAP Publ. 43. Pudoc, Wageningen, the Netherlands.
Leitch, H.W., E.B. Burnside, and B.W. McBride. 1990. Treatment of dairy cows with recombinant bovine somatotropin: Genetic and Phenotypic Aspects. J. Dairy Sci. 73:181–190.
Marsh, W.E., D.T. Galligan, and W. Chalupa. 1988. Economics of recombinant methionyl bovine somatotropin use in individual dairy herds. J. Dairy Sci. 71:2944–2958.
Maynard, L.A., and J.K. Loosli. 1969. Animal nutrition. 6th ed. McGraw-Hill, New York.
McDaniel, B.T., and P.W. Hayes. 1988. Absence of interaction of merit of milk with recombinant bovine somatotropin. J. Dairy Sci. 71(Suppl. 1):240.
McGuffey, R.K., R.P. Basson, D.L. Snider, E. Block, J.H. Harrison, A.H Rakes, R.S. Emery, and L.D. Muller. 1991. Effect of somidove sustained release administration on the lactation performance of dairy cows. J. Dairy Sci. 74:1263–1276.
McGuffey, R.K., H.B. Green, and R.P. Basson. 1990. Lactation response of dairy cows receiving bovine somatotropin and fed rations varying in crude protein and undegradable intake protein. J. Dairy Sci. 73:2437–2443.
Miller, R.W., and R.L. Donahue. 1990. Soil: An introduction to soil and plant growth. 6th ed. Prentice-Hall, Englewood Cliffs, NJ.
Mochet, C. 1987. Conséquences économiques de l'emploi de la B.S.T. dans la production laitière en France. Aspects microéconomiques et macroéconomiques. Sci. Agron. Rennes Número Spécial Thématique: 1–75.
Moseley, W.H., L.F. Krabill, and R.F. Olsen. 1982. Effect of bovine growth hormone administered in various patterns on nitrogen metabolism in the holstein steer. J. Anim. Sci. 55:1062–1070.
National Milk Producers Federation. 1990. The impact of bovine somatotropin (BST) on the U.S. Dairy Industry. Nat. Milk Producers Fed., Arlington, VA.
National Research Counsel. 1987. Predicting feed intake of food producing animals. Nat. Acad. Sci., Washington, DC.
National Research Counsel. 1989. Nutrient requirements of dairy cattle. Nat. Acad. Sci., Washington, DC.
Nytes, A.J., D.K. Combs, G.E. Shook, and R.D. Shaver. 1990. Response to recombinant bovine somatotropin in dairy cows with different genetic merit for milk production. J. Dairy Sci. 73:784–791.
Oltenacu, P.A., and M.S. Allen. 1980. Resource-cultural energy requirements of the dairy production system. p. 363–378. *In* E.D. Pimentel (ed.) Handbook of energy utilization in agriculture. CRC Press, Boca Raton, FL.
Peel, C.J., and D.E. Bauman. 1987. Somatotropin and lactation. J. Dairy Sci. 70:474–486.
Schepers, J.S. 1988. Role of cropping systems in environmental quality: Groundwater nitrogen. p. 167–178. *In* W.L. Hargrove (ed.) Cropping strategies for efficient use of water and nitrogen. ASA Spec. Publ. 51. ASA, CSSA, and SSSA, Madison, WI.
Sechen, S.J., D.E. Bauman, H.F. Tyrrell, and P.J. Reynolds. 1989. Effect of somatotropin on kinetics of nonesterified fatty acids and partition of energy, carbon, and nitrogen in dairy cows. J. Dairy Sci. 72:59–67.
Tyrrell, H.F., A.C.G. Brown, P.J. Reynolds, G.L. Haaland, D.E. Bauman, C.J. Peel, and W.D. Steinhour. 1988. Effect of bovine somatotropin on metabolism of lactating dairy cows: Energy and nitrogen utilization as determined by respiration calorimetry. J. Nutr. 118:1024–1030.
Tyrrell, H.F., and P.W. Moe. 1975. Production efficiency in the high producing cow. J. Dairy Sci. 58:1151.
U.S. Congress, Office of Technology Assessment. 1991. U.S. diary industry at a crossroad: Biotechnology and policy choices—Spec. Rep. OTA-F470. U.S. Gov. Print. Office, Washington, DC.
Van Horn, H.H. 1990. Achieving balance of nutrient flow through animal production systems. p. 15. Proc. of the American Industry Association. Nutritional Symp. Animal Agriculture for the 90's, St. Louis, MO. 5–6 Nov. 1990. Am. Feed Industry Assoc., Arlington, VA.
Ward, G.M. 1980. Energy, land and feed constraints in beef production in the 1980's. J. Anim. Sci. 51:1051–1064.
Ward, G.M. 1991. Water use in U.S. beef production. Colorado State Univ. Beef Research Rep. Dep. of Anim. Sci., Colorado State Univ., Ft. Collins, CO.
Ward, G.M., T.V. Muscato, D.A. Hill, and R.W. Hansen. 1978. Chemical composition of feedlot manure. J. Environ. Qual. 7:159–164.
Weller, R.F., R.H. Phipps, N. Craven, and C.J. Peel. 1990. Use of prolonged-release bovine somatotropin for milk production in British Friesian dairy cows. J. Agric. Sci. Cambridge 115:105–112.

CHAPTER VII

1991 NASA REPORTS

Project Title: Modelling Global Methane Emissions from Livestock: Biological and Nutritional Controls, Reports and Publications

1. Johnson, D.E., M.E. Branine, G.M. Ward, B.R. Carmean and D.W. Lodman. 1991. Livestock methane emissions: Variation, comparative warming perspectives and amelioration potential. Proceedings, Southwest Nutrition and Management Conference, University of Arizona. pp. 42-49.

2. Johnson, D.E., T.M. Hill, B.R. Carmean, M.E. Branine, D.W. Lodman and G.M. Ward. 1991. New perspectives on ruminant methane emissions. In: Energy Metabolism of Farm Animals. European Association of Animal Production Publication 58:376-379.

3. Johnson, D.E., G.M. Ward and J. Torrent. 1992. The environmental impact of bovine somatotropin use in dairy cattle. J. Envir. Qual. 21:157-162.

4. Johnson, D.E., T.M. Hill, G.M. Ward, K.A. Johnson, M.E. Branine, B.R. Carmean and D.W. Lodman. 1991. Principle factors of varying methane emissions from ruminants and other animals. In: Atmospheric Methane. NATO Advanced Research Workshop, Springer Verlag (in press). 39 pp.

5. Carmean, B.R. 1991. The persistence of monensin effects on ruminal fermentation and nutrient digestion in steers. M.S. Thesis, Animal Science Department, Colorado State University. 61 pp.

6. Ward, G.M., K.G. Doxtader, W.C. Miller and D.E. Johnson. 1991. Effects of intensification of agricultural practices on greenhouse gases. Chemosphere (in press).

7. Lodman, D.W., M.E. Branine, B.R. Carmean, P. Zimmerman, G.M. Ward and D.E. Johnson. 1991. Estimates of methane emissions from manure of U.S. cattle. Chemosphere (in press).

8. Johnson, D.E., G.M. Ward and J. Torrent. 1991. The environmental impact of bovine somatotropin (bST) use in dairy cattle. J. Dairy Sci. ?:(Abstract).

9. Miller, W.C., D.E. Johnson and G.M. Ward. 1991. Mathematical modelling of methane production from beef cattle. J. Anim. Sci. 69: (Abstract).

10. Carmean, B.R., D.E. Johnson, M.A. Ward and G.M. Trotter. 1991. The persistence of monensin effects on ruminal VFA and ammonium nitrogen concentrations in nutrient digestibility. J. Anim. Sci. 69:561 (Abstract).

NASA PROJECT 1990 REPORTS
Reports/Publications

A. Conference Proceedings

Johnson, D.E., M. Branine and G.M. Ward. 1990. Methane emissions from livestock. Proceedings, American Feed Industry Association. Nutrition Symposium, November, 1990. St. Louis, MO, p. 33.

Johnson, D.E., M. Branine, G.M. Ward, B. Carmean and D. Lodman. 1990. The potential contribution of beef cattle methane to global warming: Background information and perspectives. Proceedings, The LaCosta Conference, Cattle on the Land: Environmental Implications of Beef Production. December, 1990 (in press).

Ward, G.M. and D.E. Johnson. 1990. Methane emissions from livestock and the potential for reduction. Proceedings, Global Warming International Conference. Chicago, IL.

World Resource Review (in press).

B. Metabolic Laboratory Reports

Lodman, D., B. Carmean, M. Branine, P. Zimmerman and D. Johnson. 1990a. Determination of methane from manure sources.

Lodman, D.W., M. Branine, G.M. Ward and D.E. Johnson. 1990b. A preliminary estimate of methane emissions during manure disposal from U.S. cattle.

Ward, G.M. 1990. Estimates of feed intake as a base to calculate methane output by ruminants fed low quality diets.

Ward, G.M. 1990b. Estimates of methane production by cattle in the Sahel region of Africa.

C. National Center for Atmospheric Research

Gunther, A., P. Zimmerman, A. Hills, C. Westburg and B. Lamm. 1990. Flux measurements of methane from cattle feedlots.

D. Abstracts

Carmean, B.R. and D.E. Johnson. 1990. Persistence of monensin and induced changes in methane emissions in ruminal protozoan numbers in cattle. J. Anim. Sci. 41:517 (Abstract).

Branine, M.E. and D.E. Johnson. 1990. Level of intake effects from ruminant methane loss across a wide range of diets. J. Anim. Sci. 41:509 (Abstract).