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Reducing Methane Emissions From Livestock: Opportunities and Issues

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REDUCING METHANE EMISSIONS FROM LIVESTOCK:

OPPORTUNITIES AND ISSUES

by:

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August 1989

ACKNOWLEDGEMENTS*

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Additionally, we are grateful to all the reviewers who helped to improve the paper through their comments.

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PROLOGUE

A workshop entitled "Methane Emissions From Ruminants" was held on February 27-29, 1989 to identify and discuss issues relating to the role that ruminants and other managed animals play in the global methane (CH_4) budget. A draft version of this paper was presented and discussed at that workshop. This revised version reflects the comments and discussion at the workshop. A list of the workshop attendees is presented in Appendix E.

The following are the findings that were adopted by consensus by the workshop attendees. These findings indicate that there are promising opportunities for reducing CH_4 emissions from ruminants. Such opportunities remain to be assessed and demonstrated in the field. Undertaking such assessments and demonstrations is a recognized priority.

FINDINGS

1. Methane is increasing and will affect tropospheric air quality and global climate.

   1.1 The concentration of CH_4 in the atmosphere is currently increasing at a rate of approximately 1.0 percent per year. This rate of increase is well characterized for the recent past. Additionally, the atmospheric concentration of CH_4 has approximately doubled in the past 200 to 300 years.

   1.2 Increasing emissions of CH_4 are the primary cause of increasing CH_4 concentrations. Reduction in the rate of CH_4 destruction in the atmosphere (possibly associated with increasing emissions of carbon monoxide) is also a factor.

   1.3 Continued increases in the concentration of CH_4 in the atmosphere will lead to increases in tropospheric ozone formation (a component of smog) which is considered a threat to human health and the environment. Additionally, increasing CH_4 concentrations directly and indirectly change the radiative properties of the atmosphere, contributing to the greenhouse effect. One other hypothesis raises the concern that increasing CH_4 concentrations could contribute to polar stratospheric ozone depletion.

2. Animals, and in particular ruminants, are an important source of CH_4 emissions on a global scale.

   2.1 Although uncertainty exists regarding the global sources of CH_4, it is clear that the major anthropogenic sources include: ruminant animals (primarily cattle, buffalo, and sheep); animal wastes; rice paddies; biomass burning (e.g., forest fires); termites from disturbed forests (e.g., deforested areas);

venting and incomplete flaring of gas during oil exploration and extraction; leakage of natural gas during natural gas extraction and distribution; coal mining; and landfills.

2.2 Current estimates indicate that anthropogenic sources account for about 60 percent of current CH_4 emissions, with the remaining emissions, from natural sources, being associated with swamps, marshes, lakes, and oceans.

2.3 Animals, and in particular managed ruminant animals, produce significant quantities of CH_4 as part of their digestive processes. Based on laboratory estimates of CH_4 production by individual animals, and estimates of total animal populations, ruminant animals are estimated to account for nearly one fourth of the total anthropogenic emissions, or about 15 percent of total emissions. These estimates do not include CH_4 emissions from animal wastes, which may be significant.

3. Reductions in CH_4 emissions from animals will assist in reducing the rate of CH_4 increases, and may be one important component in attempts to stabilize atmospheric CH_4 concentrations.

3.1 Based on the current imbalance of CH_4 emissions and destruction in the atmosphere, a 10 to 20 percent reduction in anthropogenic CH_4 emissions is required to stabilize atmospheric concentrations at their current levels.

3.2 Given the diversity of CH_4 emissions sources, reducing emissions from one or two sources will not be sufficient for stabilizing atmospheric concentrations. Instead, small reductions in each of the major sources will likely be preferred.

3.3 A 50 percent reduction in CH_4 emissions from ruminants will contribute about 50 to 75 percent of the emissions reductions needed to stabilize atmospheric CH_4 concentrations.

3.4 While many uncertainties exist, it would appear that with adequate resources and appropriate policies, emissions of CH_4 from livestock could be reduced from 25 to 75 percent with current resources directed toward raising livestock. These reductions could be decreased if significantly larger amounts of resources were devoted toward growing livestock. Reductions in CH_4 emissions would ordinarily contribute to higher animal productivity.

4. In order to take rational steps to reduce CH_4 emissions from ruminants, current emissions must be better characterized and options for reducing emissions must be identified and evaluated.

4.1 Emissions from animals in developing countries remain uncertain. Techniques for measuring these emissions must be developed and undertaken.

4.2 Emissions from animal wastes have not been adequately quantified. Animal waste management practices must be characterized, and emissions rates for various practices must be estimated.

4.3 Although potential options for reducing emissions may be promising, they must be demonstrated and evaluated. Research for identifying long term options must be undertaken.

4.4 The scientific infrastructure exists to greatly increase levels of research to find solutions to limiting CH_4 emissions from livestock.

1. INTRODUCTION

1.1 SUMMARY

It is well documented that the global atmospheric abundance of methane (CH_4) is increasing. Recent rates of increase are on the order of one percent per year, or about 0.017 ppmv per year (ppmv is parts per million by volume). This increased abundance of CH_4 will have important impacts on: the stratospheric ozone layer; background levels of tropospheric (i.e., ground-based) ozone; and global climate.

Managed livestock, and in particular, ruminants, are important contributors to the increasing abundance of atmospheric CH_4, accounting for on the order of 15 to 20 percent of annual CH_4 emissions. As shown in Exhibit 1-1, the population of managed ruminants has been increasing globally for over 30 years. According to FAO statistics, the numbers of managed ruminants in 1987 included: 1.3 billion cattle; 1.2 billion sheep; 0.5 billion goats; 0.1 billion buffalo; and 19 million camels (FAO, 1988). In recent years, animal numbers have steadied or declined in the U.S. and Europe; however, growth continues among developing nations.

CH_4 production is part of the normal digestive activity of ruminants. The primary mechanism producing CH_4 in these animals is methanogenic bacteria in the rumen converting fermentation products (primarily carbon dioxide plus hydrogen or formate) into CH_4. CH_4 is also produced and emitted to various degrees from livestock wastes. Reducing CH_4 emissions from livestock-agriculture systems alone will help to reduce the rate of increase in the abundance of CH_4. In concert with reductions from other sources, it could help to stabilize the CH_4 abundance in the atmosphere at roughly current levels.

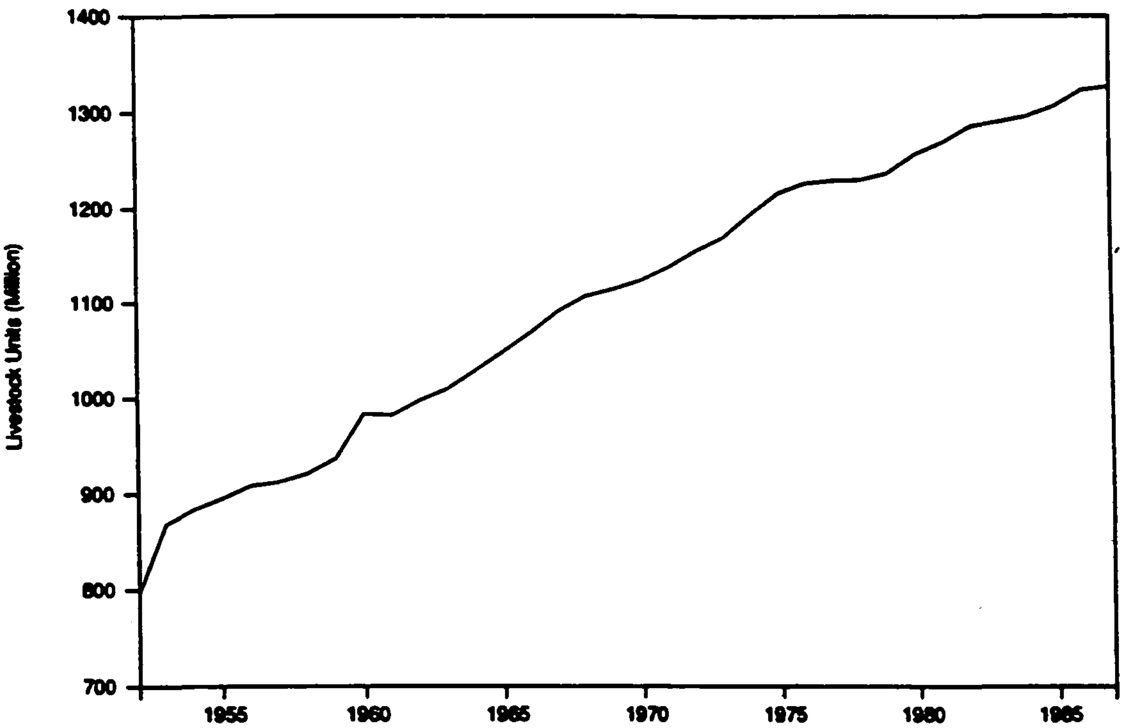
At this time, numerous questions and uncertainties remain regarding sources of CH_4 emissions and options for reducing emissions. Two points are clear, however:

- With its relatively short atmospheric lifetime (on the order of 10 years), CH_4 is a good candidate for stabilization. An overall emissions reduction on the order of 10 percent is required in order to prevent the CH_4 abundance from continuing to increase (see WMO (1986), pp. 92).

- Given the diverse nature of the sources of CH_4 emissions, addressing emissions from one or two sources will not be sufficient to stabilize the abundance of CH_4 in the atmosphere. Instead, opportunities for reducing emissions from all sources must be identified and evaluated.

EXHIBIT 1-1

GLOBAL LIVESTOCK POPULATION ESTIMATES



These data are suggestive of the recent changes in the global population of managed animals. The recent data obtained from the FAO for this exhibit are updated versions of data previously-published by FAO in their production yearbook series. Although these animal population data must be viewed as uncertain due to difficulties in counting animals (particularly in developing countries), the data are suggestive of a trend of increasing animal populations globally.

The total population of cattle, buffalo, goats, and sheep are combined into "Livestock Units" using the following population multipliers: cattle = 0.8; buffalo = 1.0; sheep = 0.1, goats = 0.1.

Sources: Data through 1960 from: FAO, FAO Production Yearbook, Food and Agriculture Organization of the United Nations, Rome, Italy, selected years.

Data after 1960 from: FAO, Livestock Numbers Database Printout, Food and Agriculture Organization of the United Nations, Rome, Italy, 1988.

This investigation of livestock-related emissions is only one part of the diverse set of analyses required to identify and evaluate options for stopping the increasing abundance of CH_4 in the atmosphere.

This paper summarizes the issues associated with reducing CH_4 emissions from livestock-agriculture systems. For those involved in addressing global change, it provides a framework for addressing CH_4 emissions from ruminants and as such is a foundation upon which additional data collection and analysis can be built. The challenge is to build upon existing data in a manner that identifies preferred opportunities for reducing CH_4 emissions as quickly and as efficiently as possible.

For those involved in animal sciences and animal management, this paper identifies important gaps in understanding and data that require research and analysis. Additionally, it demonstrates that there are opportunities to apply expertise and develop options for reducing emissions. Finally, it highlights that coordination is required among domestic and international institutions of many types.

1.2 THE INCREASING ABUNDANCE OF ATMOSPHERIC METHANE

CAUSES OF METHANE INCREASES

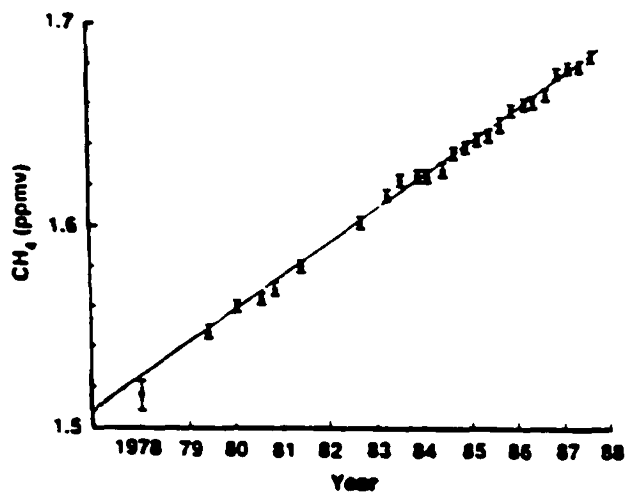
The level of CH_4 in the Earth's atmosphere is defined by emissions (from natural and anthropogenic sources) and natural destruction processes. It is well documented that the atmospheric abundance of CH_4 is currently increasing (see for example: Khalil and Rasmussen (1986) and Blake and Rowland (1988)). Recent rates of increase are on the order of about 0.017 ppmv per year, or about one percent of the current average global level of abundance of about 1.7 ppmv (see Exhibit 1-2).

Based on analyses of air trapped in the ice sheets of Greenland and Antarctica, long term CH_4 trends have been established. The data indicate that the abundance of atmospheric CH_4 has increased primarily in the last 300 years, with relatively stable levels prior to that time at about one-half the current levels (see Exhibit 1-3). This increase in abundance must be caused by an imbalance in the sources (i.e., emissions) and sinks (i.e., destruction) of CH_4. The mechanisms leading to these observed increases in CH_4 are believed to be: (1) increases in emissions; and (2) possibly decreases in its rate of destruction.

The destruction of atmospheric CH_4 is driven primarily by its oxidation in the troposphere (i.e., the lower atmosphere) and stratosphere by the hydroxyl radical, OH. Relatively smaller amounts of atmospheric CH_4 are consumed by aerobic soils. It has been postulated that the observed increase in atmospheric CH_4 may be in part due to a decline in the rate of CH_4 destruction by OH. Such a decline could be caused by a decrease in the abundance of OH, which could occur as the result of increasing emissions of both CH_4 and carbon monoxide (CO). Exhibit 1-4 displays a simplified

EXHIBIT 1-2

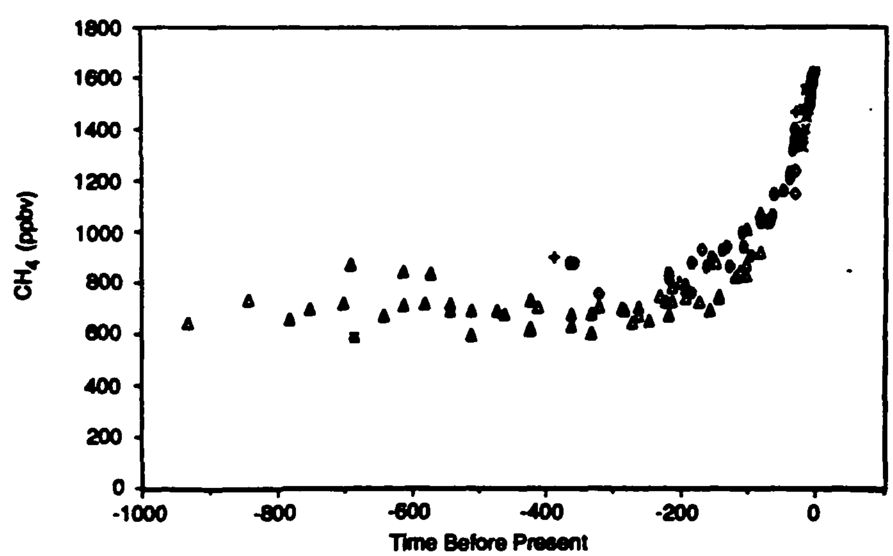
RECENTLY-MEASURED INCREASES IN ATMOSPHERIC METHANE



Source: Blake, D.R. and F.S. Rowland, "Continuing Worldwide Increase in Tropospheric Methane, 1978 to 1987," Science, March 4, 1988.

EXHIBIT 1-3

ATMOSPHERIC METHANE FOR THE PAST 1000 YEARS



Source: Khalil, M.A.K., and R.A. Rasmussen, "Trends of Atmospheric Methane: Past, Present, and Future," in: Proceedings of the Symposium on CO_2 and Other Greenhouse Gases, Brussels, Belgium, November 1986.

relationship among CH_4, CO, OH, and O_3. Although trends in the emissions and abundance of CO remain to be established, large anthropogenic sources of CO have been identified, adding support to the assumption that CO emissions and abundances have increased substantially.[1]

Unfortunately, time trends for OH are not sufficiently well defined in order to establish its relative importance in the measured increase in CH_4. It is likely, however, that decreases in OH are not sufficient to explain completely the observed increases in CH_4 (Bolle, Seiler and Bolin (1986), p. 166). The relative importance of changes in emissions and OH levels continues to be investigated.

Emissions estimates for CH_4 remain somewhat uncertain. The primary anthropogenic sources of CH_4 emissions include: ruminant animals (primarily cattle, buffalo, and sheep); rice paddies; biomass burning (e.g., forest fires); termites from disturbed forests (e.g., deforested areas); venting and incomplete flaring of gas during oil exploration and extraction; leakage of natural gas during natural gas extraction and distribution; coal mining; and landfills. Current estimates indicate that these sources account for about 60 percent of current CH_4 emissions, with ruminant animals accounting for nearly one fourth of this, or about 15 percent of the total. The remaining emissions, from natural sources, are associated with wetlands, marshes, lakes, and oceans.

In order for the atmospheric abundance of CH_4 to be increasing at the observed rates, it is believed that CH_4 emissions must be increasing. Increasing populations of ruminants, increasing area planted to rice (and increases in the "double cropping" of rice; i.e., planting two crops a year), increasing production and distribution of natural gas, and increasing production of coal have been cited as evidence of increasing CH_4 emissions from these sources. Some of the key natural sources (e.g., wetlands and marshes), have reduced in area due to development pressures in various parts of the world. Consequently, increasing emissions from anthropogenic sources are believed to be the primary cause of increasing emissions.[2]

Exhibit 1-5 presents estimates of the time trend of emissions and estimates of recent emissions. As shown in the exhibit, the time trend estimated by Seiler indicates that total emissions are increasing at an average annual rate of over 1.0 percent per year. The estimate of current emissions rates by source shows the relatively large uncertainties that remain regarding the allocation of total emissions among source categories.

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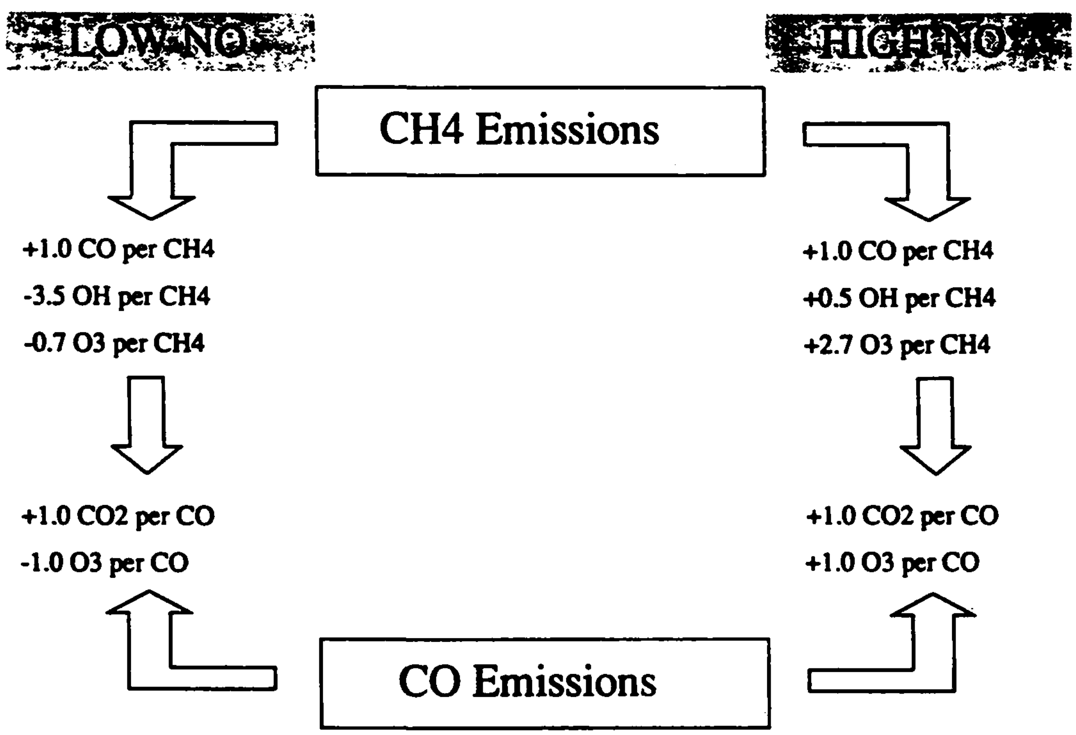
[1] Large anthropogenic sources include fossil fuel and biomass combustion as well as oxidation of CH_4 and other anthropogenic hydrocarbons. See: WMO (1986), pp. 104-106.

[2] It has also been mentioned that warming in the Arctic may be leading to increased CH_4 emissions from tundra, see WMO (1986), p. 99.

EXHIBIT 1-4

RELATIONSHIP AMONG CH_4, CO, OH, AND O_3



Based on current models, the implications of CH_4 and carbon monoxide (CO) emissions appear to differ for areas of low and high nitrogen oxide (NO) concentrations. In low NO environments (mostly over oceans), CH_4 oxidation to CO results in a loss of OH and tropospheric ozone (O_3). Oxidation of CO to carbon dioxide (CO_2) further destroys O_3. In high NO environments (mostly over continents), CH_4 oxidation to CO increases OH and O_3. CO oxidation further increases O_3.

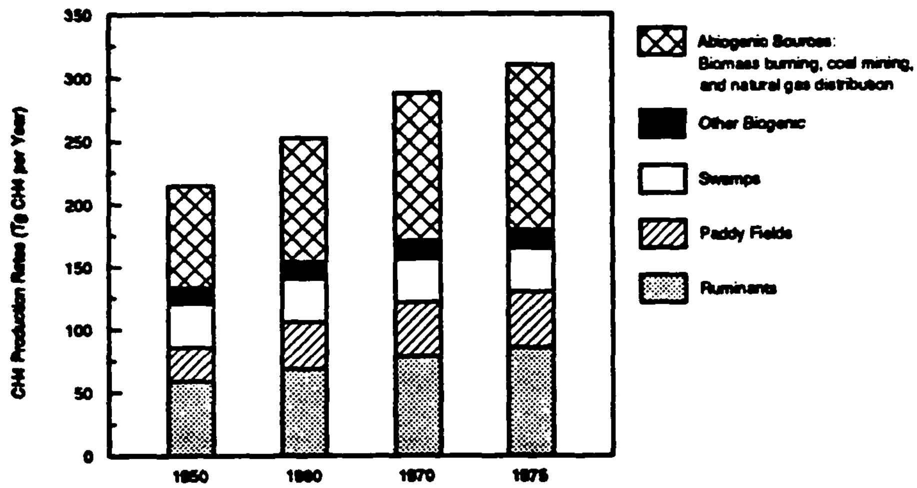
Based on current models, the atmosphere appears to be divided approximately equally between the two NO environments. Therefore, increasing CH_4 abundance will lead to reduced levels of OH and increased levels of O_3. Additionally, CO oxidation reduces the abundance of free OH that can enter into reactions, effectively reducing the level of OH. Finally, a heterogeneous CO oxidation reaction cycle (not shown above) can also reduce OH levels; the heterogeneous reaction cycle is not well quantified, however.

Source: Crutzen, Paul J., "Role of the Tropics in Atmospheric Chemistry," in: Dickinson, R. (ed.), Geophysiology of Amazonia, John Wiley & Sons: New York, 1987.

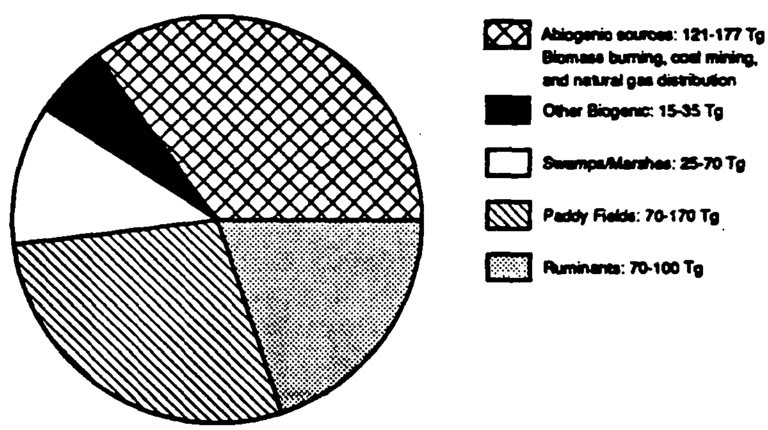
EXHIBIT 1-5

ESTIMATES OF METHANE EMISSIONS
(Tg of CH_4 per year)*

Time Trend of Emissions -- Seiler:



Current Emissions by Source -- Bolle, Seiler, and Bolin:



* 1 Tg = 10^{12} grams

Sources: Seiler, W., "Contribution of Biological Processes to the Global Budget of CH_4 in the Atmosphere," in: Klug, M. and C. Reddy (eds.), Current Perspectives in Microbial Ecology, 1984, pp. 468-477.

Bolle, H.-J., W. Seiler and B. Bolin, "Other Greenhouse Gases and Aerosols: Assessing Their Role for Atmospheric Radiative Transfer," in: Bolin, B., B.R. Doos, B. Warrick and D. Jager (eds.), The Greenhouse Effect Climatic Change and Ecosystems, John Wiley & Sons: New York, 1986, p. 163.

Despite the various uncertainties regarding both sources and sinks, it is clear from atmospheric measurements and ice core analyses that the atmospheric abundance of CH_4 is increasing. Additional research and analysis is ongoing to improve our assessment of the sources and sinks of CH_4, including: atmospheric monitoring to evaluate CH_4 trends by latitude and CH_4 isotope ratios; measurements of the emissions from key sources, including tundra in the Arctic, rice paddies in Asia, ruminants, and others.

OZONE EFFECTS IN THE STRATOSPHERE AND TROPOSPHERE

Current atmospheric models indicate that increases in the abundance of CH_4 may increase the abundance of tropospheric and stratospheric ozone (WMO (1986), pp. 730-732). Increases in tropospheric ozone, an important component of urban "smog," are considered a threat to human health, crops, forests, ecosystems and materials (EPA (1987), p. 14-3). The extent of increases in tropospheric ozone due to CH_4 depends on the tropospheric abundance of nitrogen oxide (NO). As shown above in Exhibit 1-4, CH_4 oxidation leads to an increase in tropospheric ozone abundance when in the presence of relatively high levels of NO, as are found over the northern continents, including North America (WMO (1986), pp. 730-731, and Crutzen (1987), pp. 111-114).

Based on current models, therefore, increasing levels of CH_4 are expected to worsen tropospheric ozone levels in both urban and rural locations in the U.S. Because the current understanding of the link between the levels of CH_4 and tropospheric ozone is based on models of complex tropospheric chemistry, the quantitative relationship between CH_4 and tropospheric ozone remains uncertain.

Stratospheric ozone forms the Earth's shield against harmful solar ultraviolet radiation. Conventional wisdom has been that in the stratosphere CH_4 may help to protect ozone by interfering with its catalytic destruction by chlorine and nitrogen oxides (NO_x) (WMO (1986), pp. 731-732). Thus, it has been thought that such stratospheric ozone increases associated with CH_4 could help to offset stratospheric ozone depletion due to chlorofluorocarbon (CFC) emissions, thereby reducing the risks to human health and the environment (EPA (1987), p. 18-41).

However, it has been suggested recently that CH_4 may in fact promote stratospheric ozone depletion (Blake and Rowland (1988)). The water vapor that is added to the stratosphere when CH_4 is oxidized may provide surfaces for heterogeneous reactions that destroy ozone to take place. These reactions, which have been implicated in the polar ozone losses that are currently observed (i.e., the Antarctic "Ozone Hole"), would lead to reductions in stratospheric ozone that outweigh the increases currently anticipated to be associated with increasing levels of CH_4. Consequently, the impact of rising CH_4 levels on stratospheric ozone now is less of a consensus.

GLOBAL CLIMATE CHANGE IMPACTS

By changing the radiative properties of the atmosphere, CH_4 will contribute to the greenhouse effect (WMO (1986), pp. 873-874). In fact, on a molecular basis CH_4 is a more potent greenhouse gas than is carbon dioxide (CO_2). Of note is that the potency of CH_4 as a greenhouse gas may be amplified by associated increases in tropospheric ozone (because tropospheric ozone is also a greenhouse gas) and stratospheric water vapor (see Exhibit 1-6).[3] Assuming that the growth rate of global atmospheric concentrations of CFCs is reduced considerably as the result of future reductions in the production and use of these compounds,[4] model calculations indicate that the CH_4 contribution to potential future global warming from human-related emissions will be second only to CO_2.

1.3 STABILIZING THE ABUNDANCE OF ATMOSPHERIC METHANE

The current imbalance in the sources and sinks of CH_4 must be corrected in order to stabilize CH_4 concentrations at approximately current levels. Using estimates of current concentrations and rates of emissions in WMO (1986), it is estimated that about a 7 to 14 percent reduction in current annual CH_4 emissions is required in order to stabilize its current atmospheric concentration. The range is driven by uncertainties in the atmospheric lifetime of CH_4.[5] Because some emissions are from natural (and presumably uncontrollable) sources, the reductions in anthropogenic sources required to stabilize concentrations are about 10 to 20 percent.

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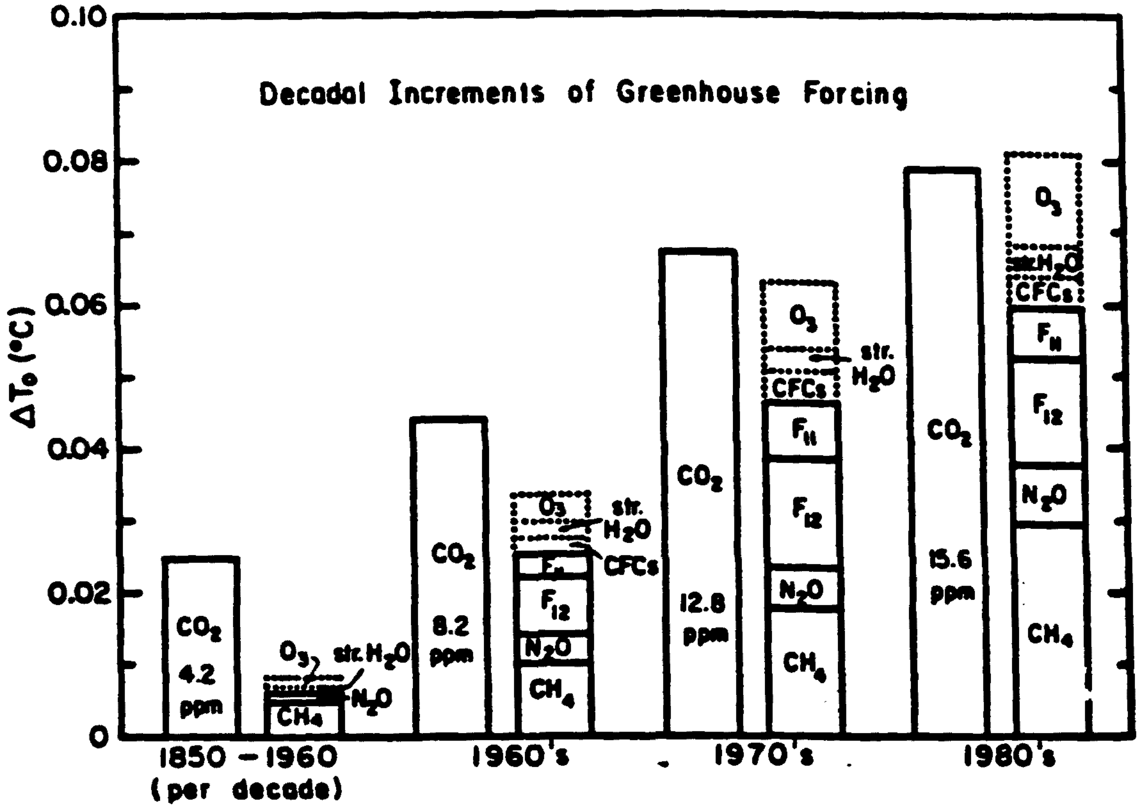
[3] The amount of global warming in Exhibit 1-6 is reported in terms of equilibrium temperature increases associated with a "direct radiative forcing," which is a measure of the extent of the change in the radiative properties of the Earth's atmosphere. The actual warming of the Earth's surface will lag behind the changed radiative properties of the atmosphere because it takes time for the Earth to come into thermal equilibrium. In addition, the amount of warming anticipated will be larger than the amounts shown in the exhibit because the direct radiative forcing is expected to be amplified by positive feedbacks in the Earth's climate system.

[4] Significant reductions in the future use and emissions of CFCs are anticipated as the result of the current and expected future provisions of the "Montreal Protocol on Substances That Deplete the Ozone Layer," which has entered into force.

[5] The higher the CH_4 destruction rate (primarily by OH), the shorter its atmospheric lifetime. The range of destruction and accumulation rates presented in WMO (1986) implies a range of lifetimes of about 7.4 years to 15.1 years, with a middle value of about 10 years.

EXHIBIT 1-6

METHANE IS AN IMPORTANT CONTRIBUTOR TO THE GREENHOUSE EFFECT



Decadal additions to global mean greenhouse forcing of the climate system. The No Feedback Warming is the computed temperature change at equilibrium for the estimated decadal increase in trace gas abundances, with no climate feedbacks included. Based on current models, global warming (including feedbacks) is expected to be larger, depending on the feedbacks assumed.

Note: O_3 - tropospheric ozone
Str. H_2O - stratospheric water vapor
F_{11} - CFC-11
F_{12} - CFC-12

Source: Hansen, J., et al., "The Greenhouse Effect: Projections of Global Climate Change," in: Titus, J.G. (ed.), Effects of Changes in Stratospheric Ozone and Global Climate, U.S. EPA and UNEP: Washington, D.C., August 1986, p. 206.

Compared to other key greenhouse gases (e.g., carbon dioxide (CO_2), nitrous oxide (N2O), and CFCs), this reduction is relatively modest. To stabilize the concentrations of these other gases, the following reductions are required from current anthropogenic emissions levels: CO_2: 50 to 75 percent; N2O: 60 to 80 percent (WMO (1986), p. 81); and CFCs: 90 to 100 percent (Hoffman and Gibbs (1988), pp. 23-27).[6]

Due to the varied sources of CH_4, it is unlikely that any single response or intervention will be capable of reducing CH_4 emissions by an amount that is sufficient to stabilize concentrations. Instead, undertaking options that result in modest reductions in each of the various sources of CH_4 will likely be the preferred approach for reducing overall CH_4 emissions. Nevertheless, as one of the larger anthropogenic sources, reductions in emissions associated with livestock could be particularly useful. For example, a 50 percent reduction target for livestock-related emissions would provide on the order of half the reductions needed to stabilize concentrations.

Even without making other possible reductions to stabilize CH_4 concentrations, a 25 to 75 percent reduction in CH_4 emissions associated with livestock would produce a significant reduction in anticipated future global climate change from the greenhouse effect. As described in Appendix B, such a reduction in livestock-related CH_4 emissions could reduce anticipated equilibrium warming increases on the order of one to six percent by 2100 (depending on the assumptions used).

Because no single human-related activity accounts for a large fraction of emissions of gases that contribute to the greenhouse effect, this impact of reducing these CH_4 emissions is similar to the impacts that can be achieved by other specific technical means, such as increasing the fuel efficiency of automobiles, reforesting large areas, or putting emissions fees on the use of coal, oil, and gas (see, for example, EPA (1989)). Additionally, unlike many of the other options for addressing global climate change, reducing CH_4 emissions from ruminants produces benefits by improving animal productivity, particularly in developing countries.

The technical feasibility and cost of achieving emissions reductions of this magnitude from livestock remain to be quantified. However, as described below, a range of opportunities for reducing CH_4 emissions from

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[6] Of note is that although a 90 to 100 percent reduction in CFC emissions will stabilize CFC concentrations over the long term, such reductions will also stimulate the use of substitute compounds (such as HCFC-22 and HFC-134a) which will also contribute to global warming. Because the atmospheric lifetimes of the substitutes are much shorter than the lifetimes of the CFCs, the anticipated impacts of the substitutes on global climate will be much smaller than what the impacts of the CFCs would have been.

livestock have been identified, indicating that some reductions, and possibly large reductions may be feasible. A major goal of this assessment, therefore, is to identify options for achieving such a reduction in livestock-related emissions. These options could subsequently be evaluated.

Such an evaluation would include:

- Improved Characterization of Emissions. Emissions rates from various animals and animal management practices (particularly in developing countries) must be better characterized. Improved emissions estimates will enable emission reduction options to be better evaluated.

- Evaluation of Impacts. Options for reducing emissions must be evaluated in terms of: impact on emissions; cost; ease of implementation; and impact on agricultural productivity. Given the obvious importance of managed ruminants throughout the world, and their unique ability to convert low quality inputs (e.g., agriculture byproducts that cannot be digested by humans) into useful products, potential technical and management options for reducing CH_4 emissions must be evaluated within the context of the overall agricultural, social, and economic systems in which they would be implemented.

- Assessment of Methods of Implementation. Institutions and organizations involved with agriculture and agriculture products must be involved in implementing emissions reduction options.

Similar analyses are required for the other sources of CH_4 emissions. For example, improved estimates of CH_4 emissions are required in order to evaluate whether additional gas recovery during coal mining is warranted. Continued improvements in our understanding of the global sources and sinks of CH_4 are required in order to have confidence that the levels of emissions reductions achieved over time are sufficient for stabilizing atmospheric concentrations.

2. OVERVIEW OF METHANE FROM LIVESTOCK

2.1 SOURCES OF METHANE EMISSIONS

Among livestock, the ruminants (i.e., cattle, buffalo, sheep, goats, and camels) are the major emitters of CH_4. The <u>rumen</u>, a large "fore-stomach," is the unique physiological characteristic of ruminants that provides the opportunity for CH_4 to be created within the animal. Within the rumen, over 200 species and strains of microorganisms have been identified, although a smaller number (10 to 20 species) are believed to play an important role in digestion (Baldwin and Allison (1983), p. 462). Rumen <u>methanogenic bacteria</u> are the source of CH_4 produced within ruminants.

To date, methanogenesis within the rumen of ruminants has been the primary focus of discussions regarding CH_4 production related to livestock. However, ruminants are generally managed as part of an overall system, which may have other parts that also contribute to CH_4 emissions. The principal system component identified that may contribute the CH_4 emissions is the disposal of manure. Significant CH_4 emissions have been measured from lagoons used to dispose of animal wastes, including non-ruminants, such as swine and poultry (Safley and Westerman (1988)).

METHANOGENESIS WITHIN THE RUMEN

Rumen methanogenic bacteria are generally a very small fraction of the total population of microorganisms in the rumen. Although they can convert acetate (a fermentation product produced in the rumen) to CH_4 and CO_2, this pathway for CH_4 production in the rumen is believed to be of minor importance in animals fed adequate and balanced diets (Baldwin and Allison (1983), p. 469). Instead, the conversion of hydrogen (H_2) or formate and CO_2 (produced by fermentative bacteria) is believed to be the primary mechanism by which methanogenic bacteria produce CH_4 in ruminants.

The creation of CH_4 in the rumen represents energy which is subsequently not available to the host animal for maintenance or growth. Methods of reducing methanogenesis in ruminants have been investigated as part of the overall attempt to improve the efficiency of rumen metabolism. However, methanogenic bacteria play an important role in the complex ecology of the rumen, so that simply eliminating or suppressing the activity of methanogens in the rumen will not "free up" energy that can be used by the animal.

The extent of methanogenesis in individual ruminants has been estimated by various authors. The rate of methanogenesis can be described in terms of a "methane yield," which is defined as the amount of CH_4 produced as a percentage of the gross food energy intake of the animal. Most CH_4 yield estimates for ruminants are in the range of 4 to 9 percent.[7]

Using an estimate of the CH_4 yield for an animal, its total annual CH_4 emissions can be estimated by multiplying its annual gross energy intake by the appropriate percentage (e.g., six percent) and then converting the energy value (e.g., in megajoules, or MJ) to a mass basis (i.e., kilograms). For example, if a cow consumes 60,000 MJ per year, and has a CH_4 yield of 6 percent, the total CH_4 emissions for the animal would be the equivalent of about 3,600 MJ, or about 65 kilograms.

Methanogenesis occurs within individual animals, and various factors affect the rate of methanogenesis on the individual animal level. In addition, however, the total amount of CH_4 produced by a population of animals can be evaluated in terms of the amount of CH_4 emitted relative to the amount of useful product produced by the population. The manner in which the population is managed will influence the size of the population required in order to produce the useful products desired, and consequently the total level of CH_4 emissions. Factors affecting methanogenesis in individual animals and populations are described in turn.

Individual Animals

The level and type of diet a ruminant consumes has a strong influence on an animal's CH_4 yield and on the amount of CH_4 produced by the animal. Blaxter and Clapperton (1965) examined the results of 391 experiments on sheep and found that the CH_4 yield is primarily a function of two factors: (1) the digestibility of the feed; and (2) the level of energy consumed in relation to the maintenance energy requirements of the animal. Exhibit 2-1 shows Blaxter and Clapperton's CH_4 yield estimates for a range of values for these factors.[8]

As shown in Exhibit 2-1, animals with low intake levels (e.g., 1.0 times maintenance energy requirements) eating low digestibility feed (e.g., 50 to 60 percent) have CH_4 yields in the 6.8 to 7.4 percent range. Such conditions may be anticipated among animals in many developing countries. Alternatively, animals with high intakes (e.g., 3.0 times maintenance) eating highly digestible feed (e.g., 70 to 80 percent) have CH_4 yields in the 5.4 to 5.8 percent range. Such conditions may be anticipated among highly productive dairy cows in the U.S., for example.

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[7] See for example: Blaxter and Clapperton (1965) and Moe and Tyrrell (1979) and Rumpler, Johnson, and Bates (1986).

[8] Care must be exercised in using the results presented in Exhibit 2-1. One would not expect to find animals consuming highly digestible feed (e.g., 70 percent or higher) at levels near maintenance. Similarly, one would not expect to find animals consuming low digestible feed (e.g., 50 to 60 percent) at 3.0 times maintenance.

EXHIBIT 2-1

METHANE YIELD AS A FUNCTION OF
DIGESTIBILITY AND LEVEL OF ENERGY INTAKE
(percent)

	Level of Intake				
	1.0	1.5	2.0	2.5	3.0
Digestibility					
50	6.8	6.7	6.6	6.6	6.5
60	7.4	7.1	6.8	6.4	6.1
70	8.0	7.4	6.9	6.3	5.8
80	8.6	7.8	7.0	6.2	5.4
90	9.2	8.2	7.1	6.1	5.0

Estimates based on an analysis of 391 experiments on sheep. Methane yield is the percent of feed energy that is converted to CH_4. Level of intake is measured as the ratio of total gross energy intake to total gross energy intake needed to meet maintenance energy requirements (e.g., total gross energy intake equals two times maintenance requirements). Digestibility in percent.

Source: Blaxter, K.L. and J.L. Clapperton, "Prediction of the Amount of Methane Produced by Ruminants," British Journal of Nutrition, Vol. 19, 1965, pp. 511-522.

These CH_4 yield estimates can be used to estimate expected CH_4 emissions per year by multiplying the rates by the associated levels of intake. Exhibit 2-2 displays these estimates for a 500 kg beef steer. The emissions rates reflect both the CH_4 yield and the influence that feed digestibility has on required energy intake. For example, at 2.0 times maintenance, the CH_4 yield (as a percentage of total feed energy intake) increases with increasing feed digestibility (see Exhibit 2-1). However, CH_4 emissions (e.g., in kilograms per year) decline (see Exhibit 2-2) because the increasing digestibility reduces the energy intake required in order to meet the 2.0 times maintenance level.[9]

Others have also examined CH_4 emissions rates. For example, Moe and Tyrrell (1979) report on a total of 404 total energy balance trials on Holstein dairy cows. Unlike the Blaxter and Clapperton model, Moe and Tyrrell estimate CH_4 emissions as a function of the amounts of the following feed constituents consumed: soluble residue, hemicellulose, and cellulose. Feeds vary in their content of these constituents. CH_4 production was found not to be correlated with the intake of other feed characteristics such as crude protein, ether extract, and lignin.

Using concentrate and hay feeds typically fed to U.S. dairy cows, and the feed characteristics reported in NRC (1988), the Blaxter and Clapperton CH_4 estimates were compared to the Moe and Tyrrell estimates. For the chosen diet,[10] the Moe and Tyrrell equation results in an estimate of about 120 kg per year of CH_4 emissions, for an implied CH_4 yield of about 5.7 percent. The analogous estimate based on Blaxter and Clapperton is 135 kg per year (for a 600 kg dairy cow), or about 12.5 percent larger than the Moe and Tyrrell estimate. Given that the two methods for estimating emissions are based on different data (in fact, different types of animals), such similar estimates are in reasonably close agreement.

Most ruminants in the world are in developing countries where levels of intake and feed characteristics are very different from the diet of U.S. dairy cows. In general, ruminants in developing countries eat agricultural

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[9] As with Exhibit 2-1, the results in Exhibit 2-2 must be examined with care. One would not expect to find animals consuming highly digestible feed at levels near maintenance or animals consuming low digestible feed at 3.0 times maintenance.

[10] Twenty pounds of concentrate per day containing barley, hominy, rolled corn, beet pulp, millrun wheat, and cotton seeds, and fifteen pounds of alfalfa hay per day. This diet is estimated to provide about 2.3 times the maintenance energy requirement for a 600 kg dairy cow, with a digestibility of about 65 percent. The diet is also estimated to contain about: 4 kg/day of soluble residue; 2 kg/day of hemicellulose; and 3.3 kg/day of cellulose.

EXHIBIT 2-2

ANNUAL METHANE EMISSIONS FOR COMBINATIONS
OF FEED INTAKE AND DIGESTIBILITY LEVELS
(kilograms per year per animal)

	Level of Intake				
	1.0	1.5	2.0	2.5	3.0
Digestibility					
50	57.	97.	NA	NA	NA
60	52.	85.	117.	NA	NA
70	NA	77.	102.	123.	NA
80	NA	NA	91.	105.	114.
90	NA	NA	82.	92.	94.

Estimates are based on CH_4 yield estimates from Blaxter and Clapperton (1965) and feed characteristics from NRC (1984). Estimates are for a 500 kilogram animal with feed energy maintenance requirements similar to that described in NRC (1984) for U.S. beef cattle. Energy requirements vary by breed, sex, and climate. Smaller animals (such as those found in many parts of developing countries) would have lower energy requirements, and consequently lower CH_4 emissions for any given combination of level of intake and digestibility.

NA = Not Applicable. One would not normally expect to observe animals at these combinations of feed intake levels and feed digestibility.

byproducts with low digestibility (e.g., wheat straw, rice straw, and sugar cane tops), with levels of intake near maintenance requirements. For these animals on relatively poor diets, Preston and Leng (1987) indicate that CH_4 yields may be in the 9 to 12 percent range, with the level influenced by the adequacy of ammonia levels in the rumen (Preston and Leng (1987), p. 40). In their assessment, (based on stoichiometric considerations) inadequate ammonia levels are related to inefficient rumen fermentation and increased CH_4 production. If this is the case, supplementing diets of these animals with urea or poultry litter (good sources of rumen ammonia) could increase rumen fermentation efficiency and reduce CH_4 emissions. Such supplements are starting to be provided to milk cows in India, for example, as a means of increasing milk production.

Considerable uncertainty remains regarding the levels of CH_4 emissions anticipated from animals in developing countries. The Preston and Leng assessments indicate larger CH_4 yields than would be indicated by Blaxter and Clapperton. Because feed costs account for a significant portion of the costs of producing milk and beef in developed countries, considerable data have been collected on the performance of feeds in these areas. However, less data are available to describe feed characteristics and performance in most developing country situations.

<u>Animal Populations</u>

The manner in which an animal population is managed will influence the overall level of CH_4 emissions. In general, a population of managed animals is maintained in order to produce some set of useful products, such as milk, meat, wool, and (in the case of animals in developing countries) work. The size of the population required in order to produce the desired level of products will depend on the productivity of the animal population.

The productivity of dairy cows is primarily measured by the amount of milk produced per cow per year. Significant increases in productivity have been achieved in the U.S. and around the world due to selected breeding and improvements in animal management. By increasing the amount of milk produced per cow, the feed requirements per amount of milk produced have declined. Concurrent with reductions in feed requirements should be reductions in the amount of CH_4 generated per amount of milk produced. This result is anticipated assuming that CH_4 yields per amount of feed energy consumed remain unchanged. The possibility that CH_4 yields of more productive dairy cows are in fact lower than average (possibly contributing to the increased productivity of the cows) remains to be demonstrated conclusively.

In addition to examining the productivity of dairy cattle on a per cow basis, the productivity of the population as a whole can be assessed. At any point the dairy cattle population includes not only lactating dairy cows (i.e., those actually giving milk) but also those between lactation cycles and those that are growing (i.e., replacement heifers that have yet to give milk). By reducing the time between lactation cycles, increasing the rate of maturity of replacement heifers, reducing losses due to disease, and increasing the success rate of replacement heifers (some replacements are not productive), the total population of dairy cows and heifers can be reduced while still maintaining the same level of milk production. Along with such reductions in the population size would come reductions in the generation of CH_4.

Similar analyses of beef cattle populations are applicable. The primary measures of productivity of beef cattle are rate of weight gain and feed efficiency. Although beef cattle breeding has not been as successful as dairy cattle breeding in improving productivity, hormone-based growth stimulants have been developed that increase feed efficiency about 5 to 10 percent during finishing. These implants are used widely in the U.S. and other countries, although they have been banned in the EEC.

As with dairy cows, the total size of the beef cattle population can be reduced by: reducing losses from disease (antibiotics are currently used); increasing the birth rate and decreasing the inter-calving interval of cows used to produce calves for meat production (current birth rates are about 75 calves per 100 producing cows per year in the U.S., and possibly lower in other countries); and increasing the success rate of replacement heifers.

In developing nations, cattle, buffalo, horses, donkeys, mules, and camels are used as draft animals, and cattle, buffalo, camels, goats, and sheep are used for meat, milk, fertilizer, fuel, wool, and hide production. In some cases, the animals also form the basis for storing wealth in many economies that are not based on a "cash" currency. The successful implementation of realistic methods of increasing the productivity of these animals within the context in which they are managed remains a challenge.

MANURE AS A SOURCE OF METHANE EMISSIONS

The amount of CH_4 generated and emitted from manure depends on the manner in which the manure is handled. If aerobic conditions exist (i.e., if the manure is in contact with oxygen) then CH_4 generation should be minimal. If the manure is maintained under anaerobic or anoxic conditions (i.e., in the absence of oxygen), then some portion of the organic matter in the manure may be converted to CH_4.

In many locations, manure is used as fertilizer. If manure is spread on dry soils, and if it decomposes aerobically, it may produce little or no CH_4. However, spreading manure as fertilizer on anoxic soils (e.g., flooded rice paddies) will likely produce CH_4, possibly in large amounts. Good field measurements are lacking in this area and need to be undertaken.

In addition to fertilizer, manure is used as an energy source. The manure may be gathered and dried, and subsequently burned. This method of handling manure should produce very little CH_4 as the organic material is oxidized directly to CO_2. Alternatively, the manure may be collected and used in a biogas (i.e., CH_4) generator. In this case the organic material in the manure is deliberately converted to CH_4, which is subsequently collected and used as fuel. The use of biogas generators would result in CH_4 emissions only to the extent that CH_4 leaked from containment or was incompletely burned.

In locations where large numbers of animals are managed in a confined location (e.g., dairies in the U.S. and Europe, feedlots in the U.S., swine and poultry farms in the U.S.) manure is a waste product that requires proper handling and disposal. The waste manure may be piled up until it can be hauled away, or it may be washed into ponds. In either case, anaerobic conditions are likely to exist, which would allow a portion of the manure to be converted into CH_4 and emitted.

The extent of CH_4 emissions from piles of manure remains to be quantified. Such emissions may be limited by the acids that are produced in the wastes during anaerobic decomposition, however. CH_4 emissions from waste lagoons and digesters have been measured, and were found to be on the order of 0.14 to 1.0 cubic meter of CH_4 per kilogram of volatile solids added to the lagoon, although in at least one case, emissions were much higher (Safley and Westerman (1988), p. 187, Hill (1984)). This rate of CH_4 emissions translates into about 12 to 85 cubic meters of CH_4 per metric ton of manure (wet weight) added to the lagoon, or about 8 to 55 kilograms of CH_4 per ton of manure. Because a 600 kilogram dairy cow produces about 15 tons of manure per year (wet weight, Ensminger (1983), p. 737), the disposal of manure wastes in an anaerobic lagoon could result in about 120 to 825 kilograms of CH_4 emissions per head per year. This level of emissions is on the order of one to 10 times the level of CH_4 emissions originating in the dairy cow's rumen. Additionally, swine and poultry wastes produce similar amounts of CH_4 emissions per ton of waste, although CH_4 emissions directly from these animals' digestive systems is relatively small.

Although the potential for CH_4 emissions from waste manure is large, it is unlikely that this potential is fully realized. Most manure is either spread as fertilizer, burned (a common practice in developing countries) or allowed to remain in pastures or on ranges. The CH_4 emissions resulting from these practices remain to be quantified.[11] Manure is probably only piled up and/or washed into ponds at intensively managed dairy farms and feed lots where there is no market for manure fertilizer. Even if these animals are a small fraction of the total animals, the emissions from these wastes would be significant. For example, if 10 percent of the manure produced by cattle were to decompose anaerobically, and if these wastes were converted to CH_4 at a rate of 0.14 m^3 per ton of volatile solids added (a lower bound conversion rate) then on the order of 15 Tg per year of CH_4

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[11] Most manure in pastures and on ranges may decompose aerobically. However, at least one researcher has detected CH_4 emissions from this type of manure (Goreau and Mello (1985)).

(1 Tg = 10^{12} g) would be produced. This amounts to 20 percent of the estimate of CH_4 emissions from livestock.

2.2 GLOBAL METHANE EMISSIONS FROM RUMINANTS

Crutzen et al. (1986) have performed the most comprehensive assessment of CH_4 emissions from ruminants to date. Based on a review of CH_4 yields and feed characteristics and consumption, Crutzen et al. estimate the following:

- Cattle in developed countries, Brazil and Argentina: average annual CH_4 emissions per head of 55 kg/yr; total annual emissions of 31.5 Tg/yr;

- Cattle in developing countries: average annual CH_4 emissions per head of 35 kg/yr; total annual emissions of 22.8 Tg/yr;

- Sheep in developed countries: average annual CH_4 emissions per head of 8 kg/yr; total annual emissions of 3.2 Tg/yr;

- Sheep in developing countries and Australia: average annual CH_4 emissions per head of 5 kg/yr; total annual emissions of 3.7 Tg/yr;

- Buffalo (virtually all are in developing countries): average annual CH_4 emissions per head of 50 kg/yr; total annual emissions of 6.2 Tg/yr; and

- Goats (virtually all are in developing countries): average annual CH_4 emissions per head of 5 kg/yr; total annual emissions of 2.4 Tg/yr; and

- Camels (virtually all are in developing countries): average annual CH_4 emissions per head of 58 kg/yr; total annual emissions of 1.0 Tg/yr.

The total of these estimated emissions is about 71 Tg/yr, over 75 percent of which is associated with cattle.

In addition, Crutzen et al. estimate an additional 2.9 Tg/yr of CH_4 emissions associated with the digestive systems of pigs, horses, mules, and humans.[12] Approximately 2 to 6 Tg/yr of emissions is estimated for wild ruminants throughout the world, and emissions from large non-ruminants are expected to be small. The overall total for these sources of CH_4 is on the order of about 80 Tg/yr.

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[12] Note that these estimates do not include potential CH_4 emissions associated with wastes.

As noted by Crutzen et al., various uncertainties remain in these estimates. Chief among them are realistic emissions rates for animals in developing countries. Appendix A summarizes various uncertainties in the estimates presented, and Appendix C presents a copy of the paper published by Crutzen et al.

2.3 TRENDS IN SUPPLY AND DEMAND

Livestock provide a diverse set of products for human consumption. Throughout the world, livestock management, processing, and product distribution are significant economic activities, providing important sources of nourishment to all people.

The current markets for livestock products reflect the complex interaction of a diverse set of factors including: genetic characteristics of animals; management practices; the availability of natural, technological, and human resources; consumer preferences; and cultural preferences and traditions. Government policies are used throughout the world to influence these various factors.

As a result of these numerous factors, the markets for livestock products vary considerably throughout the world and are constantly changing. These changes will influence the levels of CH_4 emissions from livestock, as well as the opportunities for reducing emissions.

TRENDS IN SUPPLY

Within developed nations, the technologies and methods for intensively managing ruminants to produce milk and meat products have increased productivity dramatically over the past 40 years. In particular, the productivity of milk cows has increased substantially during this time. Although feed intake per cow has increased with milk production per cow, the increases in productivity have enabled larger quantities of milk to be produced per amount of feed (and other) inputs. The result is that larger amounts of milk are produced per amount of CH_4 emitted. This trend may be an important factor influencing future CH_4 emissions from ruminants.

Several of the key trends in the supply of milk and meat products from intensively managed cattle are as follows:

- <u>Increased productivity of dairy cows through selective breeding and improved management</u>. With the development of artificial insemination techniques and methods of evaluating bulls and cows, the systematic breeding of dairy animals has been performed in the U.S. and elsewhere with considerable success. The high genetic potential of Holstein dairy cows to produce milk has been distributed throughout the dairy herd, and management methods have improved (e.g., in the preparation of balanced rations) so that the value of the genetic potential has been realized in terms of "on-the-farm" performance. Exhibit 2-3 displays estimates of milk produced per cow in the U.S. since 1950.

- Increased reproductive efficiency of beef brood cows. In the U.S. (unlike in Europe) dairy cows are not the primary source of calves that are grown into beef.[13] Instead, a separate set of cows, usually referred to as "brood" cows, produce calves that are grown into beef. The productivity of these brood cows are measured in terms of the number of offspring produced (reproductive efficiency) and their meat characteristics (such as weaning weight and carcass quality). The reproductive efficiency of brood cows in the U.S. is about 0.75 calves per cow per year. Increased reproductive efficiency reduces the size of the brood herd needed to produce a given amount of meat, and hence reduces CH_4 emissions per amount of meat produced.

- Increased feed efficiency of beef animals. The cost of feed is a major cost of growing meat. Consequently, improvements in weight gain per amount of feed consumed are desireable (i.e., improvements in feed efficiency). Two technologies that have been adopted to promote feed efficiency are ionophore feed additives and steroid implants. Each of these techniques increases feed efficiency about 5 to 10 percent (Ensminger (1987), p. 859). Ionophores are used widely in the U.S. among finishing cattle (i.e., in feedlots), and among some growing cattle in pasture situations. Implants are used in growing range, pasture, and feedlot animals throughout the world. Implants have recently been banned in the EEC, however.

These various advances in animal management, combined with a relatively saturated demand for animal products in developed nations has lead to the stabilization or decline of animal numbers in the U.S., Europe, and other developed nations, while milk and meat production continue to increase. Declining animal numbers in these areas likely indicates reduced CH_4 emissions from this source, although changes in animal management characteristics (such as level and type of feed consumed and waste management practices used) must also be considered.

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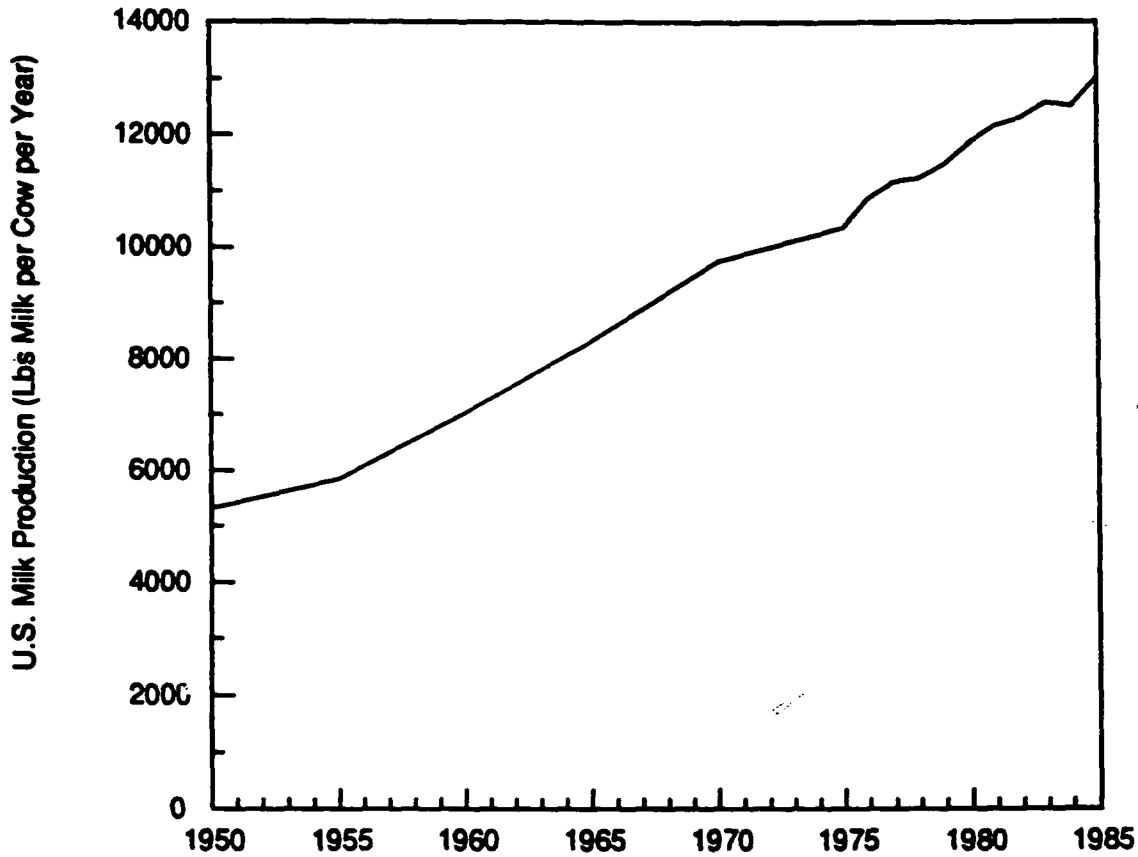
[13] In Europe, most of the beef (70 to nearly 100 percent, depending on the country) is derived from the dairy cow population through the calves produced by these cows and through the slaughter of older cows. As such, the cows in Europe are referred to as "dual purpose," i.e., they supply both milk and meat. In the U.S., most of the beef is derived from calves produced by beef brood cows. These brood cows are separate and distinct from the population of cows used to produce milk. As such, the U.S. cows are referred to as "single purpose," i.e., they produce either milk or meat.

EXHIBIT 2-3

MILK PRODUCTION PER DAIRY COW PER YEAR IN THE U.S.



Source: NMPF, Dairy Producer Highlights, National Milk Producer Federation, Arlington, Virginia, 1987, p. 5.

These trends may be anticipated to continue into the foreseeable future. Selective breeding continues to produce productivity gains, and techniques (such as embryo transplantation) are being developed that could improve the rate of improvement. New methods of improving animal productivity (such as the use of synthetic bovine growth hormone, BGH) hold the promise of making significant improvements. Cows injected with BGH produce 10 to 25 percent more milk than cows injected with a placebo (Fallert et al. (1987) and Mix (1987)). If the use of BGH is approved, the population of dairy cows required to produce a given amount of milk will decline. Whether this decline is realized, for example in the U.S., depends on how the pricing and subsidy system for milk changes in response to (or in anticipation of) the use of BGH (Fallert et at. (1987)). Whether the use of BGH reduces CH_4 emissions (as opposed to just animal numbers) also remains to be examined, because feeding practices will also likely change with the use of BGH.

While methods of intensively managing livestock have improved productivity in developed countries, the productivity of "extensive" animal management systems (such as village conditions in developing countries and range animals), has not changed significantly in recent years. Many, if not most, animals in developing countries continue to be managed in small herds (1, 2, or 3 head per household) with traditional practices. Animal nutrition and health remain well below the levels seen in developed countries, and hence productivity (measured by intensive management standards; i.e., in terms of the amount of milk and/or meat produced per animal) remains low. Consequently, increases in the demand for animal products in some developing nations have been met through increases in animal numbers. These increases probably imply increased CH_4 emissions from this source.

In many developing countries animal feed resources are constrained. In such situations, animal numbers in the countries cannot increase, even as human populations have increased. The growing demands for animal products (mostly milk products) in these countries are partially met through imports (which are limited by available economic resources), and largely go unmet.

Development projects undertaken by the World Bank and others have among their objectives improvements in animal productivity in developing countries. For example, the largest ongoing dairy development project is "Operation Flood" in India. Funded through the sale of EEC-donated dairy products and World Bank loans, this program has among its objectives to: improve transportation links between rural milk producing areas and urban population centers; improve storage and processing facilities; establish marketing cooperatives; develop cattle feed plants; and improve genetic characteristics of dairy cattle.

To the extent that projects such as Operation Flood are successful in increasing animal productivity, they likely reduce the rate of CH_4 emissions per amount of product (e.g., milk) produced. Whether they reduce total CH_4 emissions is less clear.

TRENDS IN DEMAND

The demand for milk and meat products are the primary factors driving the sizes of animal populations in developed countries. In developing countries, the needs for draft power and a mechanism for storing wealth are also important factors.

The per capita consumption of animal products in most developed nations has stabilized in the past 10 to 20 years in terms of calories, protein, and calcium consumed (FAO (1986)). In some areas, for example the U.S., per capita poultry consumption has increased while per capita red meat consumption has remained relatively constant (American Meat Institute (1987)).

Future trends in demand for animal products in developed nations will likely be driven by changes in the size and age structure of the population and by changes in consumer preferences. For example, demand for low-cholesterol and low-fat products are leading to developments of low-fat meat and dairy products (Dunkley (1982)). Changes in the complex demand for milk products (currently driven primarily by the demand for milk fat for use in milk products like cheese and ice cream) could influence breeding and feeding strategies, possibly affecting CH_4 emissions as well.

Demand for low-fat meat could influence the feeding strategies and slaughter ages of feed-lot-finished cattle. Similarly, concerns over antibiotics (used in therapeutic treatments of animals in feedlots) could also influence feedlot finishing practices. Shifts to range- and pasture-fed beef (if they occur) could increase feed requirements (e.g., ionophore feed supplements are more difficult to administer to range-fed animals), possibly increasing total CH_4 emissions.

Consumer concerns over hormone use could also affect the manner in which meat and milk are produced, and hence, CH_4 emissions. The recent EEC ban on the use of steroid implants is an example. Such concerns could also affect the potential use of bovine growth hormone and the realization of its benefits in terms of CH_4 emissions reductions (see above).

Increasing population and income among developing countries point to increasing demand for animal products in these areas. In general, stage of development has been found to be a good indicator of food consumption patterns (Rojko et al. (1978)). Consequently, as development proceeds and as incomes continue to rise in developing countries, meat and dairy product production and consumption may be anticipated to increase as well. The extent of these increases depends not only on rates of development, but on regional and local tastes and customs as well.

Given that extensive animal management systems predominate in developing countries, increasing demands for meat and milk products are expected to be translated into increasing populations of animals. Increases in animal productivity could reduce the rate of animal population growth, and the possibility of such increases being large enough to allow consumption to increase while holding animal populations constant remains to be investigated.

The demand for draft power also has an important influence on animal populations in developing nations. Virtually all buffalo are in developing nations, and many of these are used for draft power. An increasing human population will likely increase the need for draft power, while mechanization could reduce the demand for animal draft power. However, the costs of equipment, maintenance, and fuel limit the potential impact that mechanization will have in the short term.

The combined influence of these various trends in supply and demand on CH_4 emissions is unclear. Although animal numbers in developed nations are not growing and productivity is continuing to increase, animal management practices may be leading to increased energy consumption per animal and increased disposal of animal wastes in lagoons. The net effect on CH_4 emissions from these animals is therefore ambiguous and remains to be assessed. Animal numbers and feed consumption are increasing in developing nations, leading to increased CH_4 emissions. The rate of increase, however, remains to be assessed.

In its recent analysis of options for stabilizing global climate, EPA (1989) estimated future CH_4 emissions from livestock under a variety of assumptions. Assuming that policies are not pursued to reduce these emissions, EPA estimated that CH_4 emissions from animals could increase by a factor of about 2.4 by 2100. In light of anticipated population growth (by a factor of about 2.0 to 2.6 by 2100) and economic growth (historically, the consumption of animal products per capita (meat and milk) have risen along with income per capita), such emissions growth seems plausible. However, such emissions growth will not be possible if important resource constraints prevent the supply of animal products from increasing along with population and income. Such constraints have not been proposed to date.

3. STEPS FOR REDUCING METHANE EMISSIONS FROM LIVESTOCK

To reduce CH_4 emissions from livestock, systematic investigations are required in two main areas: (1) emissions characterization; and (2) option identification, evaluation, and implementation. The final objective of these efforts is the specification of a series of near-term and long-term options for reducing CH_4 emissions from animal management systems. These options could then be examined in conjunction with options for reducing emissions from other sources to identify a cost-effective approach for reducing CH_4 emissions globally. Each of the two areas of investigation is discussed in turn.

3.1 IMPROVED EMISSIONS CHARACTERIZATION

Emissions rates from various animals and animal management practices must be better characterized. Improved emissions estimates are needed in order to: assess anticipated changes in emissions over time; identify the areas where emissions reductions efforts would be most promising; and evaluate the emissions reductions that can be achieved with various options.

In order to improve estimates as efficiently as possible, investigations should be targeted at the key areas of inadequate data. Several areas that have been identified are summarized in Exhibit 3-1 and are described below.

CHARACTERIZE THE ANIMAL POPULATIONS

The population of managed ruminants throughout the world is reported by the Food and Agriculture Organization (FAO) of the United Nations based on reports to FAO from individual countries. These data are important for estimating CH_4 emissions. The accuracy of these data, in particular in developing countries in Africa and Asia, remain to be examined.

Additionally, to assess adequately recent and future trends in emissions from these animals, differences and changes in animal <u>characteristics</u> throughout the world must be estimated. For example, the sizes of mature cattle differ by a factor of at least 2 to 3 between developed and developing countries.[14] These size differences are indicative of differences in the amount of feed consumed by the animals. An assessment of animal sizes, amount of feed consumed, and feed characteristics would assist in improving estimates of global CH_4 emissions from animals.

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[14] Of note is that cattle breeds found in developing countries are not necessarily inherently smaller; instead, cattle growth is often stunted due to inadequate nutrition.

EXHIBIT 3-1

STEPS FOR IMPROVING EMISSIONS ESTIMATES

AREA OF INVESTIGATION	COMMENTS
1. Characterize animal populations along characteristics that affect CH_4 emissions.	Good animal population data are required. Defining categories of animals with similar characteristics will facilitate subsequent analysis. The numbers of animals are well described for most developed countries. However, the majority of ruminants are in developing countries where animal numbers are least well quantified. Additionally, data on animal characteristics (including animal waste management systems) are also required. These data have not been collected in a comprehensive form for the major populations of animals in the world.
2. Develop and evaluate measurement techniques.	Existing methods of measuring CH_4 emissions directly from animals and from related sources need to be evaluated. New techniques are required to measure emissions rates from grazing animals and animals in developing countries.
3. Perform CH_4 emissions measurements.	Adequate measurements of emissions rates from animals in developing countries appear to be lacking. Additionally, measurements from some categories of animals in developed countries and from animal wastes are lacking. The differences in CH_4 emissions among individual animals, and the factors that contribute to these differences (such as differences in the rumen microbial environment) remain to be measured and understood.
4. Model Development.	The animal population characteristics and the emissions measurements may be used for purposes of developing a model of regional and global emissions. The model may also be a useful tool for identifying the implications of alternative approaches for reducing emissions.

Similarly, animal waste management practices vary throughout the world. The extent to which wastes are burned, spread as fertilizer, placed in digesters, or disposed of in ponds must be evaluated. A summary of animal waste management practices is required.

One effective approach to developing this characterization is to define a set of "animal/management categories" that represent the range of animal situations that exist throughout the world. Such categories might include: intensive dairy farming in the U.S., using Holsteins and concentrate feeding; feedlot beef cattle in the U.S. on high grain diets; stocker cattle in the U.S. in pastures and on ranges; cow/calf operations in the U.S.; range/pasture cattle in South America; draft bovines in developing countries that are fed rice and wheat byproducts; cattle in developing countries that are managed by pastoralists and graze the available forage; etc.

The categories would differ along characteristics that influence CH_4 emissions. The key characteristics of each group could include: number of animals; typical type of animal ownership; type and quantity of feed consumed (including key feed characteristics); animal health services typically available; products produced from the animals.

DEVELOP AND EVALUATE MEASUREMENT TECHNIQUES

Indirect calorimetry is the laboratory technique currently used to perform in-depth evaluations of the performance of alternative feeding practices. This technique involves placing an animal in confinement for a period of several days, and measuring the amount of inputs (feed, oxygen, carbon dioxide) and outputs (excretion, oxygen, carbon dioxide, CH_4) from the confinement chamber. Because CH_4 is produced during digestion, CH_4 is measured as part of this technique.

Because indirect calorimetry is primarily used to evaluate animal energetics, its applicability for quantifying CH_4 emissions must be examined closely. Several areas that need to be addressed include:

- How representative are the CH_4 emissions estimates for an individual animal of what might be expected for that individual animal in the field? What factors could lead to the results not being representative, and are these factors important from the CH_4 point of view? Examples of experimental factors that should be examined include: (1) restrictions to the animal's intake to ensure that the experiment can be reproduced; (2) stresses on the animal from being in confinement; (3) lack of environmental stresses on the animal (e.g., lack of heat stress); (4) lack of exercise (this may be particularly important for evaluations of draft animals); and (5) experiment duration.

- Have measurements been performed on an adequate set of animals and conditions? A wide range of animal types and management practices exist. Have sufficient measurements been performed across this entire range to provide a basis for quantifying emissions on a global basis?

Because indirect calorimetry experiments are time consuming and costly, other measurement techniques should be explored. In particular, techniques for measuring CH_4 emissions from animals in developing countries, and grazing animals throughout the world need to be developed and evaluated. For each of the major categories of animals (discussed above), an appropriate measurement technique is required.

Atmospheric sampling to estimate fluxes of CH_4 may be appropriate for evaluating emissions from an entire animal management area, such as a feedlot or a dairy. The total emissions estimated with this technique should be divided into those portions associated with rumen fermentation, animal waste disposal, and other sources as appropriate. Indirect calorimetry or other methods may be appropriate for estimating the portion associated with rumen fermentation. Alternatively, the animals could be removed from the management area and the measurements repeated. To verify these measurements, it would be useful to have techniques for evaluating emissions from waste piles, waste lagoons, and soils.[15]

Methods for evaluating emissions from grazing animals and small groups of animals (e.g., one or two cows in a rural Indian household) remain to be developed. One option that may prove useful is to collect air samples near individual animals over an extended period of time. In order to estimate <u>rates</u> of CH_4 emissions from the animal, a method is required to adjust these air samples for meteorological conditions. The details of such an approach remain to be developed.[16]

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[15] As described in the previous section, CH_4 emissions have been measured from waste lagoons. The appropriateness of these methods for characterizing the range of animal waste management practices remains to be defined.

[16] One promising method for measuring CH_4 emissions rates from individual animals was suggested at the workshop. The approach, involving the use of tracers to estimate flux rates from animals, would allow CH_4 and carbon dioxide emissions rates to be measured inexpensively for individual animals without the need to isolate the animals (i.e., without the use of a calorimetry chamber.) Such an approach, if it proves viable, will allow numerous CH_4 emissions estimates to be developed for types of animals for which estimates are not currently available (e.g., grazing animals and animals in developing countries). The details of the approach are currently under development, and will be presented in subsequent reports.

As a complement to various techniques for measuring CH_4 emissions directly from animals, techniques could be explored to correlate emissions from the animal to gases produced by samples of rumen contents, and to the population (and species) of methanogens found in the samples. By developing such correlations, estimates of CH_4 emissions could be produced using laboratory analyses of rumen contents. Such an approach, if feasible, would greatly enhance the ability to estimate CH_4 emissions from ruminants.

PERFORM CH_4 EMISSIONS MEASUREMENTS

Numerous measurements of CH_4 emissions from cattle and sheep in developed countries have been made using direct and indirect calorimetry techniques. The representativeness of these measurements for the various types of animal management practices must be assessed, and gaps in measurements identified. For example, indirect calorimetry experiments have been performed on lactating dairy cows and finishing steers on various types and levels of diets. These data need to be consolidated and evaluated. Additionally, emissions estimates from brood cows, pasture animals, and range animals are also required.

The priorities for performing these measurements on various categories of the animal population should be based on the importance of the category in the overall population of animals and the availability and quality of existing emissions data. One obvious area where additional measurements are required is CH_4 emissions from animals in developing countries. There is uncertainty regarding their rates of CH_4 production, in particular for the types of diets they generally consume.

Additionally, measurements are required to improve our understanding of the variations in emissions among individual animals that (except for their apparent CH_4 emissions rates) are similar, and the factors that influence these variations. The potential existence of host-animal traits that influence methanogenesis by microbes in the rumen remains to be investigated. Potential mechanisms via which such traits could influence rates of methanogenesis (e.g., by influencing the populations of the microbes) also are unknown at this time.

Emissions measurements from animal wastes are also clearly required.

MODEL DEVELOPMENT: EMISSIONS AND ANIMAL MANAGEMENT

By performing these various investigations, the basis of information describing sources of CH_4 emissions from ruminants will be improved considerably. These data could then be used to develop models for quantifying emissions in various parts of the world and globally. For example, assuming that each of the major categories of animals will be characterized in terms of key factors affecting emissions, these categories can be used as the basis for an emissions analysis model. The extent to which each of the categories is found throughout the world, and the likely rates of emissions from each can be used to estimate emissions.

For example, Baldwin, Thornley, and Beever (1987) present the results of a dynamic simulation model of rumen digestive functions. This model can be used to evaluate the anticipated level of CH_4 emissions for a wide range of diets. Using the model with data describing the populations of animals throughout the world and the diets they consume, estimates of global CH_4 emissions from animals could potentially be improved. Of note is that the suitability of the model for analyzing animal diets in developing countries remains to be assessed.

In addition to improving estimates of global CH_4 emissions from animals, the rumen digestion model could be integrated into, or used in conjunction with an economic model of the livestock sector. Such a combined tool would be useful for evaluating the implications of undertaking actions (such as improving the nutrition of animals in developing countries) to reduce CH_4 emissions. For example, the alternative diets would be evaluated with the model of rumen digestion to estimate CH_4 emissions and animal productivity (e.g., amount of milk produced over time). The economic portion of the model would evaluate the costs of changing the diets and the implications of changes in animal productivity (e.g., increases in milk production) on the profitability of the livestock sector, prices, and animal numbers.

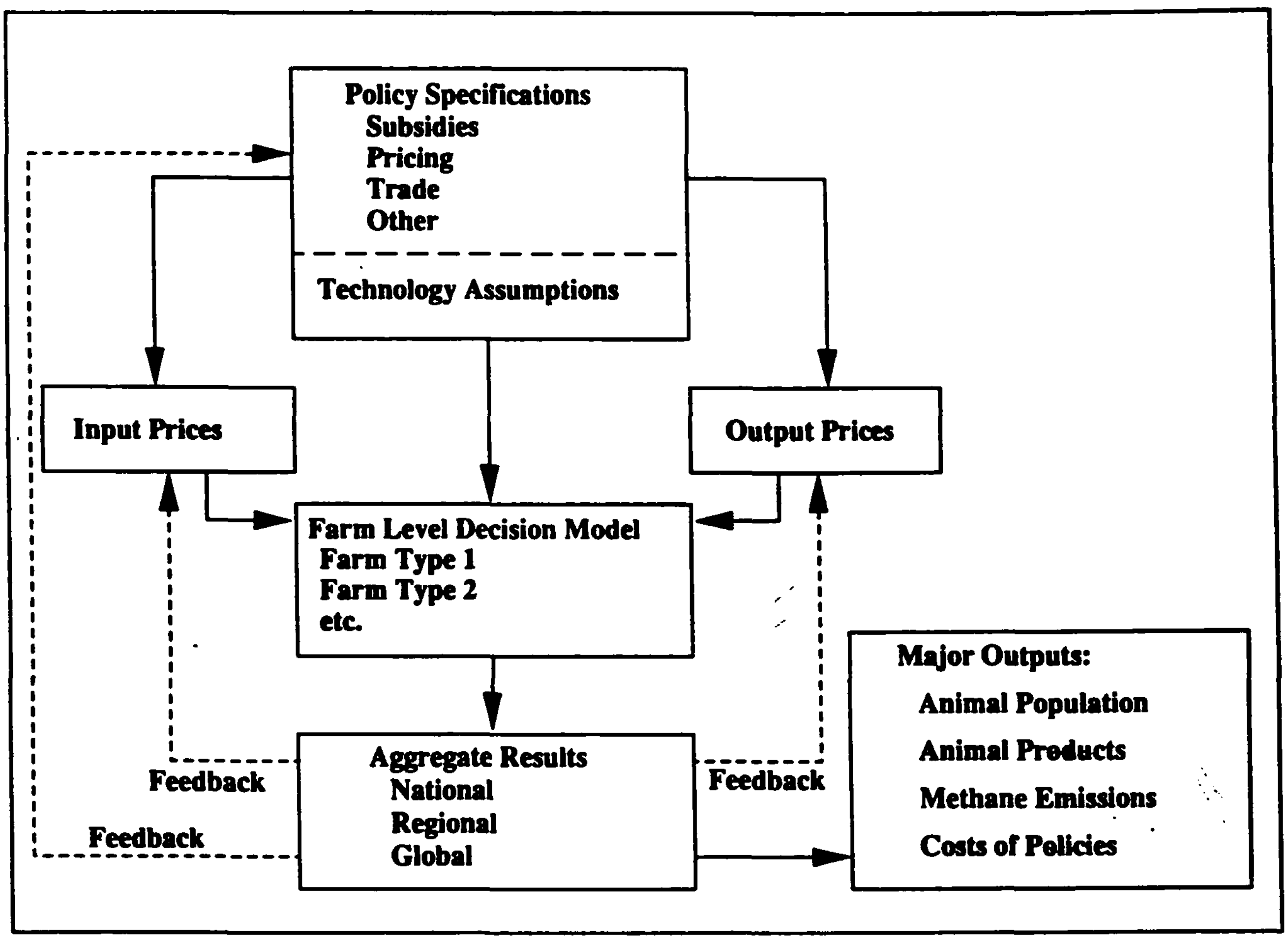
A possible framework for such a model is presented in Exhibit 3-2. As shown in the exhibit, policies for reducing CH_4 emissions would be specified (e.g., subsidizing the use of certain feeds or feed supplements). The implications of these policies for animal management decision at the farm level would be assessed using estimates of prevailing input prices (e.g., prices for feed) and output prices (e.g., prices for milk and meat), as well as estimates of animal productivity (i.e., the amount of inputs required to produce the outputs).

Based on the simulation of representative production decisions at the farm level, aggregate levels of production would be simulated, including the anticipated size of the animal populations. The extent to which these aggregate levels indicated changes in the anticipated input and output prices would also have to be evaluated (e.g., if milk production increased substantially, the price of milk could decline, depending on government pricing policies). If prices were anticipated to change, then the simulated farm level decision would have to be revised based on the new level of input and output prices. Such adjustments would be required until convergence upon a solution was achieved.

Such a model could be used to examine the implications of various policies under a wide variety of assumptions. For example, if feed supplements were to be provided in developing countries to reduce CH_4 emissions and increase animal productivity, the model could be used to assess the conditions under which animal populations would likely increase

EXHIBIT 3-2

POSSIBLE FRAMEWORK FOR A LIVESTOCK-METHANE ASSESSMENT MODEL



(thereby negating the emissions reduction impacts of the program) or decrease (thereby reinforcing the emissions reduction goal). Preferred sets of policies that reduce emissions as well as improve the production of animal products could potentially be identified.

3.2 OPTION IDENTIFICATION AND EVALUATION

Options for reducing emissions must be identified and evaluated. Given the obvious importance of managed ruminants throughout the world, and their unique ability to convert low quality inputs (e.g., agriculture byproducts that cannot be digested by humans) into useful products, potential technical and management options for reducing CH_4 emissions must be evaluated within the context of the overall agricultural and economic systems in which they would be implemented.

Potential options for reducing emissions should be evaluated in terms of:

- Time frame: the period when the option may become viable, such as near term versus long term.
- Applicability: the categories of animals for which the option may be used to reduce emissions, such as intensively managed dairy cows on concentrate feeds.
- Emissions Reduction: the extent to which the option would reduce emissions.
- Impacts on Animal Productivity: the manner in which implementing the option would affect the production of animal products.
- Costs: capital costs, operating costs, and other relevant costs.
- Implementation: methods of implementing the option, including any special challenges posed, such as social constraints.

Based on an initial assessment of possible options, the most promising alternatives should be examined and their effectiveness should be demonstrated. Exhibit 3-3 displays a partial and preliminary assessment of several options identified to date. These options represent a rich set of possible ways to reduce CH_4 emissions, increase animal productivity, and, in some cases, produce energy. As such, some of the opportunities for reducing CH_4 emissions might in fact be economically viable in their own right, or might have very small overall costs.

As shown in the exhibit, the options range from modifying the meat grading system in the U.S. to changing feeding strategies in developing

EXHIBIT 3-3

PARTIAL AND PRELIMINARY IDENTIFICATION AND EVALUATION OF CH_4 EMISSIONS REDUCTION OPTIONS

EMISSIONS REDUCTION OPTION	COMMENTS
Near Term Options	
1. Adopt alternative feeding practices to reduce methane emissions from animals in developed countries.	The use of alternative feeding practices is applicable primarily to confined animals on controlled rations, such as dairy cows and feed-lot animals. (The diets of grazing animals probably cannot be modified easily in the short term.) Given that methanogenesis is influenced by feed characteristics, opportunities for reducing methane emissions exist by modifying feeding practices. For example, based on preliminary data it has been suggested that CH_4 emissions associated with a range of commonly used rations in the U.S. may vary by as much as 50 percent. If the "low CH_4" rations were emphasized in place of the "high CH_4" rations, CH_4 emissions could be significantly reduced. Such an emphasis would, in all likelihood, increase feeding costs. This approach may be attractive in the near term because it does not require a major departure from the feeding systems currently in use. The implications of the modified feeding regimes for animal productivity and feed costs remain to be examined, however. It is anticipated that appropriate "low CH_4" diets can be identified that do not sacrifice animal productivity. A systematic evaluation of CH_4 emissions associated with commonly used feeds would provide a basis for selecting "low CH_4" feeds. Additional avenues that may be explored include the use of: (1) "by-pass" nutrients; (2) defaunation; and (3) oils as feed supplements. Depending on the costs involved and the impacts on productivity, government-sponsored research or research subsidies may be required in order to promote the development and use of these feeding techniques.

EXHIBIT 3-3

PARTIAL AND PRELIMINARY IDENTIFICATION AND EVALUATION OF CH_4 EMISSIONS REDUCTION OPTIONS (continued)

EMISSIONS REDUCTION OPTION	COMMENTS
<u>Near Term Options</u> (continued)	
2. Increase animal productivity with hormones.	Hormone implants are currently available for non-lactating beef animals (these implants were recently banned in the EEC). Emissions reduction is achieved through faster weight gain and increased feed efficiency. Bovine growth hormone (currently under development) may increase milk production in lactating animals significantly, thereby reducing the size of the animal population. Food safety must, of course, always be considered.
3. Increase animal productivity with intact males.	The use of intact males (foregoing castration) has been identified as giving similar performance to the use of hormone implants. The use of intact males would reduce CH_4 emissions by promoting faster weight gain and increased feed efficiency. Issues associated with using intact males include managing more aggressive animals, changes in meat quality, and changes in taste.
4. Modify the meat grading system in the U.S.	The current meat grading system in the U.S. attaches a premium to finishing practices that produce a given amount of fat. It has been suggested that finishing practices that produce less fat may also produce less methane per amount of meat produced by reducing slaughter weights and finishing time. Consequently, modifying the current grading system so that leaner meats were not given relatively lower grades could produce reductions in methane emissions. This alternative should be examined within the context of the overall issues associated with meat grading.
5. Modify feeding strategies in developing countries by using supplements to correct nutrient deficiencies.	This alternative is applicable to animals in developing nations with nutrient deficiencies (such as inadequate nitrogen). Emissions reductions associated with increased fermentation efficiency are anticipated at the individual animal level. For a population of animals, significant emissions

EXHIBIT 3-3

PARTIAL AND PRELIMINARY IDENTIFICATION AND EVALUATION OF CH_4 EMISSIONS REDUCTION OPTIONS (continued)

EMISSIONS REDUCTION OPTION	COMMENTS
Near Term Options (continued)	
Modify feeding strategies in developing countries (continued)	reductions may be achieved through increases in animal productivity (e.g., milk yield) and reproductive efficiency (e.g., reduced inter-calving interval). Level of emissions reductions remains to be quantified and demonstrated. Molasses/urea blocks may be appropriate supplements, or chicken litter. Domestic supplement manufacturing capability should be promoted.
6. Reduce CH_4 emissions from animal wastes.	This alternative is applicable to wastes currently disposed of in lagoons or other anaerobic environments. Capturing CH_4 emissions (e.g., for energy) would significantly reduce emissions from this source. Efforts are currently under way to develop techniques for harvesting CH_4 from anaerobic waste lagoons. These techniques involve covering the lagoons with plastic covers and using the CH_4 to produce electricity for use on site or for sale to the electric power grid. Digesters to produce and contain CH_4 are also under development and in use in the U.S. and elsewhere. Integrated animal waste recycling facilities are currently under development that not only produce and capture CH_4 in digesters, but also use the carbon dioxide emissions produced from burning the CH_4 to "fertilize" plant growth in greenhouses and/or algae growth in ponds. The plant and algae products can then be marketed or used as animal feeds on site. The electric power produced by the system (some of which can be sold to the power grid) replaces the need to burn other fossil fuels. Direct burning of wastes (i.e., for energy) is also a current waste management practice, although local air quality impacts must also be considered.

EXHIBIT 3-3

PARTIAL AND PRELIMINARY IDENTIFICATION AND EVALUATION OF CH_4 EMISSIONS REDUCTION OPTIONS (continued)

EMISSIONS REDUCTION OPTION	COMMENTS
Long Term Options	
7. Modify feed characteristics or rumen processes to increase feed digestibility or reduce methanogenesis.	Alternatives under consideration include genetically engineered bacteria to pre-treat feed or to be introduced into the rumen. Modifications in rumen digestion could lower emissions. This alternative is most likely to be applicable to intensively managed animals in developed countries.
8. Develop CH_4 inhibitors as feed additives.	In the past, efforts have been made to identify and develop CH_4 inhibitors. Although several compounds that effectively inhibit methanogenesis in vitro have been identified, most have not been marketed as a CH_4 inhibitor due to insufficient improvement in feed efficiency in the whole animal. Ionophore feed additives (discussed above) have been demonstrated to improve feed efficiency and reduce CH_4 production, and are widely used in beef animals in the U.S. The development of new options is uncertain, and possibly unlikely. The CH_4 inhibitor would have to provide an additional hydrogen sink assuming that less CH_4 is created. Additionally, the inhibitor would have to be acceptable from the viewpoint of human, animal, and environmental risks.
9. Improve reproductive efficiency to reduce brood herd requirements.	This alternative is applicable to areas with brood herds. In developing countries, nutritional management programs to increase reproductive efficiency (e.g., toward one cow per calf per year) may be appropriate. In all circumstances, it is important to ensure sufficient nutrition to new born calves to ensure survival.

EXHIBIT 3-3

PARTIAL AND PRELIMINARY IDENTIFICATION AND EVALUATION OF CH_4 EMISSIONS REDUCTION OPTIONS (continued)

EMISSIONS REDUCTION OPTION	COMMENTS
Long Term Options (continued)	
10. Breed animals that are low CH_4 producers.	The objective of this alternative is to identify whether there are heritable genetic characteristics that account for variability in CH_4 emissions among individual animals, and to breed animals that are low CH_4 producers by taking advantage of these characteristics. The existence of such traits remains to be demonstrated, although preliminary data indicate that such traits may exist. In order for such an approach to work, the relevant animal characteristics and the mechanisms via which the characteristics influence methanogenesis by microbes in the rumen would have to be identified. If such characteristics could be identified, and if they were not undesirable for other reasons (e.g., also being associated with low rates of digestion), animals could be selected for the "low CH_4" characteristics. If the characteristics were undesirable for other reasons, the mechanisms via which the characteristics influenced methanogenesis by microbes could potentially be exploited. This approach remains speculative at this time because host-animal characteristics and mechanisms that influence methanogenesis by microbes in the rumen have not yet been identified. One avenue for initiating such research may be to take advantage of the considerable amount of existing data on the breeding histories of dairy cows and some beef animals in the U.S. These data may enable hypotheses about heritability to be tested by measuring CH_4 emissions from a large number of cows and examining whether lineage explains any of the variance that exists among the individuals. In order to be successful, reliable methods for inexpensively measuring CH_4 emissions from large numbers of animals are required.

countries. These, and additional options must be described more completely and evaluated to identify the most cost effective measures for reducing emissions.

Of particular importance is identifying and involving the institutions and organizations that could play a role in evaluating and implementing the various options. Such organization would include government agencies (e.g., the Agriculture Research Service of the U.S. Department of Agriculture), universities, and private companies (e.g., those producing ionophores and other feed additives). Major organizations that influence agriculture practices in developing countries include:

- United Nations (e.g., through the Food and Agriculture Organization and other programs);
- World Bank and other development banks (e.g., as a funding source);
- Consultative Group on International Agricultural Research (e.g., through the International Livestock Center for Africa (ILCA), and the International Laboratory for Research on Animal Diseases (ILRAD))
- Winrock International, a private philanthropic non-profit organization providing technical assistance worldwide;
- Agricultural Cooperative Development International, focused on assisting and developing agricultural cooperatives worldwide;
- Volunteer International Technical Assistance, focused on providing technical agricultural assistance worldwide; and
- Programs of various national governments, such as the U.S. Agency for International Development (AID).

Coordination among these and other key institutions is required to ensure the timely development of options for reducing CH_4 emissions. The creation of an ad hoc working group for communication of ongoing and planned activities and tracking progress is planned.

4. EPA OFFICE OF AIR AND RADIATION PROGRAM PLAN

This chapter presents a plan for undertaking analyses to: (1) improve current estimates of CH_4 emissions from animals, and in particular ruminants; and (2) identify, evaluate, and implement options for reducing emissions from this source. The outline for this plan is based on the findings presented at the beginning of this document.

The following program elements are planned:

- Ad Hoc Group. An Ad Hoc group would track and coordinate the analyses and investigations needed to better quantify CH_4 emissions from animals and options for reducing the emissions. The Ad Hoc group should include researchers and practitioners in the fields of animal science, animal management, atmospheric science, and others as appropriate; different people would participate at different times. The mission of the Ad Hoc group should include:

    - develop a plan for various nations and international institutions for solving the problem of CH_4 emissions from animals;
    - provide peer review on analyses and investigations performed;
    - identify parties who may be appropriate funding sources for these investigations;
    - identify organizations who may be able to perform investigations.

- Emissions Characterization. A series of investigations will be identified that will improve our understanding of the rates of CH_4 emissions from animals. These investigations will include the following.

    - Identify those animals for which emissions estimates are particularly uncertain. For these groups of animals, develop and employ techniques for measuring their emissions within the next year. It is likely that animals in developing countries will fall into this category.
    - Develop and implement techniques for measuring CH_4 emissions from animals under field conditions. Opportunities include atmospheric measurements near animal management facilities as well as techniques for measuring emissions from individual animals.

- -- Characterize the current and potential future populations of animals along dimensions that influence CH_4 emissions and opportunities for reducing emissions, such as: quantity and quality of feed consumed; waste management practices used; trends in population size and characteristics; ownership characteristics; and products produced.

- -- Develop data on the current and anticipated methods of managing animal wastes in the U.S. and around the world. Evaluate existing measurements of CH_4 emissions from animal wastes, and identify gaps in measurements. Develop and employ measurement techniques to fill these gaps. It is likely that most waste management systems should be measured.

- -- In conjunction with field measurement efforts, develop and employ modeling approaches for assessing CH_4 emissions from animals and animal wastes. In particular, existing data on CH_4 yields and kinetics in wastes should be examined to improve estimates of potential emissions.

o <u>Option Identification and Evaluation</u>. Both near-term and long-term options for reducing CH_4 emissions must be examined. These assessments must include evaluations of: emissions reduction potential; costs; social and other barriers or constraints; and impacts on the quality and safety of the food supply. Activities will include the following.

- -- Develop and employ modeling techniques to evaluate fully alternative approaches for reducing methane emissions. Analysis of the implications for animal populations will be included in this analysis, as well as assessments of emissions from individual animals.

- -- Evaluate the potential advisability, effectiveness, and cost of modifying feed practices and/or the meat grading system in the U.S. to reduce CH_4 emissions.

- -- Evaluate the potential advisability, effectiveness, and cost of using nutrient supplements as a means of reducing CH_4 emissions among populations of animals in developing countries.

- -- Evaluate the implications of emerging technologies for CH_4 emissions, such as bovine growth hormone.

-- Identify and evaluate options for reducing or recovering CH_4 emissions from animal wastes.

-- Identify promising long term approaches for reducing CH_4 emissions and initiate investigations into these approaches. Examples may include: developing improved CH_4 inhibitors; identifying animal traits that influence methanogenesis by microbes in the rumen; modifying feed characteristics to increase digestibility or reduce methanogenesis.

These major program elements should be implemented within the coming year. For each, a more detailed plan will be developed that includes: detailed descriptions of the proposed investigations; schedule for undertaking the investigations, and approximate level of resources that is appropriate; identification of individuals and institutions that could perform the investigations; identification of appropriate funding sources (e.g., EPA, Department of Agriculture (through CSRS or ARS), NASA, NSF, and others); and methods for obtaining funding.

As soon as practicable, validations and demonstrations of the various CH_4 emissions reduction alternatives will be organized. Finally, alternatives for implementing these emissions reduction methods will be developed through national and international institutions and international forums.

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APPENDIX A

GLOBAL METHANE EMISSIONS FROM RUMINANTS

This appendix summarizes several of the published estimates of methane (CH_4) emissions from ruminants. First, the primary factors affecting methanogenesis in ruminants are discussed. Then, several of the major estimates of emissions are summarized.

A.1 FACTORS AFFECTING METHANOGENESIS

The rumen is the unique physiological characteristic of ruminants that allows them to digest the energy in forages that cannot be consumed by humans. These animals (mostly cows, buffalo, sheep, goats, and camels, but also including deer, reindeer, caribou and others) are characterized by a large "fore-stomach" or rumen. For example, a cow's rumen may have a volume of 150 liters, whereas a pig (a non-ruminant monogastric animal)[1] has a stomach with a size of about 6 to 8 liters.[2] This large "stomach" allows large quantities of forages to be consumed, and provides a location for the forages to be fermented. Other non-ruminant herbivores (e.g., horses, rabbits, guinea pigs, hamsters) are able to consume forages in amounts between ruminants and non-ruminant monogastrics due to an enlarged cecum and large intestine (Ensminger (1983), p. 21).

Within the rumen, microorganisms play an important role in digestion. Over 200 species and strains of organisms have been identified to date, although a smaller number dominate (Baldwin and Allison (1983), p. 462). These organisms form a complex ecology that includes both competition and cooperation. The organisms are important for fermenting the primary feed constituents (carbohydrates, lipids, urea, and proteins) into secondary products that can be catabolized further and subsequently used by the animal. The population mix of the bacteria is influenced by the diet consumed by the animal.

Rumen methanogenic bacteria are the source of CH_4 produced in ruminants. Although these bacteria are a very small fraction of the total population of microorganisms in the rumen, they play an important role in the complex rumen ecology. While methanogens can convert acetate (a fermentation product produced in the rumen) to CH_4 and CO_2, this pathway for CH_4 production in the rumen is believed to be of minor importance (Baldwin and

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[1] Other non-ruminant monogastric animals include inter alia: dogs, cats, monkeys, and humans.

[2] A steer's rumen is about 20 times larger than a pig's stomach, even though a steer weighs only about 5 times more than a full-grown pig (Ensminger (1983), p. 216).

Allison (1983), p. 469). Instead, the conversion of hydrogen (H_2) or formate and CO_2 (produced by other fermentative bacteria) is believed to be the primary mechanism by which methanogenic bacteria produce CH_4 in ruminants.

As shown in Exhibit A-1, on a "whole-animal" basis, the manner in which the energy intake of an animal is utilized can be defined as follows:

- <u>gross energy</u> is the total energy intake by the animal, where the energy content of the feed is defined in terms of its total combustible energy (i.e., the energy it releases when it is burned);
- <u>digestible energy</u> is the gross energy intake minus the energy eliminated in feces;
- <u>metabolizable energy</u> is the digestible energy minus the energy eliminated in urine and gas (CH_4); and
- <u>net energy</u> is the metabolizable energy minus the increment of heat produced by the animal.

Net energy is a measure of the extent to which feed contributes to the maintenance and growth of an animal.[3] The net energy received by an animal from a diet will depend on the energy intake level of the diet[4] and the form of the energy (i.e., the mix of feeds that comprise the diet). Some feeds (e.g., grains) are more "digestible" than others (e.g., hay), so that more of the gross energy is converted to digestible energy (and subsequently, net energy). Evaluations of alternative diets and diet formulation techniques continue to be an important and active area of research in animal management.

Of note is that the analysis of ruminant feeding practices in terms of these energy quantities may not be appropriate for many animals in developing countries whose diets are deficient in one or more important

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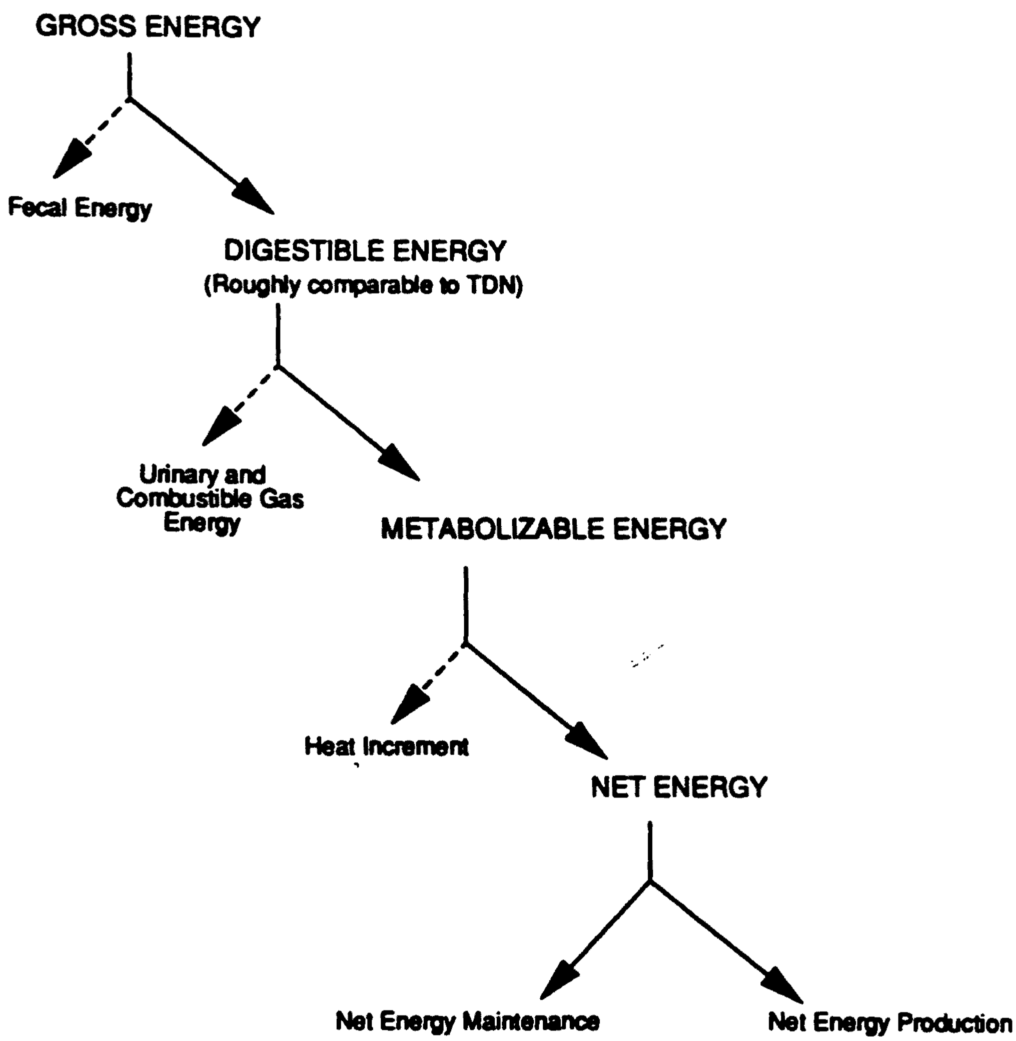
[3] Maintenance energy is the amount of energy that will result in no loss or gain in total body energy. and is defined as the amount of energy equivalent to the fasting heat production (NRC (1984), p. 3). For U.S. beef cattle, maintenance energy requirements are estimated to be about 77 kilocalories times the animal weight in kilograms raised to the 0.75 power. This requirement varies on the order of 3 to 14 percent for different breeds and sex. For U.S. dairy cattle, the maintenance requirement is on the order of 12 percent higher than for beef cattle.

[4] The energy intake level of a diet is often described as the ratio of the metabolizable energy intake to the maintenance energy requirement. For example, the level of the diet fed to lactating dairy cows in the U.S. may be on the order of two to three times the maintenance requirement.

EXHIBIT A-1

ENERGY UTILIZATION IN RUMINANTS



Source: Ensminger, M.E., The Stockman's Handbook, The Interstate Printers & Publishers, Inc.: Danville, Illinois, 1983, p. 245.

nutrients (such as nitrogen). In these cases, the efficiency of the fermentation in the rumen may be reduced significantly, so that the animal may derive much less useful energy from the feed than would be indicated by the feed's physio-chemical properties. Due to the nutrient deficiencies, increasing feed intakes (without correcting the nutrient deficiencies) would not necessarily increase the amount of useful energy "delivered" to the animal. Correcting the nutrient deficiencies would improve rumen fermentation efficiency so that current levels of feeding would provide more useful energy to the animal. The use of this approach for animal feeding in developed countries has been suggested as well, although its applicability has not been demonstrated.

The extent of methanogenesis in individual ruminants has been estimated by various authors.[5] Blaxter and Clapperton (1965) reviewed the results of 615 closed-circuit respiration indirect calorimetry experiments on sheep and cattle performed over a period of 10 years. Based on an analysis of the results for 48 different diets in 391 different experiments on 4-5 sheep for various levels of feeding, Blaxter and Clapperton identified feed digestibility and level of intake to be important factors influencing the extent of methanogenesis in the rumen, and developed the following equation to describe CH_4 production:

$$Ym = 1.30 + 0.112\ D + L\ (2.37 - 0.050\ D)$$

where Ym is the CH_4 yield (megajoules (MJ) of CH_4 produced per 100 MJ of gross energy feed intake), L is the ratio of net energy intake to maintenance energy requirements (e.g., two times maintenance), and D is the percent digestibility of the feed (e.g., 50 percent). The CH_4 yield estimated with this equation can be interpreted as the percent of gross energy intake that is converted to CH_4 within the animal. The digestibility of the diets examined ranged from poor hay (54 percent digestible at maintenance) to sugar-beet pulp (87.2 percent digestible at maintenance). The levels of the diets ranged from one to three times maintenance.

Exhibit A-2 presents estimates of CH_4 yield using the Blaxter and Clapperton equation. CH_4 yield increases with increasing digestibility for feed levels near maintenance. Conversely, at feed levels greater than 2.4 times maintenance CH_4 yield decreases with increasing digestibility. Of note is that the results for diets exceeding 2.5 times maintenance are based on relatively fewer observations, and may be less certain. Based on a comparison of methanogenesis in cattle and sheep for seven diets, Blaxter and Clapperton state that these results (based on data for sheep) may also be appropriate for evaluating methanogenesis in cattle.

[5] See for example: Blaxter and Clapperton (1965) and Moe and Tyrrell (1979) and Rumpler, Johnson, and Bates (1986).

EXHIBIT A-2

METHANE YIELD AS A FUNCTION OF
DIGESTIBILITY AND LEVEL OF GROSS ENERGY INTAKE
(percent)

	Level of Intake				
	1.0	1.5	2.0	2.5	3.0
Digestibility					
50	6.8	6.7	6.6	6.6	6.5
60	7.4	7.1	6.8	6.4	6.1
70	8.0	7.4	6.9	6.3	5.8
80	8.6	7.8	7.0	6.2	5.4
90	9.2	8.2	7.1	6.1	5.0

Estimates based on an analysis of 391 experiments on sheep. Methane yield is the percent of feed energy that is converted to methane. Level of intake is measured as the ratio of total gross energy intake to total gross energy intake needed to meet maintenance energy requirements (e.g., total gross energy intake equals two times maintenance requirements). Digestibility in percent.

Source: Blaxter, K.L. and J.L. Clapperton, "Prediction of the Amount of Methane Produced by Ruminants," British Journal of Nutrition, Vol. 19, 1965, pp. 511-522.

In reviewing the estimates in Exhibit A-2, care must be taken because it is unlikely that animals eating near maintenance will be eating highly digestible feed. Animals near maintenance (e.g., draft animals in developing nations) would most likely be eating crop residues, such as rice stalks, which have low levels of digestibility (e.g., less than 50 percent). Similarly, it is unlikely that animals eating at high levels of intake would be eating low digestible feed. The animal would be unable to consume enough low digestible feed in order to reach three times maintenance.

Another model that predicts CH_4 emissions was derived by Moe and Tyrrell (1979). A total of 404 total energy balance trials based on indirect calorimetry were performed on Holstein dairy cows. Unlike the Blaxter and Clapperton model, Moe and Tyrrell estimate CH_4 emissions as a function of the amounts of the following feed constituents consumed: soluble residue, hemicellulose, and cellulose. Feeds vary in their content of these constituents. CH_4 production was found not to be dependent on the intake of other feed characteristics such as crude protein, ether extract, and lignin. Based on their experiments Moe and Tyrrell estimated the following equation:

$$\begin{aligned} CH_4 \text{ (MJ/day)} = 3.406 &+ 0.510 \text{ soluble residue (kg fed)} \\ &+ 1.736 \text{ hemicellulose (kg fed)} \\ &+ 2.648 \text{ cellulose (kg fed).} \end{aligned}$$

The analysis by Moe and Tyrrell is distinguished from the earlier work by Blaxter and Clapperton in that it relates methanogenesis to feed characteristics in addition to level of intake and digestibility.

Most ruminants in the world are in developing countries where levels of intake and feed characteristics are very different from the diet of U.S. dairy cows. In general, ruminants in developing countries eat agriculture by-products with low digestibility (e.g., wheat straw, rice straw, and sugar beet tops), with levels of intake near maintenance requirements. For these animals on relatively poor diets, Preston and Leng (1987) indicate that methane yields may be in the 9 to 12 percent range, with the level influenced by the adequacy of ammonia levels in the rumen (Preston and Leng (1987), p. 40). In their assessment, based on stoichiometric considerations, inadequate ammonia levels are related to inefficient rumen fermentation and increased CH_4 production. If this is the case, supplementing diets of these animals with urea or poultry litter (good sources of rumen ammonia) could increase rumen fermentation efficiency and reduce CH_4 emissions.

It is clear from these various assessments, that CH_4 emissions from the digestive tracts of ruminants depends on the amounts and types of feeds consumed by the animals. Because energy requirements for maintenance and growth depend on additional factors (e.g., breed, sex, stage of lactation, heat stress), the extent of methanogenesis may also be influenced by additional factors. However, if such influences exist, they have not been sufficiently significant to be identified to date.

Given these general factors affecting methanogenesis in ruminants, the general approach to estimating CH_4 emissions from this source has been to:

- identify the average amounts of feed consumed by various types of ruminants;
- adopt an estimate of the portion of feed energy consumed that is converted to CH_4 (i.e., a methane yield);
- estimate a rate of annual CH_4 emissions per animal by multiplying the methane yield by the annual feed consumption; and
- multiply the emissions rate per animal by the number of animals.

Estimates published by various authors are presented below.

A.2 GLOBAL EMISSIONS ESTIMATES

Several authors have presented estimates of global CH_4 emissions from animals[6]. Most estimates, however, can be traced back to only a few sources:

- Ritzman and Benedict (1938): Hutchinson (1948) and Blake (1984) base their estimates on CH_4 production rates from domestic animals on work presented by Ritzman and Benedict (1938). Ehhalt (1974) and Koyama (1963) cite emissions estimates from Hutchinson. Hudson and Reed (1979) cite an emissions estimate from Ehhalt. Khalil and Rasmussen (1983) cite an emissions estimate from Hudson and Reed;
- Crutzen and Seiler: Crutzen and Seiler contributed to various estimates including: Crutzen et al. (1986); estimates by Seiler in Bolle et al. (1986); and Seiler (1984). Lerner et al. present estimates based on CH_4 production rates from Crutzen et al. (1986). Sheppard et al. (1982) cite emission data from a personal communication with Crutzen.

In addition, both Ehhalt (1974) and Blake (1984) cite Woodwell (1970) as the source of total plant material consumed by herbivores.

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[6] See, for example: Blake (1984); Bolle, Seiler and Bolin (1986); Crutzen, Aselmann and Seiler (1986); Ehhalt (1974); Hudson and Reed (1979); Hutchinson (1948); Khalil and Rasmussen (1983); Koyama (1963); Lerner, Matthews and Fung (1988); Seiler (1984); Sheppard et al. (1982).

This section presents estimates of global CH_4 emissions from ruminants published in three of the above mentioned studies:

- o Crutzen et al. (1986): The study by Crutzen et al. is the most comprehensive description of CH_4 emissions to date.

- o Blake (1984): Blake used data from Woodwell (1970) and Ritzman and Benedict (1938) to estimate global emissions via two different methods.

- o Lerner et al. (1988): Lerner et al. gathered detailed data on animal populations and estimated CH_4 emissions by latitude and longitude.

Exhibit A-3 summarizes the estimates presented by these authors. Each is discussed in turn.

CRUTZEN ET AL.

Crutzen et al. estimated total annual CH_4 emissions by: (1) estimating the average CH_4 production per animal in various regions of the world; (2) multiplying the average emissions per animal by the total population of animals in each region; and (3) summing across the regions. The average CH_4 production rates were derived from the Blaxter and Clapperton (1965) relationship (discussed above) and other sources. The population data for each region were taken primarily from FAO statistics. This publication by Crutzen et al. is the most comprehensive description of CH_4 emissions from ruminants to date. A copy of this publication is included as Appendix C.

Exhibit A-4 presents the Crutzen at al. estimates for CH_4 emissions. Bovines, including all cattle used for beef production, milk production, and draft animals, are the largest source, accounting for 70 percent of the total estimate and about 75 percent of the CH_4 emissions from managed ruminants.

As shown in Exhibit A-4, Crutzen et al. divided the world into developed and developing countries for evaluating bovine emissions. The emissions estimates for each is based on the following:

- o Developed Countries. The emissions rate for all developed countries plus Brazil and Argentina is based on evaluations in each of the following countries:

  - -- United States and Canada. This region has about 114 million cattle, which can be divided into three main groups, each with different CH_4 emissions rates: dairy cows; beef cattle on feed; and beef cattle on the range. In the U.S., these

EXHIBIT A-3

SUMMARY OF GLOBAL METHANE EMISSIONS

AUTHOR	EMISSIONS (Tg/yr)	COMMENTS
Crutzen et al.	77.7	Includes: domestic ruminants (cattle, buffalo, sheep, goats, camels); domestic pseudoruminants (horses, pigs); wild ruminants and large herbivores; and humans. Approximately 95% associated with domestic ruminants, of which about 75% is associated with cattle. Reported uncertainty of ±15% for domestic animal and human total. Average estimate of CH_4 production from wild herbivores is 4 Tg, ranging from 2 to 6 Tg. Animal population data from FAO. Feed energy intake and methane yield from bovines vary for the following regions: U.S. dairy cows; U.S., Argentine and Brazilian range cattle; other developed countries; and developing countries.
Blake	71-160	Includes: domestic ruminants (cattle, sheep, goats); domestic pseudoruminants (horses); wild ruminants and large herbivores; and herbivorous insects (i.e., termites). Lower estimate based only on domestic ruminant measurements. Upper limit based on 10% of total dry plant matter produced consumed by all herbivores, assuming 43% is eaten by cattle and converted to CH_4 with a 2% efficiency, and the remaining 57% is converted to CH_4 with a 1% efficiency. Animal population data from FAO.
Lerner et al.	75.8	Includes: domestic ruminants (cattle, buffalo, sheep, goats, camels); domestic pseudoruminants (horses, pigs); and wild ruminants (caribou). Global animal population density on a 1° latitude by 1° longitude grid from data compiled from FAO and individual country statistics. Methane emissions by latitude and longitude based on emissions rates per animal from Crutzen et al. (1986). Over 75% of emissions are associated with cattle. About 55% of total emissions is concentrated from 25°N to 55°N latitude.

EXHIBIT A-4

ESTIMATES OF METHANE EMISSIONS FROM ANIMALS
REPORTED BY CRUTZEN ET AL.

ANIMAL TYPE AND REGIONS	POPULATION (Million)	CH_4 PRODUCTION PER INDIVIDUAL (kg/year)	CH_4 PRODUCTION BY TOTAL POPULATION (Tg/year) **
Cattle in developed countries, Brazil and Argentina	572.6	55	31.5
Cattle in developing countries:	652.8	35	22.8
Buffalos	142.1	50	6.2
Sheep in developed countries	399.7	8	3.2
Sheep in developing countries and Australia	737.6	5	3.7
Goats	476.1	5	2.4
Camels	17.0	58	1.0
Pigs in developed countries	328.8	1.5	0.5
Pigs in developing countries	444.8	1.0	0.4
Horses	64.2	18	1.2
Mules, Asses	53.9	10	0.5
Humans	4669.7	0.05	0.3
Wild ruminants and large herbivores	100-500	1-50	2-6
TOTAL			75.7-79.7

** Total estimate for emissions from domestic animals (cattle, buffalo, sheep, goats, camels, pigs, horses, mules and asses) has an uncertainty of ±15 percent.

Source: Crutzen, P.J., I. Aselmann, and W. Seiler, "Methane Production by Domestic Animals, Wild Ruminants, Other Herbivorous Fauna, and Humans," Tellus, 38B, 1986, pp. 271-284.

groups represent about 10 percent, 12.5 percent and 77.5 percent of the total respectively.[7] Canada is assumed to have approximately the same distribution.

Crutzen et al. estimate the gross energy intake and CH_4 production for dairy cows in the U.S. and Canada to be about 230 MJ per day and 84 kg per year (based on a methane yield of 5.5 percent). For cattle on feed and on range the estimates are 150 and 110 MJ/day of gross energy intake, respectively, and 65 kg and 54 kg of CH_4 emissions per head per year, respectively, (based on methane yields of 6.5 and 7.5 percent, respectively). Given the distribution of animals, these values imply and average of about 58 kg per head per year in the U.S.

-- <u>Brazil, Argentina, Australia, and South Africa</u>. This group of countries has about 214 million cattle. Crutzen et al. examined these nations as a region because they have well-developed beef industries that rely primarily on range feeding. Crutzen et al. therefore assume that energy intake and CH_4 emissions for these cattle will be similar to the estimates derived for range cattle in the U.S.: feed consumption of 110 MJ/head/day, a CH_4 yield of 7.5%, and CH_4 emissions of 54 kg/head/year.

-- <u>West Germany</u>. The average CH_4 emissions for the entire West German population of cattle is estimated at about 57 kg per head per year. This estimate is based on the following: (1) dairy cows -- average intake of 260 MJ/day; 5.5 percent methane yield; 94 kg CH_4 emissions per head per year; (2) heifers and steers between 450 and 600 kg in body weight -- 7 percent methane yield; 65 kg CH_4 emissions per head per year; and (3) 6-24 month old animals -- average intake of 120 MJ/day; 6.5 percent methane yield; 51 kg CH_4 emissions per head per year.

Based on these estimates for West Germany, the estimate for the U.S. and Canada of 58 kg per year, and the estimate of 54 kg per year for South Africa, Argentina, Australia, and Brazil, Crutzen et al. adopted a value of 55 kg of CH_4 emissions per head per year as an average for all the developed nations.

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[7] This estimate was reported by Crutzen et al. (1986). Data in FAO (1987) suggests that the dairy population in the U.S. has remained at 10 percent of the total cattle herd for several years. Ensminger (1987) states that 26.1 million head or 24 percent of total U.S. cattle population are on feed, leaving 66 percent of total U.S. cattle population on range. This does not compare well with the Crutzen et al. values.

- Developing Nations. Developing nations (excluding Argentina and Brazil) have over half the world's population of cattle. FAO reports a 1984 population of 642.7 million. The nations that dominate this population in 1984 include: India: 195.6 million; China 71.2 million; Mexico: 30.5 million; and Bangladesh: 21.9 million (FAO, 1988). These nations' populations of cattle account for nearly 50 percent of the total in this region.

  Unlike the cattle in developed nations, the cattle in developing nations are not used solely for meat and dairy production, but also are used as draft animals (Odend'hal, 1972). These cattle are generally fed by-products of the production of food for human consumption.

  Crutzen et al. estimated CH_4 emissions for cattle in this region based on a study of Indian cattle performed by Odend'hal (1972). This study estimated that the daily gross energy intake of cattle in rural West Bengal was 60.3 MJ per head per day.

  To translate the daily gross energy intake into CH_4 emissions per head, Crutzen et al. used a CH_4 yield of 9 percent from a study on nine lactating cows in India (Krishna et al., 1978). This study used face-mask-based gas samples taken once daily to estimate the 9 percent CH_4 yield, which translates into CH_4 emissions of 35 kg per year. Of note is that this 9 percent estimate is much higher than what would be anticipated based on the Blaxter and Clapperton relationship. For feeds of low digestibility (e.g., 45 to 60 percent), the CH_4 yield is expected to be on the order of 6.5 to 7.5 percent. Alternatively, it is at the low end of the range reported by Preston and Leng (1987) (based on stoichiometric considerations) for animals on diets that are deficient in nitrogen. Considerable uncertainty remains regarding the contribution of animals in developing countries to global CH_4 emissions.

The estimates for other animals by Crutzen et al. are based on similar considerations. As shown in Exhibit A-4, Crutzen et al. estimate emissions from bovines and other domestic animals to be 73.7 Tg per year $\pm$15 percent. Emissions from wild ruminants and large herbivores are estimated to be 2 to 6 Tg per year.

BLAKE

Blake (1984) presents two estimates of methane emissions from animals using two different methods:

- Estimating CH_4 emissions from domestic animals based on studies by Ritzman and Benedict (1938); and

- Estimating CH_4 emissions from all herbivores (including insects) by multiplying estimated total dry matter consumption of herbivorous animals and insects by the efficiency with which the plant matter is converted to methane.

Domestic Animals. Blake estimates methane emissions from domestic animals (cattle, horses, sheep and goats) based on chamber measurements made by Ritzman and Benedict (1938) on these animals. Ritzman and Benedict's findings are summarized below:

- Cattle: Respiration chamber measurements performed on various breeds of cattle (average weight of 1400 lb (635 kg)) showed an average CH_4 production rate of 200 g CH_4/day/head which was found to be directly proportional to the body weight of the animal. The efficiency of conversion of dry matter intake (by weight) to CH_4 was 2 percent.

- Horses: Respiration chamber measurements performed on two horses (one average sized trotter, weighing 900 lb (408 kg) and a Percheron mare weighing 1500 lb (680 kg)) showed that CH_4 production in horses was dependent on the amount of feed intake rather than the animal's body weight. The average CH_4 production rates for the trotter and the Percheron were found to be 28 and 106 g CH_4/day/head, respectively. The efficiency of conversion for horses was 0.5 percent.

- Sheep and Goats: Respiration chamber measurements performed on seven sheep and three goats showed average CH_4 production rates of 15.1 g CH_4/day/head for sheep and 14.7 g CH_4/day/head for goats. The efficiency of conversion for both sheep and goats was 1 percent.

For his estimates, Blake adjusts Ritzman and Benedict's data in the following manner:

- Cattle: Blake asserts that a more representative weight for cattle would be 1000 lb (454 kg) and suggests that even this would probably be an upper limit value. If CH_4 production is directly proportional to the weight of the animal, a 30 percent decrease in size (from 1400 lb to 1000 lb) would result in a decrease in CH_4 production rate from 200 to 140 g CH_4/day/head.

- Horses: The CH_4 production rate for horses cited most often from Ritzman and Benedict's study is for the 1500 lb (680 kg) Percheron mare (106 g CH_4/day/head). Blake asserts, however, that a Percheron is 50 percent larger than the average horse and consumes more than twice as much organic material. Blake suggests that the 900 lb (408 kg) trotter, with a much lower CH_4 production rate of 28 g CH_4/day/head, is a better representative of the average horse.

- Sheep and Goats: CH_4 production rates for sheep and goats is taken directly from Ritzman and Benedict's study.

Blake multiplied population data from the 1970 FAO Production Yearbook (1971) by the adjusted emissions rates to get yearly world CH_4 production. Blake estimates CH_4 production in cattle, sheep, goats and horses to be 62, 5.5, 1.5, and 1.2 Tg, respectively. The sum of these, 71 Tg, is assumed to estimate the lower limit for CH_4 production by herbivores.

Herbivorous Animals and Insects. Woodwell (1970) reports that approximately 1.1 x 10^{17} g/year dry plant matter is produced on land, about 10 percent of which is eaten by domestic animals, herbivorous insects (i.e., termites) and wild herbivores. Ehhalt (1974) asserts that an upper limit estimate of CH_4 production by animals may be determined by assuming that all of the 1.1 x 10^{16} g/year dry plant matter consumed is converted to CH_4 with the same efficiency as cattle, 2 percent, to give 220 Tg CH_4 per year. Blake asserts that of the 1.1 x 10^{16} g/year dry plant matter consumed, 43 percent is utilized by cattle. Therefore, a better estimate of CH_4 production would assume that 43 percent of the dry plant matter is converted to CH_4 with a 2 percent efficiency and the remaining 57 percent is converted with a 1 percent efficiency. These assumptions result in Blake's upper limit estimate of CH_4 production from herbivores of 160 Tg, 95 Tg from cattle plus 63 Tg from other herbivores. Note that Blake's 95 Tg per year estimate for cattle using this method is larger than Blake's 62 Tg estimate based on the data from Ritzman and Benedict.

LERNER ET AL.

Lerner et al. (1988) present a global database of animal population densities and associated CH_4 emissions. Population statistics were compiled from FAO Production Yearbooks and other sources. Published CH_4 production rates were applied to the animal populations to obtain a global distribution of annual CH_4 emissions by animals.

Animal Population Statistics. Data on animal populations in each country were obtained from FAO Production Yearbooks. In addition, data on animal populations for the political subdivisions of the seven largest countries were obtained from other publications: Australian Encyclopedia, Atlas of Australian Resources, Anuario Estatistica do Brasil, Livestock and Animal Product Statistics (Canada), Agricultural Statistics of the People's Republic of China, Agriculture in Brief (India), Agricultural Statistics

(U.S.), and Europa Year Book (USSR). Global animal population data presented by Lerner et al. generally agreed with FAO statistics: 1 percent or less variation for bovines, buffalo, sheep, pigs, camels and horses; 6 percent for buffalos; and 5 percent for goats.

Methane Production Rates. Values for methane production rates for each type of animal are taken from Crutzen et al. (1986). These rates are as follows:

- Cattle: 55 kg CH_4/head/year in developed economies; 54 kg CH_4/head/year in Australia, Brazil, South Africa and Argentina; and 35 kg CH_4/head/year in developing economies.
- Sheep: 8 and 5 kg CH_4/head/year in developed economies and in developing economies and Australia, respectively.
- Pigs: 1.5 and 1.0 kg CH_4/head/year in developed and developing economies, respectively.
- Others: Production rates for camels (58 kg per head per year), water buffalo (50 kg CH_4/head/year), goats (5 kg CH_4/head/year), horses (18 kg CH_4/head/year) and caribou (15 kg CH_4/head/year) were constant for world populations.

Animal populations were distributed throughout a 1° latitude by 1° longitude grid of the world. Lerner et al. multiplied the CH_4 production rates by the populations in each zone to get a global distribution of CH_4 emissions. Lerner et al. found that over 55 percent of emissions from animals are concentrated between 25°N and 55°N latitude. Global CH_4 production from domestic animals is estimated to be 75.8 Tg CH_4, 75 percent of which is contributed by cattle.

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APPENDIX B

IMPACT OF REDUCING LIVESTOCK METHANE EMISSIONS ON GLOBAL WARMING FROM THE GREENHOUSE EFFECT

B.1 OBJECTIVE

The objective of this analysis is to estimate the potential benefit of reducing methane emissions from ruminant animals in terms of avoiding future global warming. By reducing these emissions, the concentration of methane in the atmosphere will not rise as quickly as it otherwise would, thereby delaying, and possibly avoiding future global warming.

As is commonly done, the amount of avoided global warming is measured in this analysis in terms of reductions in equilibrium temperature change.[1] In this appendix the equilibrium temperature change is estimated for a range of assumptions for the period 1985 to 2100.

Of note is that this analysis addresses only the global warming benefits of reducing methane emissions from ruminant animals. Additional benefits of reducing these emissions may include:

- Animal Productivity. One of the most promising options for reducing methane emissions from ruminant animals is to increase animal productivity, in particular in developing countries. Promising approaches for achieving this objective include providing supplements to animals with important dietary deficiencies (e.g., non-protein nitrogen supplements for animals with diets that are nitrogen deficient). Not only would the supplements modify the animal's rumen fermentation patterns to reduce methane emissions, the increased animal productivity would reduce the population of animals needed to produce a given amount of milk, meat, or work. Overall, the improved animal performance would be a substantial benefit.

- Animal Wastes. Animal wastes may be contributing significant quantities of methane emissions. To the extent that this methane can be harvested for energy, the methane emissions will be reduced. The value of the energy derived from the methane is a benefit. Additionally, carbon dioxide and other emissions that

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[1] Equilibrium temperature change is a measure of the change in the radiative properties of the atmosphere. This measure is used to describe the extent to which the atmosphere is trapping additional energy (like a greenhouse), thereby warming the earth's surface. The actual realized temperature increase that will occur will lag behind the equilibrium temperature change because it takes time for the feedbacks to occur in response to changes in the earth's atmosphere and because it takes time for the oceans to warm and reach an equilibrium with the atmosphere.

would have been produced by the energy production that the harvested methane replaces will be avoided.[2]

Given that these benefits may be substantial, it must be recognized that the analysis that follows includes only a portion of the benefits associated with reducing methane emissions from ruminant animals.

B.2 APPROACH

This analysis was conducted with the atmospheric module of the Atmospheric Stabilization Framework (ASF), recently developed by EPA for its report "Policy Options for Stabilizing Global Climate," (the EPA Report).[3] For the EPA Report, the EPA developed several scenarios of potential future emissions of greenhouse gases and other gases that will influence global climate. The approach used here is to:

1. estimate the impacts on global climate for two of the key scenarios developed for the EPA Report (these impacts are reported in the EPA Report);

2. for each of the two key scenarios estimate reductions in methane emissions associated with steps taken to reduce methane emissions from ruminant animals;

3. create two new emissions scenarios by reducing the methane emissions by the amounts estimated in step two;

4. for each of the two new scenarios (with reduced methane emissions) estimate the impacts on global climate using the ASF; and

5. compare the estimated impacts from the new scenarios with the impacts from the original scenarios to assess the implications of reducing methane emissions from ruminant animals.

The differences in the global warming estimates between the new scenarios and the original scenarios are taken here as the benefits of reducing methane emissions from ruminant animals.

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[2] The burning of the harvested methane produces the same amount of carbon dioxide that the methane would have produced had it been allowed to be emitted directly and oxidized to carbon dioxide in the atmosphere. Consequently, the burning of the harvested methane does not add to the carbon dioxide emissions burden. The avoided carbon dioxide emissions are associated with the burning of coal, oil, or gas that would have been required to produce the energy derived from the harvested methane.

[3] U.S. EPA, "Policy Options for Stabilizing Global Climate," Draft Report to Congress, February 1989.

B.3 SCENARIOS

To examine future global warming, estimates and assumptions are required regarding future emissions of greenhouse gases. These emissions will necessarily be very uncertain due to uncertainties in the main driving factors of the future emissions, including: global economic growth, population growth, fuel prices, land use, and technological change. Therefore, the Atmospheric Stabilization Framework (ASF) was developed by EPA to represent the structural relationships among the key activities that result in important emissions. By using plausible estimates and assumptions in this framework, reasonable scenarios of greenhouse gas emissions can be produced.

The two scenarios used here were developed for the EPA Report and are referred to as the Rapidly Changing World (RCW) and Slowly Changing World (SCW) scenarios. These two scenarios provide a range of assumptions about the future activities that will affect global warming. The main assumptions associated with these scenarios include the following:[4]

SLOWLY CHANGING WORLD	RAPIDLY CHANGING WORLD
Slow Economic Growth	Rapid Economic Growth
Continued Rapid Population Growth	Modest Population Growth
Minimal Energy Price Increases	Modest Energy Price Increases
Slow Technological Change	Rapid Technological Change
Carbon-intensive Fuel Mix	Very Carbon-intensive Fuel Mix
Increased Deforestation	Modest Deforestation

Of interest for this analysis is that although the SCW scenario has overall lower projected emissions of key greenhouse gases than the RCW scenario, it has larger methane emissions from ruminant animals. Exhibit B-1 shows the methane emissions from the two scenarios, and methane emissions from ruminant animals.

As shown in the exhibit, total methane emissions are larger in the RCW scenario. The larger emissions are driven primarily by emissions from fuel production and other energy-related activities. As also shown in the exhibit, methane emissions from ruminant animals are quite similar in the

[4] The interested reader is referred to the full EPA Report for additional details on these scenarios.

two scenarios, with the emissions in the SCW scenario being larger in the later years. The larger emissions in the SCW scenario are driven by the larger population growth in that scenario. A larger human population requires more food, leading to a larger animal population and larger methane emissions from animals. Of note is that these emissions estimates do not include methane emissions from animal wastes.

These scenarios imply that methane emissions from ruminant animals may increase by a factor of 2.4 between 1985 and 2100. The question is appropriately asked, is such an increase reasonable, or might there be important constraints that will prevent such increases from occurring. The following observations describe why the scenarios adopted for the analysis may be reasonable.

- <u>Population Growth</u>. Between 1985 and 2100 the global population will grow considerably. Precise forecasts over 115 years are not possible, however. The range of the population scenarios used in the analysis are based on demographic projections by various groups and include population growth ranging from a factor of 2.0 (Rapidly Changing World, RCW) to 2.6 (Slowly Changing World, SCW). If the intensity of animal products produced and consumed per capita throughout the world did not change over time, and if technology did not change, then in the absence of physical and economic constraints, one could expect that methane emissions from ruminant animals would increase by a factor of 2.0 to 2.6 over this period.

- <u>Economic Growth and Per Capita Consumption of Animal Products</u>. The RCW and SCW scenarios reflect a range of future GNP per capita growth assumptions. Although GNP per capita is simulated to grow throughout the scenarios (reflecting continued economic growth) these growth rates of GNP per capita decline (by assumption) over time, and are lower than recent historical experience. Nevertheless, based on existing estimates of the anticipated increased demand for animal products that have historically been associated with increases in income, and including adjustments for cultural factors and increased prices that would be expected, the intensity of consumption of animal products per capita is generally expected to increase in the future.[5] This conclusion is particularly appropriate because the largest increases in population are anticipated in areas of the world that would be expected to increase the consumption of animal products per capita with increases in income. The increase in consumption per capita is larger in the RCW scenario

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[5] If, in general, the world population moves away from the consumption of animal products, then the future will be quite different than that described here.

because per capita income growth is larger in that scenario. Because of anticipated increases in consumption per capita, one would expect that methane emissions from ruminant animals could increase faster than the rate of growth of population, in particular in the RCW scenario.

- Technology. Over time one would expect that the technology for producing animal products will change. In particular, significant advances may be anticipated in developing countries. In fact, such changes may be required in order for the anticipated future demand for animal products to be met in these regions. The question is whether such advances will significantly reduce the level of methane emissions that may be produced per amount of animal product produced. If the ratio of methane per amount of product produced does not change significantly, then methane emissions from ruminant animals will increase due to both population increases and increased demand per capita.

  The likelihood of significant reductions in methane emissions per amount of product produced, under the assumption that steps are not taken specifically to reduce such emissions, seems remote. In particular, if production increases in developing countries, the animals may be expected to be on forage-type diets, which may produce more methane per amount of product than the animals on grain-supplemented diets in the U.S. If animals are managed intensively in the future to increase productivity in developing countries, methane emissions from wastes could become more important if the wastes are decomposed anaerobically (e.g., in lagoons). Additionally, some of the most promising technologies for increasing animal productivity (e.g., the use of bovine growth hormone to stimulate milk production) has only a modest impact on methane emissions per amount of milk produced. Although the number of animals needed to produce milk may decline, the amount of methane produced per amount of milk produced changes only slightly. Finally, if existing techniques for promoting animal productivity are abandoned (e.g., the use of growth hormones) then methane emissions per amount of product produced may increase for a period of time in some areas.

Given these three observations, the scenarios of methane emissions from ruminant animals in the two scenarios in the EPA Report seem plausible. Certainly, alternative scenarios are also possible, including scenarios that presume significant reductions in methane emissions per amount of product produced due to changes in technology. Of note is that efforts are currently under way to identify and evaluate such technologies, so that they may be factored in to future climate change policy analyses by EPA and others. If such technologies may reasonably be anticipated to be implemented quickly over time due to the economic benefits that they produce in their own right (without reference to climate change at all), then we are indeed in a fortunate position in that the area of ruminant animal emissions of methane may be expected to decline without incurring any costs.

To evaluate the benefits of reducing ruminant methane emissions (in terms of global warming), the ruminant methane emissions incorporated into the two key EPA Report scenarios were reduced by a range of 25 percent to 75 percent. This range of reduction is taken from the workshop discussion and is presented in the findings. The two "reduced emissions" scenarios are also shown in Exhibit B-1.

B.4 RESULTS

Exhibit B-2 shows the resulting methane concentrations estimated for the four scenarios.[6] Both the RCW and SCW scenarios show substantial increases in methane concentrations over the current concentrations of about 1600 ppbv. Of note is that these increases in concentrations are influenced not only by the increasing methane emissions themselves, but also by reductions in concentrations of OH associated with emissions of carbon monoxide and other compounds.[7]

Because reaction with OH is the principal loss mechanism for atmospheric methane, simulated reductions in OH concentrations result in an increased atmospheric lifetime for methane. In the RCW scenario, for example, the lifetime for methane increases from about 9.6 years (used for today's lifetime) to about 11.3 years by 2100. This increased lifetime means that a given level of methane emissions produces larger atmospheric methane concentrations than would otherwise be anticipated. Using the ASF without this OH-methane lifetime relationship indicates that in the absence of the OH feedback the atmospheric abundance of methane in 2100 is simulated to be about 3400 and 2600 ppbv in the RCW and SCW scenarios respectively, or about 850 ppbv and 500 ppbv lower than the amounts shown in Exhibit B-2.

The reductions in methane concentrations associated with the emissions reduction scenarios are significant, about 200 ppbv to 700 ppbv in each of the scenarios by 2100. As noted above, these simulated reductions in future methane concentrations are influenced by the simulated changes in future OH levels that also occur. Without the OH-methane lifetime effect, the emissions reductions analyzed here would reduce methane levels by smaller amounts.

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[6] Note 1 at the end of this appendix describes the method used to estimate methane concentrations.

[7] OH concentrations are influenced in the ASF atmospheric module by the abundances of tropospheric ozone, nitrogen oxides (NO_x), methane (CH_4), carbon monoxide (CO), and emissions of non-methane hydrocarbons (NMHC).

Exhibit B-3 shows the equilibrium temperature change for the scenarios.[8] Both the SCW and RCW scenarios result in significant warming by 2100. The reductions in methane emissions associated with ruminant animals reduce the warming by about 0.1°C to 0.4°C by 2100. Of note is that the avoided warming is driven not only by reductions in the future atmospheric abundance of methane, but also by reductions in the anticipated increase in tropospheric ozone (O_3). By reducing methane emissions, the ASF indicates that a portion of future increases in O_3 can also be avoided. Because O_3 is a greenhouse gas, part of the warming avoided by reducing methane emissions is accounted for by this O_3 relationship. The ASF indicates that about 40 percent of the avoided warming is associated with this O_3 effect. However, this estimate is very uncertain and could be larger or smaller.

As shown in Exhibit B-4, the avoided warming in the RCW scenario amounts to about 1.7 to 5.3 percent of the warming by 2050, and about 1.1 to 3.3 percent of the warming by 2100. In the SCW scenario, the avoided warming amounts to about 2.0 to 6.3 percent of the warming by 2050 and 2.0 to 6.1 percent by 2100. The percentages are larger in the SCW scenario because methane emissions from ruminant animals are a larger portion of the total anticipated warming in this scenario.

To put the benefits of these emissions reductions in perspective it is useful to examine other methods of reducing global warming. Exhibit B-5 shows estimates of reductions in warming that may be achieved by specific technological means in the RCW. As shown in the exhibit, measures for reducing global warming have relatively small impacts individually. The impacts of reducing methane emissions from ruminant animals presented above are within the range of impacts achieved by these measures.

B.5 CONCLUSIONS

This analysis indicates that reducing methane emissions from ruminant animals will have an impact on future global warming. Additionally, the analysis indicates that the benefits achieved from these emissions reductions are comparable to other measures contemplated for avoiding future global warming. Consequently, understanding options for reducing methane emissions from ruminants should be pursued as part of an overall investigation into alternatives for reducing future global warming and its impacts.

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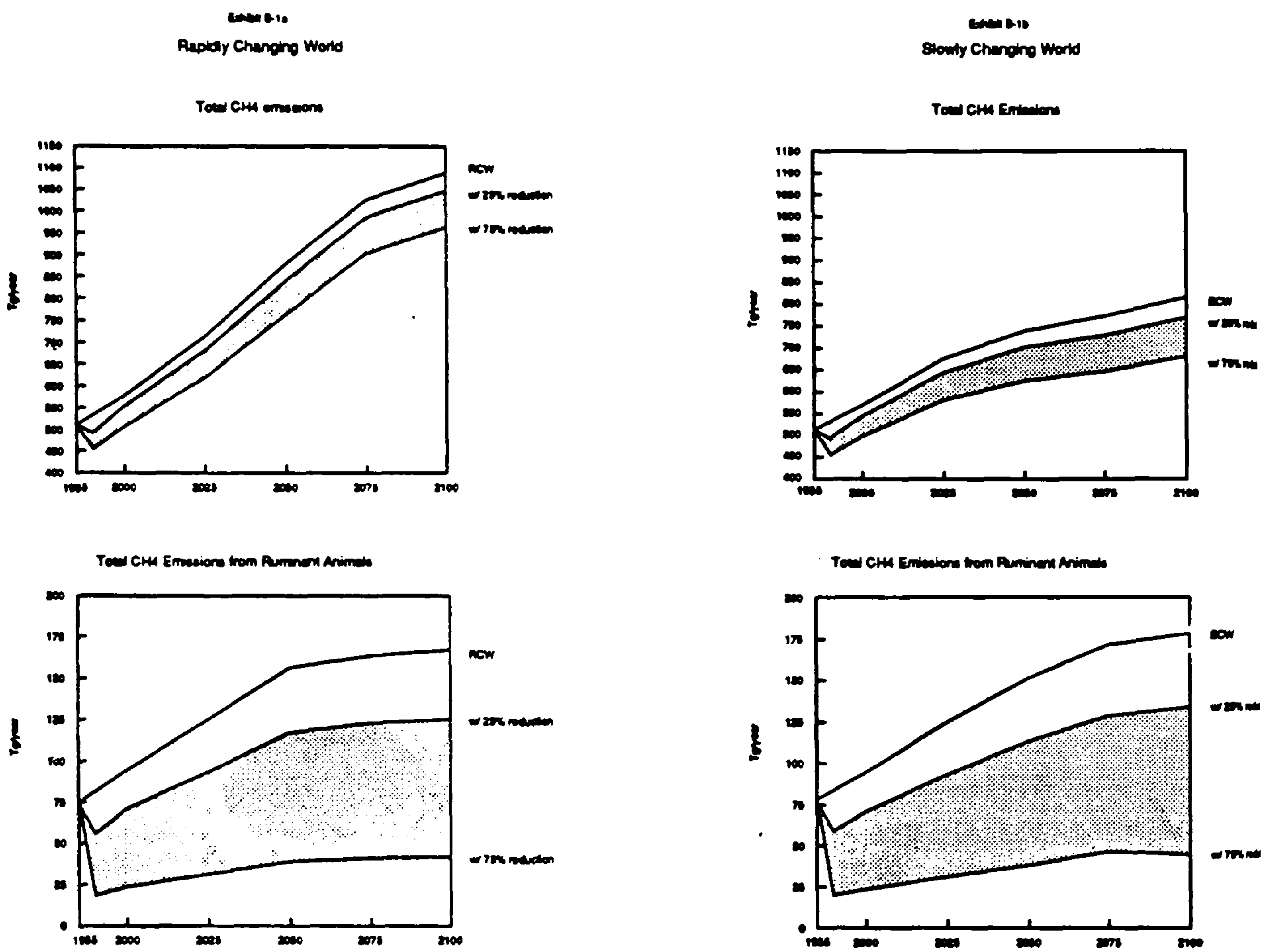
[8] These equilibrium temperature change estimates are based on a climate sensitivity of 4°C for a doubling in carbon dioxide concentrations from pre-industrial levels. The sensitivity of the earth's climate to changing atmospheric properties is uncertain, and a range of 1.5 to 4.5°C has been recognized as an appropriate range of uncertainty. Recent analyses indicate that biogeochemical feedbacks may push the range upward. Note 1 at the end of this appendix presents the method used to estimate the equilibrium temperature change.

EXHIBIT B-1

METHANE EMISSIONS ASSUMPTIONS

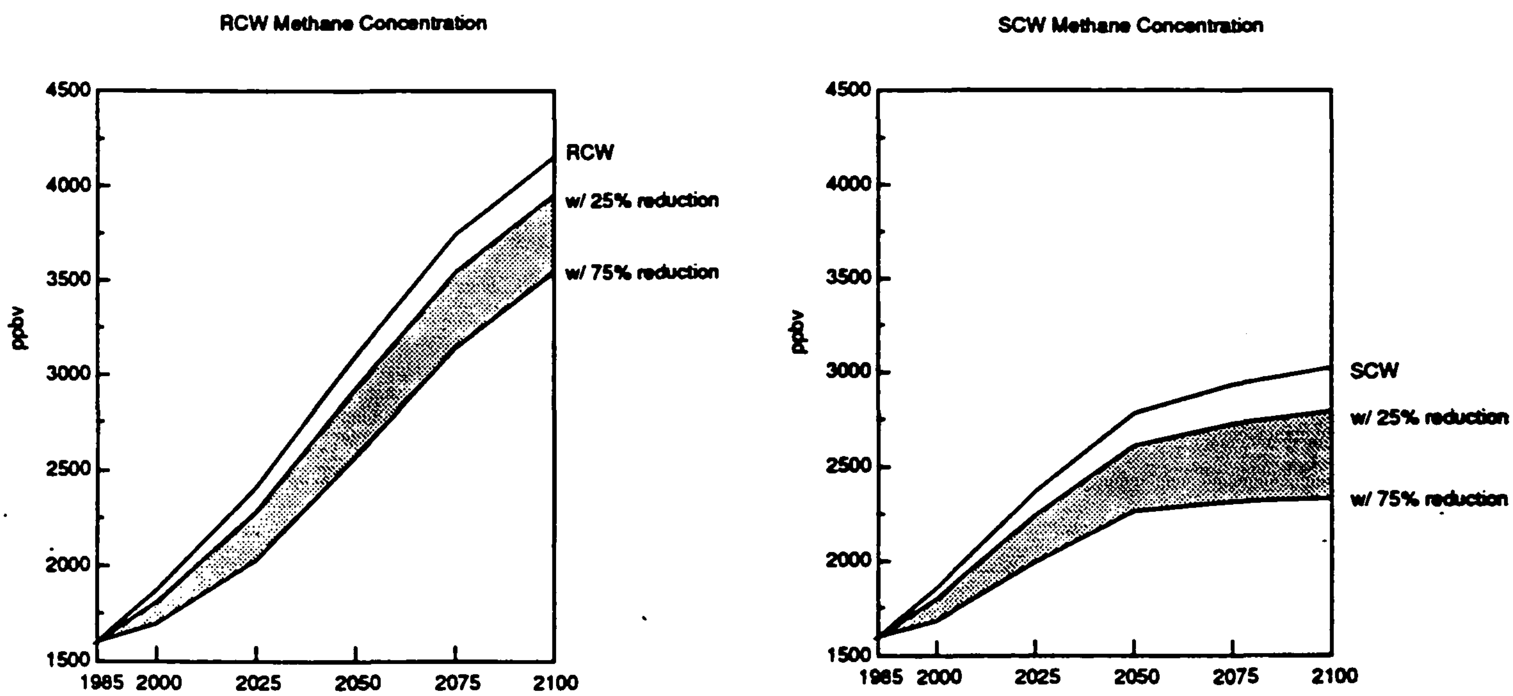


RCW and SCW refer to Rapidly Changing World and Slowly Changing World scenarios, respectively. The scenarios labeled "with reduction" show a range of 25 percent to 75 percent reduction from the baseline rate of emissions from ruminant animals starting in 1990. This range of emissions reductions is shown for illustrative purposes. The technical feasibility and costs of reducing methane emissions from ruminant animals is currently being analyzed.

Source: Taken from: U.S. EPA, "Policy Options for Stabilizing Global Climate," Draft Report to Congress, February 1989.

EXHIBIT B-2

SIMULATED METHANE CONCENTRATIONS



RCW and SCW refer to Rapidly Changing World and Slowly Changing World scenarios, respectively. The scenarios labeled "with reduction" include a 25 to 75 percent reduction in methane emissions associated with ruminant animals starting in 1990. This range of emissions reductions is shown for illustrative purposes. The technical feasibility and costs of reducing methane emissions from ruminant animals is currently being analyzed.

Source: Estimated using the Atmospheric Stabilization Framework developed for: U.S. EPA, "Policy Options for Stabilizing Global Climate," Draft Report to Congress, February 1989.

EXHIBIT B-3

SIMULATED EQUILIBRIUM TEMPERATURE CHANGE
(Degrees C)

SCENARIO	1985	2000	2025	2050	2075	2100
RAPIDLY CHANGING WORLD SCENARIO						
Base Assumptions	1.4	2.1	3.5	5.4	7.5	9.6
25% Reduction	1.4	2.1	3.4	5.3	7.4	9.5
75% Reduction	1.4	2.0	3.2	5.1	7.2	9.3
SLOWLY CHANGING WORLD SCENARIO						
Base Assumptions	1.4	2.1	3.3	4.5	5.4	6.3
25% Reduction	1.4	2.1	3.2	4.4	5.3	6.2
75% Reduction	1.4	2.0	3.1	4.2	5.0	5.9

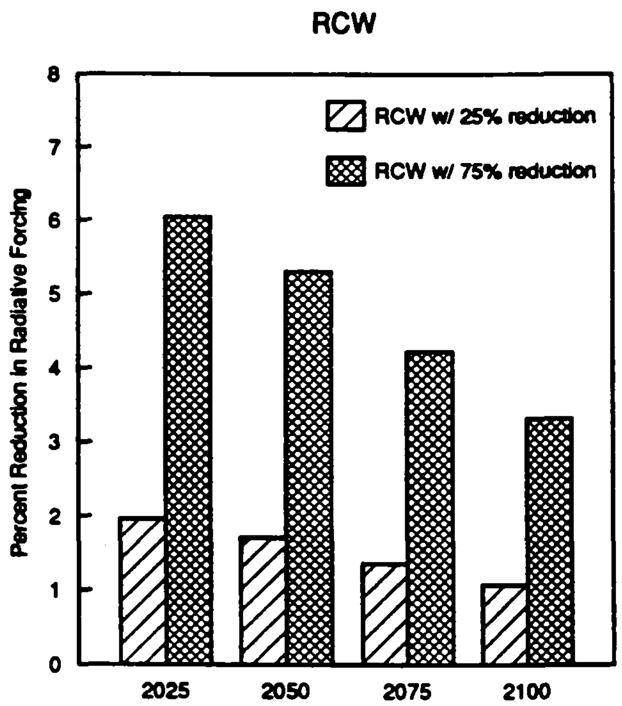
The reduction scenarios include a 25 or 75 percent reduction in methane emissions associated with ruminant animals starting in 1990. This range of emissions reductions is shown for illustrative purposes. The technical feasibility and costs of reducing methane emissions from ruminant animals is currently being analyzed.

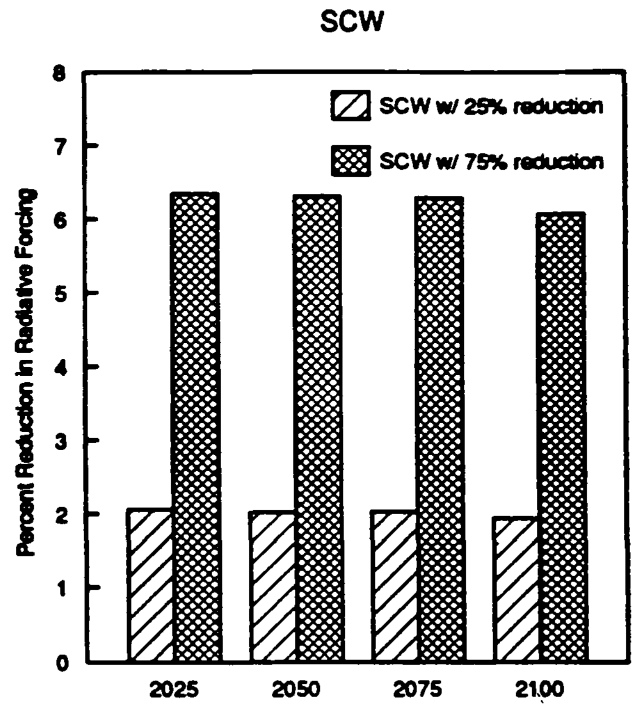
These equilibrium temperature change estimates are based on a climate sensitivity of 4°C for a doubling in carbon dioxide concentrations from pre-industrial levels.

Source: Estimated using the Atmospheric Stabilization Framework developed for: U.S. EPA, "Policy Options for Stabilizing Global Climate," Draft Report to Congress, February 1989.

EXHIBIT B-4

PERCENTAGE OF SIMULATED EQUILIBRIUM TEMPERATURE CHANGE AVOIDED
BY A RANGE OF REDUCTIONS IN METHANE EMISSIONS
FROM RUMINANT ANIMALS





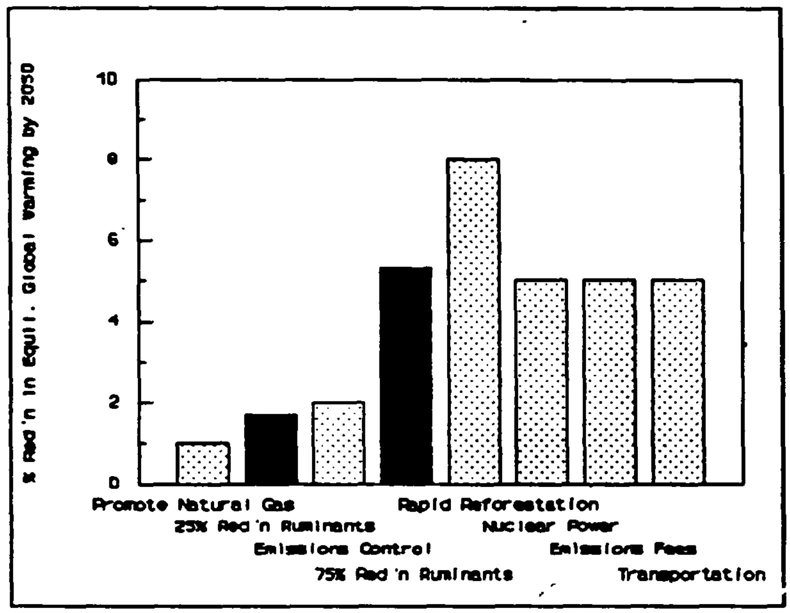
RCW and SCW refer to Rapidly Changing World and Slowly Changing World scenarios, respectively. Percentages estimated by dividing the reduction in global equilibrium temperature changes estimated to be associated with 25 to 75 percent reductions in methane emissions from ruminant animals by the global equilibrium temperature changes anticipated for the original RCW and SCW scenarios.

The simulated equilibrium temperature changes displayed in Exhibit B-3 above produce slightly different estimates of these percentage due to rounding.

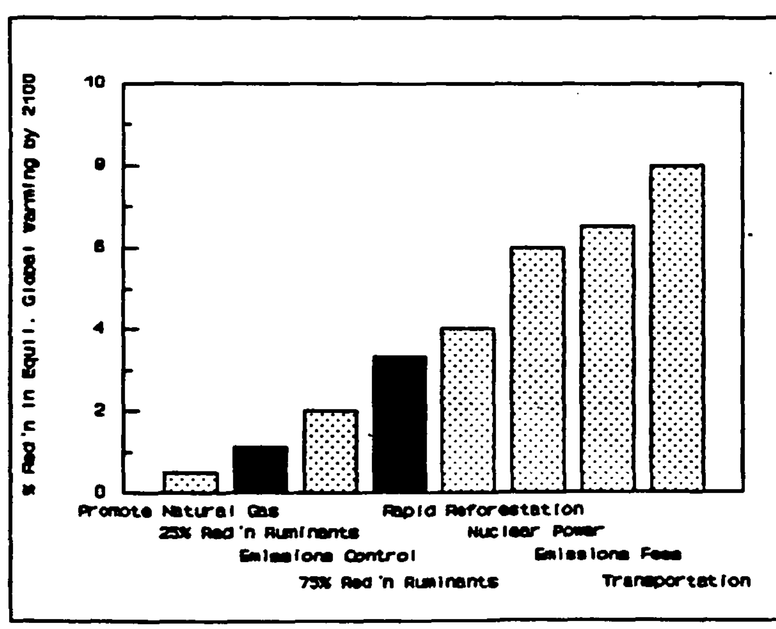
EXHIBIT B-5

REDUCTION IN GLOBAL WARMING ACHIEVABLE
THROUGH VARIOUS TECHNOLOGICAL MEANS IN THE RCW SCENARIO

ESTIMATES FOR 2050



ESTIMATES FOR 2100



Note: Scenarios explained on the following page.

EXHIBIT B-5

REDUCTION IN GLOBAL WARMING ACHIEVABLE
THROUGH VARIOUS TECHNOLOGICAL MEANS IN THE RCW SCENARIO

Explanation of Scenarios:

1. Promote Natural Gas: Assumes that economic incentives accelerate exploration and production of natural gas, reducing the cost of locating and producing natural gas by an annual rate of 0.5% relative to the RCW scenario. Incentives for gas use for electricity generation increases gas share by 5% in 2025 and 10% thereafter.

2. 25% Reduction in Ruminant Animal Emissions: 25% reduction in ruminant animal emissions from the baseline levels in the RCW. The baseline RCW emissions do not include emissions associated with manure handling. Consequently, assuming that methane emissions from manure can be reduced, this estimate is biased downward.

3. Emissions Control: Stringent NO_x and CO controls on mobile and stationary sources.

4. 75% Reduction in Ruminant Animal Emissions: 75% reduction in ruminant animal emissions from the baseline levels in the RCW. The baseline RCW emissions do not include emissions associated with manure handling. Consequently, assuming that methane emissions from manure can be reduced, this estimate is biased downward.

5. Reforestation: Rapid reforestation so that the terrestrial biosphere becomes a net sink for CO_2 by 2000. This requires reforesting 565×10^6 hectares (2.1×10^6 square miles) by 2015 and $1,185 \times 10^6$ hectares (4.4×10^6 square miles) by 2100.

6. Nuclear Power: Promote nuclear power. Assumes that technological improvements in nuclear design reduce costs by about 0.5% per year.

7. Emissions Fees: Emissions fees on fossil fuel production and consumption in proportion to carbon content. Production fees of \$0.50/GJ for coal, \$0.36/GJ for oil, and \$0.23/GJ for gas (GJ = giga-joule). Consumption fees of 28%, 20%, and 13% for coal, oil, and gas, respectively. Production fees implemented fully by 2050, consumption fees by 2025.

8. Transportation: Fuel efficiency of new cars in the U.S. increases to 40 mpg by 2000. Global fleet average fuel efficiency reaches 50 mpg by 2050.

Source: U.S. EPA, "Policy Options for Stabilizing Global Climate," Draft Report to Congress, February 1989.

NOTE 1 TO APPENDIX B

METHODS USED TO ESTIMATE METHANE CONCENTRATIONS AND EQUILIBRIUM TEMPERATURE CHANGE

The Atmospheric Stabilization Framework (ASF) developed by EPA was used to estimate future methane concentrations and equilibrium temperature change presented in this appendix. The ASF, as well as the bases for the scenarios used in the ASF, are described more fully in EPA (1989) (the EPA Report).[1] The EPA Report summarizes the working of the atmospheric composition and temperature module of the ASF as follows:

> The atmospheric composition model was developed for this study (Prather, 1988). It estimates changes in the concentrations of key atmospheric constituents and the global radiation balance based on the emissions/uptake projected by the other models. Perturbations to atmospheric chemistry are incorporated based on first-order (and occasionally second-order) relationships derived from more process-based chemical models and observations. The model is essentially zero-dimensional, but it does distinguish between the northern hemisphere, southern hemisphere, troposphere, and stratosphere. Global surface temperature change is calculated based on the radiative forcing of the greenhouse gases derived from Lacis et al. (1981) and Ramanathan et al. (1985) coupled to heat uptake by the ocean model using a specified climate sensitivity parameter. This sensitivity parameter is set to yield a global equilibrium temperature increase of 2 or 4°C when CO_2 concentration is doubled, reflecting a central estimate of the range of uncertainty ...[2]

This note summarizes the methods used in the ASF to estimate methane concentrations and equilibrium temperature change associated with methane. A more detailed description is contained in Prather (1988) and the EPA Report.

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[1] U.S. EPA, "Policy Options for Stabilizing Global Climate," Draft Report to Congress, February 1989.

[2] The sources cited in this paragraph include:

Prather, Michael J., An Assessment Model for Atmospheric Composition, NASA Conference Publication, 1988.

Lacis, A. et al., "Greenhouse effect of trace gases, 1970-1980," Geophysical Research Letters, 8:1035-1038, 1981.

Ramanathan, V. et al., "Trace gas trends and their potential role in climate change," Journal of Geophysical Research, 90:5547-5566, 1985.

METHANE CONCENTRATIONS

Methane concentrations are modeled with the following simple annual integration:

$$CONC_t = CONC_{t-1} + EMIT_t - LOSS_t \quad (1)$$

where: CONC = methane concentration (e.g., in ppmv);

EMIT = methane emissions (converted to the units of concentrations); and

LOSS = destruction of atmospheric methane.

The initial concentration (circa 1985 atmosphere) is taken as 1.6 ppmv. A variety of emissions scenarios may be used, reflecting varying assumptions about the known sources of methane emissions.

The LOSS term reflects the processes that destroy methane in the atmosphere. The dominant process is oxidation by the hydroxyl radical (OH). The overall destruction process is modeled using an atmospheric "lifetime" as follows:

$$LOSS_t = CONC_{t-1} / LIFE_{t-1} \quad (2)$$

where: LIFE = the atmospheric lifetime for methane.

The initial lifetime (circa 1985 atmosphere) for methane is taken as 9.6 years. This implies that about 10 percent of the methane in the atmosphere is destroyed by natural processes each year.

Of note is that the methane lifetime is modeled to change over time in response to modeled changes in OH and tropospheric temperature. The following equation is used:

$$LIFE_t = LIFE_i * (1 - (0.95 * \delta OH) - (0.02 * \delta T)) \quad (3)$$

where: $LIFE_i$ = initial lifetime of 9.6 years;

δOH = calculated perturbation to OH (estimated as the average of the northern and southern hemispheric perturbations) relative to the reference atmosphere (as a fraction, e.g., -0.10 is a 10 percent reduction in OH); and

δT = perturbation in global average tropospheric temperature relative to the reference atmosphere (in degrees).

The implication of this lifetime feedback is that as simulated temperatures change and as OH levels change (due to changes in the abundance of methane, carbon dioxide, ozone, nitrogen oxides, and non-methane hydrocarbons, and changes in tropospheric temperature), the lifetime of methane may increase or decrease. In the Rapidly Changing World (RCW) scenario presented in the EPA Report, OH levels are simulated to decline, leading to an increased lifetime for methane. However, tropospheric temperatures increase, thereby reducing the lifetime of methane. The net effect is that by 2050 in the RCW scenario the methane lifetime increases by about 14 percent to about 10.9 years; by 2100 the increase is to about 11.3 years.

These simulated increases in the methane lifetime cause the estimates of methane concentrations to be larger than they would be in the absence of the increases in the lifetime.

EQUILIBRIUM TEMPERATURE CHANGE

The impacts of increases in methane concentrations are estimated in terms of an "equilibrium temperature change." This value describes the manner in which the composition of the atmosphere has changed the radiative properties of the atmosphere. For purposes of evaluating the benefits of reducing methane emissions from ruminant animals, the anticipated impacts that lower methane concentrations (due to lower methane emissions) will have on the radiative properties of the atmosphere must be assessed. In addition, however, the impacts that the lower methane emissions and concentrations have on the abundance of <u>other</u> radiatively important trace gases must also be evaluated.

In the ASF, reductions in methane emissions from ruminant animals not only reduce the future anticipated methane concentrations, but also have the following impacts:

- o Reduce the level of OH reductions anticipated in the future (i.e., OH levels are higher than would otherwise be anticipated). Increases in OH tend to reduce the atmospheric lifetimes of other trace gases with destruction processes dominated by OH, including carbon monoxide (CO), methyl chloroform (MC), non-methane hydrocarbons (NMHCs), and partially-halogenated chlorofluorocarbons (HCFCs). These shorter lifetimes tend to reduce their future concentrations slightly. Because MC and HCFCs contribute to global warming, their shorter lifetimes and consequent lower concentrations reduce their global warming impacts.

- o Reduce the level of tropospheric ozone (T-O_3) increases anticipated in the future (i.e., T-O_3 levels are lower than would otherwise be anticipated). T-O_3 is influenced directly by methane concentrations in the ASF such that lower future methane concentrations result in smaller increases in $T\text{-}O_3$. Additionally $T\text{-}O_3$ is influenced indirectly by methane concentrations through the modeled impacts of methane concentrations on CO and column ozone, reinforcing the direct impacts of methane on $T\text{-}O_3$. Because $T\text{-}O_3$ contributes to global warming, its lower abundance reduces its global warming impact.

The reductions in anticipated future global warming associated with the reduced methane concentrations associated with lower emissions from ruminant animals accounts for the majority of the global warming benefits. However, the reductions in future $T\text{-}O_3$ levels are also significant, thereby amplifying considerably the global warming benefits of reducing methane emissions from ruminant animals.[3] The impact of the reduced lifetimes of MC and the HCFCs is simulated to have a small impact on global warming under the scenarios examined in this analysis.[4]

The global warming impacts of methane concentrations are modeled using equations that reflect the "overlapping" effects that methane has with nitrous oxide (N_2O), and are as follows:

$$ETC_t = (T_s / 1.26) * [DRF(CH4_t) - DRF(CH4_i) - OVERLAP_t] \qquad (4)$$

where: ETC = equilibrium temperature change due to methane;

T_s = temperature sensitivity of the atmosphere to a doubling of carbon dioxide in degrees C (e.g., 4°C);

DRF() = a function that estimates the direct radiative forcing of a given methane concentration;

$CH4_i$ = the initial (i.e., pre-industrial) concentration of methane (1.02 ppmv); and

$OVERLAP_t$ = the overlapping effect of methane with N_2O.

Equation (4) is used each year to estimate the equilibrium temperature change associated with the concentration of methane in the atmosphere. The equation used to estimate the direct radiative forcing is:

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[3] Of note is that $T\text{-}O_3$, a component of urban "smog," is recognized as a threat to human health, crops, and the environment. The non-greenhouse warming benefits of reducing the extent of future increases in $T\text{-}O_3$ are not considered here.

[4] The importance of the MC and HCFC OH-lifetime feedback could increase if, for example, the use of these compounds increases significantly in the future.

$$DRF = (0.394*CONC^{0.66} + 0.16*CONC*e^{(-1.6*CONC)})/(1 + 0.169*CONC^{0.62}) \quad (5)$$

where: CONC is the methane concentration in ppmv.

Because methane and N_2O absorb infrared radiation at similar wavelengths, the use of equation (5) overestimates the implications of increases in methane concentrations. Consequently, the following "overlap" equation is used to reduce the estimates of the impacts of methane and N_2O:

$$OVERLAP_t = OVL_t - OVL_i \quad (6)$$

where: OVL() = a function that estimates the overlap effect, once with the current concentrations (subscripted with a "t") and once with the pre-industrial concentrations (subscripted with an "i").

The overlap function is:

$$OVL = 0.14*\ln(1 + 0.636*(CH4*N2O)^{0.75} + 0.007*CH4*(CH4*N2O)^{1.52}) \quad (7)$$

where: CH4 = the methane concentration; and

N2O = the nitrous oxide concentration.

In interpreting the overlap term in equation (4), one must keep in mind that the overlap is due to both methane and N_2O, and should not be allocated entirely to methane. For purposes of the analysis performed in this appendix, the <u>change</u> in the overlap term caused by the reduction in methane emissions from ruminants (and the subsequent reduction in the future increase in methane concentrations) is attributable to the change in the methane emissions.

A separate equation is used to evaluate the equilibrium temperature change of increases in $T\text{-}O_3$:

$$ETC_t = (T_s / 1.26) * 0.00293 * \delta(T\text{-}O_3) \quad (8)$$

where: ETC = equilibrium temperature change due to $T\text{-}O_3$;

T_s = temperature sensitivity of the atmosphere to a doubling of carbon dioxide in degrees C (e.g., 4°C); and

$\delta(T\text{-}O_3)$ = perturbation to tropospheric ozone levels relative to the reference atmosphere (circa 1985) in percent.

In the analyses of reductions in methane emissions from ruminant animals presented in this appendix, the change in the anticipated future increase of $T\text{-}O_3$ associated with the reduced methane emissions account for about 40 percent of the benefits in terms of reduced greenhouse impacts. This estimate of the T-O_3 impact is uncertain and could be larger or smaller. The total impact of the reduction in methane emissions from ruminant animals is the sum of the change in the equilibrium temperature change associated directly with methane (equation 4) and associated with T-O_3 (equation 8).

APPENDIX C

"METHANE PRODUCTION BY DOMESTIC ANIMALS, WILD RUMINANTS, OTHER HERBIVOROUS FAUNA, AND HUMANS,"

by

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Methane production by domestic animals, wild ruminants, other herbivorous fauna, and humans

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ABSTRACT

A detailed assessment of global methane production through enteric fermentation by domestic animals and humans is presented. Measured relations between feed intake and methane yields for animal species are combined with population statistics to deduce a current yearly input of methane to the atmosphere of 74 Tg (1 Tg = 10^{12} g), with an uncertainty of about 15%. Of this, cattle contribute about 74%. Buffalos and sheep each account for 8–9%, and the remainder stems from camels, mules and asses, pigs, and horses. Human CH_4 production is probably less than 1 Tg per year. The mean annual increase in CH_4 emission from domestic animals and humans over the past 20 years has been 0.6 Tg, or 0.75% per year. Population figures on wild ruminants are so uncertain that calculated CH_4 emissions from this source may range between 2 Tg and 6 Tg per year. Current CH_4 emission by domestic and wild animals is estimated to be about 78 Tg, representing 15–25% of the total CH_4 released to the atmosphere from all sources. The likely CH_4 production from domestic animals in 1890 was about 17 Tg, so that this source has increased by a factor of 4.4.

A brief tentative discussion is also given on the potential CH_4 production by other herbivorous fauna, especially insects. Their total CH_4 production probably does not exceed 30 Tg annually.

1. Introduction

Methane plays a large rôle in the photochemistry of the background atmosphere. It is produced and released by various biological processes and is mainly decomposed in the troposphere by reaction with hydroxyl radicals (OH). This reaction initiates complicated reaction pathways leading to the formation of various intermediates that influence the atmospheric concentrations of ozone and hydroxyl (McConnell et al., 1971; Levy, 1971; Crutzen, 1973). The hydroxyl radical, which is present in the atmosphere at an average volume mixing ratio of only 2×10^{-14}, is primarily responsible for the breakdown of natural and anthropogenic trace gases in the atmosphere. As atmospheric methane has been increasing by over 1% per year over the past decade (Rasmussen and Khalil, 1984; Blake, 1984; Seiler, 1984), changes in the background photochemistry of the atmosphere can be expected. Crutzen (1986) has postulated that on the whole, global OH concentrations are decreasing (especially outside the northern mid-latitude zone) and ozone concentrations increasing (especially in northern mid-latitudes and in the upper troposphere).

Methane production by ruminants has been estimated in the past by several authors. The earliest figures on world-wide production rates were published by Hutchinson (1949), who estimated the CH_4 emission by large herbivores to be 45 Tg/year for the 1940's. Ehhalt (1974) calculated a global CH_4 production of 100 Tg CH_4 for 1970 from domestic ruminants. This would constitute 20–35% of the total input of methane to the atmosphere, which is now estimated by various authors to be in the range 300–500 Tg/year (Khalil and Rasmussen, 1983;

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Crutzen and Gidel, 1983; Seiler, 1984). Crutzen (1983) and Seiler (1984) estimated the global CH_4 production from ruminants in 1975 to have been about 60 Tg and 70–100 Tg, respectively. Similar values have also been reported by Khalil and Rasmussen (1983) and Sheppard et al. (1982). None of these papers, however, present a thorough analysis of the derivation of these estimates. In this paper, we will give a detailed account of the worldwide methane production by domestic livestock and wild ruminants, and by humans, using the extensive information which has now become available on methane production by animal species.

2. Energy utilization and methane production in animals

The energy content in food is transformed in the process of digestion and partly lost as chemical compounds in faeces, urine and fermentation gases. The rest is used to produce heat, to perform body work or to build new body tissue (Fig. 1). The magnitude of the various losses of energy depends on the animal species and on the kind and quality of the feedstuff. Measures of feed quality are *digestibility* and *metabolizability*, which are the fractions of the gross energy intake that are converted to digestible energy and metabolizable energy, respectively.

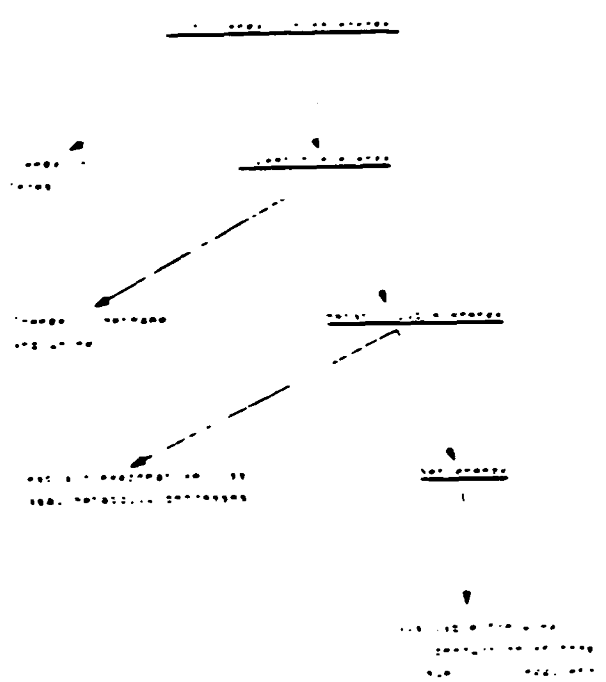

Fig. 1. Flow diagram of energy intake and utilization by animals. The magnitude of the various losses of energy depends on the animal species and utilization, and on the kind and quality of the feed stuff. Based on Kleiber (1961) and Maynard and Loosli (1962).

In adult homeotherms, *basal metabolism* defines the minimum energy demand under conditions of thermoneutrality and total rest. The daily basal metabolism, expressed in megajoules (MJ), is roughly proportional to the $\frac{3}{4}$ power of the body weight W (kg) and is given by the formula:

$$\text{basal metabolism} = 0.293\,W^{0.75}, \tag{1}$$

with an uncertainty of about 14% (Menke and Huss, 1975, p. 91). In practice, the energy demand to prevent breakdown of body tissue is higher than the basal metabolism and the actual gross energy uptake is often expressed in terms of units of *maintenance*, that is, the minimum of food needed to prevent any loss of body tissue (Maynard and Loosli, 1962). This quantity varies, depending on utilization and kind of livestock.

Both quality and quantity of the feed, together with the individual performance of the animals, have been found to determine the amount of energy that is lost by methane production. Methane is a byproduct of microbial breakdown of carbohydrates (mainly cellulose) in the digestive tracts of herbivores. Highest CH_4 losses are reported for ruminants, which host large populations of bacteria and protozoans in their rumens (e.g., Blaxter and Czerkawski, 1966; Wolin, 1981).

In the following, the loss of energy through methane generation will be expressed as a fraction of the gross energy intake. For this, we will use the term *methane yield*. Food quantities, often given in weight units, were converted to gross energy intake by using an average conversion factor of 17.5 MJ/kg dry matter (Leith, 1975). The energy content of 1 kg methane is equal to 55.65 MJ.

Early data on methane yields by cows, sheep, goats, horses, and one elephant were published by Ritzman and Benedict (1938) who found CH_4 yields ranging between 4.4% and 7% for ruminants (cows, sheep, goats) fed on maintenance level. The methane release rates by ruminants were lower when fed with protein-rich diets and higher when fed with crude fiber. The horses and the elephant showed CH_4 yields in the range of 1.5%–3%.

Blaxter and Clapperton (1965), in analysing numerous data on methane production by cows and sheep have shown that at maintenance, methane yields increased from 7.5% to 9% when the digestibility of the feed was raised from 65% to 95%. The methane yields (6.5–7%) were independent of the digestibility at a feeding level of 2 × maintenance and decreased from 6% to 5% at 3 × maintenance when the feed digestibility changed from 60% to 90%. Similar results were reported by Van der Honing et al. (1981) who observed methane yields on 5–6.5% for dairy cows fed on 3.1–3.5 × maintenance. Wainman et al. (1978) measured CH_4 yields of 7.9% from steers fed on 1.5 × maintenance and a 77% digestible diet. Krishna et al. (1978) estimated higher CH_4 yields of 9% in Indian cattle fed on a slightly above maintenance diet and low quality feed.

Published methane yields from sheep show a somewhat larger range of values. Murray et al. (1978) found CH_4 yields to rise from 3.5% to 5.6% with increasing feed intake in Merino ewes fed on protein-rich lucerne chaff with a digestibility of 63%. Kempton and Leng (1979) observed methane yields of 5.4–6.4% in growing lambs, being highest on low protein diets, while Seeley et al. (1969) measured 8.2–9.7% in adult sheep fed on ryegrass hay at maintenance level.

Non-ruminating, well-nourished pigs have much lower methane yields (0.4–0.9%) which seem to be independent of feed mixture (Schneider and Menke, 1982), but pigs given low quality feeds may be expected to show CH_4 yields between 1% and 2% (H. Steingass, personal communication).

From these data, it becomes apparent that the calculation of the global methane release from domestic animals requires consideration of different animal management and feeding schemes. Published information is scarce. We have therefore also made considerable use of information which was kindly provided to us by experts through personal communications.

3. Methane production by cattle

In the US, there are 3 types of cattle: dairy cows, beef cattle on feed, and cattle on range. In Europe and in the USSR, range cattle are rare, and the rearing of dual-purpose cattle for dairy and beef production is common practice. In other countries like Australia or Argentina, cattle are kept primarily on range and dairy cows are relatively less numerous.

Because cattle are fed at different levels of energy intake and quality of food in different parts of the world, we will next present some detailed analyses for the US, West Germany and India. From these data, we will extrapolate to other parts of the world to arrive at global estimates of methane production.

The average number of feed units (1 *feed unit* is the digestible energy contained in 1 pound of corn) consumed in the US by milk cows (including heifers), cattle on feed, and cattle on range are 10150, 6650 and 4800 per animal per year, respectively (G. Allen, personal communication). With an energy content of 6.57 MJ per feed unit, this converts to 230 MJ, 150 MJ and 110 MJ of daily gross energy intake, which corresponds to about 2–3, 1.75 and 1.3 × maintenance. Using Blaxter and Clapperton's (1965) methane yields of 5.5%, 6.5% and 7.5% of gross energy intake for these categories, and an energy content of 55.65 MJ/kg CH_4, the annual methane production per individual in the aforementioned categories are 84 kg, 65 kg and 54 kg, respectively. The US cattle population is made up of 10% dairy cows, 12.5% beef cattle on feed and 77.5% cattle on range (Food and Agricultural Organization of the United Nations (FAO), 1984). The mean methane production by cattle in the US is therefore equal to 58 kg per animal per year.

In West German statistics (Statistisches Bundesamt, 1984), cattle are grouped in age classes: younger than 6 months (2.7 million), 6 to 24 months (6.2 million) and older than 24 months (6.5 million). The latter are subdivided into dairy cows (5.4 million), and heifers or steers (1.1 million).

The feeding level for dairy cows in highly productive stages is 3 to 3.5 × maintenance, equivalent to 300–320 MJ per day (e.g., Van der Honing et al., 1981, Kirchgessner, 1985), but mean gross energy intake over a year's period, is around 260 MJ per day (H. Steingass, personal communication). With a methane yield of 5.5%, we calculate a yearly CH_4 production of 95 kg per dairy cow.

For heifers and steers with body weights of 450 kg and 600 kg, mean gross energy intakes are 125 MJ and 165 MJ per animal per day (Kirchgessner, 1985), respectively, of which 7% is lost as methane (e.g., Wainman et al., 1978). This converts to a yearly methane production of 65 kg per animal as a weighted mean for heifers and steers.

Within the age class younger than 24 months, about 10% of the animal population is kept for veal production. These animals are fed liquid, milky food which strongly limits CH_4 production. Calves younger than 6 months are also fed primarily on milk and other highly digestible feed which do not promote methane production.

Adopting a mean body weight of 340 kg in the age class 6–24 months, the gross energy intake is about 120 MJ per animal per day (Kirchgessner, 1985). As the quality of the feed changes during animal growth from highly digestible to mixtures including more roughage, we adopt a mean CH_4 yield of 6.5%. Consequently, we estimate a production of 51 kg of methane per animal per year in this age class.

Combining the derived methane yields with the cattle populations in the given age classes in West Germany, an average, annual methane production of 57 kg per head is calculated. As other European countries have relatively more beef than dairy cattle and thus slightly lower feed intakes (H. Steingass, personal communication), we will adopt a mean annual CH_4 production of 55 kg per bovin for the developed world by extrapolation of the data derived for the US and West Germany. This figure may have an uncertainty factor of about 15%, mainly due to remaining uncertainties in the methane yields.

Similar methane production rates apply for S. Africa, Australia, Argentina and Brazil. These countries have cattle which are kept mainly on range and fed on roughage (D. E. Johnson, personal communication). For these countries, we assume the CH_4 production rate to be equivalent to that of US cattle on range, i.e., 54 kg per animal per year.

Despite higher methane yields, individual methane production rates from cattle in the developing world are lower, because feed intake is near to, or only slightly above, maintenance, consisting mostly of roughage or kitchen refuse. Pandey (1981) determined the average daily gross energy intake for grazing cattle in Varanasi (India) to be equal to 52.5 MJ for cows, 19 MJ for calves and 73.5 MJ for bullocks. Odend'hal (1972) estimated the mean daily gross energy intake in a cattle population of 3800 individuals in a West Bengal district to be 60.3 MJ per animal. In this population, 14% of the cattle were dairy cows. This is close to the mean for all of Asia (15.6%) and Africa (12.6%) according to the FAO (1984). Adopting an average feed consumption of 60.3 MJ for cattle in the developing world and a CH_4 yield of 9% for low quality feed (Krishna et al., 1978, H. F. Tyrrell, personal communication), we calculate a mean annual CH_4 production rate of 35 kg per animal in the developing world.

According to the FAO (1984), the world cattle population in 1983 was 1.2×10^9. Of this, 53% was kept in the developing and 47% in the developed world, Brazil, and Argentina. Adopting the annual methane production rates of 35 kg and 55 kg, respectively, for these regions, we calculate a global mean annual CH_4 production of about 45 kg per head of cattle, which is considerably less than the 73 kg adopted by Ehhalt (1974). The global methane release to the atmosphere from cattle totals 54 Tg annually (Table 1). Of this about 40% is produced in the developing world.

4. Methane production by other domestic ruminants

Buffalos are kept in some Third World countries for milk production and for farm work. Body weight and feed demand are higher than for cattle, so that buffalos require a gross energy intake of 85 MJ per animal per day (Pandey, 1981). We again assume a CH_4 yield of 9% and therefore estimate a production of 50 kg CH_4 per animal per year. Given a total population of 124 million, the production of CH_4 from buffalos equals about 6.2 Tg per year.

Adult sheep, which weigh 60–70 kg, have a gross energy diet of 30–40 MJ per day in Germany and the US, while immatures are fed 20–25 MJ daily (Kirchgessner, 1985; National Academy of Science, 1975). In West Germany, more than 40% of the sheep population is less than 1-year-old, so that a gross energy intake of

Table 1. *Methane production by domestic animals and humans in 1983 (1 Tg = 10^{12} g)*

Animal type and regions	Population [$\times 10^6$]	CH_4 production per individual [kg/year]	CH_4 production by total population [Tg/year]	Production grand total [Tg/year]
Cattle				
Developed countries, Brazil and Argentina	572.6	55	31.5	
Developing countries	652.8	35	22.8	
Total	1225.4			54.3
Buffalos	124.1	50		6.2
Sheep				
Developed countries	399.7	8	3.2	
Developing countries and Australia	737.6	5	3.7	
Total	1137.3			6.9
Goats	476.1	5	2.4	2.4
Camels	17.0	58	1.0	1.0
Pigs				
Developed countries	328.8	1.5	0.5	
Developing countries	444.8	1.0	0.4	
Total	773.6			0.9
Horses	64.2	18	1.2	1.2
Mules, Asses	53.9	10	0.5	0.5
Humans	4669.7	0.05	0.2	0.3
Total				73.7

25 MJ per day be taken as an average. Murray et al. (1978) give smaller values of 15–19 MJ per day for adult Merino ewes in Australia, which may be partly due to a smaller body weight of about 40 kg. Similar values are given by Mathers and Walters (1982) for England. Adopting a mean daily energy intake of 20 MJ in the developed countries and 13 MJ in Australia and in the developing world and applying a mean CH_4 yield of 6% (Kempton and Leng, 1979; Murray et al., 1978), we calculate production rates of 8 and 5 kg CH_4 per animal per year for the developed and less developed world, respectively. The world sheep population in 1983 was estimated by the FAO (1984) to be 1.1×10^9, about equally divided between the developed countries and the developing world, including Australia. Sheep therefore produce about 6.9 Tg of CH_4 annually, worldwide.

The individual, average gross energy intake of goats in India was measured by Pandey (1981) to be 14 MJ per day. This leads to a methane production of about 5 kg per goat per year, similar to that for sheep. The world goat population of about 476 million produces a total of 2.4 Tg methane per year.

Data on feed intake by camels were not available but may be estimated from their average body weight of 570 kg (Nowak and Paradiso, 1983). Applying the general formula (1) for basal metabolism, we calculate a mean minimum energy demand of 34 MJ per day. The ratio of the mean basal metabolism of cattle in India with a mean body weight between 200–350 kg (H. Steingass, personal communication) to the reported gross energy intake is about 1 : 3. Applying this ratio to camels, we calculate a mean gross energy intake of 100 MJ per animal per day. Camels live essentially on roughage. With 9% methane yield as in the case of Indian cattle, we calculate the methane production from camels to be 58 kg per individual per year, which results in a global yearly CH_4 emission of 1 Tg from a total of 17 million camels. Other camelids (Llamas, Alpaca, etc.) have populations too small (McDowell, 1976) to produce globally significant amounts of CH_4.

5. Methane production by non-ruminant, domestic animals

The methane yield from pigs on highly digestible fattening feeds is less than 1% of the gross energy intake (e.g., Schneider and Menke, 1982). Taking data from Europe, gross energy intake is between 12.5 MJ per day for young pigs and about 90 MJ per day for lactating sows. Based on age and weight-class population statistics from West Germany, we calculate a mean individual gross energy intake of 38 MJ per day. Of this, about 0.6% is released as methane (Schneider and Menke, 1982), yielding 1.5 kg CH_4 per year. We assume that this number applies to developed countries. In developing countries, the animals are smaller and less well nourished, with diets consisting commonly of kitchen refuse or green fodder. With these foods, methane yields might reach 2% (H. Steingass, personal communication). Assuming the gross energy intake to be $\frac{1}{2}$ of that in the developed world and adopting a methane yield of 1.3%, we calculate a yearly CH_4 production rate of 1.0 kg in the developing world. Multiplied with the pig populations in the developed and developing world, this yields about 1 Tg CH_4 per year from pigs.

Methane yields for horses are between those for pigs and ruminants. They equal 3–4% of the digestible energy or 2–3% of the gross energy intake (Kirchgessner, 1985). The energy demand for horses with a mean body weight of 550 kg, executing medium work loads for 2 h a day, is about 78 MJ of digestible energy or 110 MJ of gross energy (National Academy of Sciences, 1973). Similar values are given by Kirchgessner (1985). If 2.5% of the gross energy intake is released as methane, we calculate a mean yearly CH_4 production of 18 kg per animal. The world population of 64 million horses therefore produces a total of 1.2 Tg CH_4 per year. Similarly, we deduce a mean production rate of 10 kg per animal per year for the global mule and donkey population of 54 million, leading to a total emission of 0.5 Tg of CH_4 per year.

6. Methane production by humans

Methanogenic bacteria in the large intestine of humans produce amounts of methane which vary greatly between individuals. The percentage of healthy humans who produce methane ranges from about 30% to more than 50% (Bond et al., 1971; Bjorneklett and Jensen, 1982; McKay et al., 1985). The methane produced in the large intestine is partly absorbed by the blood within the colon wall and exhaled through the lungs, and partly excreted in flatus gas.

Measured CH_4 mixing ratios in exhaled air from methane-producing individuals vary widely, from only a few ppm above ambient air ratios to more than 70 ppm, with an average of 14.8 ppm from 280 healthy individuals (Bond et al., 1971). Levitt and Bond (1970) reported a mean value of 21 ppm CH_4. In a series of experiments on 120 healthy humans, Bjorneklett and Jensen (1982) observed a medium methane mixing ratio in exhaled air of 16.3 ppm. This leads to mean individual CH_4 exhalation rates of 40–50 g per year, assuming a mean breathing volume of 7 l/min (Schulz, 1972). The methane exhalation by the human population of 4.7×10^9 is therefore equal to about 0.2 Tg per year. This surprisingly small quantity is totally negligible in the global CH_4 budget.

Kirk (1949) measured 2–8% methane in the flatus gases from a group of 20 individuals. The average production of flatus gas from this group was 1.5 ml/min. Extrapolating this information to the global human population, the release of methane in flatus gas is estimated to be about 0.1 Tg/year. These small methane production numbers are in agreement with other studies (Steggerda, 1968; Marthinsen and Fleming, 1982).

7. Methane release from wild ruminants and other large herbivores

The global production of CH_4 from wild ruminants is difficult to estimate due to lack of sufficient data or animal populations and feed intake. Some population assessments exist, however, for certain regions of the world and can be extrapolated to global conditions. McDowell (1976) gives a population figure of 27 million for wild ruminants in the northern temperate regions (except China). These ruminants are comprised mostly of deer and moose. In Table 2, we have listed their mean body size (Nowack and Paradiso, 1983) and feed intake (e.g. Nyström, 1980; Sadleir, 1982). As wild ruminants live entirely on roughage and herbs near maintenance levels, we assume a CH_4 yield of 9%. Using these figures, we obtain a total release of 0.4 Tg of methane by wild ruminants in the temperate regions, mostly from deer.

Information on populations and mean body weights of wild ruminants in the Serengeti is summarized in Table 3 (Houston, 1979; Western, 1979). The total population of about 2 million mainly consists of gazelle and wildebeest. Data on gross energy intake in Table 3 have been calculated from formula (1) for the basal metabolic rate, multiplied by a factor of 2 to give the likely gross energy requirement of free living ungulates (Moen, 1973; Eltringham, 1974). Again, 9% of the gross energy intake is assumed to be released as methane. With this information, the CH_4 production in the Serengeti from ruminants is estimated to be about 0.02 Tg per year. Assuming the CH_4 production in the Serengeti to be representative of global conditions, the total CH_4 production by the wild ruminant population of 100–500 million in the subtropical and tropical regions (McDowell, 1976) may be estimated to be of 1–5 Tg per year. Together with the contribution from ruminants in the northern temperate regions, the annual CH_4 production from wild ruminants in the world may, therefore, be equal to 2–6 Tg per year which is small compared to the CH_4 production by domestic animals.

Statistics on methane production by other large, non-ruminating herbivores in the Serengeti are likewise listed in Table 4. The most important contributions come from zebras and elephants. The total methane production is less than 10% of that by the ruminants. Altogether, non-ruminating large herbivores are a negligible source of atmospheric methane.

8. Methane emission by other fauna

The consumption of plant matter by the large, wild herbivores considered so far, sums up to 50–200 Tg dry matter. The average consumption of plant matter by herbivorous fauna is estimated to be 7% of the net primary productivity (NPP) of natural ecosystems, or about 7000 Tg dry matter (Whittaker, 1975). Consequently, relatively small

Table 2. *CH_4 production by wild ruminants in temperate northern regions*

Species	Populations [× 10⁵]	Mean body weight [kg]	Gross energy intake [MJ/day]	CH_4 production per individual [kg year]	CH_4 production total [Tg/year]
moose, elk	8.5	350	53	31	0.03
white and black-tailed deer, mule deer, red deer, reindeer, caribou	220	90	26	15	0.33
roe deer	40	15	5	3	0.01
Total	268	—	—	—	0.37

Table 3. *CH_4 production by wild animals in the Serengeti*

Species	Population [× 10^3]	Mean body weight [kg]	Gross energy intake [MJ/day]	CH_4 production per individual [kg/year]	CH_4 production total [10^6 kg/year]
wildebeest	72000	123	22	13	9.4
buffalo	10800	450	57	34	3.7
Thompson's gazelle	98100	15	4	2	2.0
giraffe	1700	750	84	50	0.8
eland	2400	340	46	27	0.6
topi	5600	100	19	11	0.6
impala	11900	40	9	5	0.6
kongoni	2100	125	22	13	0.3
waterbuck	300	160	26	15	0.1
Grant's gazelle	600	40	9	5	—
Total ruminants					18.1
zebra	240	200	31	5	1.2
elephant	5	1725	157	26	0.13
warthog	34	45	10	1	0.03
hippopotamus	2	1000	104	17	0.03
rhinoceros	1	820	90	15	0.02
Total non-ruminants					1.4

Table 4. *Trends in domestic animal populations and CH_4 production rates*

	1890	1921–25	1941–45	1961–65	1983
Cattle					
population [10^6]	310	640	740	1016	[illegible]
CH_4 production rate [kg/animal year]	35	38.3	40.5	42.8	[illegible]
CH_4 production total [Tg/year]	11	25	30	43	[illegible]
Sheep					
population [10^6]	590	645	755	1007	[illegible]
CH_4 production rate [kg/animal year]	5	5.4	5.6	5.9	6
CH_4 production total [Tg/year]	3	3	4	6	[illegible]
Other domestic animals, humans etc.					
CH_4 production total [Tg/year]	3	6	8	11	[illegible]
Total CH_4 production [Tg/year]	17	34	42	60	[illegible]

CH_4 yields from other fauna than that considered so far could produce substantial amounts of methane. In the following, we will briefly consider the possibilities.

According to Whittaker (1975), the consumption of plant matter by fauna is 10–15% of the NPP in grasslands and 4–8% in forest and woodlands. However, only a few investigations on the energy transfer through the food webs in these ecosystems have been published so far, which give information on the main herbivorous consumers. Norton-Griffiths (1979) and Sinclair (1975) estimated the consumption of plant matter by small mammals, mainly voles, in the Serengeti to be 1.2% of the above-ground NPP in long-grass savanna and only 0.1% in short-grass savanna. Much more, 7.6% and 4.1%, respectively, is consumed by invertebrates (mainly grasshoppers), in these two grassland sites (Bourlière, 1983).

In the palm savanna at Lamto, Ivory Coast, the main consumers are fungus-growing termites (6% of NPP), followed by grasshoppers (0.4%) and small rodents, mainly voles (0.25%). Large herbivorous ungulates play no major rôle (Lamotte and Bourlière, 1983). Certain ants and caterpillars are also important consumers but quantitative information on their rôle is not available.

In the Fété Olé savanna in Senegal, termites have also been found to be major harvesters of plant tissue, consuming 10% of the NPP (Josens, 1983). Gillon (1983) states that at this site, grasshoppers and caterpillars may consume as much as grazing mammals, but gives no data on their plant consumption.

In undisturbed temperate grassland sites, primary consumption by invertebrate herbivores is 0.5–9% of the above ground NPP, being lowest in poor, unproductive sites and increasing with productivity (Andrzejewska and Gyllenberg, 1980). Wiegert and Evans (1967) determined an upper limit of 12% for plant consumption by herbivores in an old grass field site in South Carolina, mainly by invertebrates. Only 1% was consumed by vertebrates, mainly field mice and savanna sparrows.

In tropical forests, Janzen (1983) considers defoliating animals as the most important plant consumers, mainly moth larvae, caterpillars, beetles and other invertebrates. Jordan (1983) cites data, indicating that usually no more than 3–6% of the leaf biomass is harvested by insects. In nutrient deficient, low-production forests, the consumption may drop to 2%.

Herbivorous vertebrates are not important as primary consumers in tropical forests. Owen (1983) gives a very low figure of only 72 kg/km² for the density of herbivorous mammals at the Tano Nimri Forest (Ghana), consisting of 3 ungulates and 7 primates. These low figures are also confirmed for South Eastern tropical rain forests (Whitmor, 1984). In contrast, in some South American forests, larger populations of sloths and tapirs may be found that may consume a considerable fraction of plant production within the forests (Janzen, 1983). Rodents are also present in tropical forests but apart from some population figures, no energy intake data are available.

In temperate forests, primary consumption by insects is at most 10–15% of the above-ground NPP (Remmert, 1980). Franklin (1970) cites some figures for broad-leaved trees, which range from 5–8%. However, these data contradict those from an intensively investigated forest site in the North-east US, in which Gosz et al. (1978) found less than 1% of the total NPP, including roots, to be consumed by herbivores. In approximate order of importance, these are chipmunks, mice, foliage-eating insects, birds, deer and hares.

Consumption figures from boreal forests or tundra sites are not available. Remmert (1980) gives a rough figure of 1–2% for consumption by vertebrates at Spitzbergen (Norway), but gives no estimates for invertebrates.

Summarizing the above widely different data, it appears that major consumers in natural habitats are invertebrates, mainly insects, and to a much lesser degree small herbivores. If we assume that small herbivores (mainly rodents and lagomorphs, i.e., hares, rabbits, etc.) in natural habitats consume less than 1% of the global NPP, with a CH_4 yield of 1.5% (Johnson, personal communication), we calculate for this group of animals an upper limit of methane production of 2–3% Tg per year.

An estimate for methane production by invertebrates is even more speculative. So far, methane production has only been measured in termites (Zimmerman et al., 1982; Rasmussen and Khalil, 1983; Seiler et al., 1984; Fraser et al., 1986) and in wood-boring larvae of beetles (Bayon, 1980) which utilize symbiotic microorganisms in their digestive tract to break down cellulose. According to Swift et al. (1979), most insects harbour flagellates in their guts for cellulose digestion. Thus it is likely that insects and probably other invertebrate primary consumers also harbour methanogenic micro-organisms.

Measurements from different genera of termites indicate methane yields of less than 0.01% to 1.5% (Zimmerman et al., 1982; Khalil and Rasmussen, 1983; Seiler et al., 1984). If we adopt this range for all invertebrate primary consumers, the consumption of 6% of the global NPP by herbivorous invertebrate probably could produce at most 28 Tg annually. However, this upper limit estimate is speculative as long as no data on possible CH_4 production yields by insects other than termites are available. According to Owen (1983), plant-feeding insects in tropical forests are much more abundant than commonly assumed, due to inadequate counting methods. Consequently, more work on the potential CH_4 production by invertebrates is certainly justified.

Our upper estimate of 28 Tg for invertebrate primary consumers overlaps to some degree with global production estimates for termites (including herbivorous species, wood- and dung feeders, soil feeders and others), which range from 2-5 Tg (Seiler et al., 1984) up to 150 Tg (Zimmerman et al., 1982). The most recent study by Fraser et al. (1986) suggests an annual production of 6-42 Tg with an average of maybe 14 Tg.

So far we have primarily been concerned with primary consumers. Most of the plant material produced each year by vegetation is lost to the litter layer and subsequently decomposed by a large variety of organisms. A survey through the literature on soil biology has given no hint on methane production in soils apart from anaerobic environments and termite mounds. Swift et al. (1979) report that certain cockroaches and dung beetles rely upon symbiotic bacteria and protozoans for the digestion of structural polysaccharides. This could imply possible methane production as in the case of termites. Generally, methane can most probably only be produced by macrofauna consumers of plant detritus (primary saprotrophs) as these are the only ones with true anaerobic digestive tracts. Organisms belonging to mesafauna are probably too small in size to develop anaerobic conditions in their guts (Grewe, personal communication). The macrofauna plays a major rôle in the tropics and declines in importance towards the poles. In colder climates, major breakdown of organic compounds is accomplished by microfauna and fungi (Swift et al., 1979), which implies a gradient of decreasing methane production potential from soil fauna from the tropics to the poles.

Earthworms have attained special interest in the past for their ameliorating effect on soils. These animals feed on detritus together with mineral particles and attain huge turnover rates of matter within the soil. Their guts produce a favourable environment for a diverse population of micro-organisms. However, cellulose is very badly digested (Brauns, 1968) and methanogenesis is not reported. Measurements on aerobic soils of temperate and tropical grassland sites (Seiler et al., 1984, 1986) all indicate methane decomposition in the soil and no production. If soil-dwelling organisms produce methane, it seems likely that this is readily decomposed within the soil and does not escape to the atmosphere.

9. Current and past CH_4 production from domestic animals

Data on the estimated global methane production by domestic animals and humans in 1983 are summarized in Table 1. Total methane release to the atmosphere is about 74 Tg/year with an estimated uncertainty of about 15%. By far the largest contribution, about 54 Tg, comes from cattle. About 40% of this emission occurs in the developing world. Next in importance come buffalo and sheep, which produce about 6 Tg and 7 Tg CH_4 per year, respectively. Goats and camels produce 2.4 Tg CH_4 and 1 Tg CH_4 annually. Non-ruminant, domestic animals each year emit about 2.6 Tg CH_4 to the atmosphere. The human contribution is only about 0.2 Tg CH_4 per year. In comparison with the estimated global methane emission of 74 Tg by domestic animals in the year 1983, the input by wild ruminants of 2-6 Tg is relatively small.

Because of the growing world population of humans and its growing food demand, the population of domestic animals has also increased considerably during the last century, leading to an increase in global methane production rates. According to data published by Mulhall (1892) for the end of the last century and data for the first half of this century (US Department of Agriculture, 1936-1970), the world cattle population has increased from 310 million in 1890 to 640 million in 1920-1925, and 740 million in 1940-1945. The corresponding figures for sheep are 590 million, 645 million, and 755 million, respectively (Table 4). According to the available statistics, the sheep and cattle populations show similar trends for the period 1920-1960, but large differences for 1890-1920, which is probably indicative of less reliable statistical information from the early period.

More detailed statistical information is available for the time period after 1940, particularly due to the work by the Food and Agricultural Organization of the United Nations (FAO, 1973, 1982 and 1984). According to these data, during the last two decades, the world's cattle and sheep populations have grown by 0.8% and 0.6% per year, respectively, reaching figures in 1983 of 1225×10^6 for cattle and 1137×10^6 for sheep. Similar annual increases in global population numbers are found for pigs (1.4%), buffalos (1%), goats (1.2%) and camels (0.5%). The population of mules and asses stayed about constant, while that of horses showed a slight decline of 0.25% per year. According to the available statistics, since 1960, the growth rates of the cattle and sheep populations have slightly declined.

The temporal trends of global CH_4 emission by ruminants are not only dependent on their populations but also on quality and quantity of feed intake. In the developed countries, the average, individual feed intake has increased during the last 20 to 30 years, although the corresponding increase in CH_4 emission may have been compensated to some extent by declining CH_4 yields due to higher feed quality. In the developing world, both feed intake and quality may have declined.

To estimate individual methane production rates prior to 1983, we assume that in 1890, average methane yields in the world were about equal to current yields in the developing world, while between 1890 and 1980, we adopt a linear growth in individual CH_4 emission rates. With this assumption, the CH_4 release from cattle has more than quadrupled during the last century from 11 Tg in 1890 to 54 Tg in 1983. CH_4 emission by sheep has grown from 3 Tg to 7 Tg during the same period (Table 4). Information on declining populations of wild ruminants is not available, but they can certainly not have been sufficient to compensate substantially for the growth in methane emissions by domestic animals. Altogether, our analysis indicates that the total annual CH_4 emission from all animals, including wild ruminants, has increased from 21 Tg in 1890 to about 78 Tg in 1983.

10. Conclusions

Methane is produced by the anaerobic fermentation of organic matter in the rumen and lower gut of domestic and wild animals. The CH_4 emission rate per animal is dependent on quality and amount of feed intake. Based on data that are presently available, we estimate that about 5-9% of the gross energy intake by ruminants is lost to methane production. Lower methane yields in the range 0.5-3% are derived for other domestic animals such as pigs, horses, etc.

The current global CH_4 emission by domestic and wild animals is estimated to be 78 Tg/year. From this, almost 80%, or about 60 Tg/year, comes from cattle and buffalos. The rest is produced by sheep (7 Tg/year), wild ruminants (2-6 Tg/year), and others. About 40% of the total CH_4 produced by domestic animals is emitted in the developing countries, mostly in Asia, followed by South America and Africa. The main source region for methane from cattle in the developed world is North America (11 Tg/year) followed by Europe (8 Tg/year) and the USSR (7 Tg/year).

Methane production by domestic and wild animals constitutes about 15-25% of the total tropospheric CH_4 input, recently estimated by various authors to be in the range of 300-500 Tg/year (Khalil and Rasmussen, 1983; Crutzen and Gidel, 1983; Seiler, 1984). Production by animals represents one of the most important individual sources within the tropospheric CH_4 cycle. It is about two times larger than the production from coal mining and natural gas leaks (Seiler, 1984; Crutzen, 1986; Bolle et al., 1986). The only emissions which could be larger are those from the anaerobic decay of organic matter in rice fields and natural wetlands. Methane release from rice paddies may be about 70-130 Tg/year, if information obtained in Italian rice fields can be extrapolated to tropical conditions (Holzapfel-Pschorn and Seiler, 1986).

The total emission of CH_4 by domestic and wild animals has increased from about 21 Tg in 1890 to 46 Tg in 1940 and 78 Tg in 1983, mainly due to growing populations of cattle, buffalos and sheep. According to these figures, the mean rate of increase in CH_4 emission by domestic and wild animals during the last 43 years has been 1.1% per year.

We have estimated a tentative upper limit of about 20 Tg CH_4 emission per year from other fauna, especially insects. However, this topic requires additional research. Finally, the production of CH_4 in humans appears to be negligibly low, much less than 1 Tg/year.

11. Acknowledgements

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APPENDIX D

WORKSHOP AGENDA

METHANE EMISSIONS FROM RUMINANTS

FEBRUARY 27-28, 1989
PALM SPRINGS, CALIFORNIA

WORKSHOP AGENDA

SESSION 1: FEBRUARY 27, 1989
LOCATION: GARDEN ROOM, SPA HOTEL AND MINERAL SPRINGS

8:30am	Coffee, juice, and breakfast rolls
9:00am - 9:15am	Welcome and Announcements, Michael Gibbs, ICF
	INTRODUCTION AND BACKGROUND
9:15am - 9:30am	Workshop Objectives, John S. Hoffman, EPA
9:30am - 9:45am	Methane in the Atmosphere, Don Blake, U.C. Irvine
9:45am - 10:00am	Overview of Methane from Ruminants and Key Workshop Questions, Michael Gibbs, ICF
10:00am - 10:30am	Discussion
	SOURCES OF METHANE EMISSIONS
10:30am - 10:50am	Indirect Calorimetry Measurements, Don Johnson, Colorado State University
10:50am - 11:10am	Rumen Processes and Models, Lee Baldwin, U.C. Davis
11:10am - 12:15pm	Discussion
12:15pm - 1:00pm	Lunch Brought In
1:00pm - 1:15pm	Waste Fermentation as a Source of Methane, L.M. (Mac) Safley, North Carolina State University
1:15pm - 2:00pm	Discussion

February 23, 1989

WORKSHOP AGENDA (Continued)

SESSION 1: FEBRUARY 27, 1989 (continued)
LOCATION: GARDEN ROOM, SPA HOTEL AND MINERAL SPRINGS

CHARACTERIZATION OF POPULATIONS AND EMISSIONS

2:00pm - 2:20pm	**Demography and Ecology of Cattle in Developing Countries,** Stewart Odend'hal, University of Georgia
2:20pm - 2:40pm	**Dependence on Cattle Populations in Developing Countries,** Jim Ellis, Colorado State University
2:40pm - 3:15pm	**Discussion**
3:15pm - 3:45pm	**Systems Approach to Evaluating Methane Emissions,** Jim Fadel, U.C. Davis
3:45pm - 4:30pm	**Discussion**
5:45pm	MEET IN LOBBY FOR BUS TO DINNER ON MT. SAN JACINTO

WORKSHOP AGENDA (Continued)

SESSION 2: FEBRUARY 28, 1989
LOCATION: GARDEN ROOM, SPA HOTEL AND MINERAL SPRINGS

8:30am	Coffee, juice, and breakfast rolls
9:00am - 9:15am	Announcements, Michael Gibbs, ICF
	IDENTIFYING AND EVALUATING OPTIONS FOR REDUCING METHANE EMISSIONS FROM RUMINANTS
9:15am - 9:30am	Overview, Michael Gibbs, ICF
9:45am - 10:00am	Microbial Ecology of the Rumen, Bob Hespell, USDA
10:00am - 10:15am	Productivity Enhancement and Methane Emissions, Henry Tyrell, USDA
10:15am - 12:00	Discussion
12:00 - 12:45pm	Lunch Brought In
	NEXT STEPS FOR REDUCING METHANE EMISSIONS FROM RUMINANTS
12:45pm - 1:00pm	ARS Planning and Priorities, Lewis Smith, ARS
1:00pm - 3:00pm	Discussion of:

-- Projects for improving emissions estimates

-- Projects for evaluating emissions reductions options

-- Forming and Ad Hoc Group

-- Others to involve

Workshop Adjourned

February 23, 1989

APPENDIX E

LIST OF WORKSHOP ATTENDEES

METHANE EMISSIONS FROM RUMINANTS

FEBRUARY 27-28, 1989
PALM SPRINGS, CALIFORNIA

WORKSHOP ATTENDEES

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