Working Paper

The Greenhouse Gas Methane (CH_4): Sources and Sinks, the Impact of Population Growth, Possible Interventions

Gerhard K. Heilig

WP-92-42
June 1992

IIASA

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ACKNOWLEDGEMENTS

This paper was presented at the 1992 Annual Meeting of the Population Association of America, April 30 - May 2, 1992 in the section on "Demography, the Environment and Sustainable Development."

The topics discussed in this paper certainly transcend demographic analyses. They include climatological, geological, chemical, agricultural, social, political, and demographic questions. Therefore I am grateful for the extensive discussions on many aspects of the paper with IIASA colleagues who have specialized in the respective discipline. I am especially indebted to Arnulf Grübler and Nebojša Nakićenović (Environmentally Compatible Energy Strategies Project) and to Matthias Jonas (Global Environmental Security Project) at IIASA.

ABSTRACT

Methane (CH_4) is one of the trace gases in the atmosphere that is considered to play a major role in what is called the "greenhouse effect". Despite its still extremely minute concentration (around 1.7 ppmv) this radiatively and chemically reactive gas has been accumulating in the atmosphere at the rate of 1% per year. Today the methane concentration is about double that in the preindustrial era.

There are six major sources of atmospheric methane: emission from anaerobic decomposition in (1) natural wetlands and (2) paddy rice fields; (3) emission from livestock production systems (including intrinsic fermentation and animal waste); (4) biomass burning (including forest fires, charcoal combustion, and firewood burning); (5) anaerobic decomposition of organic waste in landfills, and (6) fossil methane emission during the exploration and transport of fossil fuels. Obviously, human activities play a major role in increasing methane emissions from most of these sources. Especially the worldwide expansion of paddy rice cultivation, livestock production and fossil fuel exploration have increased the methane concentration in the atmosphere.

The paper first reviews the evidence for an increase in atmospheric methane concentration. There are several data sets available from sampling programs and ice core studies that help estimate atmospheric methane concentration up to several ten thousand years back. Then major sources and sinks of present-day methane emission and their relative contribution to the global methane balance are discussed. It is demonstrated that there are great uncertainties in the identification and quantification of individual sources and sinks. The paper also presents the most recent methane projections of the Intergovernmental Panel on Climate Change (IPCC) for 2025 and 2100 and discusses their validity. These projections are also used to estimate the contribution of population growth to future methane emission. Finally the paper discusses options and restrictions of reducing anthropogenic methane emissions to the atmosphere.

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Introduction

Methane (CH_4) is one of the trace gases in the atmosphere that is considered to play a major role in what is called the "greenhouse effect". Despite its still extremely minute concentration (around 1.7 ppmv) this radiatively and chemically reactive gas has been accumulating in the atmosphere at the rate of 1% per year. Today the methane concentration is about double that in the preindustrial era and two to six times higher than during the first emergence of the homo sapiens.

The role of methane in the chemistry of the atmosphere is complex and still not fully understood. In principle methane is oxidized by photochemical reactions to carbon monoxide (CO), carbon dioxide (CO_2), water (H_2O) and CH_2O, consuming the hydroxyl radical (OH).[1] This destructive reaction with OH is the biggest sink of methane in the atmosphere. The reaction involves a set of several other trace gases, including ozone (O_3). Atmospheric methane affects the earth's radiative balance in several ways: its oxidation produces other important greenhouse gases (such as CO_2 and water vapor); it directly contributes to global warming through its infrared absorption spectrum; and it controls the lifetime of many other gases of climatic importance, such as ozone (O_3).

1. Evidence for an Increase in Atmospheric Methane Concentration

There is abundant evidence that the concentration of atmospheric methane is rising rapidly. In 1978 a systematic sampling program of atmospheric CH_4 was started. Global monthly averages are derived from 7 specially selected monitoring sites in Alaska, Tasmania, Samoa, Oregon, Hawaii and Antarctica; in addition, 25 sampling sites around the world collect monthly data on CH_4 concentration (see Appendix Table A1).

Our knowledge about concentrations of atmospheric CH_4 before 1978 is based on ice cores drilled from the inland ice of the Antarctica and Greenland. Air bubbles, trapped

[1]For details see: Cicerone, R.J. and R.S. Oremland. 1988. Biogeochemical aspects of atmospheric methane. *Global Biogeochemical Cycles* 2(4):299-327.

in ice cores, were analyzed using the flame ionization technique and gas chromatography.[2] The depth from where the ice was recovered corresponds to its age. Until now there have been four major investigation programs of ice cores to study past levels of atmospheric trace gases:[3]

- the Soviet Antarctic Expedition at Vostok (East Antarctica);[4]
- the investigation of the U.S. Cold Regions Research and Engineering Laboratory at Byrd Station, Antarctica;[5]
- the Greenland Ice Sheet Program--an international collaboration between the United States, Denmark, and Switzerland--at Dye 3 station in Greenland;[6] and
- the joint drilling by the Polar Ice Coring Office (Nebraska) and the Physics Institute at the University of Bern at Siple Station, Antarctica.[7]

On the basis of these investigations it was estimated that the level of CH_4 increased from 0.34 ppmv some 160,000 years ago to 1.3 ppmv in 1955. Since then it further grew to 1.7 ppmv in 1988. For details see Tables 1 and 2. As Figure 1 demonstrates there was great variation in CH_4 levels during pre-historic times. However, there is no evidence that the atmospheric concentration of methane ever reached half the level of today. In fact, during ten thousands of years the CH_4 level in the atmosphere was less than 25% of today.

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[2]For details of the method see: Barnola, J.M., D. Raynaud, Y.S. Korotkevich, and C. Lorius. 1987. Vostok ice core provides 160,000-year record of atmospheric CO_2. *Nature* 329:408-414.

[3]According to: Boden, T.A., P. Kanciruk, and M.P. Farrell. 1990. *Trends '90. A Compendium of Data on Global Change.* ORNL/CDIAC-36. Oak Ridge, Tennessee: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory.

[4]Barnola et al., *op cit.*

Raynaud, D., J. Chappellaz, J.M. Barnola, Y.S. Korotkevich, and C. Lorius. 1988. Climatic and CH_4 cycle implications of glacial-interglacial CH_4 change in the Vostok ice core. *Nature* 333:655-657.

[5]Neftel, A., H. Oeschger, J. Schwander, B. Stauffer, and R. Zumbrunn. 1982. Ice core measurements give atmospheric CO_2 content during the past 40,000 years. *Nature* 295:220-223.

Stauffer, B., E. Lochbronner, H. Oeschger, and J. Schwander. 1988. Methane concentration in the glacial atmosphere was only half that of the preindustrial Holocene. *Nature* 332:812-814.

[6]Dansgaard, W., H.B. Clausen, N. Gundestrup, C.U. Hammer, S.F. Johnson, P.M. Kristinsdottir, and N. Reeh. 1982. A new Greenland deep ice core. *Science* 218:1273-1277.

[7]Neftel, A., E. Moor, H. Oeschger, and B. Stauffer. 1985. Evidence from polar ice cores for the increase in atmospheric CO_2 in the past two centuries. *Nature* 315:45-47.

Table 1. Sources and sinks of atmospheric methane: various estimates (in Tg/yr).

				IPCC: 1990		IPCC: 1992	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Natural Sources							
Total: Natural Systems: a) - e)	*36.1*	100-300	-	*175*	*116-445*	*150*	*116-300*
a) Wetlands	36.1	-	110	115	100-200	115	100-200
b) Termites	-	-	-	40	10-100	20	10-50
c) Ocean	-	-	-	10	5-20	10	5-20
d) Freshwater	-	-	-	5	1-25	5	1-25
e) CH_4 Hydrate	-	-	-	5	0-100	0	0-5
Anthropogenic Sources							
Fossil Gas Total: a) + b)	80.2	*55-95*	-	*80*	*44-100*	100	70-120
a) Coal mining	-	30-50	-	35	19-50		
b) Natural gas & pet. industry	-	25-45	-	45	25-50		
Paddy Rice Fields	98.4	60-170	100	110	25-170	60	20-100
Animals Total: a) + b)	104.7	*95-135*	75.8	*80*	*65-100*	*105*	*85-130*
a) Enteric fermentation in animals	-	75-100	-	80	65-100	80	65-100
b) Animal wastes	-	20-35	-	-	-	25	20-30
Domestic Sewage Treatment	-	-	-	-	-	25	-
Landfills	35.7	30-70	-	40	20-70	30	20-70
Biomass Burning	-	50-100	-	40	20-80	40	20-80
Total Emission	355.1		500	525	290-965	510	358-825
Sinks							
Reaction with OH	-	-	-	500	400-600	420	340-500
Removal by Soils	-	-	-	30	15-45	30	15-45
Removal by Stratosphere	-	-	-	-	-	10	-
Atmospheric Increase	-	-	-	44	40-48	37	34-40

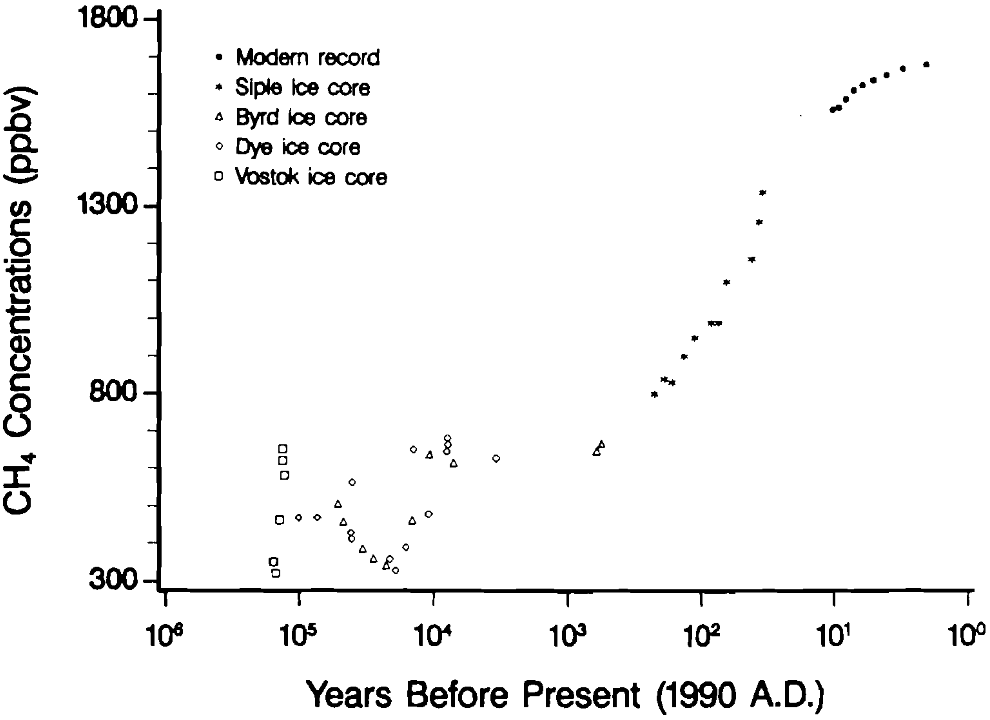
(1) G2S2 (Greenhouse Gas Scenario System), Stockholm Environment Institute, Boston Office, 1991
(2) Hogan, K.B., J.S. Hoffman, and A.M. Thompson. 1991. Methane on the greenhouse agenda. *Nature* 354:181-182.
(3) Lerner, J., E. Matthews, and I. Fung. 1988. Methane emission from animals: a global high-resolution data base. *Global Biogeochemical Cycles* 2(2):139-156.
Matthews, E. I. Fung, and J. Lerner. 1991. Methane emissions from rice cultivation: geographic and seasonal distribution of cultivated areas and emissions. *Global Biogeochemical Cycles* 5(1):3-24.
Matthews, E. and I. Fung. 1987. Methane emission from natural wetlands: global distribution, area and environmental characteristics of sources. *Global Biogeochemical Cycles* 1:61-86.
(4) Houghton, J.T., G.J. Jenkins, and J.J. Ephraums, Eds. 1990. *Climate Change. The IPCC Scientific Assessment.* Cambridge: Cambridge University Press, p. 20: Best Estimate
(5) *Ibid.*: Range of Estimates
(6) *IPCC Report 1992* (Draft Version as at 13/12/1991): Best Estimate
(7) *Ibid.*: Range of Estimates
Italics: Totals by Heilig
\- no data available

Table 2. Historical trends in selected methane-related agricultural activities.

	POPULATION		RICE (PADDY)				CATTLE		SLAUGHTERED MEAT (Beef & Veal)			
			Area Harvested		Production				Slaughtered		Production	
	Total (mill.)	Annual Growth (%)	Total (mill.)	Average Annual Growth (%)	Heads Total (1000)	Average Annual Growth (%)	Heads Total (1000)	Average Annual Growth (%)	Heads Total (1000)	Average Annual Growth (%)	Total (1000)	Average Annual Growth (%)
1961	3,020*		115,484		215,813		944,875		167,981		27,250	
1961-70		2.025		1.579		4.260		1.530		2.201		3.641
1970	3,698		133,130		316,676		1,084,388		204,786		37,819	
1970-80		1.846		0.814		2.315		1.176		0.758		1.486
1980	4,448		144,429		399,201		1,219,793		220,924		43,878	
1980-90		1.737		0.092		2.614		0.475		0.881		1.533
1990	5,292		145,776		518,508		1,279,257		241,283		51,152	

* 1960

Source: FAO. 1991. PC-AGROSTATT Data Base; annual growth rates calculated by author.



Annual atmospheric CH_4 concentrations during the past 160,000 years (derived from ice cores and the NOAA/CMDL flask sampling network).

Figure 1. Increase of atmospheric methane concentration.

Methane influences the atmospheric photochemistry and the earth's radiation budget. Some scientists have estimated that a doubling of present atmospheric methane levels would lead--everything else being equal--to a warming of some 0.61 W/m^2.[8] Presently methane is considered the third most important greenhouse gas, after carbon dioxide and the CFCs.[9,10] However, its overall contribution to the global greenhouse effect has changed during the past decades: Hansen et al. estimated that during the 1950s CH_4 contributed some 28% to the overall greenhouse effect, which made it the second most important trace gas;[11] in the 1980s, however, its contribution declined to some 15%, while the CFCs and N_20 markedly increased their importance (see Figure 2).

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[8]Smil, V. 1987. *Energy, Food, Environment. Realities, Myths, Opinions.* Oxford: Clarendon Press, p. 271.

[9]Houghton, J.T., G.J. Jenkins, and J.J. Ephraums, Eds. 1990. *Climate Change: The IPCC Scientific Assessment.* Cambridge: Cambridge University Press.

[10]Rosswall, T. 1991. Greenhouse gases and global change: International collaboration. *Environ. Sci. Technol.* 25(4):567-583.

[11]Hansen, J.E., A.A. Lacis, and R.A. Ruedy. 1990. Comparison of solar and other influences on long-term climate. In K.H. Schatten and A. Arking, eds. *Climate Impact of Solar Variability; Proceedings of a Conference*, Volume 3086. Greenbelt, MD: Goddard Space Flight Center.

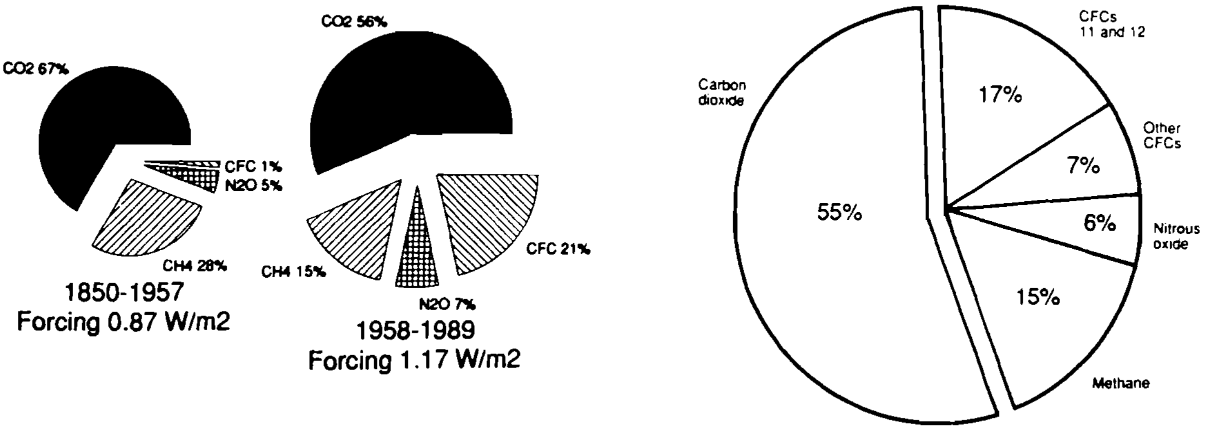

Figure 2. Contribution from greenhouse gases to the changes in radiative forcing: 1950-1957; 1958-1989; 1980-1990. Source: Houghton, J.T., G.J. Jenkins, and J.J. Ephraums, Eds. 1990. *Climate Change: The IPCC Scientific Assessment.* Cambridge: Cambridge University Press.

Recent data indicate that the growth rate of the atmospheric methane concentration declined since 1984 from some 1.3% to 0.75% per year in 1989.[12] (See also Appendix Table A2). If these data are valid, it would pose a serious problem on contemporary theories of methane emission and atmospheric chemistry, since there is no convincing explanation for the decline. There are at least three possible explanations: First, it could be a reduction of methane emission from natural sources, such as natural wetlands. The shrinking of wetlands through hydrological construction and drainage is well documented for Africa[13] and South America.[14] Land reclamation is not the only factor that might change the size and distribution of wetlands. It is also possible that natural conditions, such as changing patterns in precipitation and river discharges, have altered the wetlands. Second, the slow-down in atmospheric methane concentrations could be a consequence of rising abundance of the tropospheric hydroxyl radical (OH), which is the major sink of atmospheric methane. Many experts consider this the most likely cause for declining growth rates in CH_4 concentration. And third, we cannot exclude the possibility that the emission from anthropogenic sources declined (even if this is not very likely). For example, leakages and venting of methane during fossil fuel exploration might have been reduced since the large-scale commercial use of natural gas.

The recent trends in atmospheric methane concentration indicate that much research needs to be done before we can be sure about the basic facts of the global methane

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[12]IPCC Report 1992 (Draft Version).

[13]Howard-Williams, C. and K. Thompson. 1985. The conservation and management of African wetlands. Pages 203-210 in P. Denny, ed. *The Ecology and Management of African Wetland Vegetation.* Dordrecht: Dr. W. Junk Publisher.

[14]Junk, W.J. 1989. *Wetlands of Northern South America.*

balance. This is even more obvious when we study available data on methane emission by various sources.

2. Sources and Sinks of Atmospheric Methane

According to current knowledge there are six major (and several minor) sources of methane emission:

(1) anaerobic decomposition of vegetation in natural wetlands,[15,16]
(2) anaerobic decomposition in paddy rice fields,[17,18,19]
(3) emissions from livestock production systems which include enteric fermentation in animals[20,21] and methane release from animal waste,
(4) biomass burning (including forest and savanna fires, burning of agricultural waste, charcoal production, and firewood combustion),[22,23]
(5) anaerobic decomposition of waste in domestic sewage systems and landfills,[24] and

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[15]Matthews, E. and I. Fung. 1987. Methane emission from natural wetlands: global distribution, area and environmental characteristics of sources. *Global Biogeochemical Cycles* 1:61-86.

[16]Baker-Blocker, A., T.M. Donohue, and K.H. Mancy. 1977. Methane flux from wetland areas. *Tellus* 29:245-250.

[17]Conrad, R. and F. Rothfuss. 1991. Methane oxidation in the soil surface layer of a flooded rice field and the effect of ammonium. *Biology and Fertility of Soils* 12:28-32.

[18]Khalil, M.A.K., R.A. Rasmussen, Ming-Xing Wang, and Lixin Ren. 1991. Methane emissions from rice fields in China. *Environ. Sci. Technol.* 25(5):979-981.

[19]Aselmann, I. and P. Crutzen. 1989. Global distribution of natural freshwater wetlands and rice paddies: their net primary productivity, seasonality and possible methane emissions. *Journal of Atmospheric Chemistry* 8:307-358.

[20]Lerner, J., E. Matthews, and I. Fung. 1988. Methane emission from animals: a global high-resolution data base. *Global Biogeochemical Cycles* 2(2):139-156.

[21]Crutzen, P.J., I. Aselmann, and W. Seiler. 1986. Methane production by domestic animals wild ruminants, other herbivorous fauna, and humans. *Tellus* 38B:271-284.

[22]Delmas, R.A., A. Marenco, J.P. Tathy, B. Cros, and J.G.R. Baudet. 1991. Sources and sinks of methane in the African savanna. CH_4 emissions from biomass burning. *Journal of Geophysical Research* 96(D4):7287-7299.

[23]Andreae, M.O. 1991. Biomass burning in the tropics: impact on environmental quality and global climate change. Pages 268-291 in K. Davis and M.S. Bernstam, eds. *Resources, Environment, and Population: Present Knowledge, Future Options*. New York: Oxford University Press.

[24]Bingemer, H.G. and P.J. Crutzen. 1987. The production of methane from solid wastes. *Journal of Geophysical Research* 92:2181-2187.

(6) natural (fossil) gas losses and venting during fossil fuel exploration and coal mining.[25]

In addition some minor sources are discussed in the literature, such as the methane production of humans, of termites[26] or of the wild herbivorous fauna.[27]

The sources can be grouped into anthropogenic (2) (3) (4) (5) (6) (7) and natural (1) (9) (10) sources. It is also possible to distinguish bacterial (so-called "biogenic") (1) (2) (3) (6) from non-bacterial (pyrogenic) (4) (5) (7) methane. Bacterial methane is considered to contribute some 80 (plus/minus 10%) percent of the total CH_4 emission; non-bacterial methane is believed to contribute the rest. Non-bacterial methane results from thermal alteration of buried organic matter (7) or incomplete combustion of biomass and fossil fuels (4) (5).[28] According to the "best estimate" of the IPCC Committee the contribution of the five major sources of atmospheric methane is as follows: wetlands (23%), animals (21%), coal mining, natural gas and petrochemical industry (20%), flooded rice fields (12%), and biomass burning (8%).

The quantitative details of the global methane balance are highly uncertain. Not even the total annual flux of methane into the atmosphere is precisely quantified. A few years ago Sheppard put the total annual methane emission at 1.21 billion tonnes,[29] while more recent estimates have estimated a contribution of 300 to 700 Tg per year.[30] In 1990 the Intergovernmental Panel on Climate Change (IPCC) calculated a total annual methane emission of 525 Tg; in 1992 the IPCC will publish its most recent estimate of 510 Tg. These IPCC numbers, however, might give a false impression of accuracy. If one took the highest estimates in each emission category the total methane emission would be more than 800 Tg per year; if one would stick to the lowest estimates it would be merely 350 Tg.

There is even greater uncertainty about the contribution of each individual source to the global methane budget. Consider the case of paddy rice fields: In 1990 the IPCC estimated a total annual methane emission of 110 Tg from this source; in 1992 the committee will publish a "best estimate" of 60 Tg. But the range of uncertainty is high: in 1990 the IPCC considered estimates from 25 to 170 Tg per year to be scientifically sound; in 1992 it will publish a range of 20 to 100 Tg. In other words: if we take the

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[25] Quay, P.D., S.L. King, J. Stutsman, et al. 1991. Carbon isotopic composition of atmospheric CH_4: fossil and biomass burning source strengths. *Global Biogeochemical Cycles* 5(1):25-47.

[26] Seiler, W. 1984. Contribution of biological processes to the global budget of CH_4 in the atmosphere. Pages 468-ff in M.J. Klug and C.A. Reddy, eds. *Current Perspectives in Microbial Ecology.* Washington, D.C.: American Society for Microbiology.

[27] Especially caribous, elks, etc.

[28] Quay et al., *op. cit.*

[29] Smil, *op. cit.*

[30] Lerner et al., *op. cit.*

highest estimates from 1990 (170 Tg) and the lowest from 1992 (20 Tg) we would think that recent evidence proves paddy rice fields to be a minor source of global methane emission. If we take the lowest estimate from 1990 (25 Tg) and the highest from 1992 (100 Tg) our conclusion would be that paddy rice is a major source. According to the IPCC committee natural systems (wetlands, termites, ocean, freshwater, and CH_4 hydrate) emit some 150 Tg/yr of methane to the atmosphere--but it could also be twice as much or only half of it according to other serious estimates (see Table 1). The contribution of biomass burning is also highly uncertain: IPCC's best estimate is 40 Tg/yr of methane, but serious estimates range between 20 and 80 Tg per year.

These discrepancies are not only a matter of scientific debate, but of political confrontation. If phytomass decay and biomass burning are considered major sources of methane emission, it would be mostly the Third World which could be blamed for the global methane problem. There we have vast paddy rice fields and widespread "slash and burn" agriculture, large scale charcoal production and firewood consumption.[31] However, if methane ventilation during exploration of fossil fuels, and anaerobic decomposition in land fills and domestic sewage systems are considered major sources of global methane emission, the industrialized North would be in the dock--with its excessive waste production and high fossil fuel consumption.

3. Problems of Estimating Global Methane Emission

While there is not much doubt that the atmospheric methane concentration has been rising since the beginning of the industrial era, much disagreement still exists--as we have seen--on the relative weight of the various sources. Why is it so difficult to validate the estimates?

(1) Anaerobic decomposition in natural wetlands is probably more important than any other single source of atmospheric methane. Unfortunately, less than one would expect is known about their size, type, and geographical distribution. Many wetlands occur in remote and poorly surveyed regions, such as Northern Canada, Siberia, or the Amazon river basins. Another difficulty is the seasonal inundation and drying of small and scattered wetlands in the tropics. The most serious problem, however, is the broad range of wetland-vegetation, which largely determines the specific methane emission rate. Matthews et al. have identified 28 different types of natural wetlands, from low-organic non-forested swamps in the tropics to organic-rich forested bogs in the Northern Hemisphere. Their chemistry, plant species, morphology, vegetation physiognomy and average temperature are responsible for enormous variances in methane emission.

(2) There are reasonably good statistics on the size and distribution of wet rice areas. Some 75 to 80% of the global rice area is harvested from flooded fields. However, the specific rates of methane emission from paddy rice fields vary substantially according to rice plant variety, temperature, fertilizer input, method of cultivation, soil type and

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[31]Malingreau, J.-P. and C.J. Tucker. 1988. Large-scale deforestation in the southeastern Amazon Basin of Brazil. *Ambio* 17:49-55.

season.[32] Methane emissions from Chinese rice fields, for instance, were "found to be 4-10 times higher than emission rates from rice fields in the United States and Europe."[33] At present estimates of specific methane emission rates from paddy rice fields are based on a limited number of test-sites, which can be hardly representative for the global wet-rice agriculture.

(3) The animal population of the world is difficult to assess. While statistics are available on the size of the domestic livestock, much less is known about the wild herbivorous fauna, including (water) buffalo, nondairy cattle, camels, caribou, elks, etc. In addition, not much is known about their specific methane emission rates. They certainly vary between different kinds of animals; but they might also vary greatly with their fodder and living conditions. Methane emission from animal waste is also difficult to assess: It varies with the treatment method of the manure and with the climate.

(4) Surprisingly, methane emission from combustion of biomass can be quantified with somewhat better precision, since there are two independent methods of estimation: First, one can make an inventory of all kinds of biomass burnings, including fires in forests and savannas, and the combustion of fuelwood, charcoal and agricultural wastes. By multiplying the biomass with specific methane emission rates one will get an estimate of the net addition to the global methane balance. The second method is based on slight differences in the chemical structure of methane from different sources: While anaerobic decomposition (sources (1) to (4)) releases CH_4 that is produced by specialized bacteria during anaerobic fermentation; the combustion of biomass produces methane through thermal alteration. There is a factor which clearly distinguishes so-called non-bacterial from bacterial (or "biogenic") methane: the relative content of the ^{14}C Isotope. According to this method the IPCC committee considers the contribution from biomass burning in the upper part of the 20-80 Tg/yr range (see Table 1).

(5) Methane release from landfills can be calculated by estimating the number and size of municipal solid waste deposits, the proportion of degradable organic matter in the waste, and its specific methane emission rate during degradation. Obviously, all three parameters are difficult to assess, since they vary with the dominant type of organic waste and with environmental conditions (temperature, moisture, etc.) of the deposit. In addition, a significant proportion of the methane produced in the waste is oxidized in the cover soil of the landfill before it can emit to the atmosphere. Unfortunately the oxidative capacity varies with the type and thickness of the soil cover. There is also the problem of uncontrolled waste deposits in many parts of the Third World. No statistics are available on their size, location and waste content. On the other hand some highly developed countries have started to recover methane from landfills. It is unclear, however, whether the emission rates from these landfills could be used to calibrate the worldwide estimates. The practice is restricted to a small number of deposits in the

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[32]Lindau, C.W., R.D. DeLaune, W.H. Patrick, and P.K. Bollich. 1990. Fertilizer effects on dinitrogen, nitrous oxide, and methane emissions from lowland rice. *Soil Science Society of America Journal* 54(6):1789-1794.

[33]Khalil et al., 1991, *op. cit.*

northern hemisphere with a certain mixture of waste, specific environmental conditions and waste treatment practices.

(6) Methane is also released to the atmosphere through coal mine ventilation; small amounts are also believed to degas from coal during transport. Methane also leaks from pipelines and wells of oil and natural gas (a major component of which is fossil methane). There is also methane leakage in the processing of fossil fuels by the petrochemical industry. It is somewhat surprising that the statistical data for these sources are so poor (or non-existent). Gas ventilation from coal mines around the world is a technically controlled process, well known for many decades. The quantities of gas extracted from the mines should be known quite precisely--if not only for safety reasons. In some cases mine gas is used (and sold in large quantities) for generating energy. It is hard to understand why the petrochemical industry is not able or willing to precisely quantify methane venting and leakages.

(7) A few years ago there was a vigorous debate on the contribution of termites to the global methane budget. It was estimated that these insects could emit up to 100 Tg per year--which would have been much more than what is now considered the emission from paddy rice fields. Based on recent studies[34] the annual emission from termites was scaled down to some 20 Tg (see Table 1). However, as everyone can understand, it is extremely difficult to estimate methane emission of termites--no one has ever counted these animals or will be able to do so.

(8) Under certain conditions water can freeze around smaller gas molecules (such as methane, propane, carbon dioxide and others), building a cage-like structure. This material is called gas clathrate (or "hydrate").[35] When the clathrates melt, the captured gas can emit to the atmosphere. Methane emission due to release of old CH_4 from hydrate destabilization is currently considered a minor source (0-5 Tg). Gas clathrates can be found in deep oceans and in the Siberian permafrost.[36] Not much is known about the size and distribution of these reserves, but according to some estimates the resources could be gigantic. Conservative estimates indicate that "there is perhaps twice as much energy in hydrated form as in all other hydrocarbon sources combined".[37] There is speculation that if the reserves of natural methane hydrates would melt (due to extreme global warming, for instance) the earth's atmosphere could change dramatically--becoming a Jupiter-like CH_4 atmosphere. On the other hand this speculation is

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[34]Khalil, M.A.K., R.A. Rasmussen, J.R.J. French, J.A. Holt. 1990. The influence of termites on atmospheric trace gases: CH_4, CO_2, $CHCl_3$, N_20, CO, H_2 and light hydrocarbons. *Journal of Geophys. Research* 95D:3619-3634.

[35]Sloan, D.E. 1991. Natural gas hydrates. *JPT*, pp. 1414-1417 (December 1991).

[36]MacDonald, G.J. 1989. The near- and far-term technologies, uses, and future of natural gas. Pages 509-535 in *OECD, International Energy Agency: Energy Technologies for Reducing Emissions of Greenhouse Gases.* Proceedings of an Expert's Seminar, Paris, 12-14 April 1989.

[37]Sloan, *op. cit.*

contradicted by the fact that the atmosphere was not changed permanently during the "warm periods" in earth's history.

4. Projections of Global Methane Emission

There are three types of uncertainties in projecting future trends of global methane emission: First, there is a lack of scientific knowledge concerning the identification and quantification of current methane sources, sinks, and chemical mechanisms in the atmosphere. Second, there are uncertainties associated with possible technological advances, such as improvements in paddy rice production, livestock management, domestic sewage treatment, or waste recycling. Third, it is extremely difficult (if not impossible) to predict changes in human behavior, such as life style change, social restructuring, economic reform, and political revolution.

If anthropogenic methane sources would grow proportional to population, one could use population projections to estimate future trends in methane emission. Unfortunately, things are more complicated. Consider the following examples:

- Between 1980 and 1990 the worldwide paddy rice area (which is a major source of atmospheric methane) stagnated at an average annual growth rate of 0.09%, while the population increased by 1.74% per year and rice production grew by 2.61% annually (see Table 2). This was possible, because paddy rice areas doubled their productivity. In 1961 about 115,484 million hectares were needed to produce 215,813 million tons of rice; today only 145,776 million hectares are required to grow 518,508 million tons. If this trend continues, future methane emission from paddy rice areas would increase only slightly or even decline, despite rapid population growth and a substantial increase in rice production.

- Meat production, the second most important source of anthropogenic methane in the atmosphere, also became more efficient during past decades: In 1961 some 168 million animals had to be raised and slaughtered to produce 27 million tons of meat (beef and veal). By 1991 the meat production had nearly doubled (51 million tons), but the number of slaughtered animals only increased to 241 million. Since 1961 population growth rates were consistently higher than the increase in the total number of cattle (see Table 2). Between 1980 and 1990, for example, the number of cattle nearly stagnated (at an average annual growth rate of 0.48%) while the population increased by 1.74% annually and the worldwide production of beef and veal grew by 1.53% per year.

- Projections of future trends in agricultural land use and food production, which are based on detailed FAO food demand projections, also reject a simple proportional relationship between population growth and methane emission. In 1988 the FAO published an assessment of world food and agricultural prospects to the year 2000 *(World Agriculture Toward 2000).*[38] According to this study the paddy rice area of 93 developing

[38]Alexandratos, N., Ed. 1988. *World Agriculture: Toward 2000. An FAO Study.* London: Belhaven Press.

countries would only increase from 105 million hectares in 1982/84 to 120 million hectares in the year 2000. This would be equivalent to an annual growth rate of just 0.8%. The FAO also estimated that livestock numbers in these 93 developing countries would increase between 1.0% (cattle and buffalo) and 2.8% (poultry) annually. This would be a significant slow-down as compared to the period from 1961-63 to 1983-85 when average annual growth rates ranged between 1.2% and 4.3%, respectively.

- And finally we have estimates of future trends in deforestation, which is a source of methane emission due to associated biomass burning. In its most recent tropical forest assessment, the Food and Agricultural Organization estimated that, on average, 16.9 million hectares of tropical forests were cleared annually from 1981 to 1990.[39] Clearing rates increased from 13.2 million hectares in 1980 to 20.8 million hectares in 1990. In its 1992 greenhouse gas scenarios the IPCC assumes that between 1990 and 2025 on average between 12.0 (scenario IS92d) and 20.7 (scenario IS92f) million hectares will be cleared annually. Between 2025 and 2100 the average area cleared per year is predicted to range from only 3.1 (scenario IS92d) to 12.8 (scenario IS92f). For obvious reasons deforestation rates will decline; and consequently there will be a reduction in methane emission from this source.

These trends indicate that a decline in per caput methane emission during the next decades is very likely. The critical question is whether, and to what extent, the decline will be offset by population growth.

The Intergovernmental Panel on Climate Change (IPCC) has only recently published a projection of greenhouse gases, including CH_4. The panel defined five scenarios which combine various assumptions on population growth, economic activity, energy efficiency and technological advances. There were also several assumptions on future trends in deforestation.[40] In addition three different demographic projections were used: the 1991 World Bank projection, the United Nations medium/low variant, and the UN medium/high variant long-term projections. Table 3 gives the total population for 2025 and 2100, as well as average annual growth rates that were used in the calculation of the scenarios.

By 2100 global annual methane emission is projected to range between 546 (scenario IS92c) and 1,168 (scenario IS92f). In scenario IS92c current emissions would only slightly increase from 506 Tg to 589 Tg in 2025 at an annual growth rate of 0.43%. By 2100 the annual methane emission would decline to 546 Tg. This would be equivalent to a near stagnation of methane emission during the next century at average annual growth rates of 0.07% (for 1990-2100). However, according to the more pessimistic IPCC scenario IS92f the global methane budget could be severely set off balance: in this scenario the committee expects annual methane emission to more than double by 2100. Average

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[39]FAO. 1991. *Second Interim Report on the State of Tropical Forests.* 10th World Forestry Congress, Paris. See also: FAO. 1991. *Forest Resources Assessment 1990 Project.* Forestry N. 7. Rome.

[40]For details of scenario assumptions see: Intergovernmental Panel on Climate Change (IPCC). 1992. *1992 IPCC Supplement.* Draft Version, February.

Table 3. Selected results of 1992 IPCC greenhouse gas scenarios: global methane (CH_4) emission.

	POPULATION						METHANE EMISSION									
	World Bank		UN Medium/Low		UN Medium/High		Scenario IS92a/b		Scenario IS92c		Scenario IS92d		Scenario IS92e		Scenario IS92f	
	Total (mill.)	Average Annual Growth (%)	Total (mill.)	Average Annual Growth (%)	Total (mill.)	Average Annual Growth (%)	Total (Tg)	Average Annual Growth (%)	Total (Tg)	Average Annual Growth (%)	Total (Tg)	Average Annual Growth (%)	Total (Tg)	Average Annual Growth (%)	Total (Tg)	Average Annual Growth (%)
1990	5,297		5,262		5,327		506		506		506		506		506	
1990-2025		1.352		1.0470		1.635		0.754		0.4339		0.4096		0.894		0.914
2025	8,504		7,591		9,444		659		589		584		692		697	
2025-2100		0.379		-0.224		0.829		0.440		-0.101		-0.039		0.583		0.688
2100	11,300		6,415		17,592		917		546		567		1,072		1,168	
1990-2100		0.688		0.1801		1.086		0.540		0.0691		0.1034		0.682		0.760

Scenarios IS92a/b and IS92e are based on the World Bank 1991 population projection; scenarios IS92c and IS92d are based on the UN medium/low case projection; and scenario IS92f is based on the UN medium/high case population projection. For details of scenario assumptions see: IPCC. 1992. Table 1, p. 14.
Compiled from: Intergovernmental Panel on Climate Change (IPCC). 1992. *1992 IPCC Supplement*, February; and United Nations. 1991. *World Population Prospects 1990*. New York.

annual growth rates of methane emission would only lightly decline from 0.91% (for the period between 1990 to 2025) to 0.69 (between 2025 to 2100) (see Table 3).

An interesting result of the IPCC calculation is the minor change in projected annual methane emission for the next decades, as compared to the enormous range of uncertainty in the base data. Serious estimates of the global annual methane emission for 1990 range between 358 and 825 Tg (see Table 1); the high estimate is some 2.3 times higher than the low estimate. On the other hand IPCC's projection scenarios for the year 2025 (based on the average estimate of 506 Tg in 1990) range between 584 and 697 Tg; they differ by a factor of only 1.2 (see Table 3). This gives the impression that estimates of global methane emission become more precise when projected into the future. Of course, one could use both the high and the low (rather than the "best") estimate of current methane emission estimates; but then the exercise would become rather meaningless. It would produce absurd predictions, ranging from negligible to gigantic annual emissions.

The fact that predicted changes in methane emission by the year 2025 are well within the range of uncertainty of current quantification, explains why all projections have to be used with extreme care. It also explains why it is probably more important to validate current emission rates than to develop highly sophisticated projection models.

5. Contribution of Population Growth to Methane Emission

Future trends in global methane emission are a product of two factors: (1) population growth and (2) average per caput emission rates--which represent the combined net-effect of technological advances and expansion of anthropogenic methane sources due to life style changes. We have used a simple decomposition method for quantifying the contribution of population growth to the global methane balance, based on the IPCC methane projections.

- First we calculated average per caput emission rates according to the five IPCC scenarios (see Table 4). In 2025 they will range between 73.8 (IS92f) and 81.4 kg per person (IS92e). By 2100 the average per caput methane emission could decline to 66.4 kg (IS92f) or increase to 94.9 kg (IS92e) according to scenario.

- In a second step we calculated total methane emission by assuming constant 1990 population, but projected per caput methane emission rates. According to the IPCC scenario IS92f total methane emission was projected to reach 697 Tg in 2025. However, at constant 1990 population, the emission would be only 393 Tg. In other words: population growth would increase the global methane balance by 230 percent. In 2025 the contribution of population growth to global methane emission ranges from 44 to 77 percent. In 2100 the demographic component could reach 230 percent or decline to 22 percent-- according to scenario (see Table 5).

Table 4. Projected methane emission, projected population, and per caput methane emission between 1990 and 2100 according to the 1992 IPCC greenhouse gas scenarios.

	Scenarios IS92 a/b			Scenario IS92 c			Scenario IS92 d			Scenario IS92 e			Scenario IS92 f		
	CH_4 Project. (Tg)	Popul. Project. (mill.)	Per Caput Emiss. (kg)	CH_4 Project. (Tg)	Popul. Project. (mill.)	Per Caput Emiss. (kg)	CH_4 Project. (Tg)	Popul. Project. (mill.)	Per Caput Emiss. (kg)	CH_4 Project. (Tg)	Popul. Project. (mill.)	Per Caput Emiss. (kg)	CH_4 Project. (Tg)	Popul. Project. (mill.)	Per Caput Emiss. (kg)
1990	506	5,297	95.5	506	5,262	96.2	506	5,262	96.2	506	5,297	95.5	506	5,327	95.0
2025	659	8,504	77.5	589	7,591	77.6	584	7,591	76.9	692	8,504	81.4	697	9,444	73.8
2100	917	11,300	81.2	546	6,415	85.1	567	6,415	88.4	1072	11,300	94.9	1,168	17,592	66.4

Scenarios IS92a/b and IS92e are based on the World Bank 1991 population projection; scenarios IS92c and IS92d are based on the UN medium/low case projection; and scenario IS92f is based on the UN medium/high case population projection. For details of the IPCC scenario assumptions see: IPCC. 1992. Table 1, p. 14.

Table 5. Estimated contribution of population growth to the increase in CH_4 emission between 1990 and 2100 according to the 1992 IPCC greenhouse gas scenarios.

	Scenarios IS92 a/b			Scenario IS92 c			Scenario IS92 d			Scenario IS92 e			Scenario IS92 f		
	Actual Project. (Tg)	Const. Popul. (Tg)	Contrib. of Pop. Growth (%)	Actual Project. (Tg)	Const. Popul. (Tg)	Contrib. of Pop. Growth (%)	Actual Project. (Tg)	Const. Popul. (Tg)	Contrib. of Pop. Growth (%)	Actual Project. (Tg)	Const. Popul. (Tg)	Contrib. of Pop. Growth (%)	Actual Project. (Tg)	Const. Popul. (Tg)	Contrib. of Pop. Growth (%)
1990	506	-	-	506	-	-	506	-	-	506	-	-	506	-	-
2025	659	411	60	589	408	44	584	405	44	692	431	61	697	393	77
2100	917	430	113	546	448	22	567	465	22	1,072	503	113	1,168	354	230

Scenarios IS92a/b and IS92e are based on the World Bank 1991 population projection; scenarios IS92c and IS92d are based on the UN medium/low case projection; and scenario IS92f is based on the UN medium/high case population projection. For details of the IPCC scenario assumptions see: IPCC. 1992. Table 1, p. 14.

However, this simple method of calculating the contribution of population growth to future methane emission is not without problems. Future population growth will mainly occur in the Third World, while per caput methane emission rates might be highest in the more developed countries. In this case it would be necessary to disaggregate and to calculate the contribution of population growth separately for more and less developed regions. The contribution of population growth to methane emissions on the regional level would be very different from the global average. This is typical for CO_2 emissions, for instance, where extremely low per caput rates in Third World countries have to be combined with very high rates of population growth, while very low population growth occurs in regions with extremely high per caput emission of carbon dioxide.

There is, in fact, an interhemispheric difference in atmospheric methane concentrations which suggests that methane sources are not distributed equally around the globe. The concentration is significantly lower at the equator and across the entire southern hemisphere. There seem to be significant methane sources in the high northern latitudes (50° to 80° north)--probably natural wetlands and sources associated to oil and natural gas wells and coal mines.[41] These emissions could be associated to industrialized countries.

On the other hand the largest methane sources seem to be located between 30° and 40° north where we also find many developing countries (see Figure 3). Contrary to carbon dioxide, methane is not primarily emitted from the production and consumption sectors of affluent societies. It could rather be called the "poor man's greenhouse gas", since major sources of atmospheric methane are in developing countries with high population growth. China and India, for instance, account for 52% of the world's harvest area of paddy rice; India, Africa and Latin America are home to large numbers of cattle. There are developing countries with large natural wetlands, such as the Congo or Brazil; and biomass burning, such as forest fires, fuelwood burning and charcoal production is typical for the African savannas and Latin American forest areas.

While the precise geographic distribution of methane sources is still highly uncertain, one can at least assume a fairly homogenous distribution among countries with high and low population growth. In any case, however, methane sources are geographically much more balanced than the sources of carbon dioxide emission. Therefore it is acceptable to use global estimates for calculating the contribution of population growth to future methane emission.

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[41]Yavitt, J.B. 1992. Methane, biogeochemical cycle. Pages 197-207 in W.A. Nierenberg, ed. *Encyclopedia of Earth Systems Science,* Volume 3. San Diego: Academic Press.

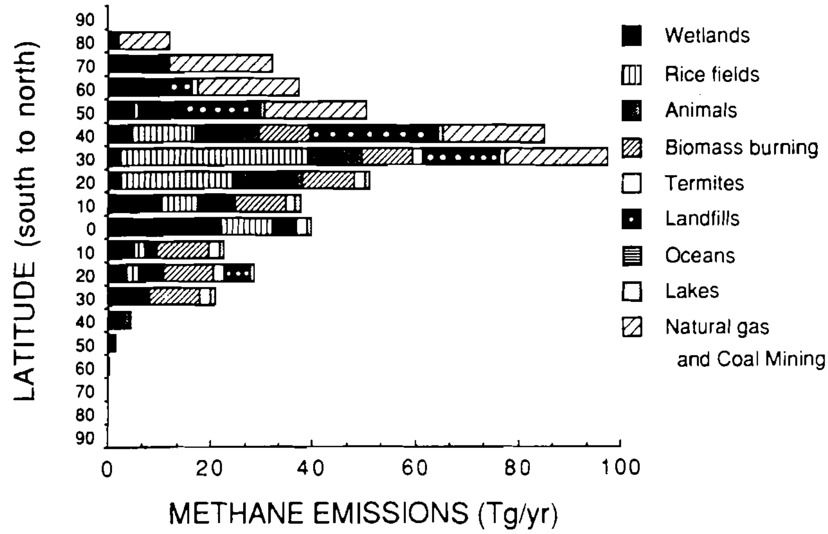

Figure 3. Latitudinal distribution of methane emissions from individual sources. Source: Yavitt, J.B. 1992. Methane, biogeochemical cycle. Pages 197-207 in W.A. Nierenberg, ed. *Encyclopedia of Earth Systems Science,* Volume 3. San Diego: Academic Press.

6. Options for Reducing Methane Emission

In its recent report the Intergovernmental Panel on Climate Change (IPCC) concluded that global methane emissions would have to be reduced by only 15-20 percent to stop the rising of its atmospheric concentration.[42] Given the enormous potential of reduction, this should be an easy target to reach. A United States/Japan IPCC working group for the assessment of technological options for reducing methane emissions from anthropogenic sources found that most emissions could be reduced by between 30 and 90 percent.

(1) The easiest method to stabilize or reduce methane emission from agriculture is to increase yields. By using high yield rice varieties and modern agricultural inputs (such as fertilizers, pesticides, etc.) farmers could significantly increase rice production without expanding the area harvested. This is precisely what has happened in China during the past 15 years: its tripling of rice production within two decades was achieved primarily by agricultural modernization--not by an expansion of wet-rice areas, which are a major source of methane. We also have to see that Africa's and South Asia's livestock are remarkably under-utilized: several African countries have more cattle than people, but their milk or meat production is a tiny fraction of what is typical in China, Western Europe or Northern America. One could probably reduce livestock in Africa and India (and thus reduce methane emission from enteric fermentation in animals) while at the same time increase the supply of dairy products and red meat in these regions.

[42]IPCC, *op. cit.*, pp. 45-46.

(2) Even if it would be necessary to expand the rice areas in some parts of the Third World to feed the growing population, the overall methane emission from this source could decline as a result of selective expansion and advanced management of flooded rice fields. The range of methane emissions from rice paddies is enormous: it can be as low as 8 $gm^{-2}yr^{-1}$ (gram per square meter per year) (as measured in Thailand) but also as high as 170 $gm^{-2}yr^{-1}$ (TuZu Szechuan Province, China). Hence, it is very important which rice fields are expanded to meet the growing demand. If one would expand only low-emission rice paddies (and reduce the high-emission areas), the global methane emission from this source would most likely decline. But there is still another option. We know that the emission of methane from flooded rice fields varies significantly with cultivation methods. A slight change in the agricultural practices, such as not putting straw into the flooded field, could dramatically reduce emission rates.

(3) In addition to introducing technology which reduces methane emission, we could change our behavior. For example, we could change our food preferences--as we have done several times in history. We might switch from rice to wheat, and from red meat to fish. There are signs that this is already the case in some parts of the world. In Northern India a clear trend to wheat instead of rice consumption can be observed, and meat consumption in Northern America and Western Europe is stagnating or even declining.

(4) The "positive" link between population growth and methane emission is partly balanced by a "negative" feedback. Let us assume for a moment that Third World population growth would require a large expansion of agricultural areas. This could only be done by using marginal land, such as steep slopes, forests--or natural wetlands. Natural wetlands, however, are most likely the largest source of atmospheric methane. If they shrink, their methane emission will decline. In Egypt, for instance, a large swampy area at the Upper Nile is presently converted into one of the country's largest cropping areas. As population grows, more and more natural wetlands are converted into agricultural areas or used for settlements and infrastructure (such as highways, railroads, airports, etc.).

(5) The burning of tropical rain forests can be stopped. Forest fires are mainly due to (a) primitive methods of clearing for agriculture, (b) ruthless logging practices, (c) natural resource exploration, and (d) real estate speculation.[43] None of these practices is inevitable. Slash-and-burn agriculture, which is practiced by some 200 million people worldwide,[44] became environmentally devastating when rotation periods declined and larger plots had to be cleared to meet the growing food demand of indigenous farmers. However, the additional food demand could have been easily met if these populations had switched to more advanced agricultural techniques. The increasing environmental impact of slash-and-burn agriculture is a sign of agricultural and social stagnation. Especially in Brazil more than enough land outside the tropical forests would be available

[43]The periodic forest fires in the South of France, Spain, and Greece are well known methods for transforming "worthless" forests into exorbitantly priced real estate.

[44]Andreae, *op. cit.*

for the rural population if the arable land was distributed more equally among the farmers.

(5) Fires in tropical savannas, which are a significant source of atmospheric methane in Africa, are almost all set by humans in order to prepare the land for cattle ranging or hunting. In tropical Africa some 9.22 Tg/yr of CH_4 is emitted through biomass burning --including forest fires (0.9 Tg/yr), firewood combustion (0.65 Tg/yr), charcoal production (2.31 Tg/yr) and bush fires in savanna zones (4.14 Tg/yr).[45] According to these estimates by Delmas et al., tropical Africa would contribute some 23 percent to the global methane emission from biomass burning; some 45% of these fires would be in the vast African savanna. Hao et al. have estimated that about 750 million ha of savanna area are burned each year--34 times the area burned in tropical rain forests (22 million ha/yr).[46] The periodic burning is to prevent the grassy savanna from being overgrown by shrubs and bushes, which would turn it into chaparral or forest, unsuitable for grazing.[47] It was also observed that fires were set to facilitate hunting. Neither reason is acceptable. The nomadic African cattle rangers consider cattle a matter of tradition and prestige, rather than a means of efficient food supply. While this region has one of the highest man-cattle ratios, it has one of the lowest meat and milk production in the world. A slight improvement of livestock management (such as keeping the cattle in a barn and feeding it with efficiently grown grass) could dramatically increase animal food production in these areas, which would easily meet the growing demand due to population growth.

(6) An important option to reduce methane emission in less developed countries is the introduction and broad acceptance of new energy sources. This could reduce methane emission from firewood and animal waste combustion. In principle, there is a broad range of alternative energy resources available which would emit much less methane--ranging from conventional hydropower or (efficiently burned) fossil fuels to solar energy and bio-gas. Probably the most important source of "clean" energy is also the cheapest and easiest to implement: energy conservation. If one could stop the senselessness of burning wood in open fires for cooking and heating, one could save enormous amounts of firewood. Manibog has calculated that closed fires in simple stoves are up to 22 times more energy efficient than open fires.[48]

However, despite great efforts to implement new energy-saving technologies, the majority of firewood collectors in Africa, Asia and Latin America still waste considerable amounts of energy by not using efficient ovens. While environmentalists are apt to criticize the

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[45]Estimates by: Delmas et al., *op. cit.*

[46]Hao, Wei-Min, Mey-Huey Liu, and P.J. Crutzen. 1990. Estimates of annual and regional releases of CO_2 and other trace gases to the atmosphere from fires in the tropics, based on FAO statistics for the period 1975-1980. Pages 440-462 in J.G. Goldammer, ed. *Fire in the Tropical Biota: Ecosystem Processes and Global Challenges.* Berlin: Springer Verlag.

[47]Andreae, *op. cit.*

[48]Manibog, F.R. 1984. Improved cooking stoves in developing countries. *Annual Review of Energy* 9:199-227.

waste of energy in industrialized countries, they are often blind to the substantial energy wasting practices in the Third World. No one is too poor to build a simple but energy efficient stove from stones. Awareness of the problem, good-will and behavioral flexibility could substantially reduce the combustion of firewood and thus methane and CO_2 emissions from this source.

(7) Methane losses in the petrochemical industry, methane ventilation from coal mines and methane degasses from coal during transport can be reduced substantially. The emission from these sources is primarily due to technological inefficiency, which in turn depends on the lack of investment capital and know-how, lousy maintenance of equipment, poor monitoring of production processes, and--rather simply--a lack of "good-will" among those responsible. It is well documented that simple and cost-efficient measures could substantially reduce methane emission from these sources. Even if population growth (and spreading industrialization) would require an increase in fossil fuel exploration, the total methane emission from these sources could decline in absolute terms due to better technology and intelligent process design.

The above mentioned IPCC expert group tried to quantify the various options for curbing methane emission.[49] They found that by 1995 to 2005 it would be possible to reduce CH_4 emissions from coal mining and landfills by up to 90%. A significant proportion of this reduction could be achieved with available "low-tech" options. Methane emissions from animal waste and sewage systems could be reduced by up to 80% in the near future (before 1995). This would also partly be possible with simple technologies. CH_4 emission from ruminants could be reduced by up to 75% and even emissions from flooded rice fields could decline by up to 30%. This, however, would take some time to be realized, since it partly would require the development of advanced technologies. Primarily by stopping the waste of fuelwood one could decrease methane emission from biomass burning by between 20 and 80 percent.

7. Economic, Social and Political Restrictions

There is a scientific consensus that it would be possible to reduce the methane emission from virtually all anthropogenic sources. Why then is it still so difficult to stop the emission of this dangerous greenhouse gas?

Lack of information can be one reason. People (and governments) might not be aware of the problem; they might not know of emission-reducing technologies; they could have a lack of technical expertise for implementation and maintenance, or they might be just ignorant and shortsighted. Access to information and education is a key variable of solving the methane problem.

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[49]IPCC, *op. cit.*

Availability of capital is another critical factor. Some anthropogenic sources of atmospheric methane can be reduced only with expensive measures.[50] To prevent impoverished farmers from burning down tropical forests for agriculture requires substantial investments: the governments would have to provide long-term alternatives, such as non-agricultural employment, land-reforms, direct subsidies, etc. Consider the problem of methane ventilation from coal mines and oil wells. Even if a company (or government) is aware of the environmental impact of this practice, even if the technology for collecting the gas is well known and easily available, it could be impossible to finance it.

Sometimes everything seems to be ready for action: we know what we should do, we have the technology, and capital is available. Yet nothing happens. It is a lack of political leadership and administrative competence combined with resistance from various interest groups which hinders the implementation of necessary measures to protect our atmosphere. This situation can be frequently found in the Third World as well as in industrialized countries. Actually, it is a phenomenon well known to politicians, social scientists and the general public. Natural scientists, however, seem to have difficulties to understand that the increase of trace gases in the atmosphere is mainly a social, political and economic problem. Their climate models use scenarios which are often rather unrealistic because they assume that critical parameters can be changed quickly. This is also true for the global methane problem. One can easily demonstrate that certain measures would drastically reduce methane emission from anthropogenic sources. This option, however, is irrelevant as long as one does not specify the political and social processes which are necessary for collective action. Amitai Etioni, a organizational and political sociologist, has demonstrated some of the prerequisites of an "active society": Among other things it would be essential that there are certain social and political institutions to increase awareness of a problem (such as a "free press"), mobilize support ("pressure groups"), canalize conflicts ("independent jurisdiction"), generate capital ("market economy") and efficiently implement and control measures of the government ("administration"). All this is usually excluded from environmental research, making it a sterile exercise in data gathering and model building.

9. Conclusion

(1) Methane (CH_4) is a powerful greenhouse gas. It affects the earth's radiative balance by being oxidized to CO_2. It is also important for the atmospheric chemistry since it controls the abundance of ozone (O_3) and the hydroxyl radical (OH) (which in turn affects the lifetime of other greenhouse gases, such as the HCFCs). According to IPCC estimates methane contributed some 15% to the changes in radiative forcing from 1980 to 1990.

(2) The concentration of methane in the atmosphere is still extremely minute (around 1.7 ppmv); but the gas has been accumulating in the atmosphere at the rate of 1% per

[50]Nordhaus, W. 1990. Greenhouse economics, count before you leap. *The Economist*, July 7, pp. 19-22.

year. Today the methane concentration is about double that in the preindustrial era (of some 0.8 ppmv).

(3) During the 1980s the growth rate of atmospheric methane concentration has slowed down--from 1.3% per year in the late 1970s to some 0.75% in 1989. There is no generally accepted explanation for this decline.

(4) About two-thirds of the global methane emission to the atmosphere is man-made. Fossil gas leakages from coal mines and oil wells, rice cultivation on flooded fields, livestock production systems, and biomass burning are the four most important anthropogenic sources of atmospheric methane.

(5) The increase of methane in the atmosphere is not inexorable. With appropriate technical and organizational measures the global methane emission could be stabilized or even reduced, despite high population growth in the Third World. It all depends on certain intermediate variables, which range from social and political conditions to economic practices and technical measures.

(6) Probably the most significant intermediate variable for controlling methane emissions is the level of technology. There is abundant evidence that methane emission rates from all anthropogenic sources can be dramatically reduced by existing technologies. The range of possible reduction is often several orders of magnitude higher than the projected increase. For example, burning methane from coal mines in power generators instead of just blowing it into the air would not only reduce the direct emission, but also save other sources of energy.

(7) Lifestyles are key factors. Food preferences will fundamentally influence the global methane budget. A worldwide adoption of American or (East) European diets could lift methane (and CO_2) emission to soaringly high levels. In fact it is rather unlikely that such a diet could be sustained for some 5.5 billion people, not to speak of the projected 12 or 14 billion. But this is not pure fate. Many people in the industrialized world have already reduced their consumption of red meat and milk products. There is also no need for Asian populations to stick to their monotonous diet of rice (which is predominantly produced on methane-emitting flooded fields). They could increase consumption of wheat products, roots and tubers, vegetables and fish.

(8) Technical know-how, awareness of the problem, and good-will--both among political leaders, administrators and the general public--are essential to minimize future methane (and CO_2) emissions. With clever agricultural practices methane emissions from flooded rice fields could be minimized without large investments or highly advanced technology; better livestock and animal-waste management would not only reduce methane emission but also utilize the gas from manure tanks for energy generation; a significant reduction of methane emission could be achieved by stopping the senseless blowing of natural gas from coal mines and oil wells into the air or burning firewood in open fires.

(9) Contrary to carbon dioxide, methane is not primarily emitted from the production and consumption sectors of affluent societies. There are significant sources of atmospheric methane in developing countries, where high population growth is projected

for the next decades. According to the most recent IPCC projections the anthropogenic emission of methane to the atmosphere would stagnate or even decline, if the population would stabilize at its 1990 level. In other words, Third World population growth is a key factor of future methane emission. By the year 2025 (Third World) population growth could increase methane emission by between 22 and 230 percent, as compared to a constant 1990 population.

(10) Methane is an attractive target for controlling the greenhouse effect. First, there would be a fast response to emission cutbacks, since the gas has a relatively short lifetime in the atmosphere of only some 11 years. Second, it would require the reduction of only 15-20 percent of total methane emission to stop the atmospheric increase of this greenhouse gas. Only recently it was estimated that reductions in methane emission "would be 20-60 times more effective in reducing the potential warming of the earth's atmosphere over the next century than reductions in CO_2 emissions".[51,52] Even very modest measures, such as reducing natural gas leakage in half, would be sufficient to stabilize the current CH_4 concentration in the atmosphere.

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[51]Hogan, K.B., J.S. Hoffman, and M. Thompson. 1991. Methane on the greenhouse agenda. *Nature* 354:181-182.

[52]Yavitt, *op. cit.*

APPENDIX

Appendix Table A1. Atmospheric methane from ice cores: selected measurements.

Year	CH_4-Concentration in ppmv	Range of successive Measurements	Source
1956	1.34	0.08	4b
1955	1.30	0.07	4a
1954	1.26	0.08	4b
1950	1.18	0.07	4a
1949	1.16	0.08	4b
1940	1.11	0.07	4a
1927	1.10	0.07	4b
1925	1.02	0.06	4a
1919	1.00	0.07	4a
1917	0.99	0.06	4b
1907	0.99	0.06	4b
1893	0.87	0.07	4a
1882	0.90	0.08	4a
1861	0.83	0.07	4a
1857	0.90	0.06	4b
1849	0.89	0.08	4a
1834	0.86	0.07	4a
1827	0.83	0.06	4b
1818	0.95	0.06	4b
1804	0.73	0.08	4a
1804	0.84	0.06	4b
1771	0.78	0.09	4a
1771	0.80	0.06	4b
Years before present			
550	0.667	0.025	2
600	0.647	0.025	2
3,400	0.627	0.025	3
7,100	0.615	0.025	2
7,700	0.663	0.030	3
7,800	0.680	0.027	3
7,900	0.645	0.037	3
10,600	0.638	0.025	2
10,800	0.477	0.025	3
14,000	0.650	0.032	3
14,300	0.460	0.025	2
16,000	0.389	0.032	3
19,000	0.327	0.030	3

21,000	0.358	0.041	3
22,400	0.341	0.027	2
27,900	0.360	0.025	2
33,500	0.385	0.025	2
39,800	0.561	0.031	3
40,500	0.411	0.032	3
41,000	0.427	0.033	3
46,600	0.457	0.027	2
51,100	0.505	0.031	2
73,000	0.468	0.025	3
100,000	0.468	0.025	3
127,800	0.68	0.04	1
131,100	0.62	0.02	1
132,400	0.65	0.04	1
138,800	0.46	0.03	1
149,100	0.32	0.03	1
153,600	0.35	0.01	1
157,300	0.35	0.04	1

Sources:

1 Soviet Antarctic Expedition at Vostok

2 U.S. Cold Regions Research and Engineering Laboratory at Byrd Station

3 Greenland Ice Sheet Program

4a Polar Ice Coring Office (Nebraska) and the Physics Institute at the University of Bern at Siple Station: dry extraction

4b Polar Ice Coring Office (Nebraska) and the Physics Institute at the University of Bern at Siple Station: vacuum melt extraction

Appendix Table A2. Atmospheric methane: global averages.

Year	CH_4-Concentration in ppmv (1)	CH_4-Concentration in ppmv (2)
1962		1.354
1965		1.386
1966		1.338
1967		1.480
1968		1.373
1969		1.385
1970		1.431
1971		1.436
1972		1.500
1973		1.624
1974		1.596
1975		1.541
1976		1.490
1977		1.471
1978		1.531
1979		1.545
1980	1.562*	1.554
1981	1.568	1.569
1982	1.590	1.591
1983	1.614	1.615
1984	1.627	1.629
1985	1.642	1.643
1986	1.654	1.656
1987	1.672	1.673
1988	1.683**	1.697

Source:

(1) The global average is based on 7 sampling sites: Barrow (Alaska, USA); Cape Grim (Tasmania, Australia); Cape Kumukahi (Hawaii, USA); Cape Matatula (American Samoa); Cape Meares (Oregon, USA); Mauna Loa (Hawaii, USA); South Pole (Antarctica)[53]

(2) Data 1962-1978: Khalil, M.A.K. and R.A. Rasmussen. 1982. Secular trends of atmospheric methane (CH_4). *Chemosphere* 11:877-883.

* August-December 1980

** January-September 1988

[53]For details of the calculation of the average see: Boden et al., *op. cit.,* pp. 144-145.