BOSTON UNIVERSITY

Center for Energy and Environmental Studies

Working Papers Series

Number 9504 **October 1995**

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Estimates of Global Anthropogenic Methane Emissions 1860-1993

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ABSTRACT

This paper provides the first time series estimates of global anthropogenic methane emissions from the mid-19th century to the present. Our purpose is to provide time series estimates of anthropogenic methane emissions for global climate models estimated or calibrated using historical time series data. Previous estimates of methane emissions include "top-down" (deconvolution) estimates of total emissions, estimates of global anthropogenic emissions for the 16th century, and various estimates of anthropogenic and natural emissions in the 1980s and 1990s. This study uses previously published point estimates for the 16th century and the 1980s and early 90s and a variety of historical time series of proxy variables to estimate a time series of global anthropogenic methane emissions. We find that anthropogenic methane emissions have increased from about 80 million tonnes per annum in 1860 to close to 380 million tonnes today. The relative importance of various activities in generating methane emissions has changed over time and continues to change. The rate of increase now may be slowing. A comparison with the estimates generated by Khalil and Rasmussen suggests that natural sources of methane have declined over the period. There are, however, great uncertainties in these estimates which future research may be able to reduce.

Estimates of Global Anthropogenic Methane Emissions 1860-1993

1. INTRODUCTION

Time series estimates for global anthropogenic emissions of several trace gases with a potential to increase radiative forcing are readily available. For example, Keeling (1994) and Marland *et al*. (1994) provide time series estimates for carbon dioxide emissions, and the Alternative Fluorocarbons Environmental Acceptability Study (1994) provides estimates for CFCs. However, there are no comparable time series estimates for methane. Khalil and Rasmussen (1994) provide a continuous time series for methane emissions from 1940 through 1990 and for many individual years between 1723 and 1940. However, these estimates are derived from a 'top down' deconvolution of atmospheric methane concentrations and do not distinguish between natural and anthropogenic emissions. Further, these estimates depend on the assumption that natural emissions and the rate of methane removal from the atmosphere have been constant over time. Several estimates for anthropogenic sources have been generated using "bottom-up" techniques for individual activities, countries, and the World as a whole (e.g. Watson *et al*., 1992; Subak *et al*., 1993; Energy Information Administration, 1994; World Resources Institute, 1994; Mudge and Adger, 1995). Ayres *et al*. (1994) estimate emissions coefficients for some activities at various points in time since 1800 in the US. Additionally Subak (1994) estimates global and regional anthropogenic emissions by activity for 1500.

In this study, we generate time series of anthropogenic emissions of methane by activity. Our purpose is to provide time series estimates of anthropogenic emissions for global climate models that are estimated or calibrated using historical time series data. These series are generated using information from some of the sources for point estimates, in particular those estimates consolidated by Subak *et al*. (1993) for the mid to late 1980s and by Subak (1994) for the early 16th century. We estimate changes over time in emissions from individual activities such as rice growing or coal mining by treating emissions as a function of variables for which historical time series data are available, such as world population or coal production. In this way, we derive estimates of emissions by activity from 1860 to 1993 which we aggregate to a time series for global anthropogenic emissions.

Section II details the methodology used to estimate emissions from each activity. Section III presents our estimates. Finally, section IV compares these estimates to Khalil and Rasmussen's (1994) deconvolution estimates, discusses the shortcomings of our estimates, and suggests directions for future research.

2. METHODOLOGY

We estimate emissions from the following activities: Flaring and venting of natural gas, oil and gas supply systems excluding flaring, coal mining, biomass burning, animal farming, rice farming and related activities, and landfills (Figure 1). This section describes how we generate each of these estimates.

a. Gas Flaring and Venting

The US Energy Information Administration (EIA, 1994) estimates that for every five molecules of CO_2 released by gas flaring in the US, one molecule of CH_4 is released through flaring or is deliberately vented. We therefore assume a ratio of 0.267 tonnes of CH_4 released per tonne of carbon in CO_2 released in flaring to estimate global CH_4 emissions from flaring and venting between 1950 and 1991. The data source for the carbon dioxide emissions is Marland *et al*. (1994). No data are available for flaring before 1950. Instead, we extrapolate the relation between gas flared and oil consumed. The data presented by Marland *et al*. (1994) indicate that the ratio of carbon released in gas flaring to carbon released in oil consumption declines 1.7% per annum from 1950 to 1991 ie. more natural gas was used as a fuel and less flared. We assume the same rate of decline for years before 1950 and apply the estimated flaring to oil use ratio to the data for carbon released by oil consumption between 1860 and 1950 presented in Keeling (1994). We also apply the same formula for 1992 and 1993 using world oil consumption data from (EIA, 1995) to project CO_2 emissions in those years. In summary the equations used are:

From 1950 to 1991:

$$CH_{4t} = 0.267\ F_t \qquad (1)$$

where F is tonnes of C in CO_2 emitted by flaring and methane is also measured in tonnes.

Between 1860 and 1949 and 1992 to 1993:

$$CH_4 = 0.267 \exp[0.017\ (1950-t\ )]\ O_t\, F_{1950} / O_{1950} \qquad (2)$$

where O is tonnes of C in CO_2 emitted by oil consumption.

Estimated methane emissions from gas flaring and venting rises from zero in 1860 to a maximum of 29.3 million tonnes in 1973 (10.2% of total emissions). Since 1973 gas flaring has declined, presumably in response to higher oil prices. In 1993 gas flaring contributed 18.0 million tonnes or 4.8% of the total.

b. Gas Supply

Subak *et al*. (1993) estimate that total releases from oil and gas systems in 1988 were 30 million tonnes. Subtracting our estimate of emissions from gas flaring in 1988 of 14.3 million tonnes implies that leakages contributed 15.3 million tonnes. To generate a time series, we assume that emissions are a constant fraction of natural gas consumption. The estimated emissions coefficient is 0.0164 tonnes CH_4 per tonne of C emitted as CO_2. A comparable estimate for the US is 0.0097 (derived from EIA, 1994). It does not seem unreasonable that supply systems in other countries may be 65% more leaky than in the US. The emissions coefficient is multiplied by the estimate for natural gas consumption generated by Keeling (1994) and Marland *et al*., (1994) and updated from EIA (1995). To summarize, the equation used is:

$$CH_{4t} = 0.164\ C_t \tag{3}$$

where C is tonnes of carbon in carbon dioxide emitted by natural gas consumption. Estimated emissions from this source rise from zero in 1860 to a maximum of 16.9 million tonnes in 1993 (4.5% of total).

c. Coal Mining

The amount of methane released by coal mining depends on the quantity of coal mined, location of coal deposits relative to the surface, and abatement technology (EIA, 1994). Surface mining releases significantly less methane than does deep mining (EIA, 1994). In the US in 1990, extracting a tonne of coal from surface mines released only 8.1 percent of the methane released in underground mining of a tonne of coal. In addition, the proportion of mining accounted for by surface mining has increased considerably over the years. In the United States, the fraction of coal from surface mines increased from 25 percent in 1949 to 63 percent in 1993 (EIA, 1995).

Unfortunately, global data for the quantity of coal mined by method of extraction are not available. We break the world into three regions: the US, the UK, and the rest of the world, and three time periods: 1860-1948, 1949-1954, and 1955-1993.

Estimates of US emissions from 1987 to 1992 are given by EIA (1994, 1995). To estimate US emissions from 1949 to 1986 and for 1993 we assume that emissions per tonne of surfaced mined coal and per tonne of deep mined coal in the USA were the same in these years as in 1990. The emissions coefficients are 0.76 kg of methane per short ton and 9.4 kg of methane per short ton respectively (EIA, 1994). The data on US production by mining type are from EIA (1995).

We apply the same coefficients to the UK data from 1955 to 1992 (British Geological Survey, various years; Central Statistical Office, various years). We assume that deep mining contributed 77 percent of total production in 1993 [1] and use the estimate of UK coal production for that year in EIA (1995).

We estimate emissions in the rest of the world based on figures produced by Subak *et al.* (1993). They estimate that coal mining emitted 49 million tonnes world-wide in 1988. We subtract our estimates for the UK and USA from this figure. Then we calculate the emissions coefficient for the rest of the World for CH_4 emitted per tonne of of C emitted as CO_2 in coal consumption by dividing the residual by the Marland *et al.* (1994) estimate of CO_2 emitted in coal combustion in the rest of the World. The coefficient is 0.023923 tonnes of CH_4 emitted per tonne of of C emitted as CO_2. For comparison, the corresponding coefficient for US deep mining in 1990 was 0.017529. This coefficient was used in combination with the Marland *et al.* (1994) data to estimate methane emissions in the rest of the world between 1955 and 1993. We project emissions of CO_2 in 1992 and 1993 using estimates of world coal production in EIA (1995).

Between 1949 and 1954 we combine together the UK and rest of the World estimates. We allow the emissions coefficient to decline exponentially from 0.023923 in 1949 to the combined emissions coefficient for the two in 1955 of 0.0227. From 1860 to 1948 all three regions are combined. We allow the emissions coefficient to decline exponentially from 0.023923 in 1860 to the combined emissions coefficient for the world as a whole in 1949 of 0.0213. To summarize the equations used are:

1860-1948

$$CH_{4t} = \exp(\ln (0.23923) - 0.0013142\ t)\ C_{WORLDt} \qquad (4)$$

where C_{WORLD} is emissions of C in CO_2 from world coal consumption in tonnes.

1949-1954

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[1] We do not have data on surface versus deep mining in 1993. The corresponding percentage was 79 percent in 1991 and 78 percent in 1992.

$$CH_{4t} = \exp(\ln(0.023923) - 0.008768\ t)\ (C_{ROWt} + C_{UKt}) + 0.000838\ S_{USAt} + 0.010362\ U_{USAt} \quad (5)$$

where S is tonnes of surface mined coal and U is tonnes of underground mined coal.

1955-1993

$$CH_{4t} = 0.023923\ C_{ROWt} + 0.000838\ (S_{USAt} + S_{UKt}) + 0.010362\ (U_{USAt} + U_{UKt}) \quad (6)$$

Based on this methodology, estimated emissions rise from 2.2 million tonnes in 1860 (2.8%) to a peak of 49.7 million in 1989 (13.7%) with a slight decline to 46.3 million in 1993 (12.2%).

d. Biomass Burning

We assume that methane emissions are proportional to CO_2 emissions from biomass burning. Using emission factors from Crutzen and Andreae (1990), Subak *et al.* (1993) estimates that biomass burning emitted 36 million tonnes in 1985. We extrapolate this total between 1860 and 1993 using estimates of anthropogenic emissions of carbon dioxide from terrestrial biota with data generated by Houghton *et al.* (1983). They estimate anthropogenic emissions of carbon dioxide from terrestrial biota starting in 1850. Updates are available from CDIAC. We assume that the growth rate from 1990 to 1993 was the same as from 1989 to 1990 in each region. We then aggregate regional estimates. The equation we use to estimate emissions is:

$$CH_{4t} = 0.021897\ C_t \quad (7)$$

where C is emissions of C in CO_2 from biota in tonnes.

Emissions rise from 9.8 million tonnes in 1860 (12.2%) to 38.4 million tonnes in 1993 (10.3%).

e. Animal Farming

Subak (1994) estimates that enteric fermentation and animal waste emitted 10 million tonnes in 1500. Using emission factors derived by Crutzen *et al.* (1986), Subak *et al.* (1993) estimates that enteric fermentation emitted 75 million tonnes in 1988. Drawing on a report by Casada and Safely (1990), Subak *et al*. (1993) estimate that animal wastes contributed 28 million tonnes in 1988.

Emissions from the combined sources are nearly constant over the entire period when measured on a per capita basis. World population in 1500 is estimated at 468 million (Europe, Asia, Africa, Oceania: McEvedy and Jones; Americas: Denevan, 1992),[2] and in 1988 at 5114 million (United Nations, 1992). These data imply that per capita emissions were 21 kg in 1500 and 20 kg in 1988. We model emissions from animals as a function of human population and assume that the per capita emissions coefficient declined linearly between 1500 to 1988:

$$CH_{4t} = (0.0213675 - 2.517E\text{-}06\ (t - 1500))\ P_t \qquad (8)$$

where P is world population.

Khalil and Rasmussen (1994) suggest that emissions from livestock may have leveled off in recent years because the number of cattle no longer is increasing significantly. However, both the average weight of individual cattle and the level of feeding per unit weight of cattle is increasing. Due to these changes estimated methane emissions per animal are greater in developed countries than in developing countries (Subak *et al*., 1993; Subak, 1994) and even in the US emissions per animal continue to increase (EIA, 1994).

Estimates of World population in 1850, 1875, 1900, and 1925 are taken from McEvedy and Jones, and in 1950 through 1991 from United Nations (1992). We assume constant growth rates between observations. We assume that population growth in 1992 and 1993 was 1.7%. Estimated emissions rise from 25.6 million tonnes in 1860 (32.3%) to 112.1 million tonnes in 1993 (29.6%). Ignoring the large uncertainties, animal farming is now the largest anthropogenic source of methane.

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[2] These sources are cited by Subak (1994). We add the population of Oceania for consistency with later estimates.

f. Rice Farming

We use the same procedure to estimate emissions from rice and similar forms of cultivation. Subak (1994) estimate these activities emitted 15 million tonnes in 1500. Subak *et al*. (1993) estimate this source emitted 98 million tonnes in 1988. Globally, emissions per capita decline from 32 kg in 1500 to 19 kg in 1988. This decline occurs even though Asia has represented a fairly constant proportion of World population over this period and rice cultivation has spread elsewhere in the world. Subak (1994) justifies this result by arguing that non-rice wetland agriculture in the pre-Columbian Americas was very extensive, that there was a higher proportion of rice in the diet in pre-industrial China, and that the intensity of rice cultivation was lower in the past.

Khalil and Rasmussen (1994) also argue that emissions from this source may have leveled off in recent years. They cite sources that show that the land under rice cultivation no longer is expanding as fast as previously. This may be offset by the Green Revolution, which has permitted double cropping where only a single crop was raised previously. Methane emissions depend on the length of time that fields are inundated as well the size of rice plants and other factors (Mudge and Adger, 1995). They are not, however, likely to be directly proportional to the output of rice because the rice grain is only a small part of the plant and higher yielding varieties produce more grain per unit weight of total plant biomass. Growth of rice production has outstripped growth in population in Asia since 1971 by a similar degree to that which population growth has exceeded the growth in area cultivated (Mudge and Adger, 1995).

In the absence of better information on the past trends in these variables and their quantitative effects on emissions, we assume that emissions per capita in 1860 were equal to those in 1500 and that the rate of change in emissions per capita has accelerated in recent years. We used the following formula to estimate the emissions per capita in internodal years:

$$CH_{4t} = P_t\,CH_{4\,1988} / P_{1988} + P_t\,CH_{4\,1860}\,[\exp(-0.004019\,(1988 - t + 1)) - \exp(-0.004019\,(1988 - t))] / P_{1860} \qquad (9)$$

Where P is world population. To understand the implication of this formula, imagine a curve describing exponential decline in emissions per capita from 1860 to 1998 at 0.4019% per year. Now flip the curve about its axis (a straight line going through the observations for 1860 and 1988) to produce a symmetric curve that declines at an increasingly rapid rate rather than at an increasingly slow rate. Using this formula, estimated total emissions rise from 40.1 million tonnes in 1860 (50.0%) to 103.1 million tonnes in 1991 (27.2%).

g. Landfills

Subak *et al*. (1993) estimate that landfills emitted 36 million tonnes of methane globally in 1985. Empirical analyses suggest that per capita municipal waste increases with per capita income (Shafik, 1994). The United States emitted 28% of the world total in 1985 which is roughly proportional to its share of world economic activity. Consistent with this link, per capita emissions from this source in the UK were approximately 70% of US levels, which is proportional to the ratio of the two countries' real per capita GDP (Summers and Heston, 1991). Without a point estimate for methane emissions from landfills in an earlier period, we assume that emissions grew in proportion to the average rate of economic growth, which we assume to be 2.5% since the industrial revolution:

$$CH_{4t} \quad = \quad CH_{4\,1985}\exp[.025\,(t - 1985)] \qquad (10)$$

Estimated total emissions rise from 1.6 million tonnes in 1860 (2.1%) to 43.9 million tonnes in 1993 (11.6%). Though modern type landfills obviously did not exist in 1860, it seems certain that some garbage did decompose anaerobically, thereby emitting methane.

3. RESULTS

Total anthropogenic emissions rose from 79.4 million tonnes in 1860 to 378.8 million tonnes in 1993 (Table 1). Per capita emissions are almost constant at 63 kg in 1860 and 68 kg in 1993. As well as the overall increase in emissions there have been shifts in the contributions of the various activities. Fossil fuels contributed only 2.8% of total emissions in 1860 and 21.4% in 1993 (Figure 2). Agricultural activities still dominate, but their proportion of the total declines and there has also been a shift in the importance of the various agricultural activities. Rice was the most significant contributor in 1860, but by 1993 livestock had become the largest emitter.

4. DISCUSSION

We wish to emphasize that the estimates presented in this paper are only a first approximation to actual historical emissions. To assess our results, we compare them to the Khalil and Rasmussen (1994) deconvolution estimates and highlight the most important uncertainties. We find that our estimates are compatible with those of Khalil and Rasmussen. As a byproduct we derive a series for net natural emissions. Despite this potential compatibility, further research is needed to reduce the most important uncertainties in our data and estimation procedures.

a. Khalil and Rasmussen's Emissions Estimates

Khalil and Rasmussen (1994) estimate total methane emissions under two scenarios for a change in OH concentrations during the last 200 years: stable concentrations and a 20 percent decline.[3] Subak (1994) compares her estimates for 1500 with Khalil and Rasmussen's (1994) estimates and concludes that they are commensurate with deconvolution estimates that assume that atmospheric OH has declined 20% over the last two hundred years. This is interesting as we use Subak's estimates as the baseline for several of activity estimates. Table 2. presents Khalil and Rasmussen's estimates of total emissions under the two scenarios together with our estimate of anthropogenic emissions and the implicit natural sources under the two assumptions about OH.

Figure 3 presents the natural sources series estimated under the assumption of no change in OH. The figure indicates that there is little or no trend in the series but its variability increases over time. Under the alternative assumption regarding OH ions the slight decline apparent in the earlier years would be more pronounced. The mean natural source is estimated at 121.5 million tonnes over the period under the first assumption and 128.7 million tonnes under the second.

We test whether the decline in natural sources is significant. It is not possible to apply usual tests for non-stationarity such as the Dickey Fuller test (Dickey and Fuller, 1979) because the frequency of observations is not constant. Nor can we difference the data to increase stationarity. We estimated a simple exponential trend using weighted least squares under the assumption that the error variance is heteroskedastic and is a function of time. For the data assuming no decline in OH the estimated trend coefficient is -0.00254 and its t-statistic -6.0622. Though this statistic is significant using conventional t tests it is insignificant because the true critical values for this particular test is much higher if the data are non-stationary (Granger and Newbold, 1974). The 5% critical level is probably near 10 if the data are non-stationary. For the data assuming a decline in OH the estimated trend coefficient is -0.00369 and its t-statistic -8.8839. Therefore, this latter t statistic may indicate a significant trend at a low level of significance.

Our data do not provide any evidence on the question of the proposed decline in OH ions. If natural sources have been constant they would suggest that the hypothesis of a decline is

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[3] OH is the principle agent removing methane from the atmosphere.

not unreasonable though not incontrovertible. In any case there is no reason to suppose that natural sources have been constant given rapid conversion of natural wetlands to other uses (Maltby, 1986; Barbier, 1994).

Despite the general agreement with estimates generated by Khalil and Rasmussen, we should note that their estimate of total methane sources for the late 1980s is lower than most. Watson *et al*. (1992) provide a midpoint estimate of 532 million tonnes which is more than 80 million tonnes higher than Khalil and Rasmussen. Watson *et al*. (1992) also estimate that anthropogenic emissions were 360 million tonnes. Our estimates are based on the estimate by Subak *et al*. (1993) of 352 million tonnes. We should emphasize that estimates for various activities may be considerably higher and we have completely ignored some potential sources such as wastewater (see Orlich, 1990; Subak *et al*., 1993). Given estimates of natural emissions in the 1980's of around 150 million tonnes (Watson *et al*, 1992) removal from the atmosphere must be faster than assumed by Khalil and Rasmussen (1994) given any of these estimates of anthropogenic emissions. This is itself an interesting question.

b. Sources and Degree of Uncertainty in the Estimates

Our time series estimates are constructed from published estimates for given points in time (point estimates), behavioral and technical assumptions relating methane emissions to the proxy variables, time series of proxy variables, and some assumptions about emissions coefficients at points in time for which no published estimates exist. Uncertainties in our estimates therefore are a function of uncertainty in each of these four categories.

Uncertainty associated with point estimates can be improved only by better estimates. Currently, estimates of methane emissions are much more uncertain than those for carbon dioxide. Many researchers provide ranges for estimates rather than single figures. The upper bounds for these estimates may exceed the lower bound by 50% as in the case of the estimate of emissions from fossil fuels provided by Crutzen (1991). Estimates also vary widely among researchers. The range reported by the IPCC indicates that the maximum estimates of emissions from specific activities are in some cases several times larger than the minimum estimates (Watson *et al*., 1992).

We have made explicit our behavioral and technical assumptions. They consist of the choice of proxy variables and the pattern of changes in the emissions coefficients over time. These were chosen to be broadly consistent with the literature. As more point estimates become available for different countries and over longer time periods, historical reconstructions also will become more reliable.

Of the time series of proxy variables, the most reliable is the extraction of fossil fuels. At the other extreme, estimates of gas flaring before 1950 are a guess. Population is the proxy for the other variables with the exception of landfills for which it is economic growth. World population is known to a reasonable degree of confidence for recent years but not for earlier years. Information on world economic activity prior to 1950 is much poorer than in the post war period. We have simply assumed that economic growth is constant in the long run. The estimates by Houghton *et al*. (1983) of carbon dioxide emissions from terrestrial biota are clearly uncertain. In particular there are sharp jumps at the beginning and ends of decades in the time series for some regions, especially South and Central America, which indicate that these estimates are not very reliable.

Estimates of emissions factors for years without published estimates and their pattern of change over time probably are less reliable than the proxy variables. For emissions of methane from coal mines in 1860 we simply assume that the coal mines of 1860 were identical to those outside the US and UK in 1988. The estimates for flaring and consequently gas supply do not seem too unlikely given the evidence presented in Section 2. For livestock, the estimates derived by Subak (1994) and Subak *et al*. (1993) from other sources strongly constrain the possible emissions factors. For rice, we arbitrarily assume no change from 1500 to 1860 and accelerating change thereafter. This latter is probably the most significant uncertainty regarding emissions coefficients.

5. CONCLUSIONS

This study indicates that anthropogenic methane emissions probably have increased from around 80 million tonnes per annum in 1860 to almost 380 million tonnes in 1993. The trend seems to be still upward though the rate of increase has slowed in recent years (Figure 4). This slow down is associated with several factors. Lower rates of population growth are retarding increases in emissions from rice and livestock. Increases in energy prices in the 1970's reduced gas flaring, though lower oil prices in the late 1980's and 1990's are leading to an increase again. This increase was offset partly by an reduction in emissions from coal mining due to interfuel substitution away from coal stimulated by lower oil prices. The reduction in gas flaring in the 1970's and 1980's also was offset by an increase in emissions from gas supply. Finally, emissions from biomass burning stopped increasing significantly in the late 1980s, consistent with reductions in the rate of tropical deforestation in South and Central America.

The estimates are more or less commensurate with Khalil and Rasmussen's (1994) estimates of total methane emissions, but imply a slight decline in the natural sources of methane emissions or an increase in sinks over the time period. This does not seem unreasonable given the conversion of natural wetlands. Natural wetlands are estimated today to contribute 75% of natural emissions (Crutzen, 1991).

Uncertainty in our estimates could be most improved by further research on technical and behavioral relationships between activities and emissions, and some historical research on likely rates of emission by the various activities in the past, especially in the 19th century.

ACKNOWLEDGMENTS

We thank Susan Subak for useful comments on an earlier draft.

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Table 1 Estimates of Anthropogenic Methane Emissions 1860-1991

Year	Gas Flaring	Gas Supply	Coal Mining	Biomass Burning	Animals	Rice etc.	Landfills	Total
1860	0.0	0.0	2.2	9.8	25.6	40.1	1.6	79.4
1861	0.0	0.0	2.4	10.0	25.7	40.2	1.7	79.9
1862	0.0	0.0	2.3	10.1	25.8	40.2	1.7	80.3
1863	0.0	0.0	2.5	10.3	25.9	40.3	1.8	80.8
1864	0.0	0.0	2.7	10.4	26.0	40.4	1.8	81.3
1865	0.0	0.0	2.9	10.5	26.1	40.4	1.9	81.8
1866	0.0	0.0	3.0	10.5	26.2	40.5	1.9	82.2
1867	0.0	0.0	3.3	10.6	26.3	40.5	2.0	82.7
1868	0.0	0.0	3.2	10.6	26.4	40.6	2.0	82.9
1869	0.0	0.0	3.3	10.7	26.5	40.7	2.1	83.3
1870	0.0	0.0	3.4	10.8	26.6	40.7	2.1	83.7
1871	0.0	0.0	3.8	11.0	26.7	40.8	2.2	84.5
1872	0.0	0.0	4.1	11.1	26.8	40.8	2.2	85.1
1873	0.1	0.0	4.4	11.2	26.9	40.9	2.3	85.8
1874	0.1	0.0	4.3	11.2	27.0	40.9	2.3	85.9
1875	0.1	0.0	4.4	11.3	27.1	41.0	2.4	86.3
1876	0.1	0.0	4.5	11.4	27.4	41.2	2.4	86.9
1877	0.1	0.0	4.5	11.5	27.6	41.4	2.5	87.6
1878	0.1	0.0	4.5	11.5	27.8	41.7	2.6	88.2
1879	0.1	0.0	4.8	11.6	28.0	41.9	2.6	89.0
1880	0.2	0.0	5.2	11.6	28.2	42.1	2.7	90.0
1881	0.2	0.0	5.6	12.3	28.5	42.3	2.8	91.6
1882	0.2	0.0	6.0	12.5	28.7	42.5	2.8	92.7
1883	0.1	0.0	6.4	12.6	28.9	42.8	2.9	93.7
1884	0.2	0.0	6.4	12.8	29.1	43.0	3.0	94.4
1885	0.2	0.0	6.3	12.8	29.4	43.2	3.0	94.9
1886	0.2	0.0	6.3	12.9	29.6	43.4	3.1	95.6
1887	0.2	0.0	6.7	13.0	29.8	43.6	3.2	96.6
1888	0.2	0.0	7.3	13.0	30.1	43.9	3.3	97.7
1889	0.3	0.0	7.4	13.0	30.3	44.1	3.4	98.4
1890	0.3	0.0	7.8	13.0	30.5	44.3	3.4	99.4
1891	0.4	0.0	8.1	13.1	30.8	44.5	3.5	100.4

1892	0.4	0.0	8.2	13.1	31.0	44.8	3.6	101.1
1893	0.4	0.0	8.0	13.1	31.3	45.0	3.7	101.5
1894	0.4	0.0	8.4	13.1	31.5	45.2	3.8	102.4
1895	0.4	0.0	8.8	13.1	31.8	45.4	3.9	103.4
1896	0.4	0.0	9.1	13.1	32.0	45.7	4.0	104.3
1897	0.5	0.0	9.5	13.1	32.3	45.9	4.1	105.3
1898	0.5	0.1	10.0	13.0	32.5	46.1	4.2	106.4
1899	0.5	0.1	10.9	13.0	32.8	46.3	4.3	107.9
1900	0.5	0.1	11.5	13.1	33.0	46.6	4.4	109.1
1901	0.6	0.1	11.8	14.5	33.3	46.8	4.5	111.5
1902	0.6	0.1	12.0	14.8	33.6	47.0	4.6	112.8
1903	0.7	0.1	13.1	15.2	33.8	47.3	4.8	114.9
1904	0.7	0.1	13.2	15.4	34.1	47.5	4.9	115.9
1905	0.7	0.1	13.9	15.7	34.4	47.7	5.0	117.5
1906	0.7	0.1	15.0	15.9	34.7	48.0	5.1	119.5
1907	0.8	0.1	16.6	16.0	34.9	48.2	5.2	121.9
1908	0.9	0.1	15.7	16.1	35.2	48.4	5.4	121.8
1909	0.9	0.1	16.4	16.2	35.5	48.7	5.5	123.3
1910	1.0	0.1	17.1	16.2	35.8	48.9	5.6	124.7
1911	1.0	0.1	17.4	15.0	36.1	49.1	5.8	124.6
1912	1.0	0.1	18.3	14.7	36.4	49.4	5.9	125.8
1913	1.1	0.2	19.6	14.1	36.7	49.6	6.1	127.4
1914	1.1	0.2	17.5	14.0	37.0	49.8	6.2	125.9
1915	1.2	0.2	17.3	13.8	37.3	50.1	6.4	126.2
1916	1.2	0.2	18.6	13.9	37.6	50.3	6.6	128.3
1917	1.3	0.2	19.5	13.9	37.9	50.5	6.7	130.1
1918	1.3	0.2	19.2	13.9	38.2	50.8	6.9	130.5
1919	1.5	0.2	16.8	14.0	38.5	51.0	7.1	129.0
1920	1.8	0.2	19.2	14.0	38.8	51.2	7.2	132.6
1921	2.0	0.2	16.2	15.1	39.1	51.5	7.4	131.5
1922	2.1	0.2	17.3	15.5	39.4	51.7	7.6	133.9

Year	Gas Flaring	Gas Supply	Coal Mining	Biomass Burning	Animals	Rice etc.	Landfills	Total
1923	2.5	0.3	19.4	15.8	39.8	51.9	7.8	137.4
1924	2.4	0.3	19.2	16.1	40.1	52.2	8.0	138.2
1925	2.5	0.3	19.2	16.3	40.4	52.4	8.2	139.3
1926	2.6	0.3	19.0	16.5	40.8	52.7	8.4	140.3
1927	2.9	0.4	20.6	16.5	41.2	53.0	8.6	143.1

Year	Gas Flaring	Gas Supply	Coal Mining	Biomass Burning	Animals	Rice etc.	Landfills	Total
1928	3.0	0.4	20.2	16.6	41.5	53.3	8.8	143.8
1929	3.3	0.5	21.5	16.1	41.9	53.6	9.0	145.9
1930	3.1	0.5	19.6	16.0	42.3	53.9	9.3	144.6
1931	2.9	0.5	17.3	16.2	42.7	54.2	9.5	143.2
1932	2.7	0.4	15.4	16.1	43.1	54.4	9.7	142.0
1933	2.9	0.4	16.1	16.0	43.5	54.7	10.0	143.7
1934	3.0	0.5	17.5	16.0	43.9	55.0	10.2	146.2
1935	3.3	0.5	17.9	15.9	44.3	55.3	10.5	147.6
1936	3.5	0.6	20.0	16.0	44.7	55.6	10.7	151.1
1937	3.9	0.6	21.0	15.9	45.1	55.9	11.0	153.5
1938	3.7	0.6	19.7	15.8	45.6	56.2	11.3	152.9
1939	3.8	0.6	21.0	15.7	46.0	56.5	11.6	155.2
1940	3.9	0.7	22.2	15.5	46.4	56.8	11.9	157.3
1941	3.6	0.7	23.2	15.4	46.8	57.1	12.1	159.0
1942	3.4	0.8	23.3	15.2	47.3	57.4	12.5	159.7
1943	3.6	0.9	23.3	15.1	47.7	57.6	12.8	161.0
1944	4.0	1.0	22.3	15.0	48.2	57.9	13.1	161.5
1945	4.1	1.1	18.7	14.9	48.6	58.2	13.4	159.1
1946	4.5	1.1	19.5	16.1	49.1	58.5	13.7	162.5
1947	4.9	1.2	21.9	16.4	49.5	58.8	14.1	166.8
1948	5.4	1.4	22.9	16.7	50.0	59.1	14.4	169.8
1949	5.3	1.5	21.8	16.8	50.4	59.4	14.8	169.9
1950	6.1	1.6	22.5	16.9	50.9	59.6	15.2	172.9
1951	6.4	1.9	23.7	21.6	51.8	60.4	15.5	181.4
1952	6.9	2.0	23.6	22.7	52.8	61.3	15.9	185.3
1953	7.2	2.1	23.6	22.9	53.8	62.1	16.3	188.1
1954	7.2	2.3	23.5	23.4	54.7	62.9	16.7	190.8
1955	8.3	2.4	25.1	24.3	55.7	63.8	17.2	196.7
1956	8.5	2.6	26.4	24.7	56.8	64.6	17.6	201.2
1957	9.3	2.9	27.3	25.1	57.8	65.5	18.0	205.9
1958	9.3	3.1	28.4	25.3	58.8	66.4	18.5	209.8
1959	9.6	3.5	29.5	23.7	59.9	67.3	18.9	212.4
1960	10.4	3.8	30.2	23.7	61.0	68.1	19.4	216.8
1961	11.2	4.1	28.8	26.6	62.2	69.2	19.9	222.1
1962	11.7	4.5	28.7	27.5	63.5	70.2	20.4	226.5
1963	12.5	4.9	29.5	28.3	64.8	71.2	20.9	232.2
1964	13.6	5.4	30.3	29.0	66.1	72.3	21.4	237.9
1965	14.7	5.7	30.7	29.5	67.4	73.4	22.0	243.3
1966	16.0	6.2	31.0	29.7	68.8	74.5	22.5	248.6

1967	17.6	6.7	30.1	29.8	70.2	75.6	23.1	253.1
1968	19.5	7.3	30.3	30.0	71.6	76.8	23.7	259.0
1969	21.3	7.9	31.1	30.2	73.1	77.9	24.3	265.8
1970	23.2	8.4	32.2	29.7	74.6	79.1	24.9	272.1
1971	23.5	9.0	32.3	27.4	76.1	80.2	25.5	273.9
1972	25.1	9.5	32.5	26.6	77.6	81.3	26.1	278.7
1973	29.3	9.9	32.7	27.0	79.1	82.5	26.8	287.3
1974	28.5	10.1	32.4	27.0	80.7	83.6	27.4	289.7
1975	24.8	10.2	34.1	27.0	82.3	84.8	28.1	291.3
1976	29.1	10.6	34.7	29.0	83.7	85.8	28.8	301.6
1977	27.7	10.5	35.8	29.6	85.1	86.7	29.5	305.1
1978	28.5	11.0	36.3	29.9	86.6	87.7	30.3	310.4
1979	26.7	11.6	37.9	30.9	88.1	88.7	31.0	315.1
1980	23.7	11.8	38.8	31.2	89.7	89.7	31.8	316.7
1981	19.2	12.0	38.1	33.4	91.2	90.7	32.6	317.2
1982	18.4	11.9	39.6	34.1	92.8	91.8	33.4	322.0
1983	16.8	12.0	40.1	34.5	94.5	92.8	34.3	324.9
1984	15.2	12.8	41.7	35.6	96.1	93.8	35.1	330.4
1985	14.7	13.3	45.4	36.0	97.8	94.9	36.0	338.1
1986	14.1	13.6	46.6	37.3	99.5	95.9	36.9	344.0
1987	12.8	14.6	48.0	38.0	101.2	97.0	37.8	349.5
1988	14.7	15.3	49.0	38.3	103.0	98.0	38.8	357.1
1989	14.1	15.9	49.7	38.2	104.8	99.0	39.7	361.5
1990	16.5	16.4	47.9	38.2	106.6	100.1	40.7	366.4
1991	18.7	16.7	46.9	38.3	108.4	101.1	41.7	371.9
1992	18.3	16.6	46.6	38.3	110.3	102.1	42.8	375.1
1993	18.0	16.9	46.3	38.4	112.1	103.1	43.9	378.8

Table 2 Total Emissions, Anthropogenic, and Natural Methane Emissions

Year	K&R d[OH] = 0	K&R d[OH] = -20%	Anthropogenic Emissions	Natural Emissions d[OH] = 0	Natural Emissions d[OH] = -20%
1861	213	234	79.9	133.1	154.1
1862	223	243	80.3	142.7	162.7
1867	223	242	82.7	140.3	159.3
1872	231	251	85.1	145.9	165.9
1875	222	241	86.3	135.7	154.7
1881	226	244	91.6	134.4	152.4
1882	228	245	92.7	135.3	152.3
1883	221	238	93.7	127.3	144.3
1885	226	242	94.9	131.1	147.1
1891	230	246	100.4	129.6	145.6
1898	236	251	106.4	129.6	144.6
1903	240	254	114.9	125.1	139.1
1913	247	260	127.4	119.6	132.6
1916	264	277	128.3	135.7	148.7
1918	268	280	130.5	137.5	149.5
1921	278	291	131.5	146.5	159.5
1923	263	274	137.4	125.6	136.6
1927	272	283	143.1	128.9	139.9
1929	289	299	145.9	143.1	153.1
1933	283	293	143.7	139.3	149.3
1935	296	306	147.6	148.4	158.4
1940	292	301	157.3	134.7	143.7
1941	273	281	159.0	114.0	122.0
1943	293	301	161.0	132.0	140.0
1944	311	319	161.5	149.5	157.5
1947	293	300	166.8	126.2	133.2
1949	303	311	169.9	133.1	141.1
1950	300	307	172.9	127.1	134.1
1951	294	300	181.4	112.6	118.6
1952	322	328	185.3	136.7	142.7
1953	309	315	188.1	120.9	126.9

1955	311	317	196.7	114.3	120.3
1958	324	330	209.8	114.2	120.2
1959	347	352	212.4	134.6	139.6
1960	367	372	216.8	150.2	155.2
1964	365	369	237.9	127.1	131.1
1965	372	376	243.3	128.7	132.7
1966	348	351	248.6	99.4	102.4
1967	338	342	253.1	84.9	88.9
1968	365	368	259.0	106.0	109.0
1969	364	367	265.8	98.2	101.2
1970	386	388	272.1	113.9	115.9
1971	410	412	273.9	136.1	138.1
1972	423	425	278.7	144.3	146.3
1973	394	396	287.3	106.7	108.7
1974	384	386	289.7	94.3	96.3
1975	377	379	291.3	85.7	87.7
1976	415	416	301.6	113.4	114.4
1977	407	408	305.1	101.9	102.9
1978	425	426	310.4	114.6	115.6
1979	413	414	315.1	97.9	98.9
1980	427	427	316.7	110.3	110.3
1981	435	435	317.2	117.8	117.8
1982	451	451	322.0	129.0	129.0
1983	447	447	324.9	122.1	122.1
1984	436	436	330.4	105.6	105.6
1985	438	438	338.1	99.9	99.9
1986	446	446	344.0	102.0	102.0
1987	452	452	349.5	102.5	102.5
1988	446	446	357.1	88.9	88.9
1989	446	446	361.5	84.5	84.5
1990	450	450	366.4	83.6	83.6

Figure 1. Methane Emissions by Activity

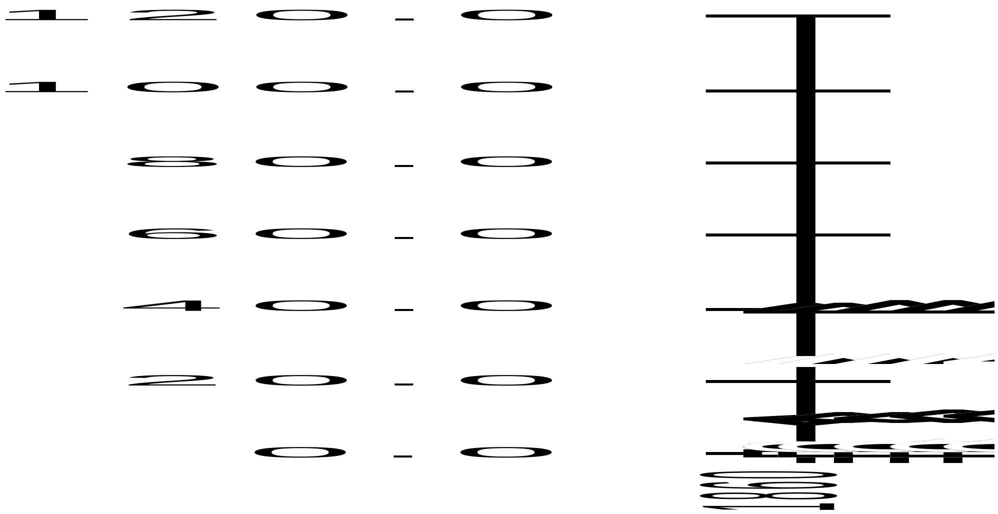


Figure 2. Anthropogenic Emissions of Methane

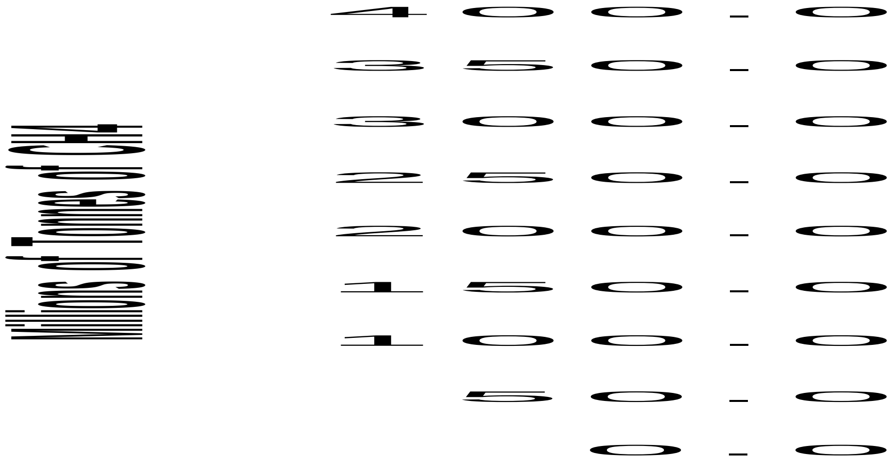


Figure 3. Net Natural Sources of Methane

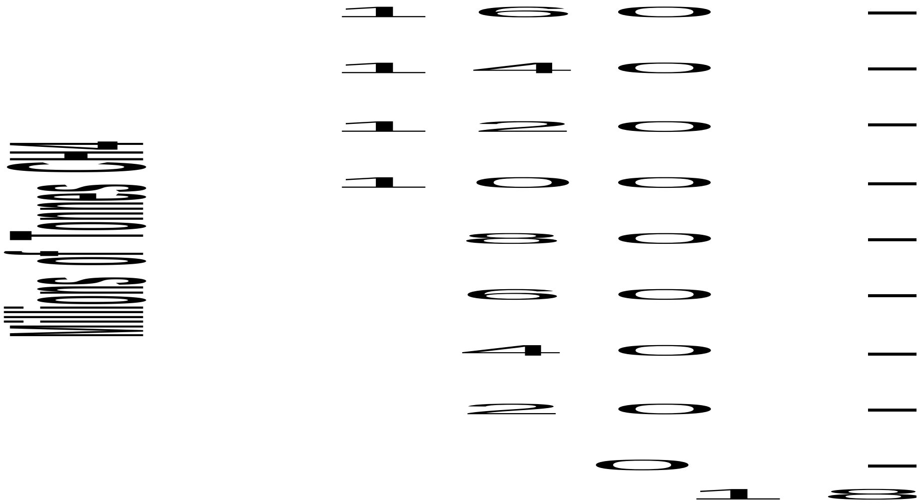
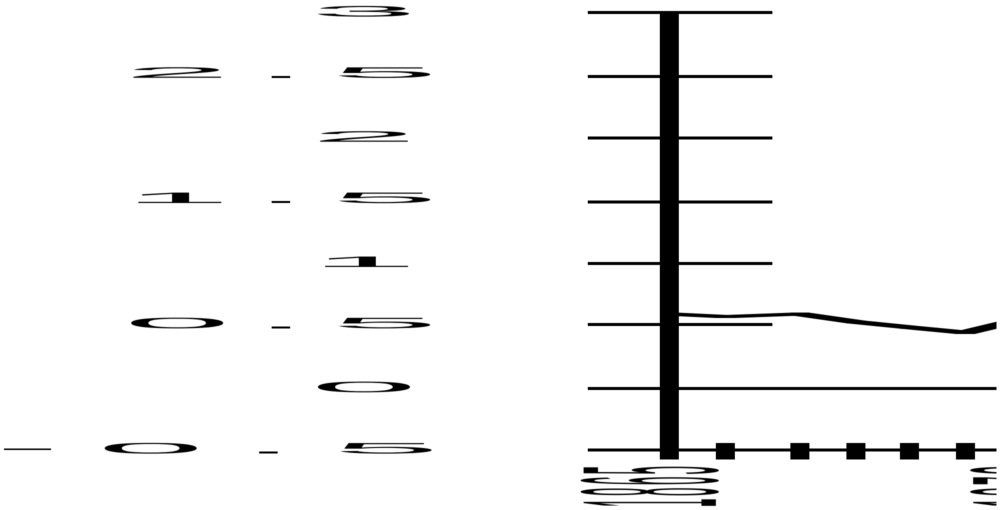


Figure 4. Percentage Growth Rate of Anthropogenic Methane Emissions (5 Year Moving Average Applied)



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